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A Structured Architecture for Advanced Plasma Control Experiments*

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Recent new and improved plasma control regimes have evolved from enhancements to the systems responsible for managing the plasma configuration on the DIII–D tokamak [1]. The collection of hardware and software components designed for this purpose is known at DIII–D as the Plasma Control System or PCS [2]. Several new user requirements have contributed to the rapid growth of the PCS. Experiments involving digital control of the plasma vertical position have resulted in the addition of new high performance processors to operate in real-time. Recent studies in plasma disruptions involving the use of neural network based software have resulted in an increase in the number of input diagnostic signals sampled. Better methods for estimating the plasma shape and position have brought about numerous software changes and the addition of several new code modules. Furthermore, requests for performing multivariable control and feedback on the current profile are continuing to add to the demands being placed on the PCS.

To support all of these demands has required a structured yet flexible hardware and software architecture for maintaining existing capabilities and easily adding new ones. This architecture along with a general overview of the DIII–D Plasma Control System is described. In addition, the latest improvements to the PCS are presented.

1. INTRODUCTION

The architecture designed for the PCS has been demonstrated to provide a reliable framework which has been well suited for the implementation of numerous control schemes. Current capabilities of the PCS include feedback control of various discharge attributes such as plasma shape and position, total plasma current, plasma energy, particle density, magnetic field error correction, loading resistance for the rf antennas, and amount of radiation from the plasma. In order to achieve feedback control in the PCS, a number of tasks are required, including processing user inputs, synchronizing with the DIII–D discharge cycle, sampling data from the tokamak, performing the real-time feedback calculations and sending the necessary control commands to the various tokamak "actuators" or output control devices such as the magnetic coil power supplies, and gas valves (Fig. 1.).

2. RUN TIME SYSTEM

The primary users of the PCS are DIII–D physicists responsible for defining the characteristics of the discharge. From the standpoint of users, the PCS is a single application. In actual operation, the PCS is comprised of several programs or "processes" active at run time. This PCS run time system is organized into three types of processes which include, the user interface, the real-time feedback control and the coordinator processes which synchronize the PCS with the discharge cycle.

2.1. User Interface

For any given discharge there are literally hundreds of parameters required for defining a plasma configuration. To simplify the task of specifying these values, a graphical user interface to the PCS has been developed.

The primary type of input to this interface is a generic construct called a "waveform". Waveforms specify values which are to be used by a set of feedback control routines. Waveforms are entered by users onto a two dimensional display grid showing the discharge time, and desired input as it may evolve over this time period. There are hundreds of possible waveforms which can be modified in the user interface. In a typical discharge, most values remain untouched by the user or are simply loaded in from an archive of a previous discharge. Some examples of waveform data include target values for

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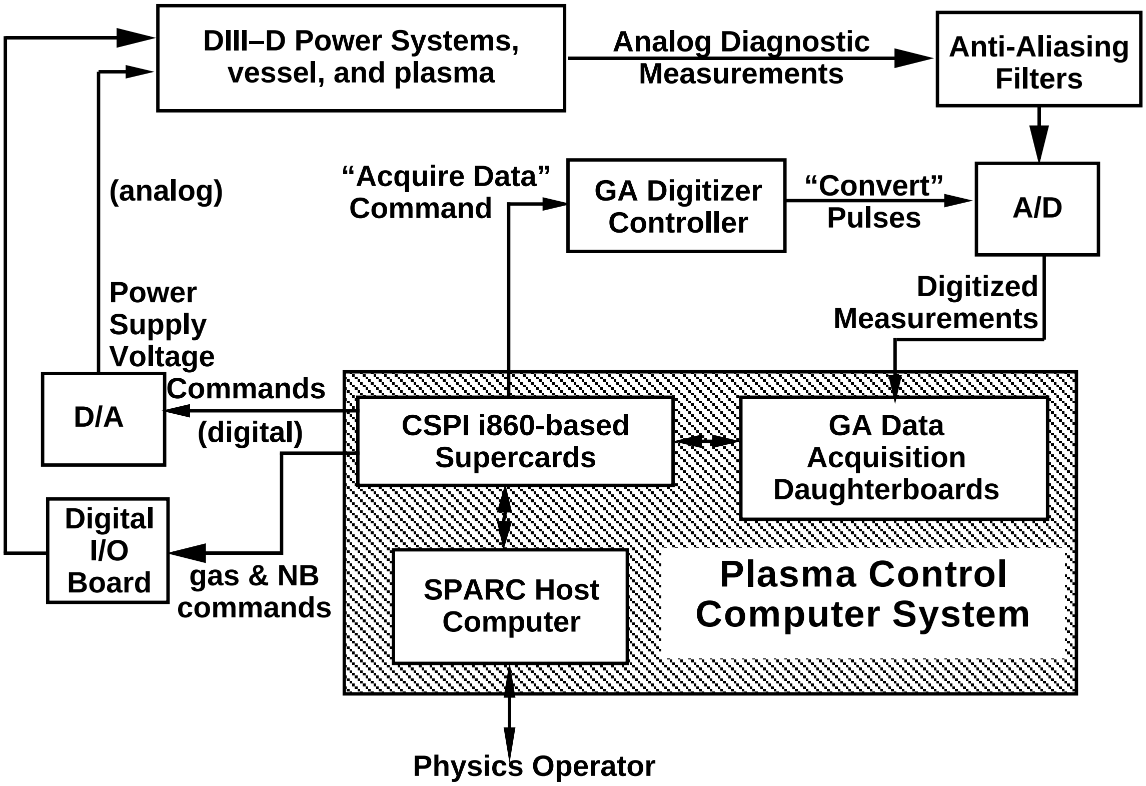

Fig. 1. DIII–D digital plasma control system (PCS) block diagram.

specifying the plasma position (inside gap distance, top gap distance, vertical position), desired density, gas flow rate, and beam modulation.

Waveforms are grouped according to the "algorithms" to which they supply inputs. An algorithm is a collection of one or more routines which execute in real-time to perform a specific function. One basic type of algorithm function is feedback control. There are numerous algorithms implemented in the PCS which serve this function. The most common are algorithms for achieving a desired plasma configuration. Examples are the algorithms for creating single and double null divertor shapes. Other kinds of control include neutral beam modulation and density feedback. Algorithms can also be used to perform calculations in real-time or execute tasks such as collect the base line data for the input signals.

The method for keeping related algorithms together in the PCS is the "category". A category is a grouping typically based on the type of actuator involved. For example, the plasma shape category groups algorithms responsible for performing feedback control for the plasma shaping coils. Another category for gas algorithms includes all routines which control the gas valves. The current implementation of the PCS contains eleven categories which include shape, density, gas, plasma current, power supplies, error field correction coils, rf, neutral beams, equilibrium, alarms and current profile.

2.2. Real-Time Subsystem

The real-time component of the PCS employs several high speed processors running in parallel to perform the calculations required for feedback control. Each real-time processor is responsible for performing one or more specific tasks. In the current PCS setup, there is a processor assigned to the primary shape control, one which serves as the master for triggering data acquisition on all of the processors and also performs vertical position control, another dedicated to running an algorithm for predicting plasma disruptions, and a set of processors which are used in a real-time equilibrium reconstruction calculation.

Each processor is capable of communicating with any other over a single VME bus. The processor for primary shape control sends its calculated commands to the processor for vertical position control on each control cycle. The processors for equilibrium calculations also communicate various pieces of information between themselves and the other processors.

The master processor runs at the highest speed of approximately 60 μs per cycle. The processor running primary shape control, has a cycle rate of about 400 μs. Data sampled from the tokamak for use in feedback calculations is available to each of the processors. The data is sampled at the rate of the fastest processor and written directly into the memory of each processor and made available on each cycle.

During a control cycle each processor performs the following tasks. A processor first acquires its latest set of input data from the tokamak after a trigger to start data acquisition from the master has arrived. The errors for a specific type of control algorithm are computed by comparing user specified target values against actual measured values from the input data. If specified, a routine to perform some transformation of the error values such as a Proportional Integral Derivative Gain filter is executed. The resultant error along with other parameters input by the user such as gains from a matrix, an output offset or cutoff values are used to derive the commands that are sent back to the tokamak for control.

2.3. Coordinator Processes

The PCS is designed to run synchronously with the DIII–D discharge cycle. A separate computer system is responsible for setting triggers which cause the PCS to transition through different discharge cycle states. At each of these states the PCS performs tasks specific to the current state it is in, such as processing inputs, locking out users from making any more changes to the discharge parameters, setting up and running the real-time feedback control, and archiving data collected once a discharge is complete. The tasks associated with each of these states and the transitioning between states is accomplished by a group of coordinator processes.

A waveform server process, or “waveserver” is used to gather and coordinate raw inputs from one or more user interfaces and convert the inputs into data needed by the real-time computers. The waveserver process manages the entire set of discharge parameters and supplies the latest information about the parameters to other requesting processes.

A lockout or “lockserver” process is responsible for coordinating all of the PCS processes to synchronize with the DIII–D discharge cycle and to transition the PCS from one state to the next. The lockserver monitors the triggers which are sent from other DIII–D computer systems.

A set of routines referred to as the “host real-time client” processes, executes shortly before the discharge to load information from the waveserver into the memory of a single real-time processor. These routines are also used to start and monitor the processing on the real-time processors at the start of a discharge. At the end of the discharge, the routines evaluate and report the return status from the real-time computers and archive the results obtained.

3. HARDWARE

Hardware for the PCS consists of the computer needed for the run time system and the interface between the PCS and the tokamak. The user interface requires an X display terminal or workstation. A unix based SparcStation server is used to run the coordinator processes. The computer for the real-time routines is the SuperCard-2 manufactured by CSP inc, a VME format, single board computer based on the Intel i860 RISC-design microprocessor.

The input from the tokamak to the PCS comes from 208 analog signals that originate from various places within the DIII–D vessel. The types of signals sampled include inputs from flux measurements, magnetic probes, measured poloidal field coil currents, chopper voltages, bus voltages, ohmic heating coil currents, soft X–ray signals, and loop voltages. The analog signals are digitized using eight channel DSP Technology TRAQ digitizers. Data from the digitizers is dumped into the memory of the real-time computers using a General Atomics custom designed data acquisition daughter board.

The output ifrom the PCS to the tokamak is through a set of five DATEL Inc., eight channel D/A converters and a VME microsystems digital I/O board. The D/A converter channels include outputs to poloidal field coil power supplies, channels for control of the rf transmitters, channels for the C supplies, a single E supply channel, d.c. power supply channels, gas valve channels and channels reserved for future use. The digital I/O board ports are used to send commands which control neutral beams, gas wave enables, a lithium pellet injector and an oak ridge pellet injector.

4. SOFTWARE

The PCS software consists of a collection of over 500 source files written mostly in C, assembly and a separate high level language for implementing graphical user interfaces. The source is organized into an infrastructure library, installation specific code and application specific code.

An infrastructure library contains code for implementing a generic real-time control system. Contained here are a number of routines which can be used in defining basic user interfaces and server processes. The installation specific source contains the hardware dependent specifications which would vary across different installations of the PCS. Different installation attributes which can be specified include the number of real-time computers used, number and types of input diagnostic channels to be sampled, and characteristics of the outputs such as number of D/A converter channels and purpose for each. The application source includes the code for specifying the types of control categories and algorithms available with the PCS.

The PCS software architecture is built upon a framework consisting of “master” files. A master file contains the definitions and source code for implementing specific functionality. Three kinds of master files are used. These include the category, the algorithm and the cpu masters. Each of these master files contains most of the information necessary for implementing new categories or algorithms or adding new real-time processors to the PCS.

5. RECENT DEVELOPMENTS

The PCS has been upgraded to employ six high speed real-time processors. A number of new diagnostic input channels have been added including signals to provide better information for determining the precise plasma shape and position. Approximately fifty different control algorithms are now available.

Digital vertical position control of the plasma tested in late 1995 has been incorporated and made available for everyday operations use. Steady progress has been made toward true multivariable control of plasma shape and position.

An algorithm known as “real-time EFIT” or rtefit which provides real-time estimates of flux values at chosen poloidal (r,z) locations has been implemented and tested on DIII–D. The rtefit algorithm is based on the EFIT code [3] which has been used for plasma equilibrium reconstruction at GA for several years. Data from flux loops, magnetic probes, and Motional Stark Effect (MSE) channels, are processed to produce the estimated plasma equilibrium.

A control technique known as isoflux control [4] which controls flux at designated poloidal “control points” has also been implemented and used for real-time plasma shape control. This technique exploits the improved accuracy in plasma shape estimation (as defined by flux contours) available from the rtefit algorithm.

6. SUMMARY

A structured system architecture for implementing advanced plasma control experiments has been described. Working within this framework, users at DIII–D have been able to demonstrate a number of new and different types of control capabilities, ranging from digital control of the plasma position to control based on flux at poloidal control points. With more enhancements, and even more control requirements being generated each day, the need for maintaining a structured and well defined system architecture for the DIII–D Plasma Control System increases in importance. A structured architecture for the PCS has resulted in a control system which has proven to be highly reliable despite undergoing numerous changes.

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