

## Hardware Controls for the STAR Experiment at RHIC

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### *Abstract*

The STAR detector sits in a high radiation area when operating normally; therefore it was necessary to develop a robust system to remotely control all hardware. The STAR hardware controls system monitors and controls approximately 14,000 parameters in the STAR detector. Voltages, currents, temperatures, and other parameters are monitored. Effort has been minimized by the adoption of experiment-wide standards and the use of prepackaged software tools. The system is based on the Experimental Physics and Industrial Control System (EPICS) [1]. VME processors communicate with sub-system based sensors over a variety of field busses, with Highlevel Data Link Control (HDLC) being the most prevalent. Other features of the system include interfaces to accelerator and magnet control systems, a web-based archiver, and C++ based communication between STAR online, run control and hardware controls and their associated databases. The system has been designed for easy expansion as new detector elements are installed in STAR.

## I. STAR CONTROLS ARCHITECTURE

The STAR Hardware Controls system sets, monitors and controls all portions of the detector. Control processes are distributed such that each detector subsystem can be controlled independently for commissioning and optimization studies or be used as an integrated part of the experiment during data taking. Approximately 14,000 parameters governing experiment operation, such as voltages, currents, and temperatures, are currently controlled and monitored. When completed the full STAR detector will require the monitoring of approximately 25,000 parameters. Hardware Controls also generates and displays alarms and warnings for each subsystem. A real-time operating system is used on front-end processors, and a controls software package, EPICS, is used

to provide a common interface to all subsystems. Most of these parameters are saved to a database at different time intervals, and they can be accessed via a web-based interface. A three-story platform adjacent to the detector houses most of the electronics for the controls system. This area is normally not accessible during the run, creating the need for a robust controls system. A second set of electronics (primarily for the data acquisition system) is located adjacent to the STAR control room.

### **A. Data Controllers and Hosts**

The hardware controls system for the STAR experiment uses EPICS running on front-end processors consisting of 15 Motorola MVME147, MVME162, and MVME167 single-board computers with 680x0 processors using the VxWorks, version 5.2, operating system. These cards handle the flow of data from the hardware to the network, so they are referred to as Input/Output Controllers (IOCs). Each subsection of the Time Projection Chamber (TPC) – the cathode high voltage, the front-end electronics (FEE), and the gating grid – has its own separate IOC; the anode high voltage has two. In addition, IOCs are used for the readback of measurements on the field cage, the interlock system, and the environmental conditions in the wide-angle hall. All these cards are housed in 6U Wiener VME crates or in 6U slots in 9U Wiener crates. Also on the platform are IOCs for the trigger system, the Ring Imaging Cerenkov detector (RICH), the Silicon Vertex Tracker (SVT), the Forward Time Projection Chamber (FTPC), and the Barrel Electromagnetic Calorimeter (BEMC). Another IOC governs crate control for the electronics platform. Additional IOCs provide control for the data acquisition (DAQ) VME crates, as well as the interface to the accelerator and magnet control systems; these processors also monitor the RHIC clock frequency and the environmental conditions in the room housing the data acquisition system.

Through the VME crate's backplane, each IOC is connected to a Motorola MV712 transition module, which has one Ethernet and four serial ports. Each module has at least two external connections. There is an ethernet connection through which all the necessary software is uploaded from the Sun Ultra-10 host, and all the parameter values are broadcast from the IOCs over the local subnet. The uploaded software consists of the VxWorks operating system, device drivers, variable databases, and user-designed control programs. Any EPICS-configured computer on the subnet can access these parameters. The IOCs may also access parameter variables (channels) stored on other IOCs. All modules also have a serial connection, necessary for changing any boot parameters. On the electronics platform, all IOC serial connections pass through a Computone IntelliServer serial port server, allowing this access pathway to be open at all times, even when the platform is not accessible.

The system is designed to allow continuous operation. With a single exception, if an IOC fails the hardware will retain the last value loaded; the exception is the FEE controller where the nodes are powered down when the corresponding IOC loses communication with the hardware. The failure of the host will not affect the operation of an IOC unless the IOC is rebooted while the host is down; IOC broadcasts will continue to be received by any remaining hosts on the network. A second SUN workstation is configured to serve as a backup host if the primary should go down. Front-end units can also be reset by remotely powering down the electronics. As will be discussed, these are relatively rare occurrences.

## **B. Field Busses**

The experiment uses the same field bus to access the front-end electronics throughout the experiment. Highlevel Data Link Control (HDLC) protocol communicating over an RS-485 link was selected for this purpose [2]. It was selected because of its ability to provide a 1 Mbit/s bandwidth communication over a distance of approximately 30 meters in the presence of a 0.5 Tesla magnetic field with a minimal amount of cabling due to a multi-drop topology. The independent access path to the front-end board memories allows the easy identification of any malfunction in the readout boards. The HDLC link has been interfaced with the EPICS software. A number of control and monitoring tasks can be performed [3]. The VME interface to HDLC is a Radstone PME SBCC1 board, which can support up to four HDLC channels. Each HDLC channel configures the readout of a single super-sector of the TPC by communicating with six readout boards. HDLC is also used for three upgrade detector subsystems (SVT, BEMC, and FTPC). On the readout boards, STAR-developed mezzanine cards received the RS-485 signals and decoded HDLC commands. The mezzanines were built around Motorola 68302 processors which communicated with the readout boards via memory mapping. Events were read out using this field bus during testing periods for the TPC, SVT, and BEMC.

CANbus is used to control the VME crates. The operation of CANbus can be found elsewhere [4]. CANbus will also be used to communicate with some of the upgrade detector modules.

Some of the subsystems use devices controlled by GPIB. For these devices, a National Instruments 1014 GPIB controller card is used, both the two-port and single-port models.

## **II. SOFTWARE DEVELOPMENT AND THE USE OF EPICS**

EPICS was selected as the foundation for the STAR control software environment because it incorporates a common means of sharing information and services and provides standard graphical display and control interfaces. EPICS was designed and is maintained by Los Alamos National Laboratory and the Advanced Photon Source at Argonne National Laboratory as a development toolkit [1].

The STAR controls system was developed at a number of remote sites with the initial system integration taking place at Lawrence Berkeley National Laboratory for cosmic ray testing of a single TPC super-sector [5]. Final integration occurred at Brookhaven National Laboratory. To expedite the integration process, a number of design rules were instituted from the start [6]. The development tools were standardized and toolkits were implemented at all collaborating institutions [7].

EPICS was selected as the source for these tools. The components of EPICS used by STAR are the Motif Editor and Display Manager (MEDM), the Graphical Database Configuration Tool (GDCT), the sequencer, the alarm handler (ALH), and the data archiver.

MEDM is the graphical software package used to access the contents of records. Its point-and-click edit mode and user-friendly execute mode allow for ease-of-use by users unfamiliar with the

details of the system. MEDM provides an operator interface with full-color, window-based screens that mimic control panels. The top level EPICS user interface for STAR is shown in figure 1.

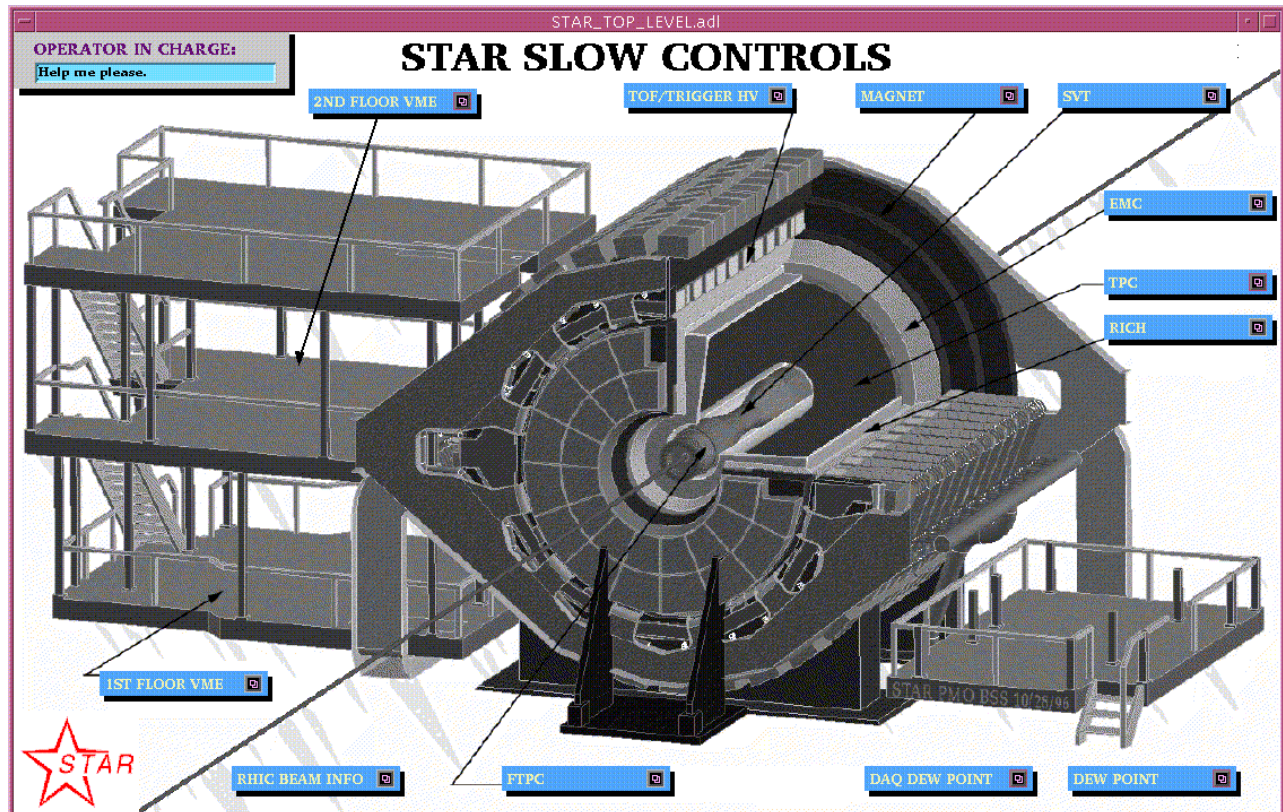


Figure 1. Top-level operator interface for STAR.

GDCT is the design tool for a distributed, runtime database that isolates the hardware characteristics of the I/O devices from the applications program and provides built-in, low-level control options. In certain applications, an EPICS sequencer was used to implement state-based control in order to support system automation. Its State Notation Language adds more features to the database design, such as an I/O connection with the host machine and the flexibility of controlling the individual records within the database. The alarm handler displays the alarm status hierarchically in real time. A data archiver acquires and stores runtime data and retrieves the data in a graphical format for later analysis. An interface to a channel access program establishes a network-wide standard for accessing the runtime database. The structure and software configuration of EPICS is shown in figure 2.

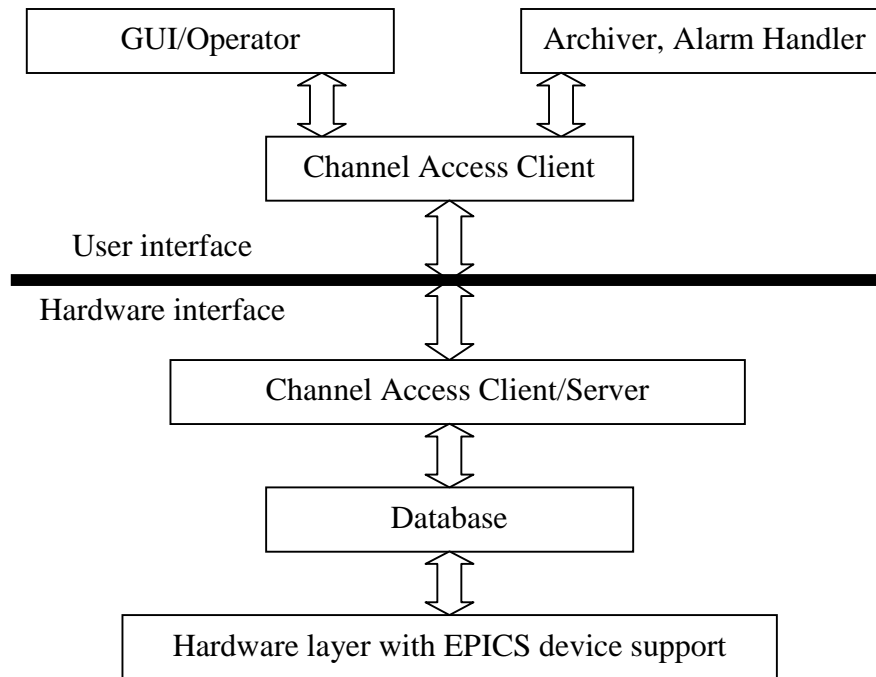


Figure 2. Structure of EPICS with interfaces to hardware.

Graphically configured databases are easier to maintain over the lifetime of the experiment, because they lack the need for extensive documentation. Graphical interfaces provide a better sense of data processing and flow than processes coded line by line. In a further effort to enhance long-term maintenance, efforts were made to limit the number of different interfaces that would be supported.

EPICS provides a straightforward method for keeping track of problematic parameters. In alarm mode, nominal values are displayed to the detector operator in green, minor deviations are displayed in yellow, and major problems are in red. If a given channel cannot be properly measured, the default color is white. An alarm handler program, run from the host, monitors selected variables, and emits an audible alarm if any channel deviates from its nominal value. In addition to displaying the color associated with the level of the alarm, the alarm handler shows a letter, for operators incapable of discerning color. The alarm handler also provides a system-wide status display and easy access to more detailed displays, related control screens and potential responses for system operators.

STAR uses a web-based archiving program, the Channel Archiver, for storing old data. A program running on the host machine reads and saves to disk a large percentage of all slow controls variables at regular intervals, ranging from once a minute to once an hour. A Common Gateway Interface (CGI) script enables a user to access past data by specifying the variable name and time range. The user can view the data in a plot or in tabular form.

### **III. BASELINE STAR DETECTOR CONTROLS**

Controls systems were developed as hardware construction progressed for most of the baseline detector components [8]. This eliminated the need for the development of controls systems for test setups, and gave the users and developers early experience with the system. Databases were constructed on the subsystem level, as such they can be used for subsystem testing and still be easily included in a larger detector configuration.

The controls system for the baseline STAR detector consists of various TPC subsystems (anode high voltage, cathode high voltage, field cage, gating grid, front-end electronics power supply, HDLC link, gas, laser, interlocks, and VME-rate control), mechanisms for the exchange of information with the STAR trigger and decision-making logic, as well as external magnet and accelerator systems.

### **IV. TIME PROJECTION CHAMBER CONTROLS**

The main tracking device in STAR is a cylindrical TPC, 4.18 meters in length with inner and outer radii of 0.5 m and 2 m respectively. The components have been described elsewhere [9].

#### **A. Anode Controls**

Two LeCroy 1458 power supplies provide high voltage to the 192 anode channels. Each supply is controlled by a separate IOC. ARCnet is used to communicate between the controlling IOC and its respective power supply. Serial connections to both LeCroy supplies are used in the case of an ARCnet crash. In normal operating mode, all inner sectors are set to one demand voltage, and all outer sectors are set to a different demand voltage. However, the demand voltages, current trip level, and voltage ramp rate can each be set on a channel-by-channel basis. The voltage and current are ramped, set and monitored using EPICS sequencer programs.

The ARCnet driver is adapted from one developed at Thomas Jefferson National Accelerator Facility Hall-B. The communication between control panels and the ARCnet is accomplished using EPICS subroutine records.

#### **B. Drift Velocity Controls**

The cathode and field cages create a nearly uniform electric field in the TPC. Any changes in the gas temperature, pressure, or composition can affect the drift velocity. The drift velocity is determined by illuminating the TPC central membrane with a laser, and measuring the time it takes for the signal to reach the TPC endcaps. A feedback loop has been implemented to adjust the field cage voltage to maintain a constant drift velocity over minor variations in the TPC gas pressure.

For the cathode high voltage, a Glassman power supply is used. It is controlled by four modules made by VMIC: a 64-bit differential digital input board (model #1111), a 32-channel relay output board (model #2232), an analog-to-digital converter (model #3122), and a digital-to-analog converter (model #4116). There is also a feedback loop that can be used to optimize the drift velocity of the TPC.

The inner and outer field cages include chains of resistors between the cathode and the anodes that determine the voltage gradient within the chamber. A Keithley 2001 digital multimeter is used to measure the voltages and currents along the chains. A Keithley 7001 switch is used to cycle through each of 13 measurement points: the current drawn by each of the four chains (an inner and an outer for the east and west sides of the TPC), the voltages before each of the last two resistors on each chain, and the current drawn by the ground shield. A National Instruments 1014 GPIB controller card is used to communicate with the two Keithley meters.

A high-power laser is used to ionize the TPC gas to create apparent straight tracks, which are used to calibrate the TPC drift volume. It also ionizes stripes on the TPC central membrane which can be used to measure the electron drift velocity in the TPC. Hardware Controls monitors and sets the laser status through a VMIC 32-channel relay output board. The same IOC used for controlling the cathode high voltage is also used for controlling the laser power supply.

### **C. Front End Electronics Controls**

There are 4344 front-end electronics (FEE) cards in the endcap regions of the TPC for amplifying, shaping and digitizing signals from the TPC pad plane [2]. The FEE cards are read out and controlled by 144 readout boards, and the 144 power supplies for these boards are controlled and monitored with a set of Acromag 948x cards.

An HDLC field bus link using six Radstone PME SBCC-1 cards can be used for debugging the readout and FEE boards. This controls link is used to configure the front-end cards for data taking at startup. In addition, the HDLC controls link can monitor voltages on the TPC readout boards and control the power on FEE cards (in groups of four). When testing, a bit pattern can be sent using the HDLC link to a readout board to initiate the creation of an analog pulse. The FEE cards that are connected to the readout board will receive the pulse signal, then amplify and digitize it. A comparison of the output data with the input data pattern facilitates an examination of the operation of the event memory buffer and the electronics. To detect cabling errors, each of the FEE boards and readout boards is tagged with a geographical address. The digitized data can be routed to the buffer on the readout boards or directly to DAQ via a fiber-optic link. If the data is sent to the buffer, it can be read back by Hardware Controls via the HDLC link. A comparison of the data between Hardware Controls and DAQ allows the integrity of the data acquisition and HDLC paths to be verified. HDLC will also be used for three other recently commissioned detector subsystems.

### **D. Gas System Controls**

A PC, running Windows NT and located in the gas room, performs the gas system measurements. Every minute, the parameters are saved to a remote disk, from which are read by the same IOC that communicates with the interlock system. In a similar manner, another NT machine measures the temperature at different places within each TPC sector, and the same IOC reads them from disk. The implementation of an EPICS frontend was not cost effective since the gas system was developed in Russia using interfaces developed especially for the STAR experiment [10].

## **E. Gating Grid Controls**

Specialized control electronics were developed for the gating grid. Its control cards reside in a VME crate on the electronics platform. EPICS drivers have been written to control the potentials on the gating grid and to monitor its status. A set of custom-designed 6U cards and a set of 9U cards control the gating grid.

## **F. Safety Interlocks**

The interlocks system for the TPC is not controlled by slow controls, but an interface exists so the status may be read out remotely. An IOC queries the Allen-Bradley programmable logic device (PLD) one 16-bit word at a time. The IOC also receives information on the four flow rates for the TPC cooling water (east and west, top and bottom) and the methane content in the outer field cage insulation gap. Additional systems monitor temperatures, humidity and cooling water flow. The safety interlock system is controlled using an Allen-Bradley PLC system. This standalone system passes status information via TTL signals to a STAR frontend, an Acromag 948x digital I/O board. STAR hardware is designed to be failsafe. All required personnel and property protection is mandated to be independent of STAR Hardware Controls.

## **V. EXPERIMENT INFRASTRUCTURE CONTROLS**

### **A. VME Crate Control**

STAR detector electronics controls are housed in 24 6U and 9U Wiener VME crates. Since during run time there is no access to the platform where these crates are physically located, remote control of the VME crates is required. This is achieved through a built-in CANbus interface. The CANbus is controlled through a Greenspring 6U CANbus controller card. There are two separate Wiener power supply daisy chains: one for the detector electronics, and one for the twenty-one DAQ crates. A separate IOC controls each chain, although the setup is identical. The control programs for 6U and 9U are essentially the same. In addition to controlling the power status of each crate, the IOC controls and monitors the speed of up to six fans, monitors the voltage and current on up to four power supplies, and monitors the bin, air, and power supply temperatures. The system can also issue a bus reset for each crate. All the VME crates are daisy-chained with a unique crate address assigned to each. To allow an orderly transition of the system during a power shutdown of short duration, uninterruptable power is supplied to the crate housing the CANbus interface as well as to the platform ethernet hub, and terminal server.

### **B. Temperature and Humidity Monitoring**

The STAR experiment uses two hygrometers, one on the platform and one in the DAQ room. Cole-Parmer hygrometers measure the ambient temperature, dew point temperature, and relative humidity. An IOC reads the information as an ASCII stream through a serial port connection in each area.



## VI. ACCELERATOR INTERFACE

Not all of the information needed during a run can be measured directly by STAR instruments. A Control DEvice (CDEV) client/server interface is used to exchange data with the RHIC controls system [11]. There is a single network connection between the client and the gateway through which all CDEV requests are routed. This gateway receives a request from the client (STAR), establishes an appropriate connection to the actual service that is requested, and returns the results to the client application program interface which is running on one of the host SUN workstations. The information is then passed using channel access to one of the IOCs, so it may be monitored and archived in the same way as all other slow controls variables. The schematic representation of this connection is shown in figure 3.

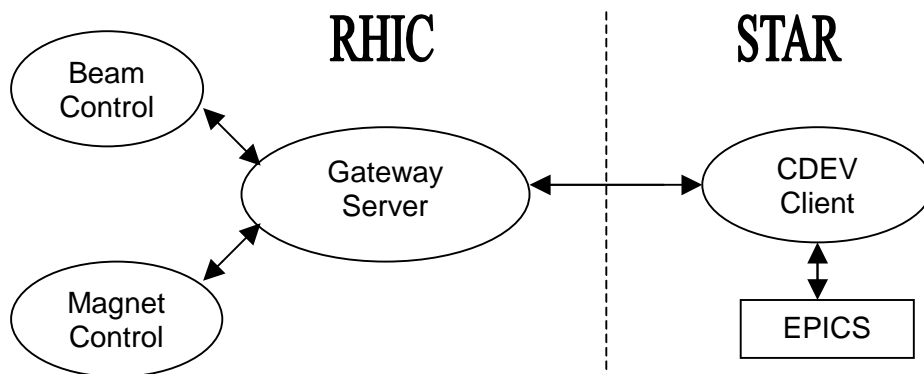


Figure 3. Gateway service between RHIC and STAR

### A. STAR Magnet Controls

A solenoidal magnet surrounds the TPC. It provides a 0.5-Tesla magnetic field, allowing for momentum measurements on the charged particles that pass through the TPC. The magnet is operated as part of the accelerator controls system. Information transferred includes the voltages, currents and status information on the magnet's five power supplies. Similarly, the potential exists for STAR measurements of the magnetic field to be transmitted to the accelerator group using CDEV.

### B. Accelerator Operating Parameters

RHIC provides STAR with many of the collider's parameters, including, but not limited to, the energy, ion species, integrated intensity, and bunched intensity in each beam. Beam scalar information and the STAR experiment status are also provided to the RHIC control group.

## **VII. TRIGGER CONTROLS**

### **A. Trigger Barrel High Voltage**

Based on rapidly digitized distribution information for each RHIC beam crossing, the trigger system determines whether or not to initiate recording of a particular event. A LeCroy 1440 high-voltage power supply is used to provide high voltage to the phototubes inside the Central Trigger Barrel (CTB) detector. Hardware Controls monitors and sets the voltage on each channel of the LeCroy 1440 via an RS232 serial connection. Communication is accomplished using the subroutine records. New subroutine functions were written for this purpose. Additional support for VME access to STAR-specific CTB trigger boards has been written.

### **B. RHIC Clock Frequency Monitor**

A Philips PM6669 frequency counter is used to measure the RHIC clock frequency. A separate National Instruments 1014 GPIB controller card is used to interface with the IOC.

### **C. Multiwire Proportional Chamber Controls**

The TPC anode wires were instrumented and read out to measure the charged particle multiplicity passing through the TPC endcaps on an event-by-event basis, for use in the trigger. The low-voltage power supplies for these FEE's were configured exactly like those for the TPC. These controls were then included in the controls for the TPC FEE's.

## **VIII. ADDITIONAL DETECTOR CONTROLS**

The TPC was the first operational detector at STAR, so its control system was the first to be developed. As each additional detector was included, choices of hardware components were made based on existing systems to eliminate the need for new device drivers. The TPC controls software provided a basis from which the controls software for newer detectors could be developed. [12]

### **A. Ring Imaging Cerenkov Controls**

The RICH uses a slow controls system closely patterned after that of the TPC. High voltage for the anode channels is provided by a LeCroy 1454 power supply, communicating via ARCnet. Low voltage for the electronics is provided by Wiener UEP6/PL5 power supplies, controlled via the CANbus network that controls all VME crates. The gas system is controlled and interlocked via an independent Allen Bradley SLC-based system, which communicates its status to the slow controls via a VMIC VMIVME-2510B TTL I/O unit. In addition, two general-purpose analog I/O boards, VMIC VMIVME-3122 and VMIVME-4116, provide control and readout for smaller portions of the system.

### **B. Silicon Vertex Detector Controls**

The SVT uses two LeCroy 1458 high-voltage power supplies controlling 72 channels. A single Radstone PME SBCC-1 card provides the field bus interface to FEE voltages, detector

temperatures and currents, and readout parameters. An NI-1014 GPIB controller card is used to control a Keithley 2700 multimeter, which measures cooling system parameters, an HP E3640 power supply and a Wavetek 81 pulse generator. The power supply controls a laser mounted on the outermost layer of the detector; the pulse generator produces injector pulses used for calibration. A different driver for the HDLC protocol is used, and it is controlled using EPICS subroutine records. The interlocks system for the SVT differs from other subsystems in that it uses relays connected to two Acromag 9480 digital I/O cards. This relay system is controlled by the Acromag cards to power the low voltage power supplies, and it provides permission for low voltage and high voltage by using STAR global interlocks and several SVT-specific interlocks.

### **C. Forward Time Projection Chamber Controls**

The slow controls system for the FTPC closely resembles the main TPC system as far as hardware and software are concerned. As with the central TPC, a LeCroy high voltage power supply powers the anode channels; the FTPC uses model 1454. The low voltage power supplies are controlled via HDLC with Radstone PME SBCC-1 and Acromag 948x cards, with exactly the same setup as the central TPC. The cathode high voltage comes from two Heinzinger power supplies which are controlled by a GPIB card.

### **D. Barrel Electromagnetic Calorimeter Controls**

For 2001, the BEMC will have a LeCroy 1450 high-voltage power supply, a Radstone PME SBCC-1 card using HDLC, and a GPIB controller card to communicate with an Agilent E3640A DC power supply and a BNC 555 pulse generator.

### **F. Future Detector Controls**

The time-of-flight detector presently uses its own slow controls system with CAMAC crates. Its values are saved to disk, and read by one of the IOCs, so the values can be archived.

A Silicon Strip Detector (SSD), a Photon Multiplicity Detector (PMD), and an Endcap Electromagnetic Calorimeter (EEMC) are currently being developed for future installation. The controls for these systems will be based on the current STAR configuration.

## **IX. INTERFACES TO OTHER STAR REAL-TIME SYSTEMS**

During the first year of running, slow controls was operated independently of other STAR online systems. As the first data-taking run progressed, an increasing number of slow controls parameters were transferred to the online database. As run control transitioned from one operating state to another, detector operators configured various detector components. Alarm systems were activated when an operator identified a sub-detector as ready for inclusion. Procedures carried out manually during the first year of running are being automated; at present, the cathode, anode, and gating grid programs have all been reduced to single-button controls, under ideal operating conditions. Hardware Controls receives the operating state from the run control system as a client. Hardware controls is also capable of pausing a run without operator intervention through the run control system when a major fault is detected. Data acquisition obtains hardware parameters from the

online database. Less than 50 of these parameters are included in the data stream. The relationship of the STAR Hardware Controls to other systems is shown in figure 4.

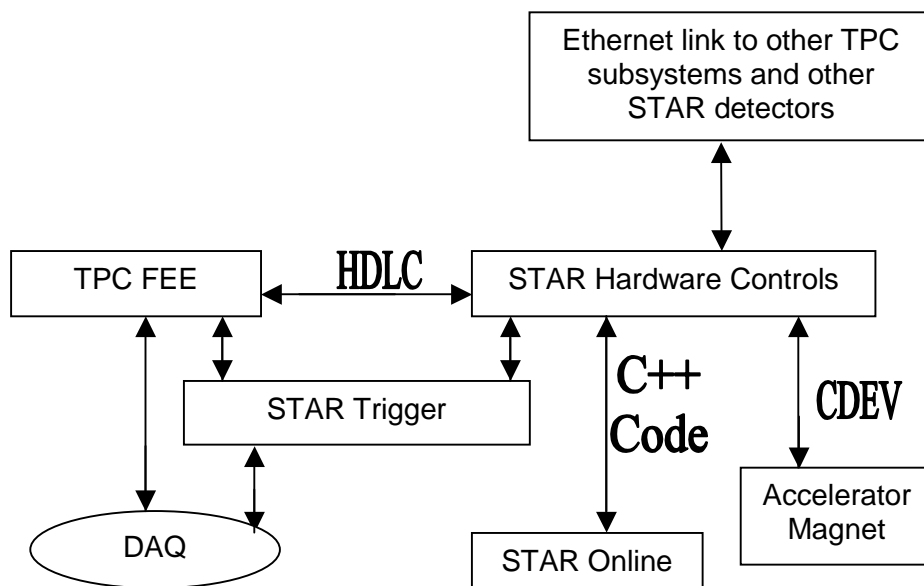


Figure 4. STAR Real-Time Systems.

## X. PROJECT ASSESSMENT

The integrated system operated effectively during the commissioning and data-taking runs. Less than 2% of the experiment's dead time could be attributed to hardware controls. The largest limitation was the speed of a single ARCnet interface to the TPC anode high voltage. The connection was slow and prone to crashing even during "stable" operations. Fortunately, this system needed to be fully functional only at run startup and shutdown. The LeCroy HV supplies maintained the preprogrammed values, allowing uninterrupted operation of the TPC. The introduction of a second controller and ARCnet interface significantly reduced this problem. The second item of concern resulted from system developers being located at remote sites during run time, delaying the process of upgrading code. This difficulty is being alleviated as more system experts are trained.

## XI. SUMMARY

STAR Hardware Controls maintains the system-wide control of the STAR detector with its EPICS databases at the subsystem level. The system developed contains a number of new EPICS implementations. HDLC provides the field bus used by the experiment for controls and as an alternate data path. Data transfer to and from external magnet and accelerator control systems is accomplished using CDEV. The fully integrated system began operation as part of an engineering run during the summer of 1999 and has continued through first year of STAR data taking. Additional detectors have been included for the second year of STAR running.

## XII. ACKNOWLEDGMENTS

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