# LBT adaptive secondary electronics

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## ABSTRACT

The adaptive secondary mirror is a fundamental part in the LBT adaptive optics architecture. The thin, continuous mirror is controlled by 672 electromagnetic actuators (voice coil motors) with local position feedback (capacitive sensor) and allows to perform from tip-tilt to high order wavefront correction, but also chopping.

The adaptive secondary is controlled by a DSP-based dedicated electronics. The control electronics does not only implement the mirror position control tasks, but does also realize the Real Time Reconstructor (RTR). The control system, while maintaining a similar architecture to the MMT adaptive secondary one, shows a substantial enhancement in terms of computational power, rising in the range of hundreds of Gigaflops. This allows to minimize the computational time required to apply the wavefront correction pattern from the wavefront sensor acquisition, even in case of high order reconstructor dynamics.

The electronics is housed in compact cooled crates placed in the adaptive secondary hub. Apart from the power supply lines, it is connected to the other components of the adaptive control system just through a very high speed fiber optic link, capable of 2.9 Gigabit/s of actual data throughput. The control system has been designed according to modular concept, so that the number of channels can be easily increased or reduced for adapting the electronics to different correctors.

A substantial effort has been dedicated to the flexibility and on-field configurability of system. In this frame, the same electronics (or part of it) can be easily adapted to become the building block for the data processing unit required for Multi-Conjugated Adaptive Optics.

**Keywords:** Adaptive optics, real time control system, parallel computation, deformable mirrors, adaptive secondary[·]

## 1 INTRODUCTION

The LBT adaptive secondary electronics is conceptually based on the MMT adaptive secondary control system. The experience gained with the MMT development, which electronics is very reliably operating since almost two years, allowed to address some specific topics in order to improve performance, reliability and maintainability of the system:

- Reliability and maintainability of the electromechanical parts (cabling, contacts)
- Capacitive sensor bandwidth
- Computational performance of the DSP control boards
- Communication bandwidth and architecture (separation between real time and diagnostic communication)

The control system is based on the same co-located control concept that allows an easy expansion to a larger number of actuators. In fact, each actuator comprehends a voice coil motor and a co-located capacitive sensor. The digital loop is run by a local computational unit (one DSP each two channels), so that the computational power requirements grows with the overall availability of computational power. This is only partially true, in fact the number of computations required by the centralized feedforward control concept (see G.Brusa in 4 and 5) is related to the square of the number of channels.

Even if the concepts of the MMT electronics have been maintained, the electronics design has been almost completely renewed in order to meet the more demanding specifications of the LBT unit. As a consequence, the computational

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According to the same criterion, one component of the adaptive secondary control system, namely the communication board, has been improved so that it can operate in standalone mode and perform separately different tasks within the adaptive control loop, like slope computation or merging of the slopes obtained by different wavefront sensors in a Multi-Conjugate Adaptive Optics scheme.

The adaptive secondary control electronics is developed by Microgate (Italy) in strict co-operation with the other partners involved in the project, namely Osservatorio Astrofisico di Arcetri (Italy), ADS International (Italy) and Mirror Lab (Steward Observatory, AZ, USA). The system is currently in advanced design phase. The first prototypes will be available in October 2002, while the integration of a 45 actuators adaptive secondary engineering prototype (named P45) with a pre-production run of the new electronics is planned for early spring 2003. The integration of the electronics on the final units is foreseen for the end of 2003, in order to meet the first light schedule of mid 2004.

An overview of the control system hardware, with a more detailed description of the major components is given in Sect.2. Sect.3 presents the control software architecture, while Sect.4 describes the communication board with its extended features for standalone operation. Sect.5 reports the computational performance of the control system.

## 2 LBT 672 ADAPTIVE SECONDARY CONTROL ELECTRONICS

The Adaptive secondary mirror is controlled by 672 identical actuators, each embedding the voice coil motor that applies a local force to the mirror (without any mechanical contact) and the signal conditioning circuit for the capacitive sensor that senses the gap between reference body and thin shell.

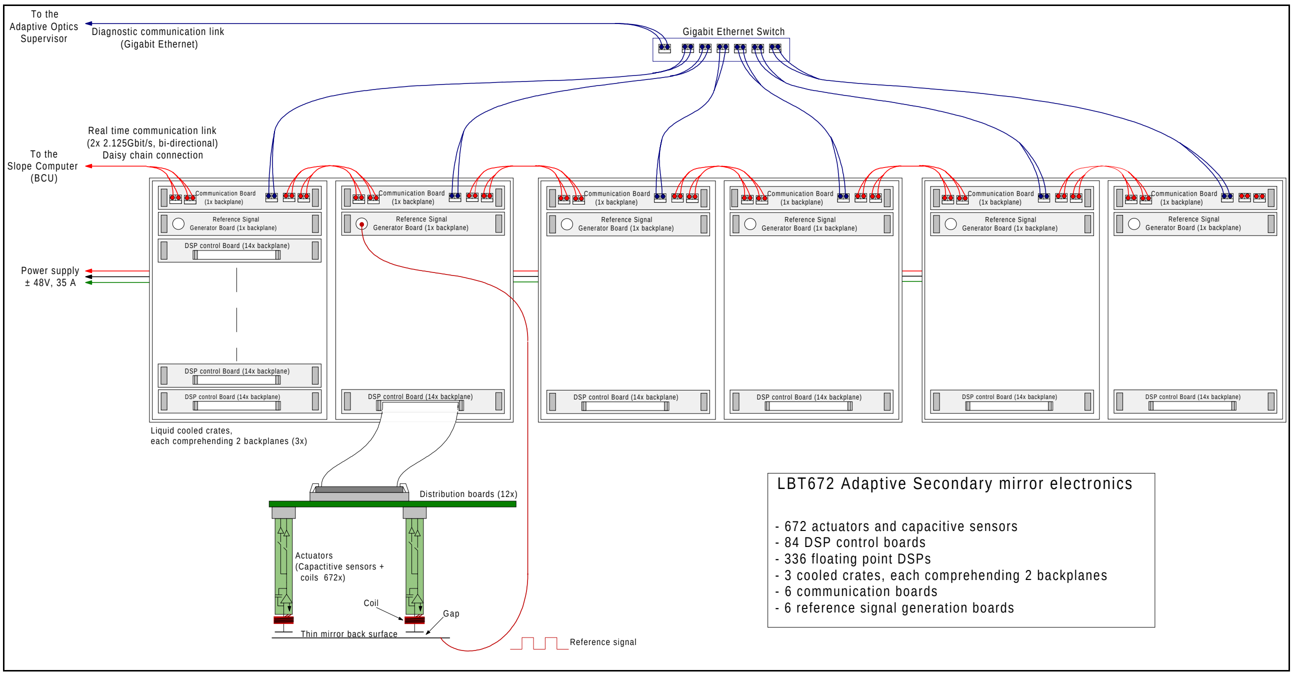

**Figure 1 – LBT adaptive secondary electronics block scheme**

The actuators are connected to signal distribution boards, placed immediately behind the coldplate. The signal distribution boards provide the connection to the DSP control boards. Each of these controls 8 channels by means of 4 floating point DSPs. Every backplane (there are 6 backplanes in the system, arranged into 3 liquid cooled crates) contains 14 control boards, one signal generation board providing a stable reference signal for the capacitive sensors, and a communication board that implements the high speed, real time communication between slope computer and adaptive mirror. Moreover, the communication board provides a diagnostic communication line over a standard Ethernet connection.

All boards have identical size (191x96 mm). Due to the high complexity and large number of components mounted on them, the boards implement the most recent Surface Mounting Technology (SMT), with a large number of components in Ball Grid Array (BGA) package.

## 2.1 CAPACITIVE SENSOR

The capacitive sensor provides the measurement of the local gap between the reference body and the thin shell. The measurement is obtained by demodulating in amplitude a reference signal which is amplified by an AC-coupled inverting amplifier, which gain is roughly inversely proportional to the gap to be measured.

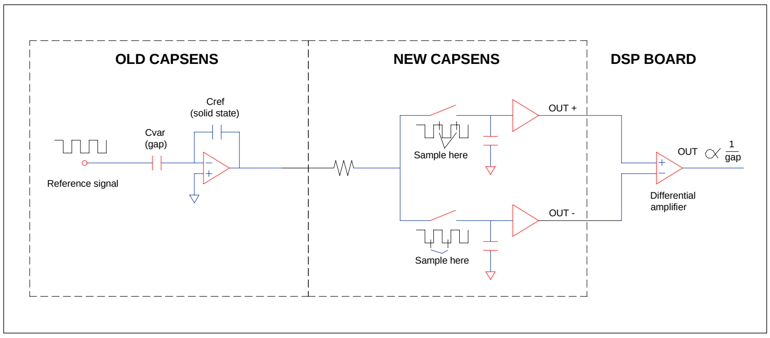

Figure 2 – Capacitive sensor operating principle

With respect to the MMT electronics, the capacitive sensor has been significantly improved, while maintaining the same operating principle. In particular, the new capacitive sensor embeds an analog de-modulator, that allows to improve the sensor bandwidth.

| | |
|---|---|
| Bandwidth | - 3dB @ 90 KHz |
| Noise | 2.4 nm rms |
| Thermal stability | 0.15 nm/°K |
| Power dissipation | 78 mW |

**Table 1 - Capacitive sensor performances (experimental data)**

The measured performances of the LBT capacitive sensor are reported on Table 1. The reported data have been measured by substituting the air gap with a solid state capacitor of the same capacitance of the reference capacitor (56 pF), therefore the reported thermal stability does refer to the electronics only, without taking into consideration the change of air dielectric constant due to temperature and humidity variations. This corresponds to a mean operating gap of ~50µm for the LBT thin shell.

The capacitive sensor electronics is integrated on a small board mounted on the actuator's cold finger (see A.Riccardi in 7 and Figure 3). The actuator, including the capacitive sensor board, is mounted from the thin mirror side (the thin shell has to be removed to insert the actuators). The board is connected to *distribution boards* by means of board to board connectors, without wires. The distribution boards, mounted on top of the coldplate, allow to simplify significantly the connection between actuators and DSP control boards, reducing by a factor of eight the number of cables with respect to the MMT implementation.

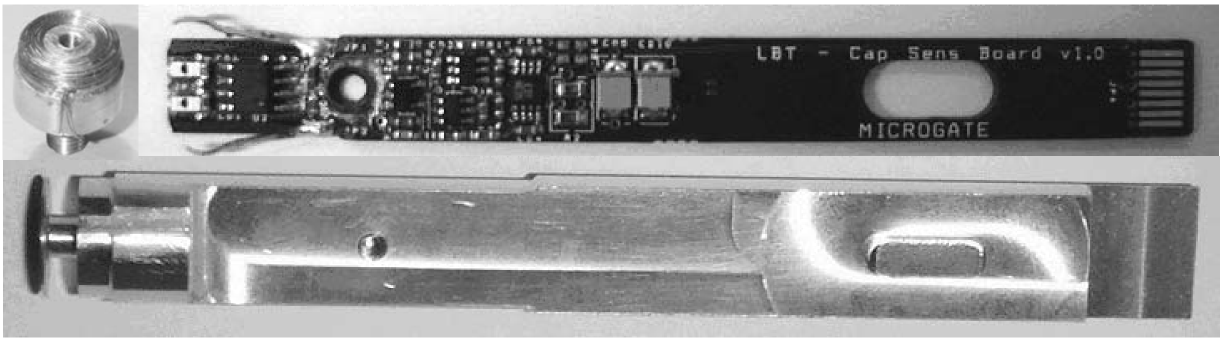

**Figure 3 – Capacitive sensor board and actuator**

## 2.2 DSP CONTROL BOARDS

Each DSP control board controls eight actuators on the adaptive secondary mirror. The board comprehends a high speed digital part (DSP, diagnostic processor and communication electronics) and an analog front-end that interfaces the board to the actuators and capacitive sensors. A block scheme of the board is given in Figure 4.

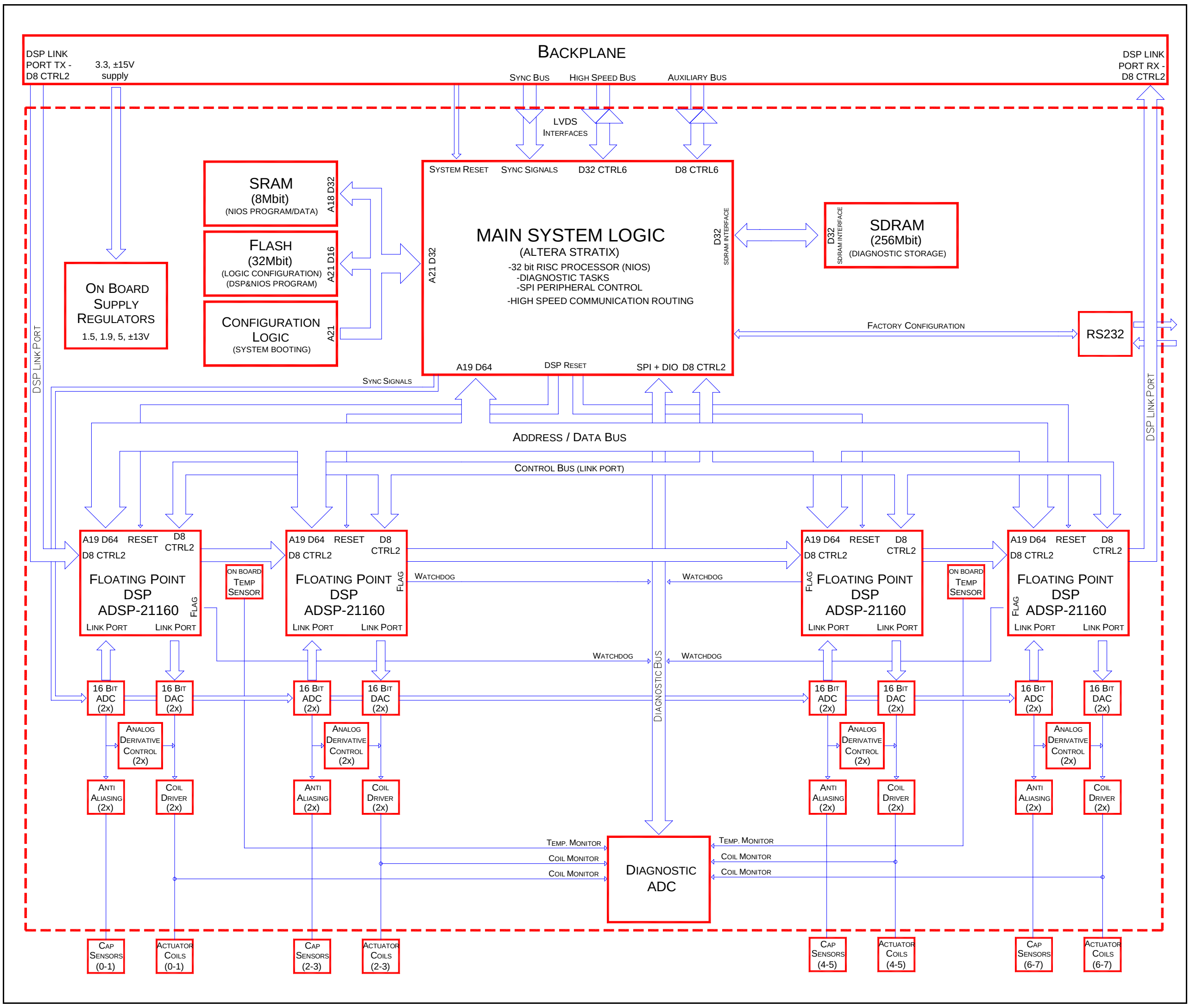

**Figure 4 – DSP control board block scheme**

The *system logic* is based on the last generation Altera Stratix CPLD device. The logic handles the communication between the parallel backplane and the four DSPs on the board. Moreover, the same component embeds a RISC processor soft-core (Altera Nios) that performs the diagnostic tasks on the board.

The real time control tasks are performed by the four DSPs, each controlling two channels. The selected component is the ADSP-21160 floating point unit from Analog Devices. The choice has been mainly driven by the large on-board available memory, that allows to store code and data even for the most demanding reconstructor algorithms foreseen for the LBT adaptive optics. Other choice-steering characteristics are the outstanding computational power, the large availability of DMA communication channels that allow a very efficient interfacing to the real time and diagnostic data links and, last but not least, the similarity with the DSP used in the MMT design (an integer unit from the same manufacturer) that allows to partially re-use the already available code.

Every DSP is connected to two 16 bit, 250 Ksamples/s analog to digital converters that performs the conversion of the capacitive sensor output. The digital control loop run by the DSP drives a 16 bit digital to analog converter that controls a wide bandwidth current driver for the voice coil motor.

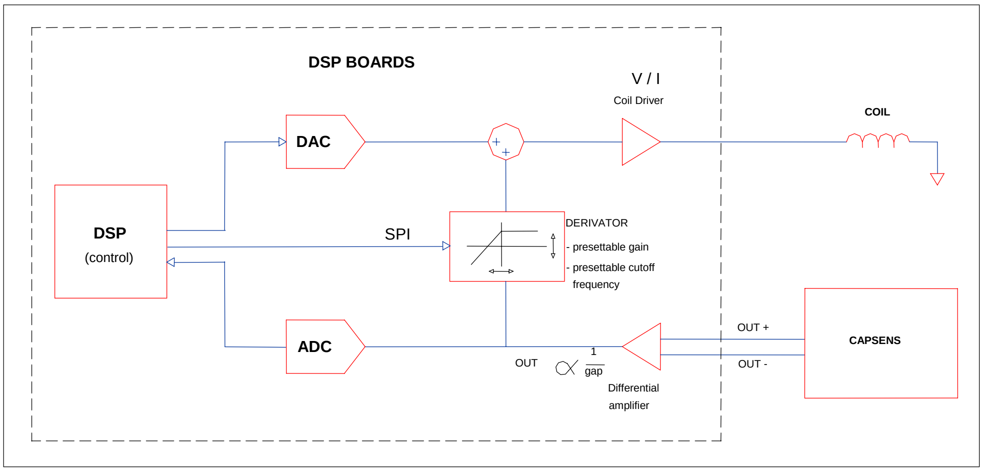

**Figure 5 - Principle of operation of the analog derivative loop**

In addition to the digital control loop performed by the DSPs, the board comprehends also an analog loop between the capacitive sensor analog output to the current driver input. In this way, a high bandwidth derivative control term can be added to the local control loop, providing an efficient electronic damping that can partially substitute the effect of the natural air damping on the controlled actuator. This feature allows to relax the operational constrains on the maximum acceptable gap between reference body and thin shell to obtain a satisfying dynamic behavior of the mirror, which is currently ~40µm (see also G.Brusa in 4 and A.Riccardi in 7). The analog derivative compensator has been designed to provide a damping term of up to 200 Nsm$^{-1}$ with a cutoff frequency of 10 KHz. These parameters are directly controlled by the DSP, and can be modified in real-time. In this way, we expect to maintain the total damping (electronic + air) constant over a wide gap range.

The on-board diagnostic measures the board temperature and allows to check the coil resistance, in order to detect possible failures or malfunctioning of the coils.

## 2.3 SYSTEM COMMUNICATION

The communication with the adaptive secondary control system is a very critical aspect of the overall system design. On the LBT electronics, we can distinguish two separated communication links: real time communication and diagnostic communication.

The *real time communication* carries only the data related to the adaptive optics control loop: it transfers the slopes from the slope computer to the adaptive secondary control system and allows to exchange intermediate computational results for reconstructor algorithms implementing IIR filter (e.g. time-dependent modal reconstructors). The real time communication interface is based on the Fiber Channel physical layer. There are two bi-directional fiber links acting as ‘logic inputs’ (i.e., they are ‘slaves’ with respect to the preceding unit in the communication path) and two identical fiber links acting as ‘logic output’ on every communication board. The raw data speed on each channel is of 2.125 Gbit/s, for an aggregate bandwidth of 4.5 Gbit/s. Considering the bandwidth reduction due to packet handling and error checking/correction, the actual data throughput is of 2.9 Gbit/s. The real time communication link allows to read/write data from/to the internal memory of all DSPs by means of a DMA mechanism that does not interfere with the normal operation of the DSPs. Time determinism is ensured by the absolute absence of software processes handling the data transfer: the whole high speed communication is managed only by hardware state machines, therefore the non deterministic jitter is always below 1µs. As a consequence, there is no actual need of additional synchronization lines to sequence the operation of the different components in the adaptive optics system: synchronization is provided by the data transfer.

The communication protocol is based on four simple primitives:

- Write_same: transmits data from the master (typically the slope computer) to one/several DSPs, writing the same data to the same internal addresses of all addressed DSPs
- Write_sequential: transmits data from the host to one/several DSPs, writing different data to the same internal addresses of all addressed DSPs
- Read_sequential: receives data from one/several DSPs, reading data from the same internal address of the addressed DSPs
- Read_write_sequential: allows reception of data from one/several DSPs, reading data from sequential internal addressed of the addressed DSPs. At same time, the data are written to the same addresses on all other DSPs

This communication architecture has been proofed by the experience gained on the MMT to be very effective and flexible, providing a way to access all control and diagnostic variables in the DSP memory.

The *diagnostic communication* is used to transfer all diagnostic data (circular buffers, boards status) and for system maintenance, as explained in Sect. 6. The external interface is based on the Gigabit Ethernet standard. The fiber link has been preferred over the copper one due to better signal integrity and immunity towards disturbances. The communication protocol is based on a standard UDP/IP layer, on top of which the same primitives already described for the real time communication are made available. The diagnostic communication transactions are handled by the diagnostic processors on the communication board and on the DSP control boards.

A *high speed parallel backplane* implements both real time and diagnostic data transfer between communication board and DSP boards. There are two synchronous parallel buses on the backplane, the first is 32 bit wide (2.9Gbit/s bandwidth) and is dedicated to the real time communication; the second is 8 bit wide (720 Mbit/s bandwidth) and is used for the diagnostic communication. The backplane has 16 slots and provides also the power supply to the boards. Due to the high speed requirements and the large number of boards with limited spacing (14 mm) on the bus, causing a very low typical impedance, the backplane is a custom design based on B-LVDS technology.

The main characteristics of the LBT adaptive secondary electronics are resumed on Table 2.

| | |
|---|---|
| Number of channels (each mirror) | 672 |
| Number of DSP boards | 84 |
| Channels controlled by every board | 8 |
| Number of crates | 6 (3 double crates) |
| DSP boards on each crate | 14 |
| Type of DSP | ADSP-21160 |
| Computational performance (single DSP)<br>(32x32 bit $\Rightarrow$ 40 bit, floating point Multiply and Accumulate operations per second – MAC/s) | 180 MegaMAC/s |
| Total computational power (one mirror) | 60 GigaMAC/s |
| Actual real time communication data throughput | 2.9 Gbit/s |
| Actual diagnostic communication data throughput | 400 Mbit/s |
| Capacitive sensor bandwidth | -3dB @ 90 KHz |
| Current driver bandwidth | -3dB @ 56 KHz |
| Power dissipation in the crates[1] | 2541 W |
| Power dissipation in the actuators (coil + capacitive sensor)[1] | 124 W |
| Total power dissipation[1] | 2665 W |
| Power supply voltage | ±48V @ 30 A |

**Table 2 - LBT adaptive secondary electronics in numbers**

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[1] Evaluated in the following conditions: $\lambda$=0.55µm, $r_0$=0.15m, mirror thickness=1.6mm, coil efficiency 0.5 N/$\sqrt{W}$, mirror flattening force 0,020 N/actuator

# 3 LBT 672 ADAPTIVE SECONDARY CONTROL SOFTWARE

Within the adaptive secondary software architecture, we can distinguish two different layers:

- Control software
- Diagnostic software

The *control software* comprehends the high speed local control loop, that implements a local position controller, and the global computations required to implement the Real Time Reconstructor and the feed-forward technique (see G.Brusa in 4).

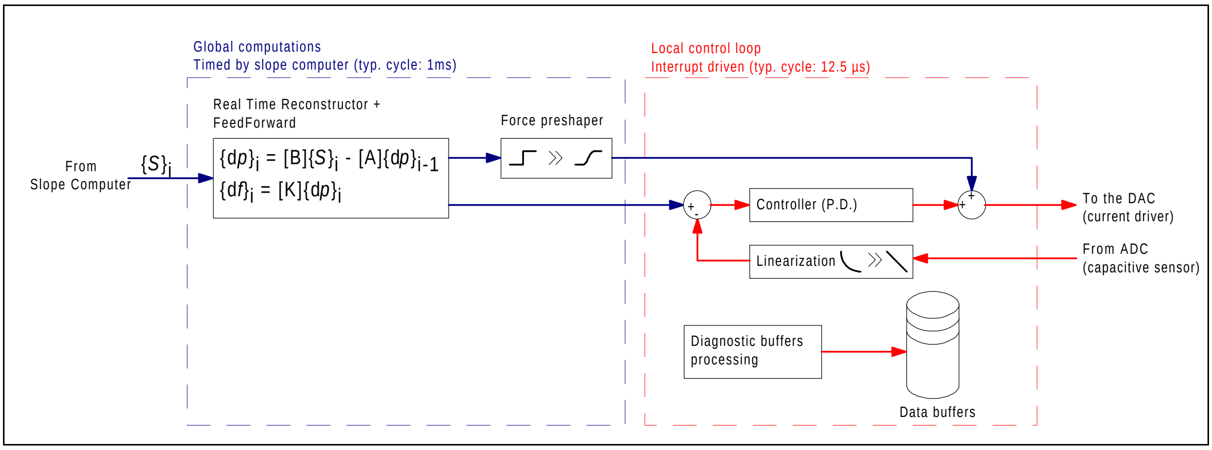

**Figure 6– LBT adaptive secondary control software scheme**

In the local control loop, the gap information acquired from the capacitive sensor is first linearized, then fed into the digital filter that implements the local controller. According to MMT experience, the local control law has typically the form of a PD controller, that can be adequately realized by a two poles, two zeros IIR filter. This part of the control software is interrupt driven and runs at 80 KHz (12.5µs cycle time).

The global computations are performed each time a set of slopes becomes available from the slope computer. The feedforward computation takes the form

$\{\Delta f\}_i = [K]\{\Delta p\}_i$ where $p$ and $f$ are, respectively, the actuator positions and forces and $[K]$ is the mirror stiffness matrix, while the reconstructor algorithm can vary depending on the type of reconstructor adopted (zonal vs. modal).

E.g., for a zonal reconstructor with a dynamic filter with one pole not in zero (pseudo-integrator), we have:

$\{\Delta p\}_i = [B]_1\{S\}_i - [A]_2\{\Delta p\}_{i-1}$ with $\{S\}$ slope vector and $[B]$ and $[A]$ the input and output gains, respectively.

All these computations can be very effectively implemented in the parallel architecture of the adaptive secondary control system. In fact, every DSP can perform only the operations related to the two controlled channels, involving just two rows of the gain matrices.

The cycle time of the global computations is the integration time on the wavefront sensor CCD. The output of these computations are the position and force vectors that feed the local control loop. Therefore, the global computation delay affects directly the mirror response time.

The *diagnostic software* allows the acquisition of circular buffers and permits an easy implementation of calibration and test procedures. Following the guideline of the MMT system, the diagnostic code running on the DSPs just provides a very flexible and powerful structure for reading and/or writing data vectors synchronously with the fast local loop. It is possible to define up to eight data vectors. Each vector can be filled automatically with the values contained in an user-definable memory location at each control step. Alternatively, the memory location can be filled with the values read from the data vector. This feature provides a powerful tool for signal generation during system response tests. The user can define the buffer length, select them as linear or circular, and set decimation factors, if required. This architecture moves to the *Adaptive Optics Supervisor* software (see S.Esposito in 8) the actual definition of the diagnostic parameters, and permits to avoid frequent updates of the DSP real time code.

## 4 BASIC COMPUTATIONAL UNIT

Within the LBT adaptive optics electronics it is possible to identify several elements with similar requirements in terms of communication interface and computational power. In particular, if we refer to a Multi Conjugate Adaptive Optics scheme, the data path follows a tree-structure, where the information sampled from several wavefront sensors has to be merged to a single device (e.g. the adaptive secondary mirror) through several computation steps (slope computation and data shifts). All the nodes within the tree structure have quite similar requirements:

- significant computational power, typically in the range of hundreds of Mflops
- typically two high speed data inputs (from the upper level in the tree) and one data output (to the next level in the tree)
- possibility to connect directly a sensor electronics (typically the wavefront sensor CCD controller)
- diagnostic interface
- possibility of expanding the computational power if required

It can be noticed that all these requirements, with the only exception of the local computational power, are common also to the communication board of the adaptive secondary control system. According to this consideration, we decided to extend the features of the adaptive secondary communication board and to develop a general purpose board, conventionally called Basic Computational Unit (BCU). The additional design effort is surely compensated by the advantages of having an unique hardware and software basis with a seamless interface between the different components within the adaptive optics system.

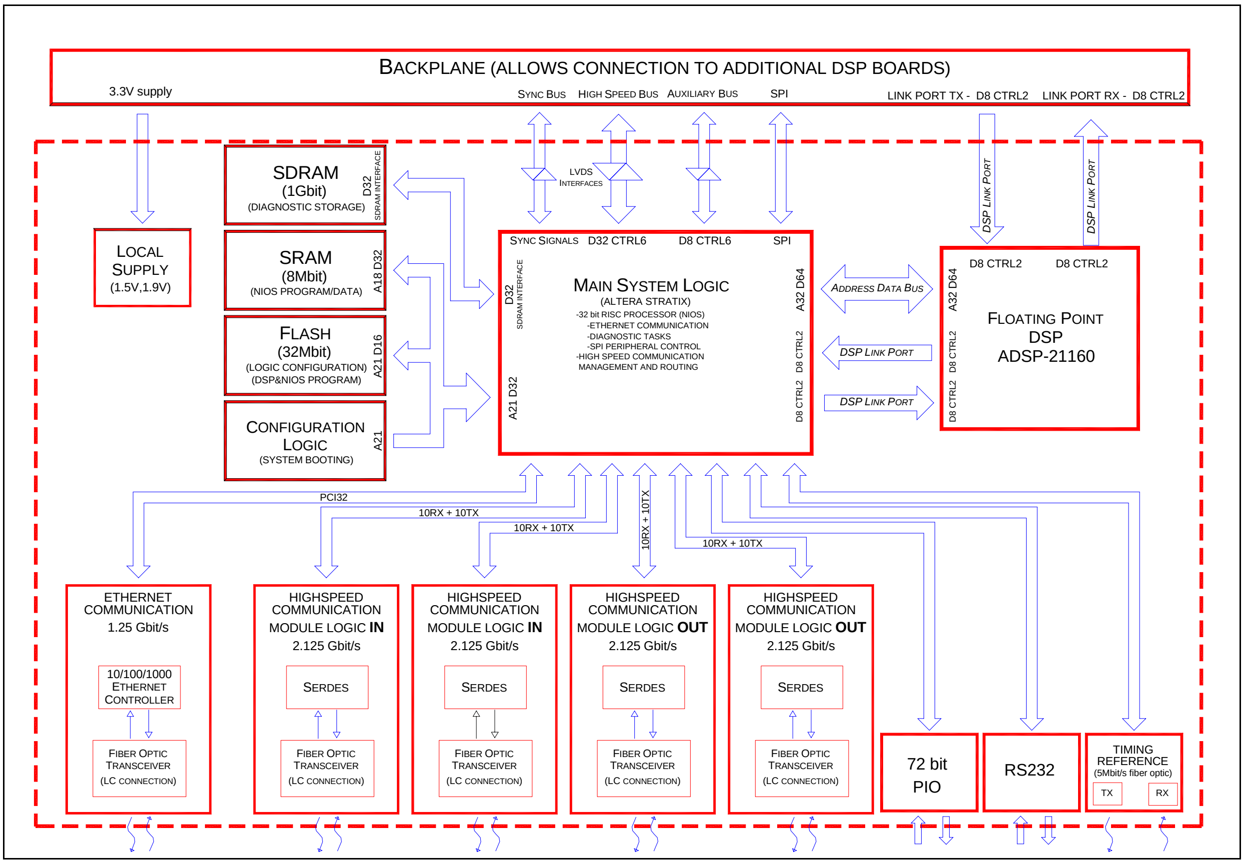

Figure 7 – Basic computational unit block scheme

Referring to the scheme on Figure 7, the following main components can be distinguished:

- Real time and diagnostic communication interfaces, already described on par. 2.3
- System logic, including the hardware dedicated to the communication management and the Nios 32 bit embedded processor that handles the diagnostic communication and the board diagnostic
- DSP unit, based on a single ADSP-21160 (identical to the processors used for the DSP control boards, see par. 2.2). The DSP allows standalone operation of the BCU, with a significant computational power of 180 floating point MMAC/s.
- Bulk memory (1 Gbit), for the storage of large diagnostic buffers like wavefront sensor frame sequences
- 72 bit Programmable Input Output port. This is a flexible, configurable interface that allows to connect the BCU to various devices. E.g., for the LBT first light configuration (see S.Esposito in 8 and Figure 8) it is foreseen to use this port to interface the Wavefront Sensor CCD controller to the BCU, acting as slope computer
- timing synchronization interface, providing a mean for synchronizing all adaptive optics control system components to a unique timing reference

## 5 CONTROL SYSTEM COMPUTATIONAL PERFORMANCES

To give an estimate of the control system computational performance, we considered some realistic configurations, always related to the use of a single wavefront sensor:

- CCD 39, 80x80 pixel, no binning, 30x30 subapertures, off-the-shelf SciMeasure Analytical Systems acquisition board (4 pixels x 12 bits parallel acquisition @ 2 MHz = 8 Mpixel/s)
- CCD 60, 128x128 pixel, 2x2 binning, 30x30 subapertures, acquisition board by Osservatorio di Arcetri (under development), with fiber interface (1 pixels x 16 bits @ 16 MHz = 16 Mpixel/s)

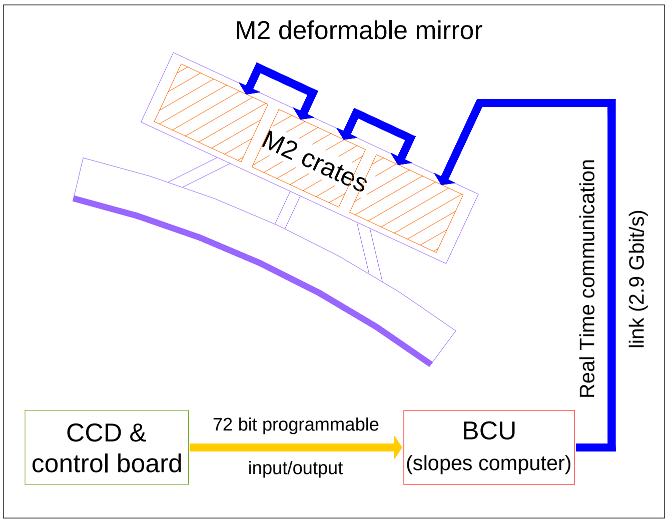

**Figure 8 – LBT first light AO computing configuration**

In particular, the first configuration considered is the one foreseen for the LBT first light (see Figure 8 and S.Esposito in 8).

The slope computer is always realized by a single BCU board. No pipelining has been assumed for the data transfer from the slope computer to the adaptive secondary. The computational time on the adaptive secondary always takes into account the load of the fast real time control loop and of the diagnostic tasks, leaving a conservative 75% of available computational power to the global computations. Additionally, we considered 32bit accuracy for the slopes to evaluate the transmission time.

The reconstructor algorithms considered in this estimate implement a dynamic filter with a single pole (pseudo-integrator) for both the zonal and the modal case. Therefore, the computational times include also the time required to make the intermediate results (delta-positions and modal amplitudes) available to all DSPs, using the real time communication.

| Configuration (CCD type, number of subapertures) | CCD readout time ( μs ) | Slopes computer latency after end of CCD readout ( μs ) | Real time comm. slopes transfer from BCU to AM2-RTR ( μs ) | RTR (zonal) + FeedForward( μs ) | Total time from CCD frame to M2 start ( μs ) |
|---|---|---|---|---|---|
| | | | | RTR (modal) + FFWD ( μs ) | |
| CCD 39 30x30 | 800 | 0 | 20 | 44 | 864 |
| | | | | 57 | 877 |
| CCD 60 30x30 | 256 | 132 | 20 | 44 | 452 |
| | | | | 57 | 465 |

**Table 3 – Adaptive optics control system performance, including slope computer, real time reconstructor and adaptive mirror local control**

The results are resumed on Table 3. In the first considered case (CCD 39, 30x30), the slopes computational time is zero due to the fact that slope computing can be started once half of the pixels have been acquired from the CCD (this is true for the pyramid wavefront sensor). This allows to partially pipeline the slopes computation with respect to the CCD pixel acquisition. It shall be noticed that the delay is always dominated by the CCD readout time, even considering the fast CCD acquisition board.

## 6 MAINTAINABILITY

Designing the LBT adaptive secondary electronics, the maintenance problem has been addressed carefully. To this aim, the system can be entirely reconfigured through the Ethernet connection, both for what concerns the hardware configuration of the system logic and the software running on the diagnostic computer and on the DSP. A safety mechanism is provided in order to guarantee that the system can be always recovered from any wrong configuration: a safe factory setup is always loaded automatically at system booting if the system does not recognize a valid user configuration. This remote maintenance system applies to the DSP control boards, to the communication boards and to the Basic Computational Units.

For the sake of reliability and easy maintenance, there are no electromechanical devices like potentiometers or dipswitches on the system. The calibration of the analog parts is performed automatically during system factory testing and is handled directly by the DSPs. The calibration and setup parameters are stored on permanent memory on each DSP control board.

## 7 CONCLUSIONS

The paper presents the architecture and the performance of the control electronics for the LBT adaptive secondary. The design, while maintaining the same concept of the MMT electronics, has been completely reviewed not only in order to improve the weak points, but also to reach a performance level adequate to fulfill the most demanding computational schemes for traditional and Multi-Conjugate Adaptive Optics. Once completed, the same electronics could also represent a baseline for further developments for systems with larger number of actuators, like ELT adaptive optics.

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