STATUS AND PROSPECT OF JT-60 PLASMA CONTROL SYSTEM FOR ADVANCED TOKAMAK DISCHARGE SCENARIOS

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Abstract

A large tokamak fusion device JT-60 is expected to explore more advanced tokamak dischrarge scenarios toward the ITER and a future power reactor. Since various experimental issues are to be adequately discussed, and possibly to be solved in JT-60, the plasma real-time control system has been drastically improved with remodeling in hardware as well as in software. To satisfy the requirements, the "multiple network" structure is employed for a basic principle in remodeling. The distributed processors for the diagnostics, actuators, and supervisory controllers are linked through a “reflective memory (RM)” network for fast, real-time communication. Similarly, advanced and complex calculations to reproduce plasma shape and profiles are performed by several processors connected to a same RM network. Timing signal distribution needs another independent network. For this purpose, we will adopt a RM network again. In this report, we discuss the developments to improve the JT-60 plasma control system. In addition, a future plasma control system leading to a standard design for a power reactor is envisaged on the basis of the 18-year plasma operation experiences.

INTRODUCTION —REQUIREMENTS—

Since tokamak magnetic fusion research has just made a step forward to an international collaborative project ITER (International Thermonuclear Experimental Reactor), the existing tokamaks including JT-60 are focused on challenge of various experimental issues. We believe the following experimental issues at least are expected to be solved in JT-60: To clarify how to keep a steady-state plasma with high performance, and how to avoid plasma instabilities almost completely. By stimulus of this motivation, several essential developments of the JT-60 plasma real-time control system (shown in Figure 1) for exploring advanced scenarios have been accomplished or are being conducted as follows: (1) A complete plasma shape is precisely reproduced in real time. (2) Profile data such as the current profile, which is the function of 2-space variables and time, are also computed. (3) Sufficient number of actuators are connected to the real-time control frame through networks, so that various feedback control schemes with complex use of actuators and data could be checked.

On the basis of the experimental facts, the expected scenario is likely to be as follows:

a. Plasma current is built up through inductive coupling with a center solenoid (CS) coil and/or radio frequency (RF) heating.
b. The initial state of plasma current profile is formed so that a plasma could attain high energy confinement, by controlling the CS coil current, neutral beam (NB) and/or RF heating power.
c. In the above process, the bootstrap current is excited as a plasma pressure (temperature x density) increases.
d. Plasma shape is also controlled to keep an optimal triangularity.
e. For the plasma density control, fuel particles are fed into a plasma through gas puffing, pellet injection, and/or compact toroid (CT) plasma injection.
f. Plasma current is steadily driven as the bootstrap current in combination with the CS coil. The current profile should be carefully controlled to avoid excitation of a plasma instability.
g. Throughout discharge, plasma profiles are reproduced from various measurements with the advanced algorithm, and other necessary state parameters in a plasma and a plant should be provided fast and accurately.

To build up the control system to carry out this operation scenario, the requirements can be listed below:

- Distributed subsystem controllers near their controlled device should work consistently.
- Measured data, provided by a subsystem connected to a sensor, could be utilized by several supervisory controllers. Some of the measured results should be converted to the more macroscopic parameters.
- A supervisory controller produces commands to a subsystem connected to an actuator.
- Control cycle should be less than several milliseconds, that is short enough to suppress the plasma macroscopic instabilities. Fast computers should execute their calculations in parallel or in a pipelined process.
- Feedback control methods could be frequently improved for exploration of better control methods to attain a plasma with higher performance, which is one of the major objectives for JT-60 as an experimental device.
- Timing signals and clock signal for inter-processor synchronization should be distributed to appropriate subsystems.

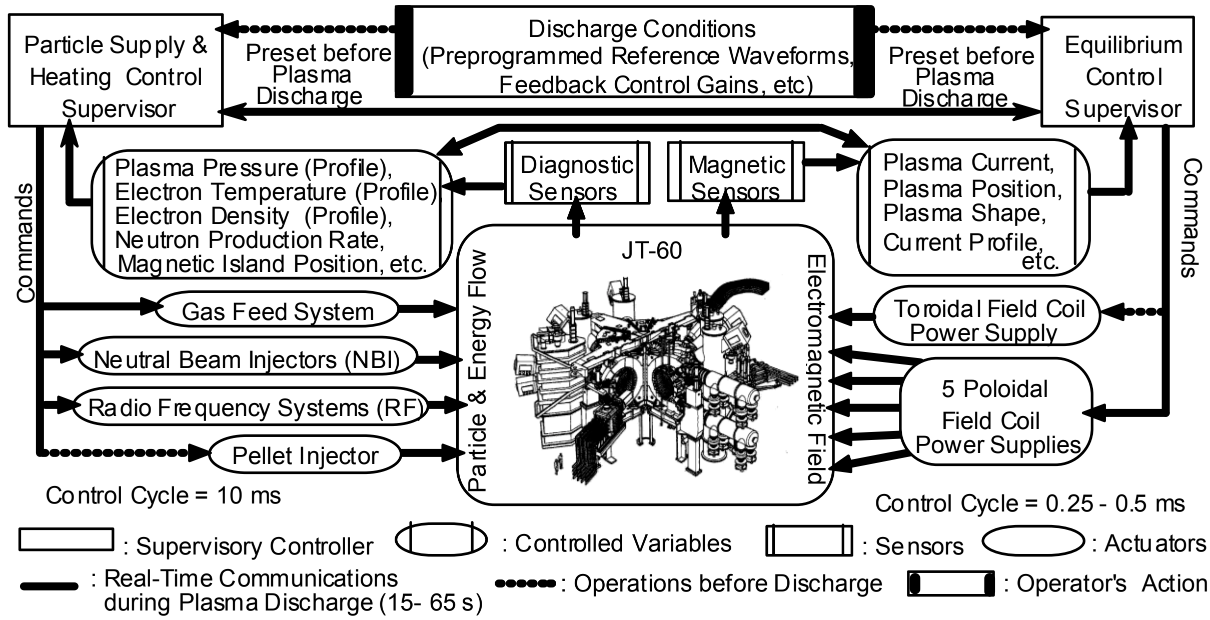


Figure 1. Configuretion of the JT-60 remodeled plasma control system

- Necessary discharge conditions should be preset for every controller before discharge. After a pulse discharge,
  the control results data produced by all subsystem and supervisory controllers should be collected. They should also be stored in the database files.
- Programs working in the controllers should include debugging capability in parallel with real-time operation. This point often determines the system availability, which is a lesson learned in our experiences.

To satisfy these requirements, the "multiple network" structure has been employed as a major principle for our remodeling in JT-60. The following sections deal with the current essences of JT-60 plasma control system with prospect to the future reactor.

STRUCTURE OF THE CONTROL SYSTEM

Since complex control methods should be applied toward exploration of various operation scenarios, most data produced by the distributed subsystems should be centralized to the main supervisory computers. By natural consequences, we adopted the network linkage through all dispersed controllers. Although each controller performs its own peculiar functions, necessary communication to the external devices is considered common. Therefore, we discuss a basic configuration of standardized-bus modules for each controller.

Reflective Memory Networks

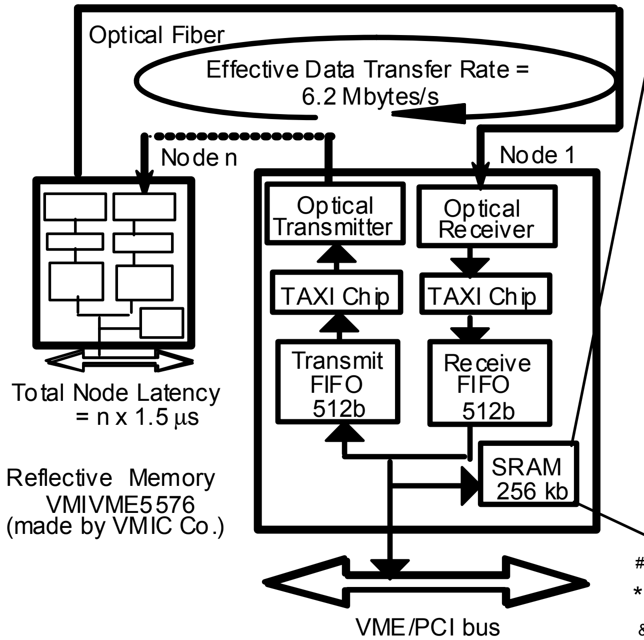
We determined the number of networks corresponding to the required data amount and transfer rate. Plasma equilibrium reconstruction requires parallel computing with handshake of small data amounts (less than a hundreds words) between the processors through the exclusive network #1. The weight center of plasma current is calculated every 0.25 ms. The full shape of plasma is reproduced every 1.0 ms. The macroscopic parameters (several words) and the shape data (a few hundreds words) are transferred to the equilibrium control loop through another network (#2), and to the visualization system .

Plasma equilibrium control loop is triggered every 0.25 ms for the unstable vertical position, and every 0.5 ms for the stable horizontal position, shapes, and plasma current. The supervisor of this loop generates the voltage commands (several words) to the power supplies of poloidal field coils for control of equilibrium, through the exclusive network #2.

Heating and fuel supply control loop is triggered every 10 ms. Similarly, the supervisor of this loop uses measured data (several tens words) from the diagnostic system, and generates appropriate commands (several words) to the actuators through the exclusive network #3.

We selected "Reflective Memory (RM) (VMIVME 5576, made by VMIC Corp. 6.2 Mbyte/s at maximum)" for these fast networks, as shown in Figure 2. The block diagram of the RM network is also shown in Figure 2 [1].

The contents of the JT-60 RM data transfer packet are categorized as follows: (a) Commands. (b) Actuator status. (c) Measured data, (d) Processed data. (e) Up counter incremented at every update timing signal. (f) Status flags indicating data qualities, if necessary. The contents of real-time communication belonging to these categories with the updating cycles are also given in Figure 2. The RM network simplifies the structure of control system significantly. Of many standardized



Contents	ch	Update cycle
Commands		
PFC voltage	5	0.25/0.5 ms
Gas flow rate	4	10 ms
NBI On/Off#	14	10 ms
RF On/Off	4	10 ms
Actuator status		
NBI ready/not	14	10 ms
NBI On/Off	14	10 ms
RF ready/not	4	10 ms
Measured data		
Magnetics	50	1 ms
Coil current	6	1 ms
Plasma position	4	1 ms
Diagnostics *	10	10 ms
Processed data &	volume	
Plasma shape	1 kW	1 ms
Electron temp. profile,	15 kW	10 ms
Current profile, etc.	/profile	or longer
Counter (Clock)	1 ms/10 ms	

#: Timing pulses are used at present.
*: neutron production rate, radiation power, gas pressure, etc.
&: having a more physical meaning.

Figure 2. The reflective memory network linking the controllers in JT-60

networks such as Ethernet, ATM, and other customized communication hardware, the RM network seems to provide the best choice in terms of transfer speed for distributed systems and in flexibility for future improvement of plasma control functions.

Ethernet for Slow, Large Data Communication

The discharge conditions (less than a few thousands words) must be preset to every controller before discharge sequence initiation. After a pulse discharge, the control results data (several millions words) produced by all subsystem and supervisory controllers must be collected and stored in the database files having the identification number of that discharge. In addition, the programs working in the controllers must include debugging capability independently of real-time operation. Therefore, a subsystem or a supervisory controller must have slow sequential control and program development functions. We chose Ethernet for the network due to cost effectiveness and reliabilities. A computer in each subsystem communicates with the host computer (workstation) through Ethernet network.

Basic Configuration for a Controller

Since fundamental functions required for each controller are considered similar or almost the same, a basic configuration of modules, based on an internationally standardized bus, could be composed. We employed the "VME/PCI-bus" standard, and the single rack contains the following modules, as shown in Figure 3.

- A fast board computer for real-time processing with the real-time OS.
- A reflective memory for the real-time communication.
- A board computer for slow sequential control processing and for program download through the Ethernet network.
- Input and output modules for measurements, controls, clock/timing pulse, etc.

In the original system, signals of clock (pulse series with a constant frequency) and timing (trigger of start/stop) pulses were basically composed of the "one-to-one" links of a cable with hardware-based logical operations. This resulted in that so many cables with complex connection from/to many modules had been built in the system, and that it has cost much for its maintenance or replacement. We would like to propose a solution for this later in this article.

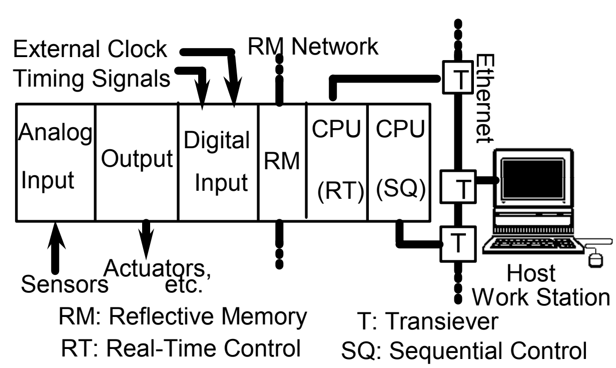


Figure 3. Configuration of the basic bus system

NECESSARY ELEMENTS FOR THE TOKAMAK PLASMA CONTROL

On the basis of the plasma operation experiences in the JT-60 tokamak, necessary elements have been clarified for the future plasma control system, which could lead to a standard design for a power reactor. The major points are discussed in this section.

Parallel Computing for a Real-time PDE Solver

Plasma shape in a tokamak has been considered one of the key parameters for energy confinement, stability, and safe operation. In particular, remarkable advances in understanding of shape reproducibility [2,3] stimulated us to build up the real-time shape reproduction system. Since the shape can be defined as an outermost magnetic surface, this problem is to find magnetic field distribution from measurements. From the mathematical point of view, this is a boundary value problem for a static Maxwell equation that is classified into a Dirichlet problem of the second-order partial differential equation (PDE).

If we solve the PDE in a simple way, calculations of special functions and matrix inversion are unavoidable, which could not be done within a short time enough for real-time application. Magnetic flux at a certain point is provided by linear combination of sensor signals, that coefficients depend on the point location. The coefficient vectors are stored in a tabular form (occupied in the core memory of approximately 400 Mbyte) prior to the discharge. In realtime, necessary number of vector products of signals and coefficients provide flux distribution and plasma shape, as shown in Figure 4. Since calculated area of the shape can be divided into several parts, we chose 6 processors (fast Alpha chip (COMPAQ Corp.)) for the parallel computing.

The reproduced position, shape, and plasma current, transferred to the other controllers through the RM network, are directly utilized for their feedback control. The control cycle is 0.25- 0.5 ms, depending on time constants of the controlled parameters. In addition, the controller connecting to the same RM network visualizes the full plasma shape on the display. It takes approximately 20 ms for the graphics processor to draw the shape on the display.

Fast Computing for Feedback Controls

In the tokamak experiments, various feedback controls should be tested to seek conditions for higher plasma performance. Control performance in a digital computer system could be degraded by dead time (= time delay in calculation). To minimize the delay, a parallel and/or pipeline computing system with fast processors is employed as a basic principle. The necessary data handshakes in such a system require "trigger" signals that indicate "the data or commands are ready to be read." We adopted the fast board computers' linked through RM modules. Each computer with a large memory is synchronized with an appropriate control clock. Two

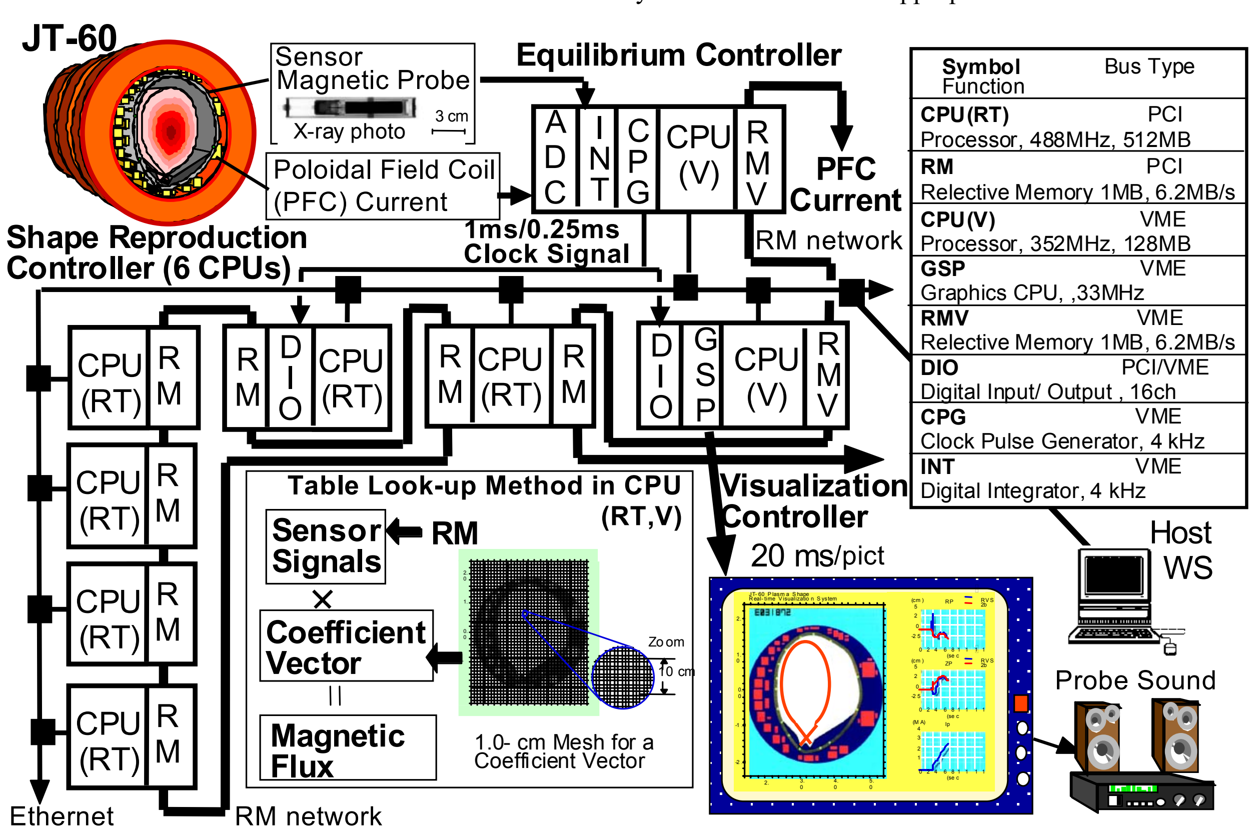


Figure 4. System configuration of real-time shape reproduction and the equilibrium control

methods can be implemented to provide trigger signals: (a) An external hardware clock, or (b) A counter in a specific RM register updated by the supervisor, which itself is synchronized with an external clock.

The first method needs a digital input module and electrical/optical wiring. In contrast, the second method is easily built in the subsystem controllers.

Figure 5 shows an example of the parallel and pipeline time chart where external hardware clocks are applied in the JT-60 equilibrium control system. To suppress plasma positional instability in the vertical direction, the equilibrium controller and the corresponding poloidal field coil (PFC) power supply controllers execute their real-time programs synchronized with the 0.25-ms and 0.5 ms cycle clock. The delayed clock signals of 0.25 or 0.5 ms can be generated from master clock signals by delay timers having a precision of 0.01 ms.

Heating and fuel supply control system has another

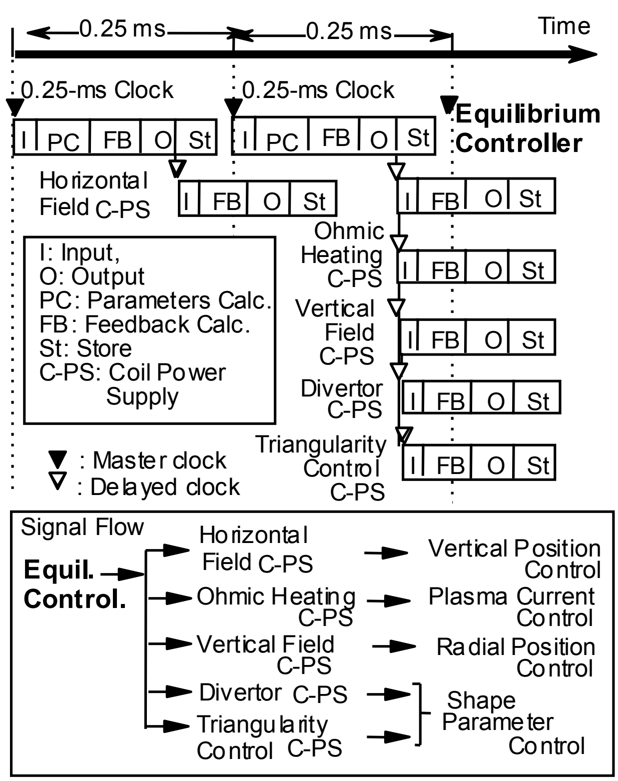


Figure 5. Time chart of parallel, pipeline process in the equilibrium control

feedback control loop, which deals with plasma parameters with longer time constants than that of equilibrium ones (plasma density, neutron yield, radiation power, etc). Multiple single feedback loops are available now for experiments. The more complex feedback loop can be quickly composed if requirements are specified.

Timing Signals Transfer

In the original system, a timing signal is transmitted through a single cable from the source to the end device to minimize time delay. This implies that many cables and logic boards are necessary, and they make the timing system costly and inflexible. We propose a new timing system composed of RM network. An RM module, a fast computer, and digital input/output module(s) are equipped in a single VME/PCI rack. Logical calculation programs, developed using the "MATLAB" code, are installed in the computer. In addition, a pair of optical fibers is the only cable necessary for the network. This system would attain high flexibility for modification, and cost minimum in most cases. The transmit delay time is estimated several micro-seconds, a tenth of the original system (40 micro-seconds).

CONCLUDING REMARKS

As an understanding of tokamak plasma is made deeper, new advanced discharge scenarios have been proposed, and will be proposed in the future. The plasma control system should have such a flexible structure that can realize the scenarios as shortly and cost effectively as possible in both hardware and software. In this sense, we believe the system has been improved on the basis of plasma operation experiences in JT-60.

Although the current level is yet insufficient toward optimality, we can envisage the plasma control system in the future will have the similar structure and the necessary elements mentioned in this article.

We have now arrived at the "base point" toward the final goal in realizing a fusion power plant, that would lead to the ultimate release from a world energy problem.

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