The JET Fast Central Acquisition and Trigger System

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Abstract

This paper describes a new data acquisition system at JET which uses Texas TMS320C40 parallel digital signal processors and the HELIOS parallel operating system to reduce the large amounts of experimental data produced by fast diagnostics.

This unified system features a two level trigger system which performs real-time activity detection together with asynchronous event classification and selection. This provides automated data reduction during an experiment.

The system's application to future fusion machines which have almost continuous operation is discussed.

I. INTRODUCTION

Fusion machines such as JET[1] and ITER[2] magnetically contain plasmas that undergo unpredictable and rapid changes. To measure and record these phenomena requires data acquisition systems capable of sampling many signals, each at rates of hundreds of kHz, over a pulse of many seconds or even minutes. It is not practical to store all of this data and analysis of such large amounts of data would be difficult for the physicist.

During the pumped divertor upgrade to the JET tokamak, several diagnostics are being developed which will produce data at high rates (250KHz-1MHz). This has presented an opportunity to produce an advanced data acquisition system that reduces the amount of data stored by selecting, during an experiment, those events and phenomena that are of interest and then only storing the related data.

Previous experience at JET with the Soft X-Ray Trigger System [1][2] has shown that such a scheme can be successfully used to automatically detect plasma phenomena. For example, the "spontaneous snake"[2] shown in Fig.1, was first detected by this system and provides confidence that automatic systems are capable of detecting new phenomena in addition to events which have been previously observed.

The new Fast Central Acquisition and Trigger System (CATS) has been adopted by all suitable fast diagnostics at JET. This provides a unified system enabling easy co-ordination of data acquisition and more accurate event detection through the use of data from more than one diagnostic.

Section II. describes the requirements of the system. An overview of the function of the system is given in section III. The hardware and software implementation are described in section IV. Possible future developments are discussed in section V.

II. SYSTEM REQUIREMENTS

A. *Event Detection*

An 'event' is a variation in diagnostic signals that is characteristic of phenomena which are of interest in studying fusion and plasma physics. Examples of events include a periodic variation in signal output, with complex phase and amplitude relationships between channels, as shown in Fig.1; or some dramatic change in a single signal that is characteristic of a specific shift in plasma state.

These phenomena must be detected among the highly chaotic variations which are always present in diagnostic signals due to the complex and turbulent motions and interactions of the plasma.

The data acquisition system must analyse the signals in real-time and detect these events as the experiment progresses.

The nature of the plasma being measured varies greatly during the experiment and between different experiments, and therefore any event detection system must be flexible. The events of interest are likely to vary during an experimental programme, and new ways of detecting them are being constantly developed. These changes must be readily integrated.

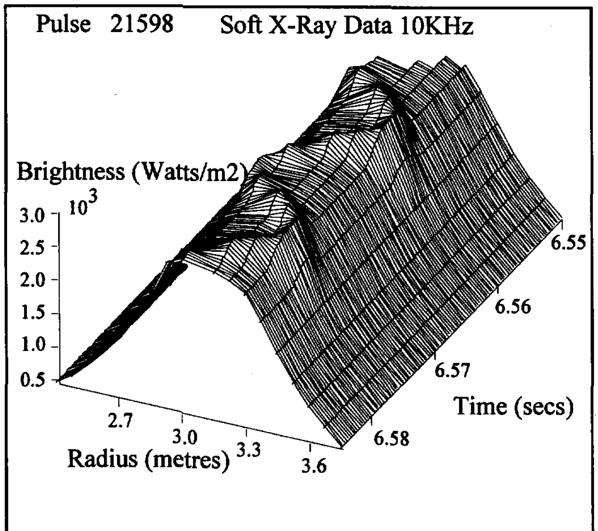

Figure 1 - An example event, the "Spontaneous Snake" as measured by the Soft X-Ray diagnostic.

[1]The Joint European Torus
[2]The International Thermonuclear Experimental Reactor

JET is an experimental project in which the underlying plasma physics is not completely understood. Thus there are likely to be events and phenomena occurring that have not yet been observed or described. It is therefore an important requirement that the system shall not be inherently biased in the type of events detectable. The system must also operate on data from several diagnostics which are very diverse in nature and behaviour. For example, the Soft X-Ray diagnostic measures the distribution of a combination of temperature and density, whilst another diagnostic provides the strength of magnetic fields around the perimeter of the plasma.

B. Event Classification

As plasma activity is detected, the system must determine the class of event and the time it occurs. This information is then used to create a database of events throughout an experiment. The actual data associated with the event will usually be stored for later review and analysis by a physicist. The type of event will determine the amount of data saved from each diagnostic.

Each event must also be assigned a priority to determine the importance of that data. This can be a dynamic process such that an event's priority could be reduced as an experiment proceeds if many of these events have already been recorded.

Many events occur regularly and it may not be necessary to store the actual data, but to simply record the type and time of the event. These may be subsequently used to study the statistical distribution or periodicity of events under different plasma conditions.

C. Data Storage

The data associated with each event must be held until the experiment is over, when it is written to more permanent storage. Storage will be limited due to cost and space constraints and so must be used as efficiently as possible.

Many plasmas terminate part way through their expected evolution. To prevent the system being under utilised in these cases, all detected events are initially stored, so rapidly filling up the memory. If the experiment continues to completion, and events with a higher priority occur later, these may overwrite low priority events recorded earlier.

Thus the system can freely store events early on in an experiment whilst guaranteeing that a period of interesting physics will not be missed later due to the storage being full. The memory will always be fully used, and not left half empty in anticipation of later events, which may not materialise.

D. Multi-diagnostic support

Many events cannot be fully identified by observing a single diagnostic measurement and therefore the classification system must be able to select channels from any participating diagnostic.

III. SYSTEM STRUCTURE

As shown in Fig.2, the system is divided into two parts, the Acquisition system which is responsible for receiving and storing data, and the Trigger system which performs activity detection and event classification. Data is communicated to the Trigger System as required, and results passed back to the Acquisition System as messages. These systems are described below in sections A and B respectively.

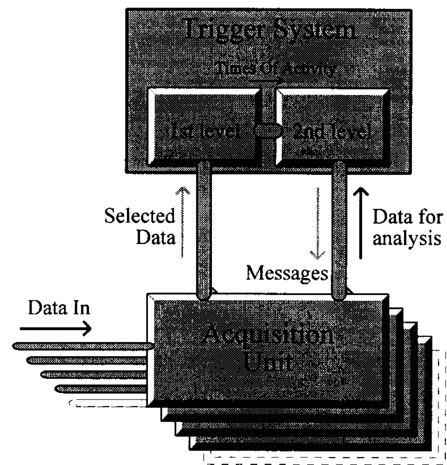

Fig.2. Overall system structure

A. Acquisition System

The Acquisition system is responsible for handling the flow of data from the diagnostic system and for its storage during the experiment; and for supplying the Trigger system with data, as required, for analysis.

To allow for any number of channels of data from any number of diagnostics, the system is constructed from a number of simple, small Acquisition Units. A single Acquisition Unit is designed to accept data from several data streams or channels. Typically a data stream will represent a logical collection of channels, for example a complete camera or group of magnetic pick-up coils. There may be any number of these units operating in parallel. Different units may receive data from different diagnostic systems.

Each Acquisition Unit must perform two distinct functions, data reception: the reading of data from the diagnostic, and data storage: the holding of this data for later analysis and eventual archiving.

A.1 Data reception

An Acquisition Unit receives a continuous stream of multiplexed data from a group of channels. This stream is broken into packets of data, each containing a short time sequence.

Any preselected data channels are then copied from the packet and sent to the trigger system. The entire packet is then placed in a short term ring-buffer while the trigger system evaluation proceeds.

Data is continually written into the buffer which eventually wraps around and the packet is overwritten. The Trigger System must have made a decision before this time, and copied any required data to longer term storage.

A.2 Data storage

When activity is detected in a packet, all corresponding data from all Acquisition Units is moved to a large, long term memory. It is held here indefinitely while further analysis is performed. If the trigger system eventually classifies this activity as an event of interest, a priority is assigned, and the data marked for long term storage. If memory becomes short, events with a higher priority may be written over lower priority packets, thus making best use of the available space.

B. Trigger System

It is not possible to perform event detection on all data because of the number of channels being received in parallel and the rate of data acquisition. In addition, the processing required to completely classify an event is non-trivial. During periods of high activity processing may not be completed between events. However there will be periods of low activity during an experiment, and these may be used to complete analysis on earlier data.

To overcome these problems the Trigger System is split into two levels. The first level implements a number of simple, fast algorithms; processing a few carefully selected channels of data in real-time. These provide a simple detection of plasma "activity". The corresponding data is then held by the Acquisition system allowing the second level to asynchronously complete the analysis and classify the events.

B.1 First level Trigger system

Each routine in the First Level receives a small number of preselected key channels of data for analysis. The routines are simple and capable of executing at the rate of data reception. Example routines include neural networks to detect the characteristic perturbation in the Soft X-Ray emission during a "Sawtooth Crash", which signifies an important change in plasma state. Simple digital-filter routines will detect the presence of regular oscillatory variations in the plasma, another key indication of important plasma conditions. Further routines may simply detect times of unusual or energetic signal change.

There may be any number of these routines, and each produces a simple yes/no result. The times of positive results are passed as a message to the Second Level Trigger System.

B.2 Second level Trigger system

The second level system can also contain any number of routines. These perform more complex analysis of data from the short packets highlighted by the First Level as containing activity. The analysis performed by each routine can require data from any participating diagnostic, allowing much more accurate identification of events. Some events may be identified by applying formal, rule based algorithms to the results of the first level, for example the simultaneous detection in different channels of specific activity.

Indeed, the analysis performed here may be quite time consuming. Some routines may only operate when a certain type of activity has been detected. Routines may be chained, later ones only running after a positive result from an earlier one, for example.

As messages from the first level are received, predefined rules are used to determine the suitable amount of data to be held by the Acquisition System until the various asynchronous event classification routines are ready to fully process and identify that event.

There are likely to be many messages during periods of high plasma activity, and fewer during other times. The second level routines are not required to run in real-time and will fall behind during these high activity periods.

During times of low activity the routines will catch up and will request appropriate data from the Acquisition System. The results of the various routines are collected and a decision made on the value of the data. The Acquisition system is instructed either to discard it, or to store it with a certain priority.

IV. IMPLEMENTATION

It is clear that this Data Acquisition and Trigger System must analyse high rates of data flow and perform a great many simultaneous computations. Current expectations are that data will be received by the Acquisition system at approximately 150Mbytes/s, a total of 4.5Gbytes of data per experiment. Parallel processing techniques provide the most flexible and extendible paradigm for such a system.

A. Hardware Implementation

A network of 40MHz Texas TMS320C40 (C40) parallel digital signal processors [6] is used in the system. These are high speed 32-bit microprocessors (200 MPOS / 50 MFLOPS) with six parallel 20Mbyte/s inter-processor comports and are available in an industry standard module (TIM-40). They can be directly compared with the INMOS Transputer which has four 10Mbit/s serial links, is available in TRAM format and is strongly linked with parallel processing.

The C40 is descended from the TMS320 family of digital signal processors and features a highly optimised processing unit, which is capable of performing several operations simultaneously.

There is a separate DMA processor for each comport, each theoretically capable of transmitting and receiving data at 20Mbytes/s (18Mbytes/s is typically the fastest rate achieved in practice). The DMA processors can self-program upon completion of a transfer and are, for example, capable of implementing a complex ring-buffer without intervention from the processor.

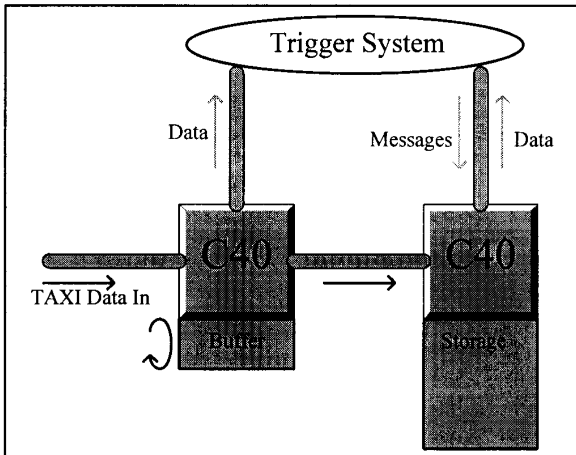

Fig.3. An Acquisition Unit

The C40 processors used in this system are hosted in industry standard TIM-40 modules [7] held on VME format motherboards. Each motherboard has four TIM-40 module sites. The TIM-40 module definition makes all C40 comports accessible to the motherboard, which may then route them to any other sites, or to other motherboards.

The C40 comport is not able to reliably drive signals a distance of more than 8cm. Therefore links between motherboards, and in some cases even between processors on the same motherboard, are required to be buffered. This reduces the bandwidth of the comport by approximately 25%.

For distances of up to 1m buffered links may be connected using standard, high quality ribbon cable. Over longer distances, special individually-screened ribbon cable is used. This is capable of carrying the link 5m or more.

A.1 Data Transmission

The signal conditioning electronics for each group of channels in a diagnostic are required to be in the most appropriate location, which may be some distance away from the acquisition system.

The TAXI protocol is used over fibre-optic cables to transmit the data to the acquisition system, permitting distances of several hundred metres to be covered without any loss in bandwidth.

Each time-slice of 16-bit data is multiplexed together and transmitted as a packet. This is received and converted into C40 comport format by a TAXI-C40 Receiver, designed to JET specification by Hunt Engineering [8]. This operates at up to 12Mbytes/s and incorporates error detection and correction. Although both the TAXI protocol and C40 comport are byte wide (8-bit), the C40 processor is a 32-bit device. Data can only be read from the comport in multiples of 4 bytes. If a single byte were to be lost due to line errors then the data read would become misaligned, making processing difficult.

To correct this, each packet of data received from the fibre is verified and padded out to a multiple of 4 bytes. A single error can therefore only affect a single time-slice of data. The TAXI-C40 receiver is built as a standard TIM-40 module, although it contains no processor. The data is transmitted through an un-buffered motherboard link.

A.2 Acquisition System

As shown in Fig. 3, each Acquisition Unit consists of two C40 processors. The first reads the data through a comport from a single TAXI-C40 converter. This is written into static RAM (SRAM) memory using one of the C40's DMA processors implementing a ring-buffer.

The TAXI protocol contains no facility for flow control, and therefore the processor must continue to read data from the comport at the rate it arrives. SRAM ensures that other, interleaved, DMA transfers from the same block of memory do not degrade the performance of this transfer due to repeated page-boundary hits.

The size of the ring buffer determines the maximum delay permissible in the first level trigger system, and before selected data is saved into longer term memory. A typical ring buffer size is 1Mbyte, which provides storage for 100mS of data. This is a standard size TIM-40 module.

The second C40 processor has a large amount of dynamic RAM (DRAM). This holds data highlighted by the first level trigger system while the second level further analyses it, and provides long term storage for selected events. The amount of memory ultimately limits the total amount of data that can be stored. Typically this is 16Mbytes, which represents a maximum total of approximately 1½ seconds of data. This is a double size TIM-40 module.

Each Acquisition Unit, consisting of one TAXI-C40 receiver, one SRAM TIM-40 and one DRAM TIM-40 occupies a complete motherboard. Links to the trigger system are made using buffered links.

A.3 Trigger System

Each level of the trigger system consists of a highly interconnected network of C40s. These processors do not need to store any data, but must perform their calculations as rapidly as possible. Therefore, each one uses SRAM memory to reduce wait states. Each network is contained on a small group of motherboards, the exact number depending on the number of processors. Un-buffered comports are used where possible, to provide faster communications.

In the first level network shown in Fig. 4, each C40 is responsible for receiving data from the Data Readers of several Acquisition Units and communicating it to the processors running the appropriate routines. When only a few channels are being processed each routine will generally be loaded on the nearest processor. This scheme allows great flexibility, for example several routines could all examine the same set of channels. Different arrangements can be installed without having to reconnect the network.

A single comport communicates messages between the networks of the first and second level trigger systems. In the second level trigger system each processor in the network is connected to several Acquisition Units and is responsible for communicating any requests for the storage and retrieval of data from those units. The memory requirements for these processors will vary depending on the analysis to be performed but for most cases 2Mbytes of SRAM will be sufficient for each.

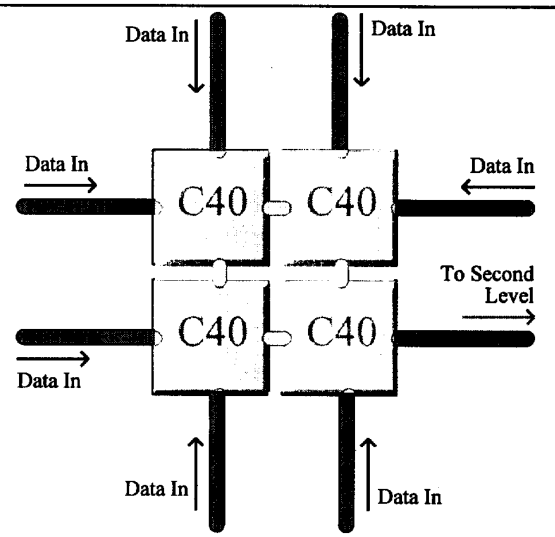

Fig.4. The first level trigger network receives data from many Acquisition Units.

B. Software Implementation

The software is hosted under Perihelion Software's HELIOS Parallel Operating System[5]. This provides a convenient, fault-tolerant development and operating environment, while imposing a minimal overhead micro-kernel when not required.

Where necessary, HELIOS allows no-overhead, low-level access to the C40 hardware, including the DMA processors, for highly efficient data transfers. HELIOS also provides the necessary support for a CSP[3] system, such as task scheduling and message passing, which are not provided by the C40.

Routines are loaded into the network using HELIOS's CDL[4], which enables individual routines to be independently rewritten, compiled and linked. Routines may also be moved to a different processor, or added and removed with only a simple CDL script change.

B.1 Acquisition System

In each Acquisition Unit, data is read from a comport by a DMA process, which is self-programming and follows a linked-list of commands, one for each packet of data. This implements a ring-buffer and also copies preselected channels to the trigger system via another comport.

The CPU is responsible for extracting data packets that will be required for further analysis by the second level Trigger System from this ring-buffer. These are written to another comport.

From here, this data is read by a second C40 and entered into a library of data waiting to be processed. Second level trigger routines request data from this library as required. When all routines have completed and a decision is made, the data is discarded or marked, with a given priority, for long term storage.

B.2 Trigger System

Each level of the Trigger System consists of multiple routines, each running as an independent process. Data is received by a routine through a simple interface, which allows detection algorithms to be implemented without requiring an understanding of the underlying data transfer mechanisms. Detection algorithms can be implemented in any of the languages supported by HELIOS (C/C++, FORTRAN etc.).

In the first level Trigger system each routine runs on a separate processor to avoid time-slicing delays. Data is analysed in small packets of 250 samples per channel, and in general each routine will only examine a single channel. Any positive results are independently transmitted to the second level, in order to prevent a single slow or faulty routine from halting the system.

Upon receipt of this message, a decision is made on the amount of required data to hold pending analysis. Messages are broadcast to all Acquisition Units which recover the data from the ring-buffer before it is overwritten. This data is then queued for analysis.

The second level Trigger system can run several algorithms on each C40 processor. These communicate using high level HELIOS message passing services.

[3]Communicating Sequential Processes
[4]Component Distribution Language

Each routine is called with the time of some detected activity. It then requests data from a central server process, which routes this request onto the appropriate Acquisition Unit.

B.3 Parallel processing implementation

This system is designed to be flexible and expandable and the CSP model of parallel processing provides the most suitable paradigm. If new or more powerful trigger routines are required, or the amount of data to be processed increases, then more processors can simply be introduced into the trigger networks and more Acquisition Units created.

The acquisition system will typically contain 25 Acquisition Units, and the trigger system 15 C40s. Any alternative scheme involving, for example, shared memory or a bus-back-plane topology would be impractical and have a limited bandwidth.

V. FUTURE DEVELOPMENTS

The type of algorithms available for the trigger system are currently very simple, being predominately based on those used for the previous Soft X-Ray system[2]. These will be extended as experience increases and with further research. In particular, the applications of neural networks are currently being researched. The use of expert systems or fuzzy logic for imposing rules based second level trigger algorithms has also been proposed, these would reduce the amount of re-coding required when requirements change.

A. Event Database

The complete set of results produced by the trigger system will be used to produce a database of events. This will allow searches on patterns of events to be made and statistics to be calculated for common events without the necessity of storing a complete data profile. This however requires confidence that any bias in the system is minimal. Bias can be present in any manual or automated data selection system.

B. Real Time Processing and Control

The data paths in the system allow transfer of data, in real-time, to external systems. This permits implementation of more advanced real-time data processing and analysis, for example in a control system or real-time data display.

C. Future Fusion Experiments

The next generation fusion experiment (ITER) is currently under design. The ITER tokamak will have linear dimensions 2½ times those of JET, and will support a plasma pulse length of 1000+ seconds (cf. 30 seconds at JET).

With this 3000% increase in data production, neglecting developments in diagnostic systems, it is clear that even low speed diagnostic systems will need to use advanced techniques to selectively reduce the data they collect.

Machines such as the ITER tokamak will also have more requirements for machine control and error detection and prevention systems. There requirements will have to be incorporated into diagnostic systems.

During extended pulses it will also be desirable for an operator to tune plasma operating parameters. Therefore diagnostic data must be analysed during the experiment, and not simply collected until the end. A system such as the one presented here could be readily extended to allow this.

VI. CONCLUSIONS

It seems clear that experimental data production in fusion will continue to outstrip practical storage facilities, and certainly will make subsequent data analysis ever more difficult. Advanced techniques must therefore be used to reduce the data collected to that actually required for the further study of plasma physics.

These problems are common to many experiments outside the fusion area which create large amounts of data with only short periods/events of interest.

Parallel processing techniques are essential to solve these problems due to the increasing processing requirements and high data flow rates.

The Fast Central Acquisition and Trigger System at JET illustrates the use of these techniques to provide a solution to the problems of storing and analysing increasing amounts of data.

VII. REFERENCES

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