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VETA X-ray data acquisition and control system

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ABSTRACT

We describe the X-ray Data Acquisition and Control System (XDACS) used together with the X-ray Detection System (XDS) to characterize the X-ray image during testing of the AXAF P1/H1 mirror pair at the MSFC X-ray Calibration Facility. A variety of X-ray data were acquired, analyzed and archived during the testing including: mirror alignment, encircled energy, effective area, point spread function, system housekeeping and proportional counter window uniformity data. The system architecture is presented with emphasis placed on key features that include a layered UNIX tool approach, dedicated subsystem controllers, real-time X-window displays, flexibility in combining tools, network connectivity and system extensibility. The VETA test data archive is also described.

2. INTRODUCTION

The Advanced X-ray Astrophysics Facility (AXAF) Verification Engineering Test Article (VETA) consists of the largest paraboloid and hyperboloid pair of Wolter type I grazing incident mirrors contained within the AXAF telescope and represents the first elements of the flight mirror to be manufactured. The VETA P1/H1 mirror pair was aligned and tested with X-rays in the X-ray Calibration Facility (XRCF) at Marshall Space Flight Center (MSFC) during 1991 September and October. The alignment and PRF characterization was performed with the VETA X-ray Detection System (VXDS) comprised of imaging and non-imaging focal plane detectors, beam normalization and monitor detectors, motorized detector and aperture stages, gas control system, thermal monitoring system and central data acquisition and control computer system[1].

The X-ray Data Acquisition and Control System (XDACS) performs the control, data acquisition, monitoring, analysis and logging functions of the VXDS. The XDACS consists of the computers, busses, controllers and software required to perform these functions and is the subject of this paper. We describe the network and software architecture (§3 and §4), and the VETA data archive and data base used to retrieve data for detailed analysis (§5). A summary is given in §6.

3. NETWORK DESIGN AND SUBSYSTEM DESCRIPTION

The VXDS design was based on the detection system used to test the Technology Mirror Assembly (TMA), a 2/3 scale model of the next to inner AXAF mirror[2]. The TMA test system consisted of a number of independently controlled subsystems, some of which were retained and incorporated into the VXDS. A key requirement of the VXDS design was to provide the VETA test operator with integrated procedural control and monitoring over all subsystems from a single central workstation. In order to meet this requirement a network architecture was developed that employed synchronized controllers interfaced to hardware subsystems and connected to a central SUN Microsystems 4/330 workstation via one of three different bus or network types: RS232, IEEE 488 or ethernet. A variety of bus types was required to integrate existing TMA subsystems.

The network architecture (Figure 1) shows the central workstation and peripherals, XDACS and some XRCF subsystems, analysis workstations, busses (ethernet, IEEE 488 and RS232), external network connection and InterRange Instrumentation Group (IRIG) analog time signal used for synchronization.

The subsystems shown in Figure 1 are briefly described in Table 1 and explained in more detail in Reference 1. The basic components and operation of the system are also described here to provide a context for the software description.

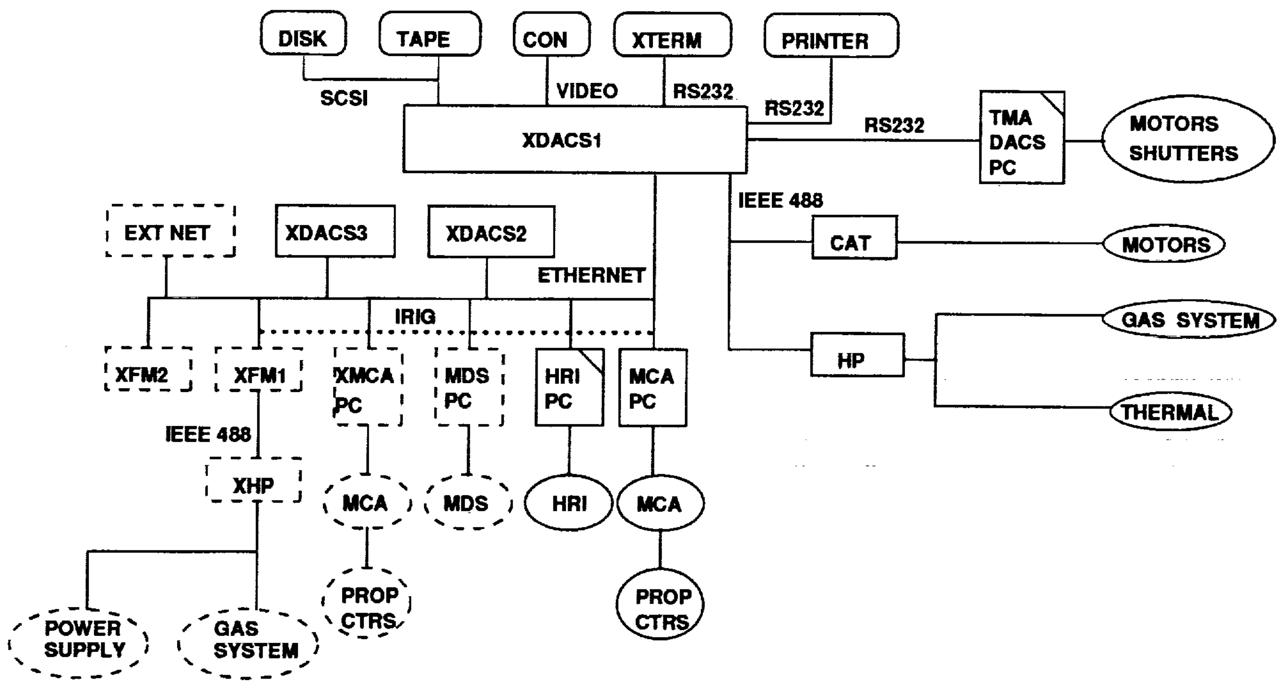

Figure 1: The XDACS/XRCF network architecture combines a variety of bus types. Hardware components are denoted by ellipses, network components (controllers and computers) by rectangles and XDACS perhipherals by rectangles with rounded corners. XRCF subsystems that interface with XDACS1 but were not delivered by SAO have dashed lines. The TMA DACS and HRI subsystems were inherited from the TMA system and are marked with a diagonal line.

X-rays reflected by the VETA-I along the $-x$ axis were detected by instruments located in the focal plane (FP). The FP detectors include a High Resolution Imager (HRI), a Flow Proportional Counter (FPC) and a Sealed Proportional Counter (SPC). The SPC and FPC are mounted on orthogonal ($y - z$) motor stages behind the aperture plate which contains apertures of various sizes and shapes. The apertures include pinholes ranging from 2 μm – 20 mm in diameter, annuli, and horizontal and vertical slits. The aperture plate is mounted on orthogonal ($y - z$) motor stages such that the counters are carried when the aperture plate moves. The counter and aperture plate motor drives constitute the Counter Aperture Translation (CAT) subsystem which is mounted on the Prime X and Prime Y coarse motor drives. The HRI motion is controlled by Prime-X, Prime Y and the HRI Z motor drive and is located in the $-y$ direction from the CAT, along Prime-Y. A set of four quadrant shutters located at the entrance to the VETA-I allows X-rays in each quadrant to be blocked for mirror alignment and focus tests. The Prime drives, HRI-Z and shutter motors are controlled by the Test Mirror Article Data Acquisition and Control System (TMA DACS) subsystem. The Prime drives, CAT and FP instrumentation are collectively called the X-ray Detection Assembly (XDA).

In addition to the FP detectors two Beam Normalization Detectors (BND), a large area flow and large area sealed proportional counter, are mounted on the BND structure located at the entrance to the VETA. The Gas Supply System (GSS) controls the type and flow of gas to the two flow counters and 19 thermistors located throughout the XDA constitute the thermal monitoring (THM) system. The central workstation and controllers constitute the XDACS which provides the controls and data acquisition functions for all subsystems. The X-ray Flux Monitor (XFM) subsystem consists of a flow and sealed proportional counter, gas system and analysis workstation and is used to monitor the X-ray source flux. The Motion Detection System (MDS)[3], detects the relative motion between the FP instruments, VETA and X-ray source. The XDA, BND, GSS, THM system, XDACS, analysis workstations, MDS and XFM interfaces are collectively named the VETA X-ray Detection System (VXDS).

TABLE 1: XDACS SUBSYSTEM DEFINITION AND DESCRIPTION

SUBS.	DEFINITION	DESCRIPTION
XDACS1	X-ray Data Acquisition & Control System 1	Central controlling workstation provides operator command interface and displays. Issues low level subsystem commands, receives data and status streams, archives all data, and performs limited analysis.
XDACS2		Analysis workstation.
XDACS3		Analysis workstation.
TMA DACS	TMA Data Acquisition & Control System	TMA motor drive system provides movement in x, large scale y moves and moves the HRI in z. Four quadrant shutters located in front of the VETA may be opened and closed.
CAT	Counter Aperture Translation	Accurate (2 μm) motor stages move the focal plane proportional counters behind the aperture plate and move the aperture plate. The CAT is mounted on the TMA motor drives.
HP	Hewlett Packard	HP 3752A IEEE488 controller contains the GSS (Gas Supply System) and THM (Thermal) monitoring system cards. The GSS controls gas flow through the Focal Plane and Beam Normalization flow proportional counters and the THM provides thermal monitoring at 19 locations on the instruments, motors and structure of the XDA.
MCA	MultiChannel Analyzer	Controls and receives data from the FP and BND flow and sealed proportional counters.
MCA PC	MCA Personal Computer	Interfaces with the MCA via Ortec board. Receives commands from and transmits data to XDACS1 via TCP/IP.
HRI	High Resolution Imager	Focal plane imaging detector.
HRI PC	HRI Personal Computer	Interfaces with the HRI via custom board. Receives commands from and transmits data to XDACS1 via TCP/IP.
MDS PC	Motion Detection System PC	MDS detects relative motion between the FP instruments, VETA-I and X-ray source. The PC transmits TCP/IP packets to XDACS1.
XFM1	X-ray Flux Monitor 1	Workstation controls a smaller version of the MCA and HP (GSS and THM) subsystems. The XFM subsystem is located near the X-ray source and monitors the source flux. The software used to control and acquire data from the XFM was based on the HP and MCA software subsystems (little change was required).
XMCA PC	XFM MultiChannel Analyzer	Analogous to the MCA PC.
XFM2	X-ray Flux Monitor 2	Workstation used as a display station for XFM spectra, gas and temperature data and status.
XHP	XFM Hewlett Packard	Analogous to the HP in controlling the XFM gas system and thermal monitoring, but in addition controlled the proportional counter high voltage power supply.
EXT NET	External Network	Internet network connection.

During testing, the operator issued high level commands with appropriate parameters at the XDACS1 console. Examples of tests performed by high level commands included: generation of VETA-I alignment errors using the quadrant shutters and FP instruments (either HRI or scanning proportional counters), beam centering with successively smaller apertures, encircled energy measurements and 2-D mapping of the PRF and HRI images.

The XDACS1 acquired both autonomous and non-autonomous data during a test. For example, a 19×19 2-D scan of the PRF made with the FPC behind the 10 μm diameter circular aperture was performed by first moving the FPC behind the 10 μm pinhole and then scanning the aperture plate in a 2-D raster about the current beam center. At each point in the scan, proportional counter spectra were acquired in both the FP and BND counters and stored in files, one per point. Logs of operator keystrokes, motor positions, command parameters and low level subsystem commands were also generated. Upon completion of the scan the FP integrated line counts were normalized at each point with BND data and an image file was generated. The 361 files containing spectral data, the image file and logs constituted the non-autonomous data from the test. Data from the MDS, GSS and THM subsystems were acquired, displayed and stored continuously and independently of a given test, and were the autonomous data streams.

Data acquired during testing were time stamped with either the XDACS1 clock or IRIG-B time signal depending on the required accuracy. The MDS data allowed time tagged events recorded by FP instruments to be corrected for excessive motion in the $y - z$ plane. Synchronization to 10 ms between the MDS, HRI, MCA and XFM was required to support such corrections, and these subsystems accessed the IRIG time signal at the controller level via a PC board. Data from other subsystems were archived with $\sim$ 1 second accuracy. We note that the stability of the XRCF, test benches and XDA were such that MDS corrections were never needed.

The synchronization at the front-end controller level illustrates how the XDACS1 was isolated from direct hardware control. In general, the XDACS1 issued commands to the controllers and received back status and data streams. The controllers were designed to operate safely in the event of XDACS1 going off-line. Time critical data were transferred using TCP/IP (e.g., MDS, HRI and proportional counter data) and displayed with $\sim$ 1 sec resolution and other data such as gas pressure or temperature were displayed after archiving with $\sim$ 5 sec resolution.

4. SOFTWARE ARCHITECTURE

The software architecture is shown in Figure 2 and employs a layered structure which includes software resident on the hardware controller devices, low level and high level subsystem commands, procedural commands and the user interface including real-time displays. A brief description of each element contained within Figure 2 is given in Table 2.

The software layers allow the system to be viewed with increasing abstraction typical of an object oriented design. Information about a subsystem is available only at the appropriate layer and complex high level commands and procedures are built from simpler lower level commands. For example, the `hri` command (or object) allows the operator access only to the HRI detector, and the `xdamain` command allows access only to the motors. The `hridata` command located at a higher level has access to both the HRI and the motors and implements the concept of an HRI image taken at different locations in the focal plane. The `mcascan` command combines the acquisition of proportional counter spectra (`mcadata`), shutter motions (`flapper`) and motor stage motions (`xdamain`) to implement arbitrary scanning capability. The highest level commands apply specific analysis to data obtained from the lower levels (e.g., `mcaalign` calculates the mirror alignment error), or further combine functions (e.g., `hrialign` coordinates the shutter motion and HRI image acquisition, then calculates the mirror alignment errors).

The concept of information hiding also applies to the coordinate systems found within the XDACS1 software. The low level `xdamain` program receives motor move requests in XDA coordinates which are transformed and maintained in the motor-specific coordinates required by the motor controllers. At the highest level, the mirror alignment errors are calculated by `hrialign` and `mcaalign` in the XRCF coordinate system.

The client/server model featured in the software architecture also resulted from the object oriented design approach. For example, the implementation of `mca ds` as a server allows multiple real time displays of proportional counter data to execute simultaneously on workstations located in different locations. The clearly defined dependence of a client on a server also allows straightforward startup and shutdown sequences for the multiple processes constituting the system. The client/server model was also applied between the PC controllers and the SUN 4/330 using TCP/IP sockets.

Commands at all levels are available to the operator from the shell. High level commands are shell scripts written in korn shell (ksh) that integrate low level commands typically written in C or C++. The ksh is used both as a familiar interface for the operator and as an integration 4GL. The string manipulation and pattern matching features of ksh were used to construct file names in the high level scripts and relieved the lower level C and C++ programs from such manipulation. Other standard UNIX tools such as `awk`, `bc`, `date`, `wc`, etc., were also used extensively. The UNIX philosophy was extended to provide online documentation in the "man" page format.

The layered software architecture is extensible. New hardware subsystems may be added in a straight forward

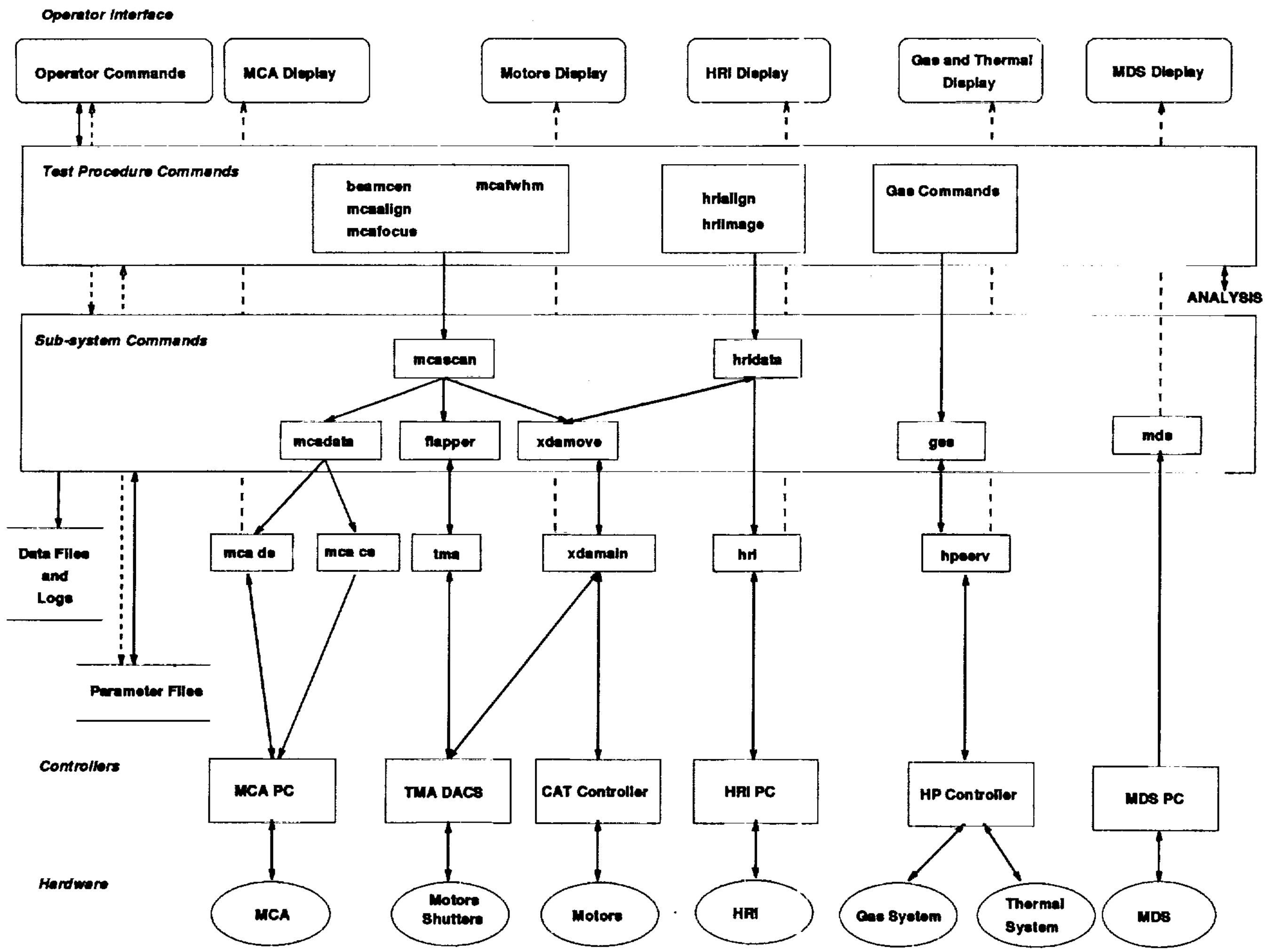

Figure 2: The XDACS software architecture employs a layered structure with hardware denoted by an ellipse and programs denoted by squares. Arrows indicate the direction of information flow (there is no significance in dashed arrows other than they pass behind another box). Commands flow down the Figure and data and status flow from the hardware up to the displays and data archive.

manner, often reusing code. Typical steps are (a) writing a hardware controller program, (b) creating a format for the archived data product, (c) writing a display/monitor program, and (d) writing the appropriate scripts to integrate with other existing subsystems.

A variety of analysis software was required by both the high level software and the operator. Access to analysis functions is shown from the `test procedure commands` layer in Figure 2 and is described at the end of Table 2. The majority of analysis routines were developed within the Image Reduction and Analysis Facility (IRAF) environment and the remaining functions were coded as standalone programs. IRAF is an analysis environment used extensively by Astronomers for multiwavelength data reduction and analysis, and provided many of the tools required for VETA test data analysis.

TABLE 2: SOFTWARE MODULE DEFINITION

MODULE	DESCRIPTION
	Operator Interface Layer
Operator Commands	Commands are entered at the keyboard and the operator is prompted for parameters. Statistics and status information, in addition to real-time data, are displayed as commands execute. Operator may access commands from the Test Procedure and High/Low-level Subsystem levels.
MCA Display	Displays proportional counter spectra from four MultiChannel Analyzer (MCA) buffers simultaneously in an X-window. The display program is a client of the MCA data server program (mca ds) and requests data every second. The operator may zoom on a region of interest and display specific channel counts with the cursor. Statistics and status displayed and updated include: counts in the region of interest, max and min counts, integration time and dead time.
Motors Display	Positions of motors are updated as commands execute. Current position, min and max allowed ranges and limit switch status are displayed for the three TMA motor stages, four CAT motor stages and four shutters.
HRI Display	Displays High Resolution Image (HRI) photon event data in X-window as received from the hri server. Operator may pan, zoom, alter color map and read pixel values with mouse.
Gas/Thermal Display	Displays gas pressures, valve status, temperatures and other status information with updates every 5 seconds. Parameter permitted ranges are also displayed and operator is required to acknowledge alarms for out of range conditions. The display program requests data from the hpserv server.
MDS Display	Displays Motion Detection System (MDS) data received from the mds server. Average displacements in the $y-z$ focal plane are updated each second and displayed as a scatter plot and in projection. Operator may select scale of plot.
	Test Procedure Command Layer
beamcen	Beam centering command. Performs 1-D counter/aperture scan in y and z centered on current beam location. Calculates centroid of each scan, updates beam center and outputs plot/data sheet. Used iteratively with smaller apertures to find X-ray beam center.
mcaalign	Generates mirror alignment errors. Performs 2-D counter/aperture scan around current beam center with the four shutters opened and closed at each scan point. Builds four images from completed scan, calculates P1/H1 mirror alignment tilt and focus errors from centroids, and outputs data sheet. Used iteratively with smaller apertures to provide VETA-I alignment corrections < 1 arcsec.
mcafocus	Generates focus error. Performs 2-D counter/aperture scan around current beam center with two shutters opened and closed at each scan point. Builds two images from completed scan, calculates the focus error, moves to new focus and outputs data sheet. Used to fine tune focus once alignment process is complete.
mcafwhm	FWHM scan. Performs 1-D counter/aperture scan around current beam center, calculates FWHM and outputs plot/data sheet. Used to characterize the VETA-I PRF.
hrialign	Generates mirror alignment errors. Acquires HRI images of the X-rays from each quadrant of the VETA-I by successively opening each shutter with the other three closed. Calculates tilt and focus errors from the centroids of each image, and generates data sheet. Used iteratively to provide VETA-I alignment corrections > 1 arcsec.
hriimage	HRI image. Acquires a single HRI image, calculates simple statistics (centroid, min, max) and generates a data sheet.

TABLE 2: SOFTWARE MODULE DEFINITION (CONT.)

MODULE	DESCRIPTION
`gas commands`	Gas system procedures are implemented as operator defined scripts of sequences of gas system commands, e.g., change gas, startup and shutdown procedures. Commands include open and close valves, read pressure transducers, set pressure set points and read thermistors.
	High-level Subsystem Command Layer
`mcascan`	Counter/aperture scanning program. The program is capable of performing a general 3-D scan with any counter/aperture pair. Consolidates all scanning calls from upper layers in one program and incorporates shutter (flapper) movements.
`mcadata`	Program is run every time data are taken with proportional counters. Clears the four MCA buffers, sets the requested integration time, starts the integration and stores the resulting spectra in an XDACS1 archive file. `mcadata` sends commands to the MCA command server (`mca cs`) and receives data from the MCA data server (`mca ds`).
`flapper`	Performs open/close operations on the four shutters located at the entrance to the VETA-I. The program is called from `mcascan` during alignment and focus tests such as `mcaalign` and `mcafocus`. Calls the low level `tma` program.
`xdamove`	Performs coordinated counter and aperture motor moves, backlash removal, applies offsets to current beam center if requested, determines if motors need to be moved based on current configuration and knowledge of motor accuracy, writes to high level motor log and file headers. Operates as an interface to the lower level `xdamain` program.
`hridata`	Program moves HRI to desired position and acquires a single image. Sends commands to the HRI via `hri` and makes motor moves with `xdamain`.
`gss`	Gas system commands, either single or as part of gas system procedures, are implemented as requests to the HP server (`hp serv`).
`mds`	Program is a client of the MDS server running on the MDS PC, makes a request every second for MDS data and passes average 1 second data to display. Stores raw and average MDS data in XDACS1 archive file.
	Low-level Subsystem Command Layer
`mca ds`	MCA data server returns MCA display client with data received from MCA PC. Communicates with MCA PC via TCP/IP.
`mca cs`	MCA command server passes MCA commands to the MCA PC via TCP/IP.
`tma`	Passes TMA commands to the TMA PC controller software via RS232. Performs low level string parsing, error checking and logging.
`xdamain`	The program interfaces with both the CAT and TMA motor controllers via IEEE 488 and RS232 respectively, to move motors and monitor motor status. Motor moves are made in either the XDA coordinate system (thereby hiding the motor specific coordinate systems) or in the motor specific system.
`hri`	Communicates with the HRI PC controller software via TCP/IP. Provides a command line interface to the HRI command set allowing exposure start and abort.
`hp serv`	HP server interfaces with the HP 3752A controller via IEEE488. Serves the `gss` client, performs bus level error checking and logging.
	Hardware Controller Layer
`MCA PC`	Software interfaces with the MCA hardware, passes on commands from the `mca cs` and returns data and status to the `mca ds` via TCP/IP. Data files are written directly to the XDACS1 archive via an NFS mounted disk.
`CAT Controller`	Sequences of COMPUMOTOR controller commands allow single axis motor moves and control parameters such as motor speed, limits and acceleration. The sequences are used by `xdamain` only and are not available to the operator.

TABLE 2: SOFTWARE MODULE DEFINITION (CONT.)

MODULE	DESCRIPTION
`TMA DACS`	The software was inherited from a previous test and was left unchanged. The `tma` and `xdamain` programs pass commands as strings which are executed as though they are typed by an operator at the TMA PC keyboard.
`HRI PC`	Software interfaces with the HRI electronics via a custom board and implements commands received via TCP/IP from the `hri` program.
`HP Controller`	The HP 3752A code is written in BASIC and applies the voltage-to-temperature transformation to thermistor readings, and sends and receives status from gas system commands.
`MDS PC`	Interfaces with the MDS hardware and executes the MDS data server process[3].
	Other Architectural Elements
`ANALYSIS`	Software called by programs in the `Test Procedure Commands` layer. Analysis routines were developed in the IRAF environment[4] and made available from the shell. File conversions into IRAF compatible formats are performed by analysis routines. Other analysis software available included `PVWAVE` and standalone programs.
`Data Files & Logs`	Programs in the `Subsystem Commands` layer generate the XDACS1 archive data files containing raw and processed data e.g., raw MCA spectra, reduced 1-D and 2-D scan data, and raw HRI images. Logs are created at this and higher levels, e.g., gas system commands and alarms, all scan motor moves and operator commands.
`Parameter Files`	Each command is associated with a parameter file containing the current values, allowed ranges, type and default values of all parameters required to execute the command. The set of all parameter files are maintained in a single directory and represent a parameter data base for the entire system. The parameter files may be accessed through either a parameter interface library or from the command line[5].

5. VETA DATA BASE AND ARCHIVE

During the VETA test a variety of data were archived by the XDACS1 including X-ray image data, proportional counter scan data (1D and 2D) thermal monitoring, gas system monitoring, motion stability measurements and other logging data.

The VETA test data archive was created during the VETA test as shown in Figure 3. Raw data streams were received from the various subsystems, processed and stored as formatted archive data. HRI and MCA X-ray data were stored together with a set of header keywords containing information about the data and test environment. Examples of header keywords include date, start time, finish time, integration time, operator, peak counts and filename. In the case of MCA scan tests two levels of data file were stored: raw spectra (one file for each point in the scan) and reduced scan data files containing the integrated counts as pixel values. In both cases header keywords were stored together with the data. The scan pixel values derived from the raw spectrum during the test represent "quick look" analysis since the integrated counts were derived by simply summing counts in a region of interest rather than correcting the spectrum for known physical effects.

In addition to the quick-look analysis performed during testing, more rigorous reduction and analysis was performed post-test that required flexible access to the archive. A set of data bases were constructed containing the header keywords generated during the test and information derived from the data file attributes. Data base queries typically generate a list of X-ray data filenames and their location within the archive.

The data base is comprised of four data base files in ASCII `/rdb` format:

- mcahriscn: common fields to both HRI and MCA data bases

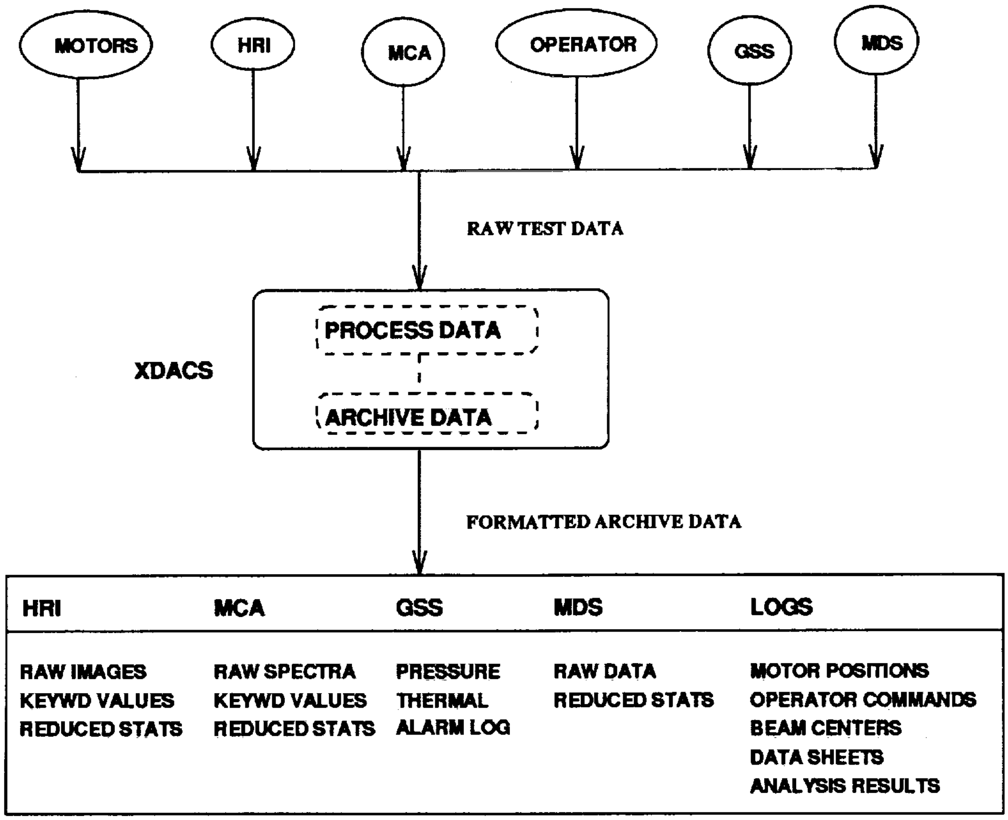

Figure 3: The VETA test data archive was constructed during the testing from both autonomous and non-autonomous data streams.

- hriscn: HRI image file keywords
- mcascn: MCA scan file keywords
- mcapch: MCA raw proportional counter spectra keywords.

There are numerous fields in the data base, for example the names of the first 10 fields (of 79) within the "mcascn" data base are: `scanId, apsize, aptype, bchan0, bchan1, counter, date, dcain, dcamv` and `dcbin`.

Queries are made using `/rdb` in the UNIX environment, for example the command:

```
column date filename aptype < mcascn | row 'aptype=="annulus"'
```

selects the fields "date", "filename" and "aptype" from the mcascn database and then selects only those rows with the aperture type of "annulus". In this example the commands "column" and "row" are `/rdb` commands.

Archive extraction functions were developed to retrieve subsets of autonomous data sets such as gas system, thermal and MDS data. These subsets are combined with the data files accessed through data base queries to construct time correlated test data sets. The process is usually performed automatically using a shell script.

6. SUMMARY

We have presented the network and software architecture of the X-ray Data Acquisition and Control System used to control, archive and display data during the AXAF VETA-I X-ray test. The key features of the network architecture include: diverse hardware subsystem control from a single SUN workstation, isolation of critical functionality on front-end controllers, integration of a variety of bus types and extensibility. The key features of the software architecture include: layered object oriented design, access to commands at all layers, client/server model, use of ksh for 4GL integration and extensibility. The VETA test data base provides convenient access to data stored in the data archive from the UNIX shell.

The VXDS system will form the basis for the next generation of equipment for testing of the assembled AXAF flight mirrors and science instruments. The software and network architecture developed for the VXDS system proved robust and will be extended to accommodate the new hardware anticipated for the next generation system.

7. ACKNOWLEDGEMENTS

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