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Status of the control system on the National Spherical Torus Experiment (NSTX)

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Abstract

In 2003, the National Spherical Torus Experiment (NSTX) plasma control system was used for plasma shape control using real-time equilibrium reconstruction (using the rtEFIT code). rtEFIT is now in routine use for plasma boundary control. More recently, the system has been upgraded to support feedback control of the resistive wall mode (RWM). This paper describes the hardware and software improvements that were made in support of these physics requirements. The control computer is an eight processor embedded system. The real-time data acquisition system now acquires 352 channels of data at 5 kHz for each NSTX plasma discharge. The latency for the data acquisition, which uses the Front Panel Data Port (FPDP) protocol, is measured to be ~8 μs. A Stand-Alone Digitizer (SAD), designed at PPPL, along with an FPDP Input Multiplexing Module (FIMM) allows for simple modular upgrades. An interface module was built to interface between the FPDP output of the NSTX control system and the legacy Power Conversion Link (PCLink) used for communicating with the PPPL power supplies (first used for TFTR). Additionally a module has been built for communicating with the switching power amplifiers (SPA) recently installed on NSTX. In addition to the hardware developments, the control software on the NSTX control system has been upgraded. The device driver software for the hardware described above will be discussed, as well as the new control algorithms that have been developed to control the switching power supplies for RWM control. A reliable mode detection algorithm for RWM feedback is currently under development.

Keywords: Plasma control; Real-time electronics; Software structure

1. Introduction

The National Spherical Torus Experiment (NSTX), which began operations in 1999, has been operated with purely digital plasma control system from the first plasma onwards. The initial development plan for this

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system, which was originally described in Reference [1], has now been completed. The current status of the system hardware and software are described in this paper.

2. Hardware

2.1. Real-time computer

The NSTX plasma control system computer consists of eight 333 MHz processors in a shared memory architecture. The processor cards are built by Sky Computers (http://www.skycomputers.com). Each processor motherboard contains four G4 processors (Motorola) and one Front Panel Data Port (FPDP—ANSI/VITA 17) high-speed low-latency direct memory access i/o port. The two mother boards are connected together by a VME P2 backplane known as "Skychannel" (ANSI/VITA 10-1995). The real-time computer is not available for interactive processes, but is instead accessed over the VME backplane from a single-board workstation built by Force Computers (http://www.forcecomputers.com). The Force computer runs the Solaris operating system and also acts as the VME Slot 0 controller. A block diagram showing the layout of the components of the NSTX control system is shown in Fig. 1.

2.2. Data acquisition

Data are acquired in real-time at 5 kHz over a distributed network of point-to-point connections from VME crates that contain one or more 9421 (12 bit) or 9422 (16 bit) FPDP digitizers (http://www.merlinvme.com). There are currently 352 channels of data being acquired in 4 different locations. The data consist of magnetic field and flux measurements, power supply currents and voltages for shape control. Gas control data and current, voltage, and phase data for the antenna elements of the RF heating system [2] are also acquired in real time, but are not yet used in the shape control system. The distributed data acquisition system is required due to the rather complex ground-

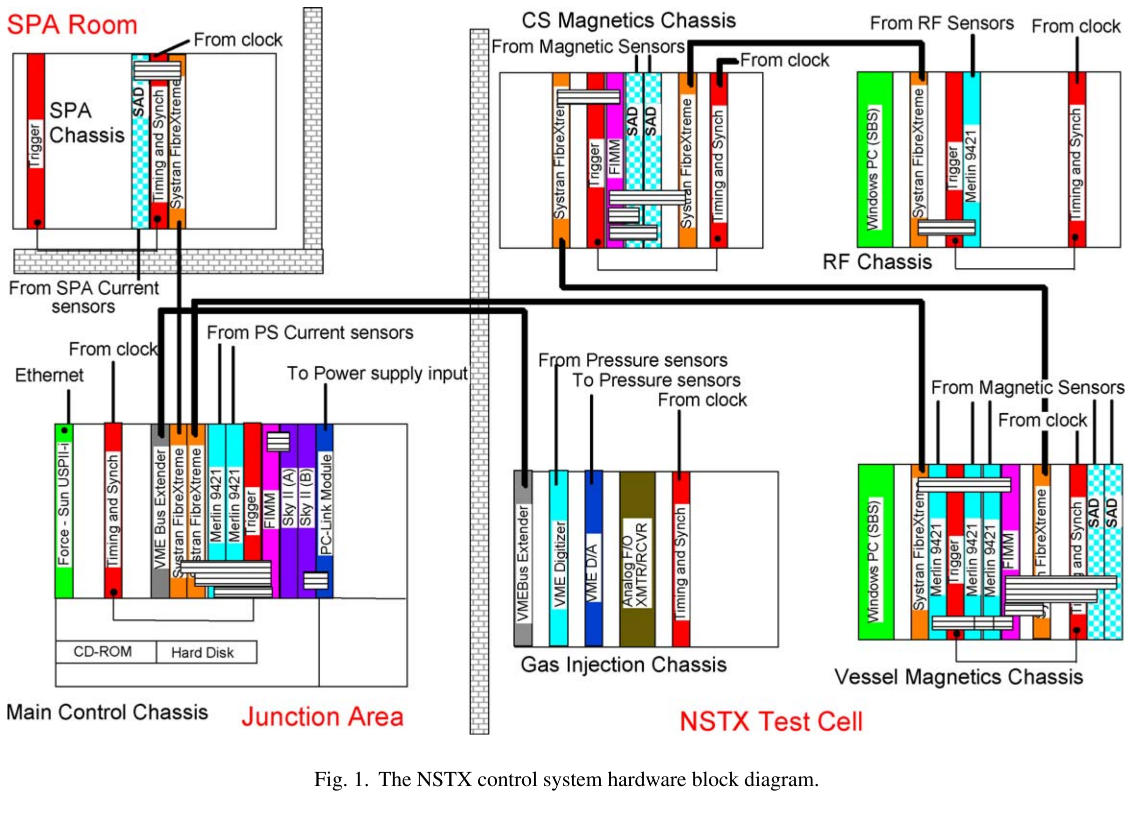

Fig. 1. The NSTX control system hardware block diagram.

Fig. 2. Shown on the left, the Stand-Alone Digitizer (SAD) developed at PPPL, is a simple 32 channel FPDP digitizer. Shown on the right is the Front Panel Data Port Input Multiplexing Module (FIMM) developed at PPPL combines multiple FPDP streams.

ing scheme on NSTX needed for the coaxial helicity injection system [3] which biases a large fraction of the NSTX vacuum vessel to ∼1 kV potentials.

In addition to the Merlin digitizers, a Stand-Alone Digitizer (SAD), shown in Fig. 2 has been designed and built for use at PPPL. This module, which is intended for use in combination with a multiplexing module (see below) has a VME form factor, but uses the VME crate only for power. The digitizer is clocked externally and data are sent out via an FPDP port on the front panel. The unit requires no setup, and is an elegantly simple solution for real-time data acquisition.

Data for the gas system are still taken via the VME bus using VME based digitizers. The acquisition latency for this system is higher, and it is planned to replace the VME system with FPDP based i/o in the near future.

2.3. Telemetry

The data are transmitted over a fiber optic serial link known as Serial FPDP (ANSI/VITA 17.1-2003) built by Systran Corporation (http://www.systran.com). Each module is capable of converting the parallel FPDP data stream to a serial FPDP (1 Gbit fiber optic) stream or vice versa. The independent point-to point data streams are multiplexed into a single data stream by a module, shown in Fig. 2, which is known as a FPDP Input Multiplexing Module (or FIMM, developed at PPPL) which does a simple concatenation of the individual streams into a single stream after First-In-First-Out (FIFO) buffering. The data are then streamed into the FPDP port on one of the Sky Computer boards (which will be referred to as the input computer). The measured latency of the data acquisition system is ∼8 μs (time from the acquisition trigger pulse until the final data bit arrives at the computer FPDP input port).

2.4. Output hardware

Power supply commands are output through the second FPDP i/o card to a module, shown in Fig. 3, which was developed at PPPL and is known as a PC-Link Interface Module (PCLIM). This module converts data into the digital format of the Power Conversion Link (PCLink), described in Reference [4], which was developed for use on Tokamak Fusion Test Reactor (TFTR) in the early 1980s. Each 32 bit FPDP data word writ-

Fig. 3. The PCLIM module (left) interfaces the FPDP output stream with the legacy PCLink interface that was inherited from TFTR while the SPAIM (right) interfaces FPDP to a switching power amplifier with analog inputs.

ten from the output computer consists of both data and routing information, with 16 bits of routing information and 16 bits of power supply command data. The digital commands are converted to rectifier pulses in firing generators inside the individual rectifier supplies after the routing information is stripped out.

A new high-speed switching power amplifier (SPA) has recently been added to NSTX in order to power the resistive wall mode (RWM) feedback system. Unlike the legacy TFTR power supplies, which accept a digital firing angle as input, the SPA accepts either an analog current or an analog voltage request. An FPDP D/A interface module that was compatible with the existing PCLIM was required. A module, also shown in Fig. 3, referred to as a SPA interface module (SPAIM) was designed to create the required analog signal. The SPAIM utilizes 12 bits of the FPDP data word and generates a ±10 V output and also passes through the enable bit from PSRTC.

3. Software

3.1. Infrastructure software

The basic infrastructure for the NSTX plasma control software is borrowed in large part from the Plasma Control System (PCS) developed at General Atomics for use on DIII-D, and has been described in detail previously [5]. The system was modified to operate with the MDSplus archiving system in use on NSTX and to be compatible with the Sky real-time operating system.

3.2. Real-time information flow

The flow of information during a pulse sequence is represented by the block diagram in Fig. 4. Data are acquired in real-time from the direct memory access (DMA) and is converted to meaningful physical units by the acquisition program running on one of the processors on the input board. It is then distributed to each processor across the Skychannel bus. The PCS and power supply real-time control (PSRTC) software receive and process this data. The PCS generates voltage requests for the plasma control actuators and sends them to PSRTC, which applies engineering constraints to the requests. After constraining the data the voltage requests are converted to the appropriate output units and sent out through the FPDP output port. The gas system is handled separately, with out puts being sent out through the VME port without passing through PSRTC.

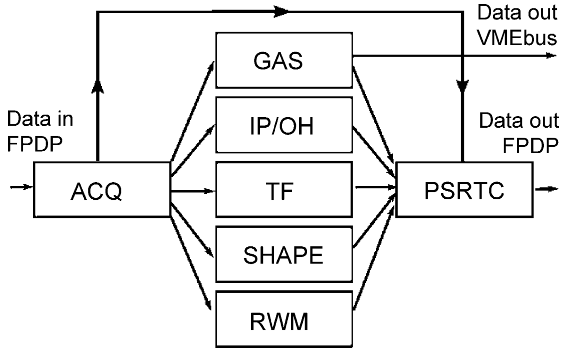

Fig. 4. Real-time information flow chart for the NSTX control system.

3.3. Control algorithms

The PCS supports modular control algorithm development. Different categories of control on the NSTX PCS are currently:

1. toroidal field;
2. plasma current/transformer control;
3. discharge shape;
4. equilibrium;
5. isoflux;
6. system;
7. data acquisition;
8. gas injection;
9. error fields and resistive wall modes.

Category 1 controls the toroidal field coil current with a simple PID algorithm. Category 2 consists of three different phases of control; (1) control of the ohmic heating coil current through PID control up until the point of plasma breakdown, (2) control of the plasma current up until the point of the end of the plasma current (determined by $I_p < I_p^{min} = 60\,kA$, $I_p < I_p^{min} = 60\,kA$), and (3) control of the ohmic heating coil current back down to zero after the discharge ends. Categories 3–6 correspond to plasma shape control. The discharge shape category contains a rudimentary control algorithm which controls the plasma radial and vertical position with preprogrammed control of the other coil currents. The equilibrium category inverts the Grad–Shafranov equation using the rtEFIT code; the resulting equilibrium solution provides input to the isoflux category. The isoflux category uses the errors between the flux at the requested boundary and the real-time calculation of the plasma boundary flux as input to a PID type controller that determines the poloidal field coil voltages. The various isoflux algorithms in use in the isoflux category are described in Reference [6]. The system category is used to choose between the discharge shape category and the isoflux category as a source for the poloidal field coil voltage commands. The system category has been recently upgraded to allow for a continuous hand-off from one category to the other using "fuzzy" logic, which has been beneficial for avoiding jumps in the plasma position and shape at the category transition. Reference [7] has more detail on plasma shape control on NSTX. The data acquisition category has no explicit real-time algorithm, but rather controls parameters of the data acquisition functions of the PCS. The gas injection category controls (1) the pre-fill pressure using measurements of the torus pressure form ion gauges, (2) the gas injection flow rate from the low field side gas injectors on NSTX, and (3) the status of several solenoid valves which control pulsed gas flow from the high field side and divertor gas injectors on NSTX. The final category, resistive wall mode control is the newest control category. Currently this category controls the SPA current using PID. Algorithms are being developed to implement error field feedback control and resistive wall mode feedback control.

In addition to the above named categories of control, a new category, tentatively named real-time mode detection, is under development which will be used in conjunction with the resistive wall mode feedback system. Its primary function will be to attempt to sense the presence of a resistive wall mode as input to the feedback algorithm.

4. Recent upgrades and results

4.1. Latency reduction

In addition to the RWM category mentioned above, the PCS was recently upgraded in order to reduce the system latency. This was achieved by purchasing a more recent implementation of the Sky FPDP i/o board and by optimizing the processor to processor communications on the Skychannel bus.

The optimization resulted in a substantial reduction in the latency of the NSTX control system. The overall latency was measured to be almost 3 ms before the upgrades, and was reduced to 750 μs afterwards. These optimizations led to a marked improvement in plasma performance on NSTX. The hardware and software optimizations each contributed roughly equally to the latency reduction, with a factor of $\sim$2 coming from each improvement. In particular, the vertical position control was improved so that plasmas with elongations up to $\sim$2.8 have been achieved. Plasma theory indicates high elongation is very important for plasma performance.

4.2. Data acquisition upgrade

The number of real-time data acquisition channels was recently increased from 192 to 352 in order to support more accurate shape reconstructions and to support the planned development of an RWM mode detection algorithm. All new channels are acquired using the SAD and FIMM modules developed at PPPL (described above).

5. Summary

The NSTX plasma control system has been upgraded to support the physics requirements of the device. These upgrades have been central to the achievement of recent records for the spherical torus, including high elongation and stored energy.

Acknowledgements

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