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EVALUATION OF PLC-BASED ETHERNET/IP COMMUNICATION FOR UPGRADE OF ELECTROMAGNET POWER SUPPLY CONTROL AT RIBF

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Abstract

In the Radioactive Isotope Beam Factory (RIBF), a front-end controller consisting of a computer automated measurement and control (CAMAC)-based system and I/O devices are utilized for the power supplies of many electromagnets upstream from the RIKEN RING Cyclotron. The CPU installed in the system is an x86-based CAMAC crate controller known as “CC/NET”. An experimental physics and industrial control system (EPICS) input/output controller (IOC) running embedded Linux is used to remotely control the electromagnet power supplies. However, these CAMAC-based systems are outdated and require replacement. The FA-M3 programmable logic controller (PLC) is an alternative candidate device that can be incorporated into the magnet power supply. However, a high-reliability network between the EPICS IOC and the device is required compared to a conventional socket connection via Ethernet. Therefore, we evaluated a system that uses EtherNet/IP to communicate between these devices and the EPICS IOC. The EtherNet/IP system is based on the TCP/IP protocol, which is widely used for field bus communications via Ethernet. An advantage of using EtherNet/IP is that it enables cost-effective reliable communication despite the use of TCP/IP. It is possible to improve the reliability of the interlock output even when using conventional TCP/IP-based network.

INTRODUCTION

RIKEN had the former accelerator facility, RARF (RIKEN Accelerator Research Facility), consisting of the RIKEN Ring Cyclotron (RRC), and RIKEN Linear Accelerator (RILAC) as an injector since 1986 [1]. Three new cyclotrons, the FRC, IRC, and SRC, were constructed downstream of the RRC in the new Radioactive Isotope Beam Factory (RIBF) project, and beam commissioning of the new cyclotrons was completed in the 2006 fiscal year [2]. RIBF is currently a heavy-ion accelerator facility with five cyclotrons and three injectors [3]. Furthermore, the original RARF power supplies are still in use while beam-tuning the electromagnets upstream of RRC because RIBF is an upgrade of project RARF. Thus, outdated I/O modules and communication boards used to control electromagnet power supplies are still in use.

Figure 1 shows a block diagram of the control system at the time of RARF. Furthermore, electromagnet power supply control in RARF is a computer-automated measurement and control (CAMAC) system. The system consists of a communication interface module (CIM), which is a communication module attached to the CAMAC crate, and a device interface module (DIM)[4], which is an I/O built into the electromagnet power supply and is connected via an optical fiber to enable serial communication. CAMAC was initially controlled by the MELCOM 350-60/500, a minicomputer manufactured by Mitsubishi Electric Corp [5]. The minicomputer was replaced in 2001 by a VME CPU board with a VxWorks OS to operate via the Experimental Physics and Industrial Control System (EPICS) [6]. To stabilize the control system, a CPU board running EPICS was replaced in 2004 with an x86 CAMAC crate controller, CC/NET manufactured by Toyo Tecnica [7]. This system is unique because it is an embedded system that runs EPICS on Debian 3.0, a Linux operating system for CC/NET. Figure 2 shows the CAMAC-based system for the electromagnet power supply that is currently in operation.

The VME CPU board has been replaced with CC/NET as the CAMAC-based controller of the electromagnet power supply systems, but CIM/DIM system have already been used for more than 30 years since the beginning of RARF operations and have become obsolete. For example, poor CIM/DIM communication causes a bottleneck in some cases during operation; hence, these CIM/DIM systems must be urgently replaced. The FA-M3 programmable logic controller (PLC) manufactured by Yokogawa Electric Corporation was chosen as a potential replacement for the DIM built inside the power supply chassis while considering replacing the outdated CIM/DIM system. Figure 3 shows the DIM functional part currently under development. The FA-M3 PLC is a candidate device for the function corresponding to the DIM, we designed the communication between the controllers corresponding to the CIM, and the EPICS implementation method.

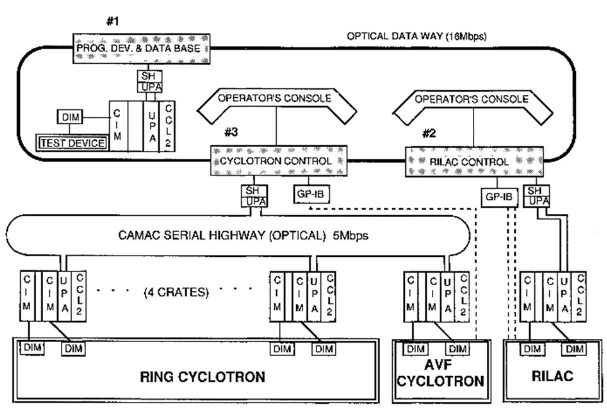

Figure 1: Block diagram of RARF control system (the original figure is Fig. 2 in reference 5).

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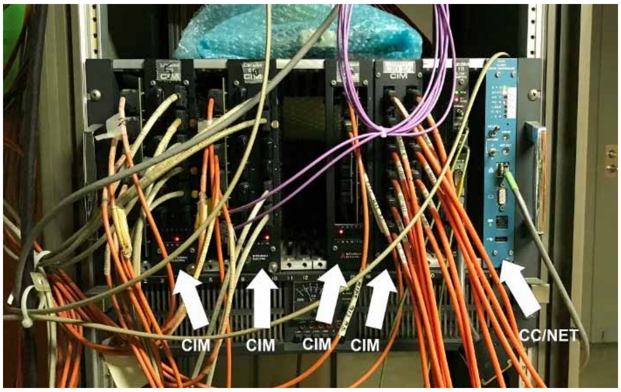

Figure 2: CC/NET, CAMAC-based controller with CIMs installed for communication to DIM.

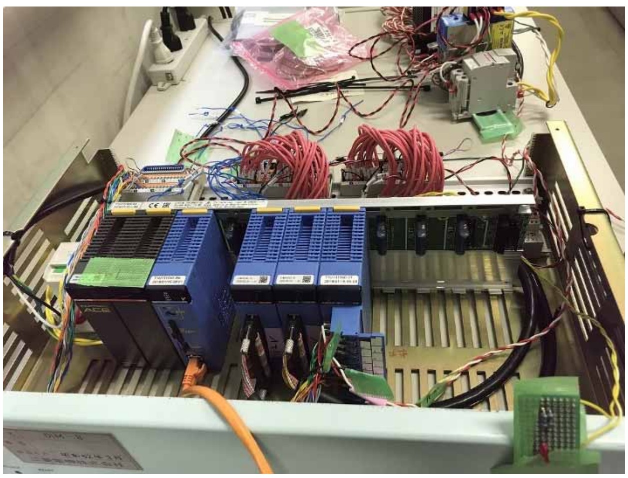

Figure 3: Photograph of DIM functional part by FA-M3 currently under development.

DEVICE INTERFACE LAYER OVER TCP/IP

When developing the DIM compatibility function with the FA-M3 PLC, the sequence CPU module (F3SP71/F3SP76 [8]) is equipped with standard Ethernet port and its EPICS device support software using NetDev [9] is already provided. Hence, it is possible to develop low-cost control systems with EPICS. In this case, TCP/IP is used for communication between the EPICS Input/Output Controller (IOC) and devices, which is the device interface layer. TCP/IP-based devices are helpful for reducing development cost, and various types of TCP/IP-based devices are utilized for the RIBF control system; they are operated remotely via the EPICS channel access (CA) protocol. However, TCP/IP-based devices occasionally do not reconnect to the EPICS IOC after a power failure or unintended device restart, which causes operational concerns. The RIBF control system frequently restores the connection by restarting the EPICS IOC process, even though it is preferable if the reconnection is reliably established after restoration.

For example, the EPICS IOC start-up script can output a message informing the user of the EPICS IOC's disconnection from the device. However, such features are just for developers, not a mechanism to alert accelerator operators as an EPICS CA client. In addition, the EPICS management system [10] can monitor the TCP/IP-based device status using ping and port scans. However, it cannot be decided to the socket connection status between the EPICS IOC and TCP/IP-based devices because it bases an alive monitoring by an external program.

FIELD NETWORK COMMUNICATION

The RIBF control network is usually placed in the power supply and accelerator rooms, so TCP/IP-based devices' advantage is that they require minimal Ethernet cable installation. Conversely, they are unreliable owing to their low real-time performance, slow I/O communication, and reconnection problems in RIBF control systems. On the other hand, development of a new proprietary dedicated protocol, such as NIO [11], used in the RIBF control system, would be too expensive. Therefore, we considered Ethernet-based field networks (EtherCAT, FL-net, EtherNet/IP), which are general-purpose protocols and standard FA-M3 modules, for the interface between the FA-M3 PLC-based DIM (included in the electromagnetic power supply) and the EPICS IOC. FL-net and EtherCAT, further require a dedicated network and cannot be mixed with the control network, reducing convenience. As a result, we evaluated EtherNet/IP.

EtherNet/IP

EtherNet/IP is a network widely used in Ethernet industrial fields [12]. There are various industrial devices that use it, and it is managed as an open standard by the Open DeviceNet Vendor Association (ODVA). EtherNet/IP is compatible with conventional Ethernet, and shares the same physical layer, such as the frame structure, connectors, cables, and is also compatible with TCP/IP. Furthermore, it utilizes a Common Industrial Protocol (CIP) in the application layer. Thus, the main features allow general-purpose network switches with other TCP/IP protocols, low-cost wiring, and relatively high real-time performance. Additionally, an Allen-Bradley Control-Logix PLC and the EtherNet/IP were used by the Spallation Neutron Source (SNS) to build a subsystem as an illustration of how they could be used in an accelerator control system [13]. Furthermore, SOLARIS Synchrotron has used PLCs in a TANGO-based control system to implement machine protection and personal safety systems. PLC nodes communicate via EtherNet/IP [14].

SYSTEM DESIGN

An EtherNet/IP-based system generally consists of a scanner and adapter. The scanner is on the EPICS IOC side of the system designed for electromagnetic power supply control, and the adapter is the DIM integrated into the electromagnetic power supply. The network segments are point-to-point connections in star topology designed for installation in an existing RIBF control network.

The scanner consists of FA-M3 series PLCs, and the dedicated module F3LN01-0N [15] realizes inter-PLC communication via EtherNet/IP with the DIM functional part.

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The sequence CPU F3SP76 was installed in the first slot to of the proposed system to realize the interlock function of the beam interlock system (BIS) [16] for machine protection. In the second slot, a Linux CPU, F3RP71-1R [17], is installed in the second slot to implement the CA protocol for interfacing high-level applications, resulting in a multi-CPU configuration. The link register (W register) is used to exchange I/O between the FA-M3 PLC, adapter, and scanner. As a result, developers use the FA-M3 PLC system's standard development method because it is cost-effective and only requires the link register, regardless the EtherNet/IP protocol.

EPICS INTERFACE

This system realizes the EPICS IOC using the F3RP71-1R installed in the second slot of the scanner. The DIM installed in the electromagnet power supply becomes an adapter(s) and exchanges data with the node that becomes the scanner via Ethernet/IP using the link register. However, the link register in a multi-CPU environment does not support by the EPICS device support for F3RP61/71 [18]. As a result, the link register is sent and received by F3SP76, the sequence CPU installed in the first slot, and the use of shared memory realizes the interface with the EPICS IOC installed in F3RP71-1R. Figure 4 shows the system chart of the pro-posed EPICS-based system. At this point, the internal register of the sequence CPU enters the connection status of the adapter and scanner, while it is available to activate an interlock output and alerting the operator of a disconnection

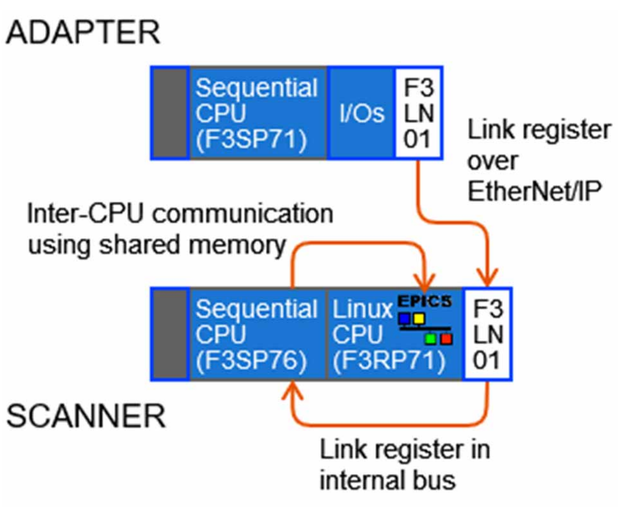

Figure 4: System chart of the proposed EPICS-based system. Data is exchanged between PLCs using link registers on EtherNet/IP. Data is exchanged from the sequential CPU to the Linux CPU using shared memory.

IMPLEMENTATION TEST

We tested the response using a configuration of one Ethernet/IP scanner and one adapter connected in one 1Gbps switching hub. Figure 5 shows the response test environment. Table 1 lists the settings of the adapter used to connect the scanner. The scanner's sequence CPU was used to generate a 10 Hz internal signal for the test, which was trigger output to the scanner and adapter simultaneously. The time difference was calculated based on the EtherNet/IP communication. As a result, the difference in the average response time was approximately 2.3 ms. This result is comparable to the performance of a previous application with a minimum number of nodes connected to the FL-net [16]. In addition, while the transmission time of FL-net becomes proportionally slower as the number of connected nodes increases, the transmission time of EtherNet/IP related to the switch latency [19]. As a result, unlike the FL-net, the response time is not expected to slow in proportion to the number of adapters.

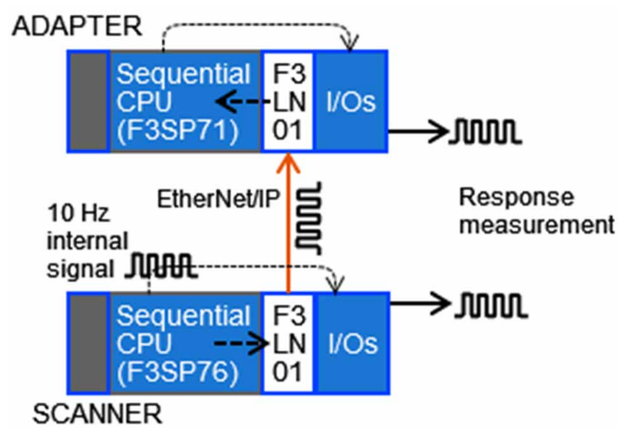

Figure 5: System chart of the response test environment. It generates an internal signal, triggered and compared with its node and via EtherNet/IP.

Table 1: Adapter Connection Setting for Implementation Test

Communication type	Symbolic Segment
Trigger	Cyclic
Requested Packet Interval (RPI)	1 ms
Connection type	Point-to-point
Data size	100 bytes

Because EtherNet/IP is a field network with soft real-time, the real-time performance could be a bottleneck. Furthermore, we measured jitter to calculate the arrival time of signals caused by EtherNet/IP to the equipment varied in the implementation test. Figure 6 shows the test environment for the jitter measurement. The scanner, adapter, and switching hub had the same configuration as the response measurements. In this test, a function generator generated a 100 Hz external signal and input it to the scanner. Additionally, the sequence CPU of the scanner triggered the input signal and output to both the scanner and adapter simultaneously to measure jitter. As a result, the jitter of the scanner output was 1.08 ms, and the jitter of the adapter output was 1.8 ms. Therefore, the jitter was approximately 0.7 ms larger via EtherNet/IP. The Ethernet/IP of the requested packet interval was set to 1 ms, and the timing of that communication and the scans of both sequence CPUs caused a slight increase in the jitter. Based on these responses and jitter results, field communication using EtherNet/IP can be used not only for electromagnet power control, but also for outputting slower interlocks with reaction times of a few milliseconds [20].

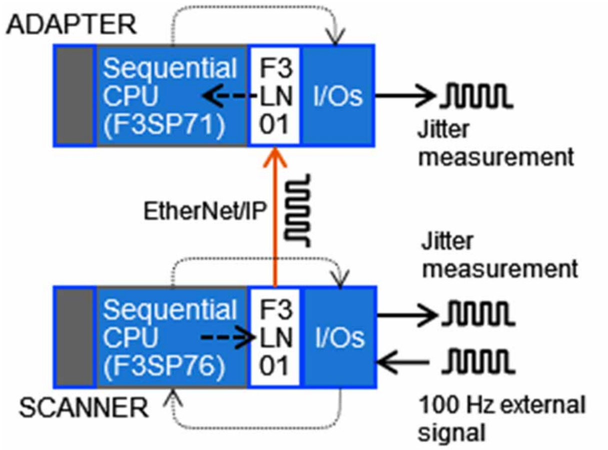

Figure 6: System chart of the jitter test environment. The scanner inputs an external signal of 100 Hz and compares it with the output of its node and output via EtherNet/IP.

CONCLUSION

In this study, we studied the EPICS IOC and device interface layer, which is a network between devices, to upgrade the outdated electromagnet power supply control in the RIBF control system. The part corresponding to the DIM built into the electromagnetic power supply is under development in FA-M3 as a candidate. Therefore, we evaluated EtherNet/IP for interfacing with the DIM and EPICS. The data received over EtherNet/IP by the sequence CPU installed in the first slot were passed to the Linux CPU with EPICS installed in the second slot via shared memory. Hence, a dedicated network is unnecessary as a field network. Thus, a conventional network system can be used without modification. The performance is sufficient, and the system is efficient and convenient. In the future, we plan to test the operation of the electromagnetic power supply by connecting it to the DIM under development. The requested packet interval was set to 1 ms, which is the fastest F3LN01-0N in the implementation test. However, only five adapters are available to be used per scanner in this situation. In the actual implementation, when the interlock output is not required for the BIS, setting the interval to 10 ms allows one scanner to hold approximately 30 adapters.

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