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ABSTRACT

Real-time feedback control of the JET experiment is based upon a collection of diagnostics providing signals which are processed by various controllers that manipulate actuator parameters for plasma current, shape and heating. The real-time data network (RTDN) connects the diagnostic, controller and actuator systems to form a flexible feedback and protection system for plasma monitoring and control. The controllers are mainly VME systems based on the Motorola 680X0 (68K) processor with some computationally intensive systems utilising Texas Instruments TMS320C40 (C40) digital signal processors (DSP), though lately there has been a move towards PowerPC 750 based processors. The majority of 68K VME systems use VxWorks, a hard real time operating system.

There is an ongoing requirement to improve the efficiency of the real-time control systems at JET. This is driven by a desire to either add more input signals, reduce the feedback cycle time or increase algorithm complexity. New technology has a major role to play in the upgrade of the real-time control systems but the novel redeployment of existing equipment can also be used to enhance performance.

This paper examines the configuration of existing systems, both hardware and software, and how new technology can be gradually integrated without jeopardising the current functionality. The adoption of Asynchronous Transfer Mode (ATM) as the connection medium for the RTDN is key to the evolutional development of the control systems. The ATM network is extremely flexible to configure and benefits from low message latency and deterministic delivery time, essential properties for a real-time network.

1. INTRODUCTION

Real-time feedback control for plasma experiments at the JET facility can be grouped into two areas, “local” and “global” (Figure 1). Local feedback is provided by many autonomous systems that have mostly hard-wired diagnostic signal connections required for closed loop control. The Real-Time Central Controller (RTCC) and Real-Time Signal Server (RTSS) [1] form the basis for global feedback control. The RTSS continuously receives signals from many diagnostic systems, and uses some of these raw signals to calculate new “processed signals”. The RTSS forwards the raw and processed signals to the local systems and the RTCC. The RTCC executes user scripted feedback algorithms [2] to control the various plasma actuator systems. Each local system can be configured to use a pre-defined waveform or signals generated by the RTCC and to operate with or without local feedback control. Several diagnostic measurement systems themselves process data in real time. This is especially true for the diagnostic systems that provide signals used for feedback control, of which the main categories are magnetic, density, temperature and radiation.

Real-time feedback control has been used increasingly for various experimental campaigns since the introduction of the RTCC in 1994. This, coupled with the development of new diagnostic systems, has led to a desire to reduce the feedback calculation cycle time whilst increasing both algorithm complexity and the number of diagnostic signals available in the RTSS. By 1997 the feedback control system was proving very flexible but not easily expandable. There were a number of goals for the future development of feedback control:

- increase functionality and flexibility
- overcome the current expansion limitations
- provide a method for safely prototyping new systems during online operation of the JET machine
- coalesce technologies (especially communications) to reduce the burdens of future upgrades, support and spares
- stagger implementation, rather than use a "big bang" approach
- provide compatibility with legacy systems

2. REAL-TIME CONTROLLERS

The diagnostic, controller and actuator systems utilise a variety of hardware spanning decades of technology. A combination of analogue and CAMAC auxiliary controllers used in the 1980s has largely given way to all-digital processing in VME systems and PC platforms. The local feedback controllers that manage the heating, gas and pellet introduction actuators are multiprocessor 68K VME systems running VxWorks software. These "local manager" systems all have the same basic design concept of a communication processor and one or more real-time processors. The real-time processor(s) perform time-critical calculations and real-time control. VxWorks is disabled during pulses to prevent interrupts and task switches affecting the stringent real-time deadlines. The communications processor manages all the external asynchronous events generated by Ethernet and the central timing system (used to co-ordinate JET pulse experiments). This processor relies upon the flexibility of VxWorks to schedule tasks in response to the external events. The majority of the feedback controllers are multiprocessor systems using shared memory on the VME backplane. The Vessel Wall Protection and Plasma Shape Controller [3] systems are based on a network of C40 DSPs hosted in a VME rack. The C40s are used to perform time-critical and computationally intensive calculations without the use of an operating system but they do benefit from remote debugging tools. C40s are also the basis of several diagnostic pre-processing systems, notably magnetic and density measurement. Transputers, hosted by PCs, were employed for the early real-time calculation of plasma X-point position. PCs running Microsoft Windows 95 or Windows NT are also used for various diagnostic systems, such as
Spectroscopy.

3. DIVERSITY IN SYSTEM INTERCONNECTION

The gradual introduction of new feedback control systems and diagnostics, with their associated signals, has led to the use of a plethora of interconnection technologies, Fig. 2 shows the situation by the end of 1998. Electrical connections are still appropriate for local equipment but are inflexible for links that are "one-to-many" and become harder to install and manage as the number of signals increases. There are also physical and logistical problems in routing large numbers of cables across the site and in providing electrical isolation. The local managers and RTSS were connected using a private 10Mbit Ethernet sub-network.

A real-time response was achieved by rigorously controlling the communication time windows for the connected systems. This solution was adopted to guarantee packet delivery and has worked well since 1994 but has drawbacks:

- it is relatively slow by today's standards
- there are a finite number of time windows, currently none spare but there is a demand for several additional systems
- an error on one system can affect the reliability of the network as a whole

"Reflective memory" uses optical fibre to link shared memory interfaces in a group of systems. It is a proprietary technology which was used successfully from 1996 to interconnect three VME systems. It is a fast and efficient communication method but is vulnerable to programming errors that overwrite memory. This makes a reflective memory architecture unsuitable for commissioning new systems during live experiments. TAXI and Transputer links were used in high performance DSP systems that were "state of the art" in the early to mid nineties. Optical TAXI links, fast point-to-point serial connections, were developed for JET in 1993 to interconnect the C40 systems. The Plasma Position system, which calculated the real-time X- point, was fed with magnetics data by a Transputer link.

4. A REAL TIME NETWORK BASED ON ATM

The future of the real-time systems was seen to depend on a new network technology [4]. ATM was selected in 1997 because it has a number of features especially suited for use in real-time environments.

- **Optical transmission medium.** The OC3 form of ATM was chosen because its links are optical and therefore, electrically isolated.
- **Data transmission speed**. Each ATM connection from an OC3 ATM switch can handle 155Mbps which, at the time of evaluation, was 50% faster than Fast Ethernet.
- **Small transmission cell size.** The minimum transmission cell size is important in a real-time environment where small data packets are frequently transmitted. L arge cell sizes, such as those used in Ethernet, would waste transmission bandwidth and incre ase the latency of the messages.
- **Permanent Virtual Connections (PVC) .** PVCs are managed in the ATM Switch. This centralised administration prevents any unauthorised transmissions on the ATM network, thereby making it safe to connect development systems.
- **One-to-many or multicasting.** Multic asting enables the RTSS to send several systems the same data without duplicatin g data packets. Multicasting also aids development; a system can be connected to the network in a passive mode, receiving real-time plasma data and performing calculations that can be verified later offline. Another use for multicasting is the recording of all network traffic that can then be replayed offline to simulate a pulse.
- **Multi-platform.** ATM is available for a wide range of hardware and operating system configurations, especially VME/VxWorks, PC/Windows and PC/Linux.

- **Expandability.** ATM Switches can be added in various topologies.

In 1998 we started to replace the disparate network technologies formerly connecting the various real time control systems by an ATM network (Figure 3). The existing Ethernet remains as the medium used for booting the systems, downloading initialisation parameters and data collection. Where appropriate, we would use ATM for real-time data communication during pulsing. Closely coupled processes on the same VME backplane, such as the RTSS, RTCC and Real-Time Plasma Protection systems, continue to use shared memory for communication.

Early on in the evaluation of ATM we decided not to use TCP/IP over ATM because this would mix real-time with non real-time communications as well as complicating network administration. It was also decided to use ATM at one of its most basic levels of communication, ATM Adaptation Layer 5 (AAL5), also known as Simple and Efficient Adaptation Layer (SEAL). The AAL5 protocol should improve communication performance because it is a "no frills" transmission service requiring the least amount of bandwidth and processing by the both the transmitting and receiving processors. Unlike PC Windows NT platforms, this expectation was not born out on VxWorks VME systems. VxWorks ATM test results revealed relatively poor performance gains using AAL5 compared with a higher level protocol. The reason is that the standard VxWorks ATM device driver is geared towards using TCP/IP over ATM and does not provide an efficient path through the TCP/IP network stack for the low level ATM protocols. This has forced JET to write its own VxWorks ATM device driver that caters only for AAL5. Fortunately, this fits in with the earlier decision to keep Ethernet as the medium for all non real-time communication.

5. ATM REPLACES REFLECTIVE MEMORY

We are installing ATM in stages on either a system-by-system basis or an encapsulated group of systems. In the first instance, we decided to keep any hardware and software modifications to a minimum and not to introduce any extended features. This would provide the best method for direct comparisons of performance and continued functionality. Reflective memory was chosen as the first communication method to be replaced because it has the simplest application interface. Existing 68K processor cards could not communicate directly with an ATM interface card so a VME PowerPC processor card, complete with ATM interface, was installed to act as an intermediary. We developed software which behaves as a memory mapped device, similar to reflective memory, to allow messages to be sent from the 68K to the PowerPC and then over the ATM network. This software package is known as the "ATM Gateway".

Shared memory is one of the simplest and most common forms of communication within a VME system and is supported, in one way or another, by all the 68K and DSP cards used on JET. The ATM Gateway combines the benefits of shared memory with ATM interconnectivity, therefore providing an upgrade path for legacy hardware.

The systems that used reflective memory had to be upgraded simultaneously, but the old communication hardware was not removed. This meant that we could "roll back" systems to use the old software and hardware in a matter of minutes, simply by rebooting with an alternative configuration definition. Once the systems had been verified as working correctly then more radical upgrades could begin. First, the redundant reflective memory hardware was removed. The next step, to replace the 68K processor with a PowerPC connected directly to the ATM network, will be completed in the 2001 JET shutdown period. This will remove unnecessary shared memory transactions and provide access to the huge computational and memory resources offered by the PowerPC cards. Cycle times can be reduced and more complex calculations performed whilst storing more data samples.

6. PHASING OUT TAXI LINKS

The Magnetic Diagnostic has TAXI links to the Plasma Shape Control and Vessel Wall Protection systems (Figure 2). All these systems are currently based upon DSP C40 multiprocessor networks. The Magnetic Diagnostic and the Vessel Wall Protection systems will be upgraded to use the ATM Gateway software in the 2001 Shutdown. This has the added advantage that extra magnetic information will be available to all systems connected to the ATM network. This, in turn, may lead to new global feedback control algorithms being developed in the RTCC [5]. A new "Extreme Plasma Shape Controller" is being designed using PowerPC processors connected to the ATM network. This will enable the development of new algorithms for extreme plasma shapes to be investigated whilst the standard Shape Controller continues with overall monitoring and control.

7. REPLACING ETHERNET WITH ATM

The most complex upgrade is the replacement of the Real-Time Synchronised Ethernet with an ATM network. The 68K communication processors within the local systems will be replaced by PowerPC processors enabling each system to migrate from an Ethernet to an ATM connection. The RTCC has been operating at a 10ms cycle time since its introduction. This was determined by the time division multiplexing communication mechanism used to connect the Ethernet based systems to RTSS. The combination of the more powerful processors and the use of ATM will enable more systems to be added to the RTSS whilst reducing its cycle time. The target cycle time is 2ms, the rate at which the majority of the local feedback controllers currently operate.

8. DISTRIBUTING REAL-TIME SIGNAL PROCESSING

There has been an increase in interest in the RTSS and RTCC since the plans for ATM have become known. In addition to the integration of existing magnetic controllers, extra local feedback systems are required for new heating and fuelling actuators. Extra signals and new algorithms for existing and new diagnostic systems are also planned. The RTSS, in its centralised form, would be unable to meet these demands, even taking into account the performance gains offered by ATM and PowerPC processors. Therefore, we are distributing RTSS processing nearer to the sources of the raw signals, especially for systems that have complex algorithms to process hundreds of signals [6]. These real-time plasma diagnostic and physics analysis systems will process the raw instrument data into physics parameters which will be transmitted over ATM to the RTSS and feedback control systems. The following diagnostic systems are to be upgraded to incorporate real-time processing:

- Electron density profile
- Electron temperature profile and internal transport barriers
- Ion temperature profile
- Current profile
- Plasma confinement parameters
- MHD equilibrium

9. IMPROVING THE DEVELOPMENT CYCLE

The adoption of ATM with its robust administrative controls as the real-time network makes the commissioning of new systems much safer and easier. The old network transport mediums were susceptible to errors caused by rogue transmissions from unproven systems. This meant that commissioning new systems during experimental campaigns was almost impossible. ATM not only makes the commissioning process safe, it also provides the opportunity for speculative development systems.

10. DATA CAPTURE AND REPLAY

All the ATM network traffic is monitored, timestamped and stored during a normal pulse. Then in subsequent simulations, data packets from different systems can be enabled or disabled using the real systems to transmit the disabled packets. This is an ideal way to commission system changes to ensure that data is either unaltered or has been corrected as intended. This replay facility will not be limited to the online systems; it will also be invaluable for offline development. It will enable a single component to have access to all the real-time network traffic without requiring expensive hardware duplicated offline.

CONCLUSION

The introduction of ATM has been a great success that has contributed to the growing interest in feedback control at JET. Old systems have been integrated into the new network using the ATM Gateway software interface, giving them a new lease of life. The data capture system is working and has been used to commission single systems online. In the past, it simply was not possible to connect experimental systems to the real-time data networks because of the dangers presented by such systems. Now, with ATM, it is possible to experiment with ideas that may evolve into diagnostic or control systems in the future.

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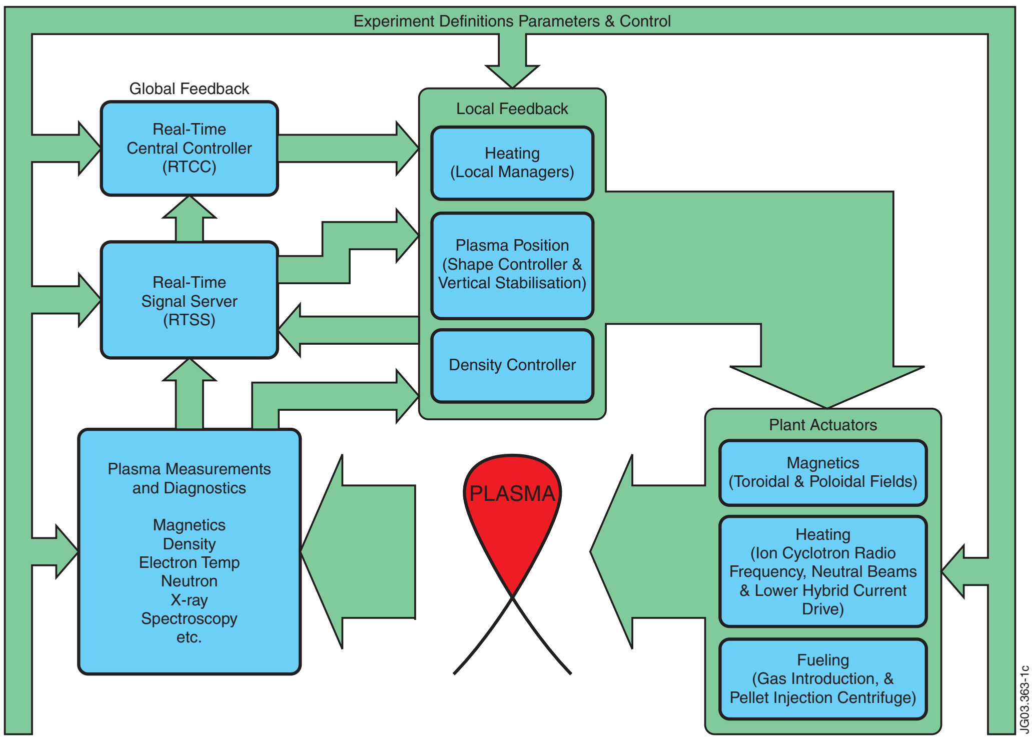

Figure 1: Overview of Feedback Control

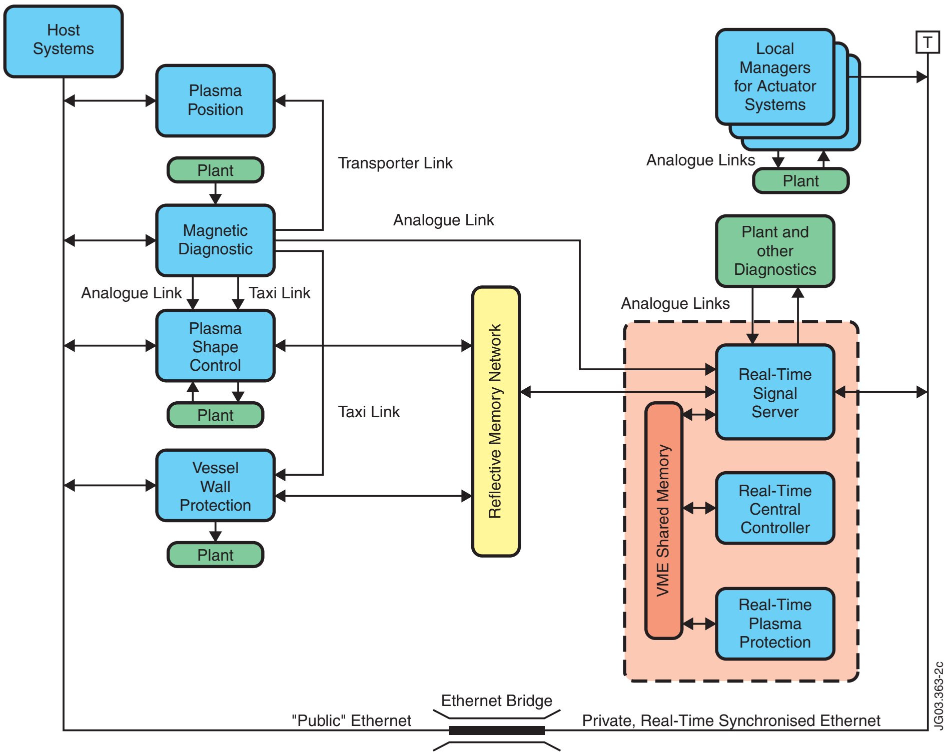

Figure 2: Original Real-Time Communication Links

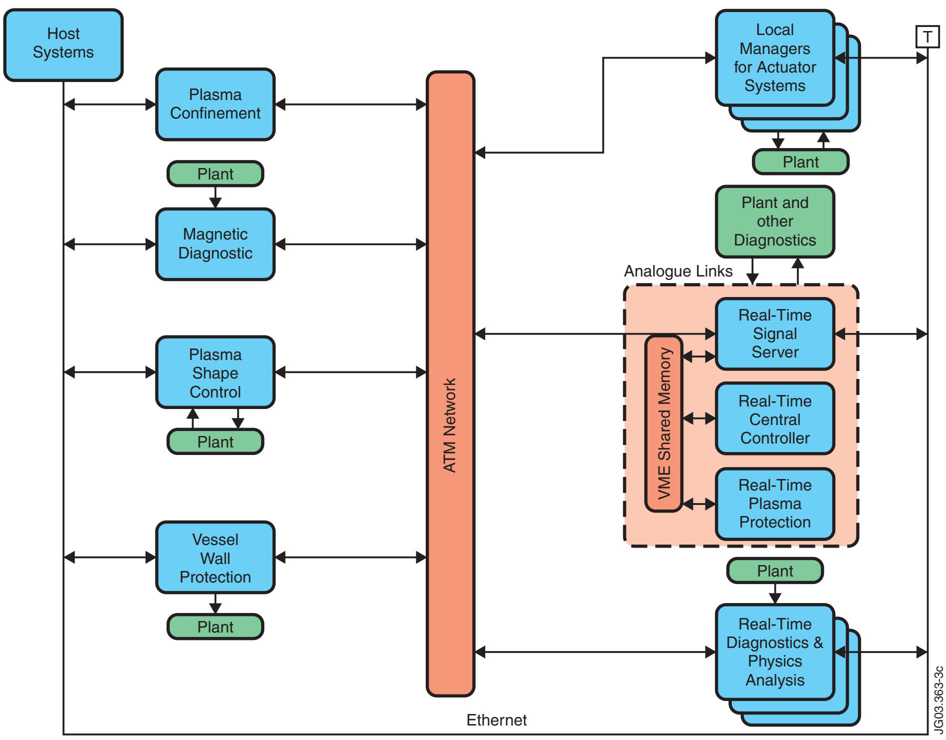

Figure 3: ATM Real-Time Data Network