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Current State of DIII-D Plasma Control System

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ABSTRACT

The DIII-D Plasma Control System (PCS) is a comprehensive software and hardware system used in real-time data acquisition and feedback control of numerous actuators on the DIII-D tokamak. It regulates many plasma characteristics including shape, position, divertor function, and core performance. The custom software developed at DIII-D provides an expandable platform from which new control algorithms can be incorporated. PCS has been expanding with the needs of the DIII-D research program, national, and international institutions that have adapted the PCS for use on their devices.

The DIII-D PCS group in collaboration with many national and international groups have been instrumental in steadily improving the effectiveness and capability of the system. Enhancements on two key areas have been made: computer infrastructure upgrades and real time diagnostics control.

1. Introduction

The DIII-D PCS has undergone a number of extensive software and hardware upgrades in recent years. PCS now has 7 distributed real-time computers running CentOS 6 Linux Operating System, connected to each other using high bandwidth and low latency InfiniBand network capable of transmitting 40 GB/s. New digitizers have been added to the PCS real-time network to increase the amount of analog data read from DIII-D diagnostics and to control hardware in real-time. Several real-time control algorithms have been added, namely GPU-based Resistive Wall Mode (RWM) control [1], dynamic target for β control [2], Neutral Beam Injection (NBI) control [3], ECH density limit, and Disruption Prediction via Random Forests (DPRF) algorithm to predict plasma disruptions [4]. Supporting software infrastructure to broadcast PCS real time data to external entities such as web servers have been added. Industry standard practices in software engineering have been expanded to ensure high quality and consistent code base for PCS.

Today, PCS is operated at various fusion research facilities including DIII-D (U.S.), K-STAR (South Korea), EAST (China), MAST (U.K.), NSTX (U.S.), and Pegasus (University of Wisconsin).

2. Data acquisition and computer infrastructure

Since 2000, real-time connectivity for the PCS was provided by Myricom 2 Gb/sec. hardware [5]. This allowed for PCS interprocess communication across a deterministic connection (fiber or copper) using easily available commercial off the shelf (COTS) network interface cards (NICs) for both Peripheral Component Interconnect (PCI) and PCI Express (PCIe) bus compatible systems [6]. The DIII-D facility has always required a distributed PCS solution given the physical locations of input diagnostic data. In the current version of the DIII-D PCS, the Myricom network has been replaced with a 40 Gb/sec InfiniBand network based on the Mellanox Connect-X 3 hardware set. This new network retained the previous deterministic characteristics and adhered to the goal of utilizing easily obtained COTS components. An in-house software application programming interface (API) was developed around the Mellanox Remote Direct Memory Access (RDMA) capability which provides inter-system communication between any PCS node with average latency times of 1.5 µs for PCS real-time data.

In an effort to improve the performance and maintainability of PCS, two of the older D-TACQ ACQ196 data acquisition digitizers have been replaced by the next generation D-TACQ ACQ2106 digitizers [7], one for controlling (RWM) feedback and the other for electron cyclotron emission (ECE) data. ACQ2106 is a 19″ rack-mountable carrier designed to accommodate up to six D-TACQ ELF or FMC modules, allowing up to 192 simultaneous analog data acquisition channels in one enclosure. ELF and FMC are electronic board module form factors. ACQ2106 provides multiple high-speed communications links for high

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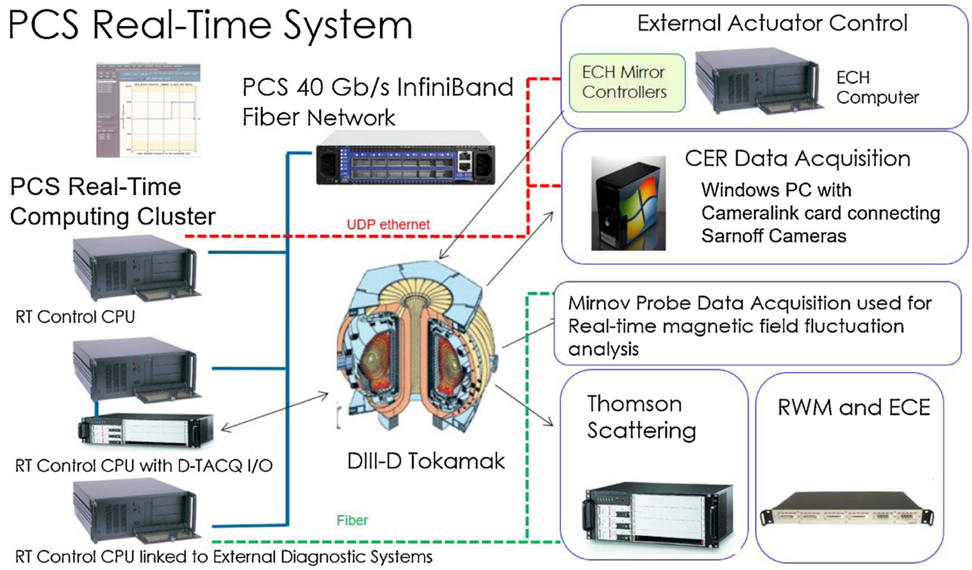

Fig. 1. The DIII-D PCS network has been enhanced by the installation of a 40 GB/s InfiniBand fiber network.

data throughput as well as gigabit Ethernet or USB 2.0 options. The system uses a Xilinx Zynq-7000 All Programmable System on a Chip (SoC) Z-7030 running Linux [7].

Computing hardware in the DIII-D PCS has also greatly changed since the initial generation of Intel based PCS computers were used. The current DIII-D PCS consists of 7 real-time nodes, with a total of 188 cores. Among these is also a system equipped with a general purpose graphics processing unit (GPGPU) by NVidia. In collaboration with Columbia University, the NVidia Tesla P40 GPU is a next step upgrade to previous efforts to optimize RWM feedback control [1]. The previous implementation utilizing a GPU was a standalone system intended to be operated in parallel with the existing DIII-D PCS RWM algorithm. This current implementation uses a NVidia Tesla P40 which has now been integrated into the DIII-D PCS alongside new digitizer hardware to give users the ability to easily switch between non-GPU and GPU based RWM control. The GPU implementation is based upon Nvidia's CUDA API with customizations made to interface to shared I/O and standard PCS software interfaces such as programming and archiving [1,8].

The overall networking diagram of DIII-D PCS is depicted in Fig. 1.

The DIII-D PCS Operating System (OS) is recently upgraded to CentOS Linux 6.9. This upgrade along with centralized software and library location using the distributed Network File System (NFS) and centrally managed environment management allows for a more stable kernel, improved kernel memory management, and a more secure OS while simplifying administrative tasks by providing uniform software location and environment variables across PCS computers. PCS OS kernel is equipped with in-house customizations to achieve high scheduling priority and interrupt free response for the real-time processes [5].

The Linux environment module package is used for PCS software development to manage the many shell environment variables required for compilation and testing. Individual modules may be created to package necessary environment settings for a particular software and they can be linked to other modules using dependency map. For instance, the PCS module is written with necessary environment variables, such as $PATH, $MDSPLUS_HOST, $PORT_NUM. It also is configured to load MDSplus and IDL modules as pre-requisites. The aim of this module is to achieve a uniform and portable environment for all DIII-D PCS developers.

3. New PCS control algorithms

The following control algorithms have been implemented allowing a wide variety of novel experiments to be performed at DIII-D and other research devices. The extensive and varied set of hardware inputs and outputs used highlights the flexibility and extendibility of the PCS.

3.1. Plasma disruption prediction using machine learning technique

A new PCS control algorithm that can calculate the probability of plasma discharge disruptions in the DIII-D tokamak has been developed. The algorithm, called Disruption Prediction via Random Forests (DPRF) [4] is a supervised binary classifier based on machine learning. During the 2017/2018 DIII-D experimental campaign, this algorithm was routinely used in real-time.

TokSearch [9], a high speed data mining platform allows the rapid searching and caching of a large quantity of historical DIII-D discharge data providing fast data access to offline queries from DPRF. The machine learning-based algorithm is then trained offline using open-source Python libraries, and then translated to C and compiled as a linkable library in the PCS. For each CPU cycle, the input features are evaluated and the inference is stored as a disruptive signal, i.e. the probability of an impending disruption. An example is reported in Fig. 2, where the disruptivity for an impending flattop disruption starts to rise above 60% with more than 200 ms warning time. Random Forests are sufficiently fast to evaluate in real-time; the second panel of Fig. 2 shows the computing time of the real-time PCS CPU. It ranges around 250 μsec.

DPRF has been trained on over 5000 DIII-D plasma discharges from 2014 to 2017 experimental data and not tailored to any specific disruption dynamics. It focuses only on unintentional flattop disruptions, by minimally preprocessing the input data by using only causal filtering, and discarding any hardware-related fault.

3.2. Resistive Wall Mode (RWM) GPU control

To further improve real-time Resistive Wall Mode (RWM) control, a control technique called Linear Quadratic Gaussian (LQG) has been implemented. This improves on previously implemented feedback control [1] and have been proven on the Columbia HBT-EP experiment. The feedback routine works together with PCS to manage I-coils and current control amplifiers (SPAs). This control algorithm is the first major algorithm to run in a GPGPU at DIII-D. The GPU exposes up to

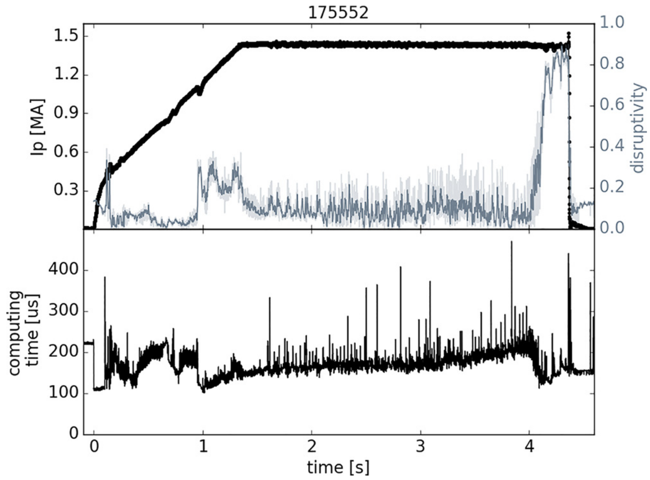

Fig. 2. In the top panel, the plasma current Ip [MA] in black for a flattop disruption, with the associated predicted probability to disrupt, i.e. disruptivity (in grey). In the bottom panel, the computing time of the real-time CPU in μsec (Rea 2019) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

61,440 computing threads to any digitized real-time signal. During the 2017 experimental campaign, the GPGPU feedback algorithm was verified versus the CPU based feedback algorithm.

A reusable code library has been developed to do calculations on the GPGPU, such as fast CPU-GPU memory transfer. With this pioneering work, future researchers and engineers will be able to easily implement new and higher fidelity refurbished parallel control algorithms on the GPGPU. Such algorithms could produce more accurate controls.

3.3. Dynamic target for β control

To enhance PCS control of plasma in super H-mode [2], a real-time dynamic β control is being used for linking β evolution with density evolution to maintain the discharge evolution in Super H-mode. The control algorithm reads density data from CO2 interferometers or Thomson Scattering diagnostics. It then generates a new β target that changes with density with the goal of making pedestal pressure (related to β) track the evolution of pedestal density. The dynamic β target replaces the pre-programmed β target in the standard PCS neutral beam control algorithm.

3.4. Radiated power (Prad) control to dissipate power from scrape off layer (SOL)

This real time control is designed to prove that the PCS would be able to control power dissipation from SOL [10]. In the ITER scenario, the divertor heat load must be mitigated by radiating ~70% of the power. PCS reads radiated power from bolometers in the lower divertor area of the DIII-D tokamak. The measurement is then compared to a target value and the error is fed back into the gas input control system; setting flow rate for impurity seeding to control power radiation and detachment.

3.5. Real-time NBI control

For DIII-D plasma operations, it is now possible to control Neutral Beam Injection (NBI) via two modes. The first mode establishes a static program for an NBI source for the given shot. The second mode, utilizing the PCS, allows for dynamic programming in both open or closed feedback control. DIII-D currently has eight active NBI sources capable of providing a total of 20 MW of injected power.

Recent changes to the NBI system such as co/counter injection, off axis injection and variable beam energy injection of certain sources has expanded the need for PCS control of NBI to regulate beam energy in real-time [3]. Changes to one NBI beamline to allow for in beam injection angle control will further alter the PCS calculation of potential beam energy.

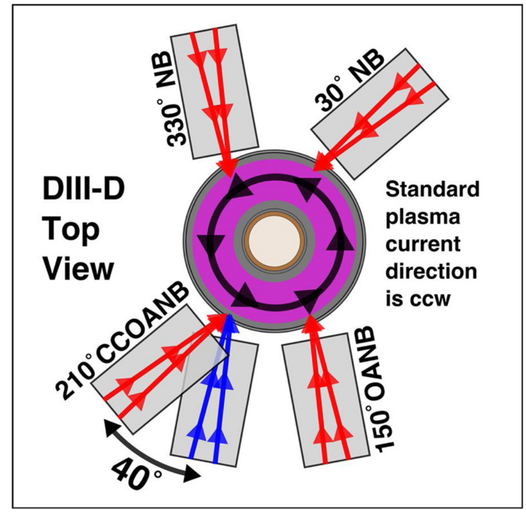

Fig. 3. Top view of DIII-D tokamak with standard plasma current direction in black and 8 neutral beams - two of which can now inject with or against his plasma current.

The new 210 °CCOANB (Co-Counter Off-Axis Neutral Beam) will inject permanently at 18.3° with respect to DIII-D's horizontal midplane. By rotating the entire beamline 40° around the vessel (Fig. 3). Switching from injecting neutral particles in the same direction of the standard plasma current direction (co-injection) to the reverse direction (counter-injection) can be accomplished within one week.

This upgrade allows the PCS to utilize all eight neutral beams to drive high performance plasmas with high applied torque. In addition, experiments will now have access to more beam sources that can deliver the effects of off-axis current drive that have been investigated in 2011 (Fig. 3).

3.6. ECH density feedback capability and safety feature

A new PCS algorithm which sends a command to shut down the ECH gyrotron heating sources when the PCS calculated density exceeds a preset limit has been developed. Density is measured using Thomson Scattering and CO2 interferometers. This interlock safety system is critical for the protection of sensitive equipment and sensors inside the plasma vessel. When the plasma density reaches a predetermined limit, the automated ECH shutdown is activated in order to prevent refraction of ECH beams to undesirable areas of the vessel, such as diagnostic ports, cameras, and other sensors.

4. Visualization software and best practices

4.1. Advanced visualization

To improve the functionality of the PCS human-computer interface, a “Real-Time Scope 2 Editor” has been added. This interface allows users to adjust the ranges of real-time scope signals displayed live in the DIII-D control room. Previously these signals had fixed ranges. If during a shot, a signal had values outside the fixed range, it would be clipped and therefore some parts of this signal would be invisible. The new feature allows scientists to widen or narrow the signal range for current and future plasma discharge, based on the feedback encountered in previous discharge.

Fig. 4. PCS real-time data can be visualized via a web browser without impacting operation.

4.2. Web based real time PCS monitor

The Real Time Web Scope is a web based time series graphing application. It was implemented in 2018 for DIII-D with the intention of supplementing the Qt based real-time series graphing application. The benefit to DIII-D would be that the web application allows remote collaborators to render live PCS data without having to install the QT application on their local machine or open a remote X session to the onsite computers.

This is a major upgrade to the 2012 web data visualization tool which used Scalable Vector Graphics (SVG) and Protovis [11].

The new web application is built using HTML5 canvas and d3.js in order to provide the ability to efficiently serve and render large sets of data in real-time (Fig. 4). The HTML5 canvas is the visual element on the webpage and its API is used to draw the time series data. The d3.js library is used to bind data to the canvas element. HTML5 canvas manipulates onscreen pixels instead of adding Document Object Model (DOM) elements, addressing the primary rendering bottle neck of the previous SVG based web application.

The web application makes a secure WebSocket connection to the data subscriber on the web server which listens to Redis (in memory database) events for the next available data set. PCS time series data resides in PCS RT computer memory and is shared to the web application via InfiniBand RDMA technology and Redis database.

4.3. Software engineering best practices

DIII-D PCS source code was migrated from SCCS to Git in 2017. This lends itself well to integration to a Jenkins continuous integration service. Jenkins is an open source software that can be instructed to perform custom software builds when a pre-defined event happens. Jenkins subscribes to PCS Git repository. When a developer commits a new code or edits existing code to PCS source trees, a Jenkins job is launched on a remote Linux build system. A pristine environment is built first, then Jenkins clones the top of the master branch of PCS code and starts the PCS software build process. This includes preprocessing, compiling, linking, installing binaries, and simple regression testing. If any of the build steps fails, an e-mail alert is generated.

This early warning system ensures that no broken code should be deployed in a PCS production cluster at DIII-D or elsewhere, or any known defect to linger for a long time thus increasing code robustness and quality. The continuous improvement idea has been extended to benefit other PCS installations, such as EAST and KSTAR.

In addition to on-demand software build, there is a regularly scheduled nightly build as well. The goal of this exercise is to detect software environment changes that adversely affect software build outcomes, even when no developer had changed any line of code.

5. Conclusions

The DIII-D PCS software continues to gain new control capabilities due to a flexible and scalable design. This achievement would not be possible without contributions from experts from the DIII-D program and national and international collaborating institutes and universities. This community will be adding a new machine that utilizes the PCS in 2020 with the addition of the Southwestern Institute of Physics' HL-2 M tokamak in Chengdu, China.

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Declaration of Competing Interest

None.

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