Latest Advancements in DIII-D Plasma Control Software and Hardware

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Abstract—**A number of important software and hardware changes have recently been made to the DIII-D Plasma Control System (PCS) to further its capabilities in support of fusion research. The PCS is a highly customizable real-time control application developed at General Atomics used to manage the many parameters that affect plasmas produced on the DIII-D tokamak. Included in the most recent updates to the PCS are refinements to the real-time Electron Cyclotron Heating (ECH) capabilities which have improved overall performance and reliability for fast and precise aiming of the mirrors used to control direct ECH power into the plasma. The introduction of new real-time streaming data acquisition hardware has provided a means for acquiring plasma electron temperatures and densities from the Thomson scattering System along with data from the Electron Cyclotron Emission (ECE) diagnostic for use in PCS feedback control algorithms. The new fiber optically connected streaming digitizers allow PCS computers located in one part of the tokamak facility to easily communicate with remotely located diagnostic systems in other parts of the lab, in addition to being able to transfer high frequency data (sampled at 500 Hz) for a large number of channels in real-time. Details of the most recent PCS enhancements will be provided along with a more thorough description of the latest software and hardware architecture.**

I. Introduction

The DIII-D PCS is a real-time data acquisition and feedback control system that provides a structured yet flexible and easily expandable framework for rapid development, testing and deployment of complex control algorithms for fusion tokamaks. Initially developed at GA for plasma shape and position control on the DIII-D tokamak it has since been adapted for use on a number of collaborative fusion experiments worldwide [1]. The PCS software consists of an infrastructure library core which provides all the routines that are necessary for implementing a basic and generic control system, and a set of installation specific routines which are used to customize the control system for use on a given tokamak. PCS software also includes a set of common codes, which can be shared between different tokamak sites including sources for performing real-time equilibrium reconstructions [2] and routines for implementing Proportional Integral Derivative (PID) controllers.

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A number of testing options are available in the PCS to assist in the development and validation of new control capabilities. A simple software test operation mode allows users to run the complete collection of PCS real-time processes from a single computing platform in a non real-time environment. This allows users to easily test changes to the PCS software without requiring access to all of the real-time computers and data acquisition hardware that are necessary for running the full operations version of the code. A data software test mode allows users to exercise PCS control algorithms by feeding them diagnostic information obtained from previous plasma discharges. This has been particularly useful in demonstrating reproducibility of PCS results and determining how changes to the software may affect the outputs. A third PCS testing option referred to as software simulation mode provides a closed loop simulation environment in which a custom tokamak simulation process sends data to the PCS and receives back commands computed by the PCS algorithms at the end of a control cycle. These commands can then be used by the tokamak simulator to modify the set of data that will be sent back to the PCS on the next control cycle, in accordance to a specific model of the tokamak's expected behavior. This specific test capability [3] has been highly effective in speeding up development of new control techniques for DIII-D [4] and played a critical role in the validation of the initial implementations of the EAST and KSTAR versions of the PCS. A fourth PCS testing option known as hardware simulation test mode allows users to test the complete PCS installation on the actual hardware used during operations. In this test configuration, data from a previous discharge is preloaded into PCS memory and used in place of the data that would normally be acquired by the PCS acquisition hardware during live plasma discharges. This test provides a means of validating all software changes in an environment that is closest to how the PCS would typically be used during DIII-D plasma operations.

The current DIII-D specific PCS hardware configuration utilizes a collection of ten Intel Linux based multi-processor computers running in parallel to perform the real-time analysis and feedback control that are necessary for achieving the desired plasma characteristics on every discharge. The number of processor cores for each computer ranges from two to twelve and are assigned to either a specific real-time control process or control processing thread through Linux cpu affinity binding. The PCS real-time computers, which are spread throughout various locations in the DIII-D facility, are connected together in a deterministic low latency network

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using 2.1Gbit Myrinet [5] hardware and software that enables highly efficient Direct Memory Access (DMA) transfer of data between nodes in the network. Real-time responsiveness in the PCS computing cluster is achieved through a GA developed customization to the Linux operating system kernel used on each of these computers. The custom solution disables all system and device interrupts giving the PCS processes complete uninterrupted control during plasma discharges.

II. Recent Improvements to Real-Time Hardware and Data Acquisition Capabilities

One of the key features of the DIII-D PCS is its ability to acquire and provide important plasma and tokamak information from various DIII-D diagnostics to the real-time computing system for use in feedback control. The PCS real-time acquisition system utilizes both Peripheral Component Interconnect (PCI) and compact PCI digitizers from D-TACQ Solutions [6] providing over 500 diagnostic channels of data sampled at frequencies ranging from 20 Hz to 1 MHz. Up until recently all data acquired in the PCS was tied to specific computers and digitizer hardware installed in the same locations as the diagnostic areas from which the signals were available. With the introduction of new real-time fiber optic data streaming hardware into the PCS, this restriction has been removed allowing the PCS computers to be separate from the digitizers acquiring the data and located away from them. One major advantage of this to DIII-D is that it allows the real-time computing hardware to be in a more centralized and easily accessible location from which to manage and maintain these systems. Also, by removing the dependency of the computer from the data acquisition hardware, the likelihood that a digitizer failure could take down the rest of the PCS real-time computing system is reduced. Specific examples where the new data streaming hardware have been incorporated into the PCS include the Thomson scattering diagnostic and a recently upgraded electron cyclotron emission (ECE) diagnostic.

Data from the Thomson diagnostic was initially made available to the PCS in 2004 utilizing a combination of VME and CAMAC based hardware. A single VME based PCS computer located in the Thomson diagnostic area was used to read the raw data from VME memory modules attached to a set of CAMAC FERA digitizers, to transfer to the PCS analysis computers over the Myrinet network. The original system proved to be fairly unreliable due to the reliance on aging legacy CAMAC equipment and the complexities involved in passing data from CAMAC to the PCS computers. An upgrade to the Thomson acquisition hardware to replace the old VME and CAMAC equipment with 96 channel D-TACQ ACQ196 cPCI digitizers was completed in 2010. The upgrade has provided numerous benefits resulting in overall improvements in performance, reliability and maintainability of the system. The increased dynamic range of the D-TACQ digitizers from 11 to 16 bit has improved the resolution quality of the raw data. A greater memory capacity has allowed for longer pulse lengths to be acquired and for the inclusion of new 50Hz lasers with higher repetition rates.

The new Thomson acquisition system uses the D-TACQ RTM-T cPCI module to send fixed sized packets of 8192 byte sized data comprised of 960 channels read from ten ACQ196 digitizers. A new set of data is acquired with each pulse of a specific Thomson laser and immediately transferred over a fiber optic link to a PCS analysis computer located outside of the Thomson diagnostic lab where it is placed into a memory buffer for use in the real-time analysis codes. The Thomson lasers are typically pulsed in sequences of bursts where multiple lasers fire in rapid succession (100 microseconds apart) with longer delays (20 milliseconds) between bursts. The latency period from the time that the data is acquired on the Thomson acquisition end to the time it appears on the PCS analysis computer for processing is 100 microseconds. The real-time Thomson analysis codes, which compute the plasma temperatures and densities for 58 distinct spatial locations, take approximately one millisecond for each packet of raw data received.

Real-time data streaming using D-TACQ RTM-T has also been implemented for use in the acquisition of the (ECE) diagnostic in the PCS. For this specific implementation a single D-TACQ 96 channel digitizer fitted with RTM-T is used to acquire ECE data at 500 Hz frequencies to stream to the PCS in real-time. Data is sent to the PCS in 65536 byte sized packets containing 341 sample sets acquired from all channels once every 682 microseconds. This new capability has served a dual purpose at DIII-D by providing high frequency sampled ECE data to the PCS in real-time in addition to supplying an upgrade for the ECE diagnostics data acquisition hardware used in the DIII-D standard (non PCS) acquisition systems.

III. Enhanced connectivity to external DIII-D diagnostics and actuators

PCS capabilities have been further enhanced by connections to external DIII-D diagnostic systems and remote actuators using the PCS Myrinet real-time network. Examples of this include camera data from the Charge Exchange Recombination (CER) diagnostic made available to the PCS to compute plasma rotation and ion temperatures, acquisition of Mirnov probe signals used in computing MHD instabilities, and sending of commands to a Myrinet connected ECH computer controlling the steerable ECH mirrors in real-time.

In the case of CER data obtained in the PCS, the Myrinet network has been successfully adapted to connect the PCS Linux based real-time computing core to a CER Windows PC used in capturing raw pixel data from a single Sarnoff camera viewing eight CER chords. A custom GA developed code running on the CER Windows PC scans for new camera data appearing on a Camera link pci card which is immediately transferred over the PCS Myrinet network to a DMA region allocated on one of the PCS analysis computers. Approximately 4096 bytes of camera data is uploaded to the PCS from the CER systems at a fixed frame capture rate typically set to once every five milliseconds with minimal latency and interruption to either the CER acquisition systems or the PCS computers themselves. Both the CER and PCS systems have been set up to run independently of one another, so that a failure in one system will not impact the other. The analysis time required to compute the CER rotations and temperatures in the PCS is 500 microseconds for a single chord or 4 milliseconds for all eight CER chords on a single processor.

Diagnostic data from eight Mirnov probe signals is acquired using a D-TACQ 16 channel cPCI ACQ216 digitizer attached to a computer, which is also connected to the PCS real-time systems over the Myrinet. Data from each of the eight Mirnov probes sampled at a 1MHz frequency is sent to a PCS real-time analysis computer once every 512 microseconds where an FFT based analysis code is run to compute magnetic field fluctuations around the tokamak, extracting the amplitudes and frequencies for several toroidal mode numbers. This information is routinely being used in the DIII-D PCS to monitor plasma perturbations such as toroidal n=1 modes which can be unstable and disrupt the plasma. It has also been successfully utilized in a number of feedback control experiments involving early detection of these deleterious modes and suppression through directed microwave injection into the plasma [7].

A Myrinet based connection between the PCS real-time systems and the ECH mirror control computer has allowed the PCS to be able to send control commands to a set of steerable mirrors, which in return change aiming of the ECH power to specific locations into the plasma. Each mirror is associated with a specific gyrotron and waveguide at DIII-D and is capable of being moved in both the toroidal and poloidal directions. A GA designed and assembled mirror controller provides a high performance low latency UDP interface for sending mirror position commands to the mirror motors and reading back their current positions from the ECH control computer. A private Ethernet network is used to connect the eight ECH mirror controllers to the ECH mirror control computer where a server process runs in real-time to provide access to PCS control and read back the positions of the mirrors over the PCS Myrinet network (Fig. 1). PCS control of the ECH mirror positions is currently limited to movement along the poloidal direction at a rate of approximately one degree of motion in 16 milliseconds. Plans are currently in place to upgrade the controllers, motors and encoders used for position read back in order to increase this performance by a factor of three.

IV. Experimental Applications of Recent PCS Improvements

The new real-time diagnostic information in the PCS has enabled novel control algorithms to be implemented at DIII-D. Real-time Core Thomson is used to obtain the density profile, which enables real-time ray tracing. Real-time Divertor Thomson is used to obtain the temperature profile in the lower divertor region. When the plasma detaches, the temperature reduces to 1-2 eV. This temperature is used to control gas feedback into the private divertor plasma flux region to control and stabilize the detachment level in the plasma. Heat fluctuations are obtained from the real-time ECE. Across an NTM (Neoclassical Tearing Mode) island, the phase of the heat fluctuation changes in 180 degrees. This knowledge is used to localize the NTM island. A new high resolution ECE system has been added this year along with real-time acquisition. The NTM control system is being upgraded to use this capability to identify the NTM in higher resolution with minimal interference from the sawtooth activity. Real-time bolometer channels have been added to the PCS this year as well, enabling radiation measurements. This diagnostic was used to control the plasma core and divertor radiation in the experimental campaign.

Real-time analysis of CER rotation measurements is being incorporated into an extremum seeking (ES) algorithm that will allow for real-time optimization of non-axisymmetric (3D) magnetic fields in tokamak plasmas [8]. The ES algorithm exploits the well-known connection between maximizing the plasma rotation and optimal minimization of magnetic field errors [8]. With optimal error field correction, an increase in the rotation is brought about by a reduction in the resonant and non-resonant magnetic braking torque from error fields and the resulting plasma response. Although present feed forward techniques are effective at identifying the optimal error field control currents, they require multiple discharges to find an operating point for single plasma equilibrium. Besides being inefficient, these techniques are incapable of adapting to evolving plasma conditions including changes in plasma pressure and safety factor profiles. The ES algorithm under development tracks changes in the plasma rotation that result from low-level sinusoidal variations of the control currents (a dither signal) in order to identify the optimal operating point, and will enable multi-harmonic error field correction strategies using multiple coils.

V. Conclusion

A proven, well defined and flexible architecture has allowed for a steady stream of improvements and additions to be made to the capabilities of the DIII-D Plasma Control System. The DIII-D PCS has now been integrated to collect data from many major diagnostics at DIII-D including recently upgraded acquisition systems for Thomson, CER and ECE. In addition to the increased data collection capabilities the PCS has also undergone recent improvements in its ability to connect to and control a wider range of actuators affecting plasmas on DIII-D such as the ECH steerable mirror controllers. All of these improvements have provided significant benefit to the physics program at DIII-D, broadening the set of tools made available to researchers planning fusion experiments. Despite all of these increases in the capabilities and overall complexity of both the hardware and software, the PCS has consistently demonstrated high reliability during operations and has been easy to maintain.

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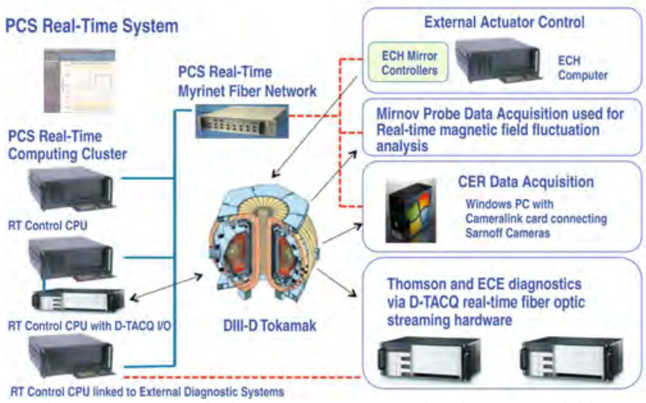

Figure 1 – PCS Real-Time Computer, Control and Data Acquisition Systems

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