Orthogonal Transfer Array Control Solutions Using the MONSOON Image Acquisition System

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ABSTRACT

The development of the Orthogonal Transfer Array CCD provides unique control mechanisms that allow a rich set of operating modes necessary to meet the demands of very wide-field imaging programs. The exclusive control modes of the OTA place strong requirements on the CCD controller to support the capabilities of the device while providing detector-limited performance. NOAO and WIYN Observatory have developed a controller based on the MONSOON Image Acquisition concept with the specific application for testing and characterizing the OTA performance and capability. The OTA controller implements control solutions for on-chip cell multiplexing, multiple read modes, high-speed guiding with multiple stars, predictive algorithms for temporal and spatial image motions, and application of electronic tip-tilt corrections. The MONSOON image acquisition system provides the flexibility needed to support the full capabilities of the OTA, while it's extensibility can facilitate large mosaics of devices to meet the demands of future very large focal plane instruments.

Keywords: CCD, OTA, MONSOON, orthogonal transfer, focal plane array, electronic tip-tilt

1. INTRODUCTION

Inspired by the revolutionary attributes of the Orthogonal Transfer Array (OTA)[1,2], the WIYN Observatory is undertaking a project to build a giga-pixel camera, the WIYN One Degree Imager (ODI)[3], that fully exploits the superb optics, excellent seeing characteristics, and large natural field of view of the 3.5 meter telescope located on Kitt Peak, AZ. WIYN is currently involved in a collaboration to design and fabricate OTA devices and a foundry run for the first lot of devices was completed in May 2004. If the OTAs meet expectations, they will provide a lower cost alternative to conventional CCDs, four-side buttable packages to maximize the fill factor of the focal plane, eight high-speed output stages for fast readout, and spatially independent electronic tip-tilt to allow wide-field image motion corrections.

The MONSOON Image Acquisition System being developed at NOAO for large focal plane arrays was chosen as the basis for the OTA CCD controller. ODI will require 64 OTAs to populate the focal plane and the MONSOON system provides the scalable architecture needed to parallel process the many CCD outputs (eight per OTA). The CCD version of the MONSOON controller reuses much of the technology developed and demonstrated for IR applications. The hardware design of the system is complete and is currently being fabricated and tested. The completion of a 32-channel controller and the availability of a packaged OTA is well synchronized and lab tests of OTAs are expected to begin in summer 2004. We anticipate that a science demonstration camera, incorporating a quad array of OTAs (QUOTA), will be functional on the timescale of 16 months, and science operation of ODI will begin in 2008.

The OTAs are complex devices that require unique control features and place new demands on the controller. In this paper, we provide a brief overview of the OTA devices and MONSOON controller, describe the unique control requirements of the OTA, and explore the control solutions to be implemented using the MONSOON image acquisition system.

DESCRIPTION OF THE ORTHOGONAL TRANSFER ARRAY

The orthogonal transfer CCD developed at MIT/LL[1] implements a new pixel structure that replaces the channel stops with gates allowing charge to be transferred horizontally as well as vertically in the image area. This feature allows charge to be shifted in all four directions and provides a means for local tip/tilt correction in the silicon (rather than through expensive optics) to remove local seeing effects, such as telescope shake, as well as low-order atmospheric effects.

The OTA is an 8x8 array of 480x494 12μm pixel OTCCDs (cells) on a four-side buttable device roughly equivalent to a 4Kx4K CCD (see Figure 1). The cells are independently addressed through control logic for charge shifting and read out. Eight output amplifiers (one in each column of eight cells) can be read out simultaneously to provide a 2 second readout for the full device.

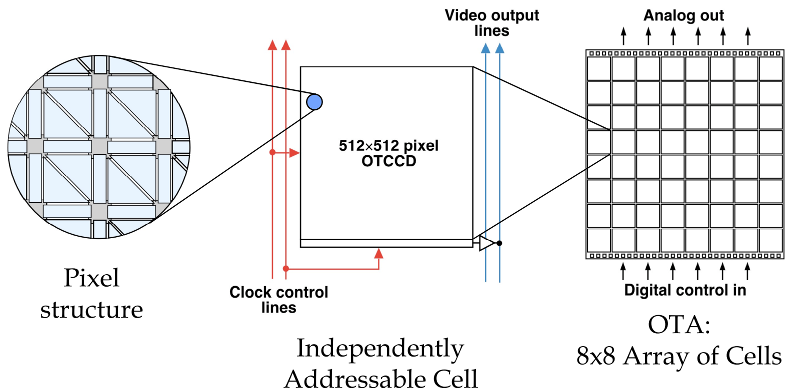

Figure 1: Structure of the Orthogonal Transfer Array detector

During typical observing with the OTA the cells will be configured for different uses as shown in figure 2. In cells were gross fabrication defects exist, such as gate shorts, it may be necessary to disable the (dead) cell. Several of the cells across the OTA will contain bright stars that will be selected as "guide star" cells. These guide cells will be read out at a rapid rate (~30 Hz) during integration to allow image motion (centroids) to be determined. The magnitude and direction of the centroid motion is then fed back to the OTA to shift the charge in the remaining "science" cells to keep the charge underneath the moving objects (OT correction). Since image motion from the atmosphere may not be correlated over the extent of the field of the OTA, and since the guide cells are readout independently, each science cell could have unique OT corrections applied during the observation, giving localized image motion corrections over an arbitrarily large field of view.

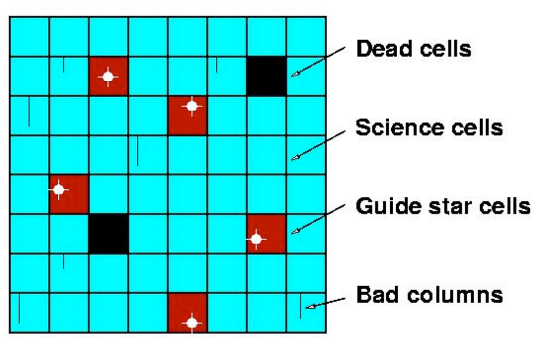

Figure 2: Typical cell configuration for OTA during observing

DESCRIPTION OF MONSOON CCD IMAGE ACQUISITION SYSTEM

The MONSOON Image Acquisition System was conceived as a scalable, multi-channel, high-speed data acquisition system. It encompasses the control, sequencing of low-level components, and acquisition of pixel data that form an exposure. MONSOON will address IR and OUV detector needs, both present and future. To accomplish this, the System requires a modular and scalable hardware and software architecture. Different subassemblies for device interface or processing will be added and developed as needed[4].

MONSOON is based on a scalable network of powerful yet low-cost of LINUX-based PC's, each supporting a commercial 1Gb/sec (or 2.4Gb/s) fiber optic link. Every PC node is known as PAN (Pixel Acquisition Node). The architecture is shown below in Figure 3.

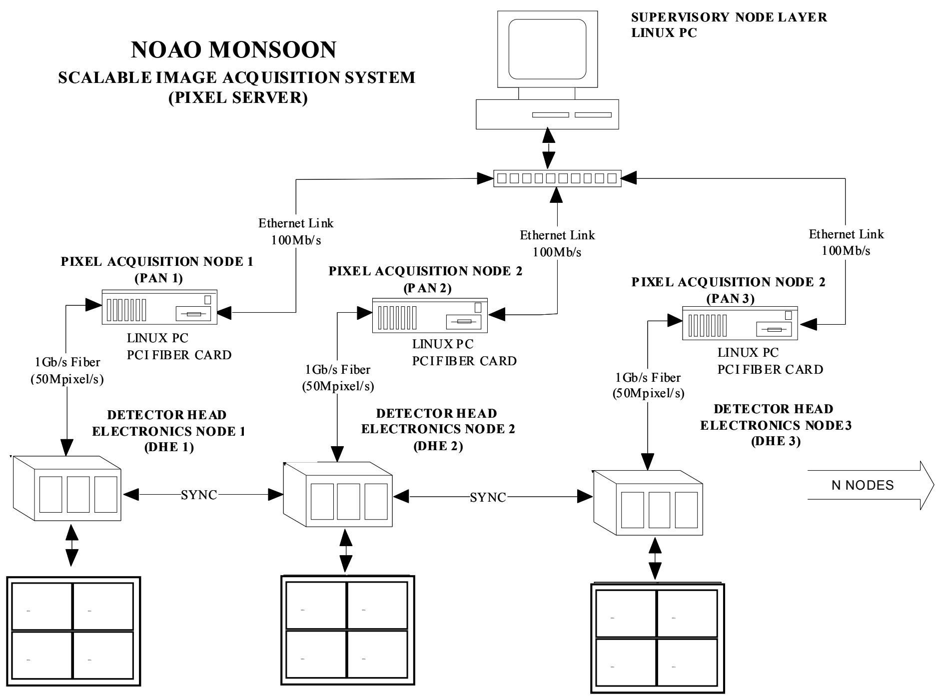

Figure 3. MONSOON Scalable Image Acquisition System Architecture. *Illustrates an N node implementation. Nodes are added to the system as needed and or as costs permit. The particular application shown for ODI would require 16 nodes for a full 32k x32k implementation of Orthogonal Transfer Arrays (OTA).*

In the case of a 1-node system, which is the case for the QUOTA system, the "Supervisory Node" is not needed. The supervisory node and the supervisory layer of the software acts to combine data from each Pixel Acquisition Node and provide a single entry point to the MONSOON system for the observatory or instrument control systems. Whether or not multiple Pixel Acquisition Nodes are needed in a given application is unnecessary information to higher levels of a system and can therefore be hidden. In this design, nodes can be added as needed up to an arbitrarily large limit.

The DHE (Detector Head Electronics) nodes shown above and in Figure 4 are typically comprised of three types of boards: 1) Master Control Board, 2) Clock (and Bias) Board, and 3) Video Acquisition Board. The current standard configuration for the DHE is a 6U Eurocard format, using a standard 6U Compact PCI (cPCI) backplane, for both the digital and analog interface, including the power distribution and interface to the focal plane. The digital part of the backplane follows cPCI signal integrity standards, but not the cPCI signal protocol in order to maximize system performance for our applications.

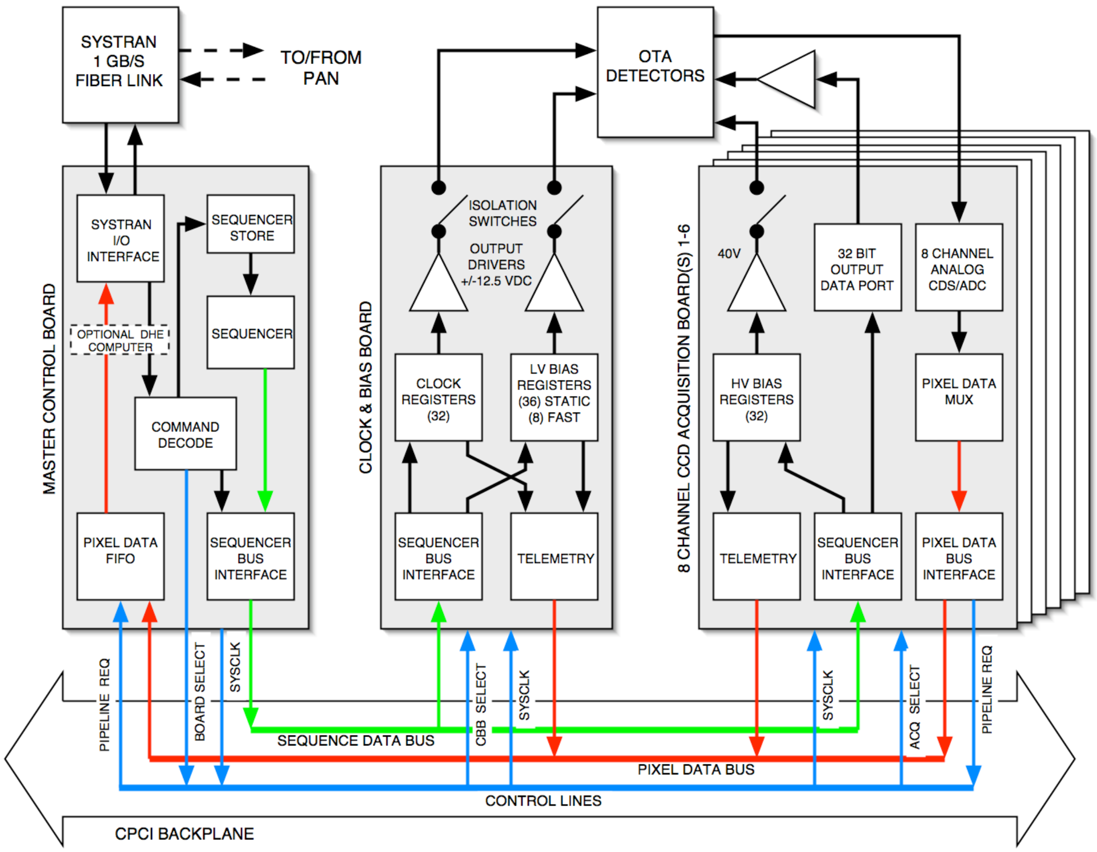

Figure 4: Block Diagram of the MONSOON Detector Head Electronics

The Master Control Board constitutes the "digital domain" boundary of the system, and it is common to all applications, independent of detector technology. The analog portions of the system are best served with a variety of boards that can be used as needed, tailored and/or even repackaged for individual project needs.

The Clock (and Bias) Board and the Video Acquisition Board(s) are the analog boards that will be used for the OTA CCD Controller System. The Clock and Bias Board has 32 clock channels and 36 Bias channels, plus 8 Fast Bias channels (which can be updated in a single system clock cycle). The output voltages can have a range of up to +/-12.5V, and are set by 8-bit DACs. The board includes telemetry of all voltages and current sensing for the Bias channels. In the specific case of OTAs we will use this board for the generation of low voltage biases and clock signals. The Video Acquisiton Board will provide the high voltage bias voltages.

The CCD Video Acquisition Board includes 8 Acquisition channels, 32 bias channels, and a 32-bit Digital Output Data Port specifically designed to address the OTA cell multiplexing feature. The main characteristics of the video acquisition channels are: AC-coupled input, four selectable gains, DC-restore switch, dual-slope CDS, and 18-bit ADC. The maximum sampling rate for the video channels will be 750 Kpix/s, although the ADCs themselves are 1Msps. The Bias channels are generated using 12-bit DACs, and the voltage range can be configured at build time to accommodate up to +/-36V. Like the Clock and Bias Board, telemetry is available for all voltages.

Although the most basic DHE configuration (MCB, Clock Board and Video Board) is enough to operate a single OTA device, QUOTA will require three more Video boards, with a total of six DHE boards, which fits exactly in our standard 6-slot DHE box. ODI, with 64 video channels, will certainly require a repackaging of the electronics to a smaller form factor, as was foreseen from the beginning of the project.

OTA CONTROL ISSUES AND IMPLEMENTATION SOLUTIONS

1. OTA Cell Multiplexing

The array design of the OTA includes on-chip circuitry that allows the cells to be multiplexed for various configurations. The cells can be individually configured to allow the parallel clock signals to actively shift charge in a cell, or group of cells. The cells must also be multiplexed to the output amplifiers since each column of eight cells shares one amplifier. This multiplexing control of the OTA adds a level of complexity to the controller since the clock sequences must include signals for cell configuration. For instance, to apply unique shift corrections to a specific cells, the controller must first enable the clock lines of the appropriate cell(s), apply the required clock sequence pattern, and then disable the clock lines before selecting the next cell.

Another complication of cell multiplexing is that each cell may have unique offset positions for specified regions of interest that could change during every OT loop iteration. As a result, a large database of information must be stored in the controller to efficiently multiplex and control the individual cells.

The shared memory architecture of MONSOON supports this requirement well. Since the DHE control registers appear to the PAN node as simple memory locations, the maintenance of this database appears transparent to the DHE sequencer logic that utilizes the data. Offset data for each OTA cell is assigned by the PAN to a structure at a particular address within the pattern memory segment of the DHE. In turn, the DHE sequencer accesses this data to control the multiplexing and clock loop sequences to the OTA.

Once the control structures have been updated the DHE sequencer is triggered to read out the guide cells. The DHE sequencer begins this process by sequentially enabling each guide cell and clocking each region of interest to the origin point of the cell. This is done by issuing 2 bits of mode data plus 16 bits of select data (8 row selects, 8 column selects) to the OTA through a 32 bit latch, then clocking the relevant parallel clocks to perform the horizontal and vertical charge transport to the end of the serial register closest to the output amplifier. The cell is then disabled via the 32 bit latch while the other guide cells are treated in an identical manner. At this point all guide cells are again enabled and a readout is performed of the cells in a manner similar to conventional CCDs.

The structure of the DHE sequencer program is designed with a one-unit cell granularity but the actual clock assignments are not generated directly by the sequencer program, rather a pointer is generated that points to a particular pattern memory segment location which is then clocked out to the detector. In this way, by utilizing the pattern memory shared memory feature, flexibility is preserved to select at a higher level in the hierarchy (the PAN) just which and how many guide cells to read out in any particular loop iteration. Hence the selective repositioning of regions of interest for each cell can utilize the same DHE sequencer code but point to different database values in shared memory, and the same readout code can be utilized for all cells read out in parallel or singularly whether for guide readouts or science readouts. It is this flexibility, coupled to the capability of MONSOON for processing many video channels simultaneously; that we hope will allow us to reach detector-limited performance with the OTAs.

2. OT Loop Control

The fundamental operational difference between the OTA and traditional CCDs is that the OTA allows certain cells (guide stars) to be readout very rapidly during integration so that OT corrections can be applied to the science regions. Figure 5 illustrates the control loop for orthogonal transfer functionality during a typical observing mode where electronic tip-tilt image motion corrections are applied. The OT control loop must operate at a rate fast enough for effective image motion correction. Our goal is to maintain a 30Hz loop rate for up to eight guide stars per OTA (one for each amplifier for each column of cells). During each loop iteration, the OTA controller will have to readout the guide star, perform image and data processing to determine image motion vectors, and then apply shift corrections to the OTA.

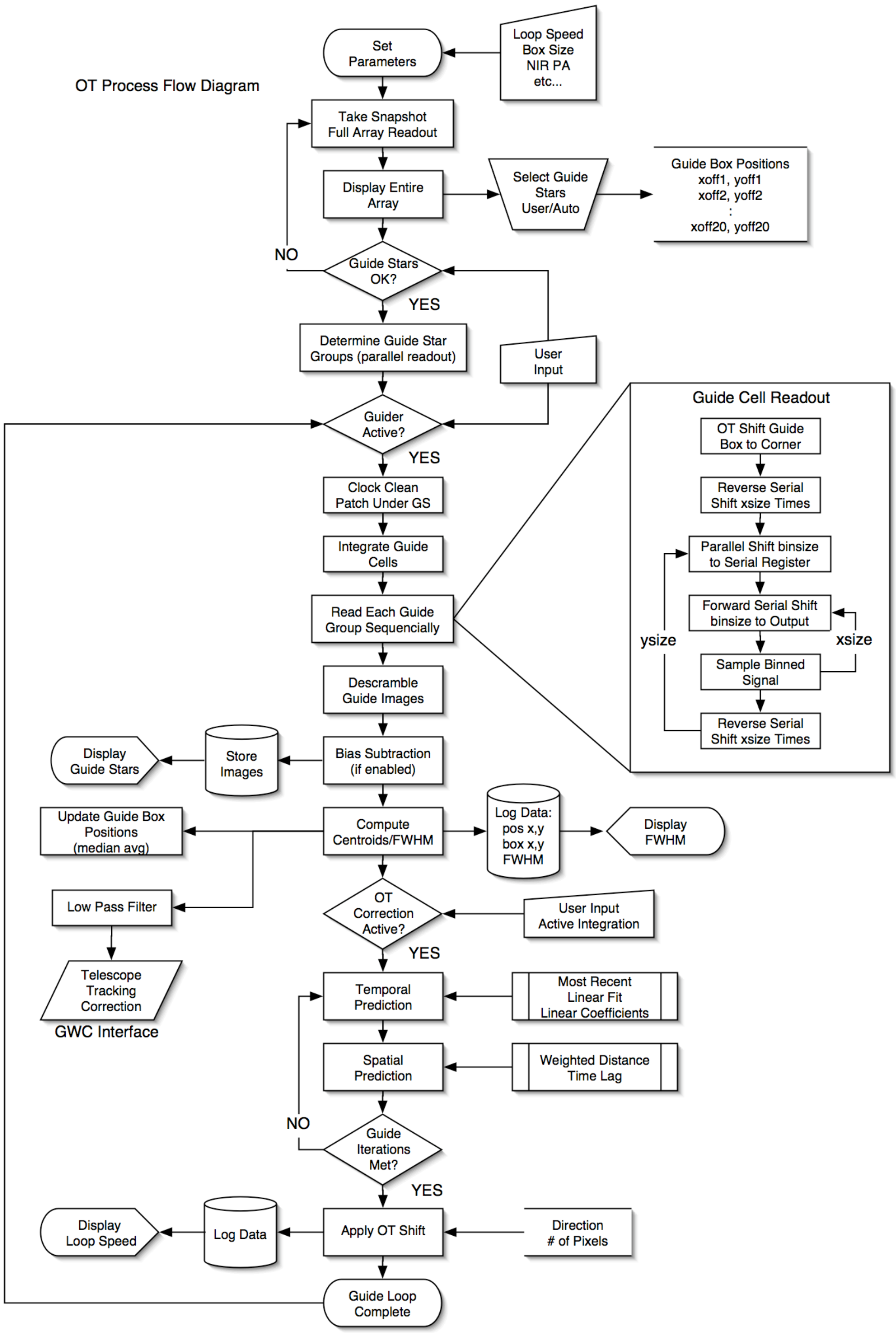

Figure 5: Process Flow diagram for orthogonal transfer setup and control.

2.1. Guide Star Readout

The process to readout a guide star fast will involve using a shutterless video mode for small regions of interest (ROI) defined around each guide star. The shutterless readout will involve first shifting the guide star ROI to the corner of the cell rapidly, using OT clocking, to minimize the image smearing. After moving each of the guide regions to the corner of up to eight cells, their pixels will be binned and read out in parallel through independent controller channels. The read out process will be similar to traditional CCDs with the exception that the serial register will have to be cleared after each serial transfer. This is because, for speed, the serial register will only be clocked the number of pixels in the guide region. Thus, since the serial register is not emptied, pixels from the unused portion of the serial register, which will contain noise, will be left under the guide region pixels ready for transition into the serial register. The serial register will be cleared by be "reverse" clocking the residual charge into a drain prior to each parallel transition.

Since the OTAs have an output amplifier for each column of cells, it will be possible to read out eight guide stars simultaneously as long as the stars fall on cells in different columns. In the case where more than one guide star falls on a given column, the readout process will have to be done serially and the readout time will increase thus reducing the OT loop speed. As such, the controller software will use an algorithm to determine the optimum groupings of guide stars for the most efficient readout depending on their location on the OTA. The algorithm will first determine the number of guide star groups that will be needed based on the maximum number of stars in any given column of an OTA (serial reads). Based on many parameters, the software will then assign the guide stars to the guide groups based on processing efficiency. For instance, guide stars of similar magnitudes may be grouped since fainter stars may require more integration time than brighter star.

2.2. Guide Star Image Processing

The MONSOON controller is capable of processing many analog channels simultaneously and thus the pixel data is scrambled to maximize the bandwidth of communication between the analog electronics and the processing computer. Typically, the data would be descrambled into images by a data handling system downstream of the MONSOON controller. However, for guide star images the latency of descrambling and retransmitting the images would be unacceptable for closed-loop OT operation. Instead the controller will build a reference table for pixel positions every time new guide star configurations are chosen. The reference table will allow the software to point to the appropriate pixels to process a given guide star image without actually generating the image.

Since the serial register is not being emptied during the guide star readout process, it is not possible to get a typical overscan to use for bias subtraction. In addition, the rapid readout of small regions will not produce a very flat "bias". As such, different options will be provided in the controller to allow us to explore different bias subtraction schemes and determine the optimum technique(s). One example for a possible bias subtraction scheme is to reverse clock and readout the serial register some number of times to generate an "overscan" prior to, or just after, readout. Another example would be to analyze the first few iterations of each guide region and "model" the bias.

2.3. Data Processing

The data processing required for the OT control loop includes determining centriods for the guide stars, prediction the temporal positions of the guide stars, and predicting the spatially dependent OT corrections. For speed, the first two calculations will be done in the Pixel Acquisition Node (PAN) layer of the software that will control 32 channels of CCD data. The spatial predictions will be done in a supervisory layer that sits above the PAN and coordinates the data from multiple PANs. The spatial calculation must be done in the supervisory layer so that the information from the entire focal plane can be used to determine the optimum vector map for wide-field image motion correction.

The centroid routine will use simple X and Y plots with Gaussian approximations to determine the guide star position to within a quarter of a binned pixel. The centroid algorithm will provide estimations for FWHM and total star flux. If the total star flux falls below a certain value, a null offset will be generated that will have the effect of disabling that guide star (e.g. the centroid of that guide star will not be used in the algorithm for determining spatial OT shift corrections). The software must also allow a threshold level to be specified for the signal to be used during centroid computations so that the "star trail" effects of shutterless video can be mitigated.

Once the centroid of the guide stars has been determined, it is necessary to make predictions of where they will be at the next iteration. The accuracy of the prediction will influence the level of success in removing image motion in the science regions. Because of uncertainty in how the observing conditions may affect the accuracy of the prediction, the software will provide options for choosing different prediction methods to allow experimentation and optimization for a given application. A simple temporal prediction method will be that the predicted position is just the last measured position. Whereas, a more complicated method will be to find linear coefficients for some number of past measurements to more accurately predict the position.

Spatial predictions are used to determine the appropriate shifts of the science regions (OT shifts) based on the temporal predictions of the guide stars. The level of success of the prediction will be influenced by variable and unpredictable observing conditions. Thus, the software will provide many options for choosing different prediction methods to allow experimentation and optimization for a given conditions. One spatial prediction method will be to apply a common shift to all science regions based on the median shift of all guide stars for some number of past iterations. Another prediction method will be to simply shift the science region by the temporal prediction of the nearest guide star. A more sophisticated spatial prediction method will be to weight the shifts applied to science regions based on the distance of guide stars from the center of the science region.

3. Operating Modes

Due to the flexibility of the addressing and clocking of the OTA, multiple operating modes will be possible. One mode could be to integrate without OT corrections for operation similar to traditional CCDs. The standard mode would be to integrate with OT corrections enabled for image motion compensation. Yet another operating mode could be to operate the devices in shutterless video mode for short-time resolution imaging. As such, the OTA controller must be flexible and adaptable to the various configurations and formats of data transmitted between the analog electronics and the processing computer.

Here again the architecture of the MONSOON system provides the platform to achieve such flexibility. During the architectural design phase of MONSOON, any processes requiring intelligence for the normal operation of a detector controller was pushed ‘up the pipe’ to the PAN computer residing in the control room. This approach means that the PAN (essentially a powerful PC) has a very high degree of control over the overall functioning of the controller because the control granularity is very small – down to the bit level. In addition this has allowed the DHE electronics, the electronics most intimate to the detector, to be totally synchronous and so reduce noise contributions from the camera system. To accommodate the flexibility of different modes required by the OTA detectors, the configuration data of the DHE is predetermined for each mode and grouped into a named operating mode in the configuration database. To reconfigure the camera at any time the detector is made safe, a new set of configuration data is downloaded to the DHE electronics, telemetry checks performed and the detector re-enabled. In the same way (but without disabling the detector), operational parameters such as guide loop rate, temporal and spatial filter constants, guide box regions, etc., can all be dynamically adjusted by writing to the assigned shared memory space in the DHE electronics.

4. Data Handling

The OTA devices create unique problems for the data handling in MONSOON. Normally MONSOON systems produce large amounts of science data at infrequent intervals[5]. This data is then pre-processed, de-scrambled and sent to the archive process. Since the data capture process (panCapture) is mostly idle, there is plenty of time for the required processing to take place while the next exposure is being taken. The OTA’s create data with a different cadence. During an exposure a large number of small guide images are captured, processed, stored and sent to the DHS to be displayed for the user. In addition between each data burst image and guide box position shift data must be sent down to the DHE controlling the OTA. All of the information on the image shifts must be stored for later archiving by the DHS.

A prime requirement for the MONSOON software[6] was flexibility and the design of a MONSOON system to control an OTA focal plane shows we have achieved our goal. With no changes to the base software we can create a system to use an OTA focal plane to do science.

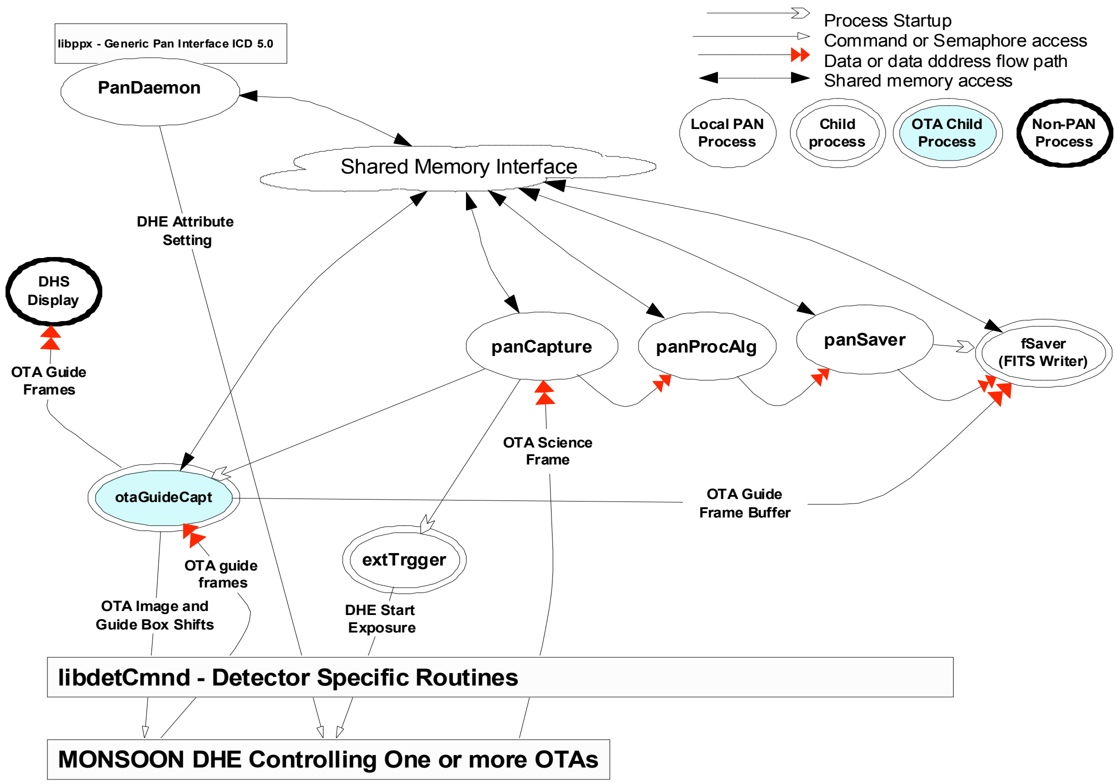

Figure 6: MONSOON Processes for OTA Control

Figure 6 shows the processes for a MONSOON PAN modified to handle the OTA requirements. Normally, a PAN software system consists of four main processes, and one or two sub-processes[7]. The OTA PAN software version adds a single additional process designed to handle the guide data for the OTA's. The normal PAN processes will continue to handle the science data for the PAN. This allows us to minimize the changes required for the standard MONSOON PAN software and concentrate the special requirements of the OTA's in a separate process.

In order to modify the standard PAN software to run an OTA we will have to modify the detSaveImage routine and write the processing and communications routines required to capture, descramble, process the centroid, display and save the guide images. These changes will be contained in libdetCmnds and will not change the standard PAN data processing. All of the changes can make use of code previously written to perform the required tasks.

In addition the control commands required by the OTAs are included in the GPX command set so the upper level software will have to change little if at all to make use of the OTA functionality[8,9].

CONCLUSION

The effort to adapt the MONSOON controller for OTAs is well along toward a timely implementation for testing our first lot of OTA devices in June 2004. The exclusive control modes of the OTA presents new requirements for CCD controllers and the MONSOON architecture proved to be very adaptable to meet the demands. The flexibility of the MONSOON design allows the changes to be implemented with modifications to only small pieces of the system. In the future, the changes implemented in the MONSOON controller will allow further flexibility for operating other types of CCD devices with minimal configuration changes. In addition, the modular expansion of MONSOON will allow the controller to be easily scaled from operation of a single OTA to QUOTA, ODI and other large focal plane applications.

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