INTERFACING TO ACCELERATOR INSTRUMENTATION*

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Abstract

As the sensory system for an accelerator, the beam instrumentation provides a tremendous amount of diagnostic information. Access to this information can vary from periodic spot checks by operators to high bandwidth data acquisition during studies. In this paper, example applications will illustrate the requirements on interfaces between the control system and the instrumentation hardware. A survey of the major accelerator facilities will identify the most popular interface standards. The impact of developments such as isochronous protocols and embedded digital signal processing will also be discussed.

I. INTRODUCTION

Survey of Instrumentation Groups

In September and October of 1995, instrumentation personnel representing 21 facilities and projects were contacted via email and asked to answer several questions about instrumentation interface technologies. The results are concisely summarized as follows:

- Less than 10% have built a GPIB instrument
- About 20% currently include VXI based instruments and nearly 50% plan to use VXI in the future
- nearly 60% use LabVIEW for bench measurements
- About 40% use portions of the control system during system development

In addition, their other comments were used to select the topics covered in this paper.

Accelerator Measurements

A very simple measurement setup is illustrated in Figure 1 with the accelerator as the device under test. The stimulus might drive a broadband kicker, the quad bus, or a steering magnet. The response might be measured by a wide band position monitor, a tune meter, or an orbit monitor. In any case, a correlation plot is produced. Since time is the implicit free variable, the measurement equipment is almost always synchronized with the accelerator timing system. If automatic control of the measured parameter is desirable, the measurement system could be converted to a feedback system.

An accelerator instrumentation system provides the response measurement. Figure 2 illustrates the signal flow through a generic instrumentation system. For continuous data streams like those produced by storage ring and CW linac instrumentation, buffer size is determined by the worst-case latency of the interface. If this data is used in a feedback loop, the performance of the loop is limited by the loop delay as determined by the total worst-case latency. Therefore, the interface should provide deterministic latency as well as adequate throughput. An example of low latency interface is the VME-based reflective memory used for an orbit feedback test at SPEAR [1]. Although the sampling rate for this experiment was 37 Hz, the goal for a similar system at the Argonne APS is to use a 4 kHz sampling rate and provide a - 3 dB closed orbit correction bandwidth of 100 Hz [2]. Given the high performance processor and network hardware currently available, it is unfortunate that these systems must still utilize a data path that is independent of the accelerator control system.

Referring again to Figure 2, a current trend is to reduce analog complexity and digitize closer to the source. This can lead to fairly high raw data rates. If calculated parameters are desired, a local digital signal processor

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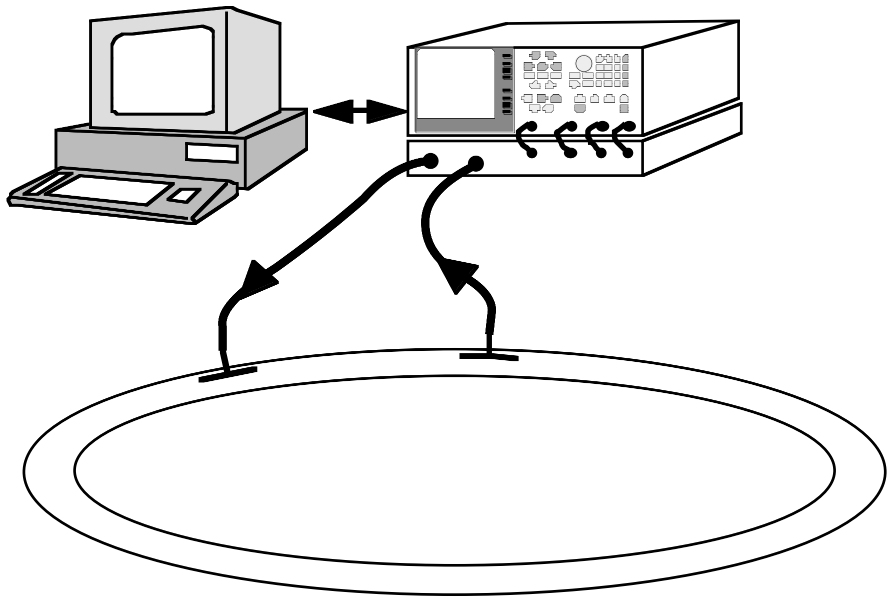

Figure 1. **Simplest stimulus-response measurement**

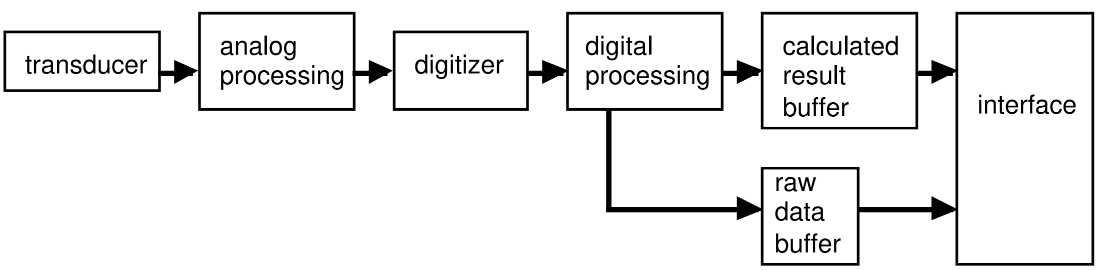

Figure 2. **Generic signal flow diagram**

(DSP) can write them to the result buffer at a reduced rate. An example of this simple DSP application is the low intensity position detector proposed for the fixed target areas at Fermilab [3]. Here, a 1.8 Msample/s 12 bit data stream is digitally down converted and filtered to a much lower rate, higher resolution stream that can be read through the control system interface.

II. INSTRUMENTATION SYSTEM LIFECYCLE

Development

Throughout system development, bench measurements are made using commercial test and measurement equipment. Software may be developed to fully exercise the system and obtain complete calibration data. This single user, benchtop environment is well supported by the commercial test equipment and software vendors. The accelerator control system is often immature during this phase and may lack the extensive instrument drivers, data analysis tools and the rapid turnaround environment of commercial software packages like National Instrument's LabVIEW. Therefore, it is not surprising that much instrumentation is developed without control system support and that system integration activities dominate a lengthy commissioning phase.

Even with the vast array of commercially available hardware, it is rarely possible to meet system performance and cost goals with exclusively off-the-shelf purchases. This is particularly true with systems that have high channel multiplicities. However, the in-house development timeline can be compressed by dividing a system into concurrently developed modules. Obtaining a fine grained modularity through the use of mezzanine cards allows the following benefits: chances are better that some modules might be reused in other systems, reduced module complexity improves testability, off-the-shelf modules are less likely to include expensive unwanted features, and late design changes will have a reduced schedule impact. In the Relativistic Heavy Ion Collider (RHIC) Beam Instrumentation Section, Industry Packs are used to achieve this modularity [4][5].

Commissioning and machine studies

Due to the desire to constantly improve accelerator performance, commissioning and machine studies are ongoing activities that share the following characteristics:

- unusual beam parameters and acquisition scenarios
- limited faith in system performance and reliability for these operating scenarios
- large data sets
- flexible, rapid turnaround application development tools required
- experts on hand to solve problems and provide support

Operations

During operations, required data rates are typically lower than those required by studies and some system features may not be used. It is convenient to use parameters derived locally from the raw data rather than acquire and display large data sets. Built-in self test sequences can instill confidence in system performance without requiring the additional test equipment that was used during the development phase.

Upgrades

As a result of operational experience, some systems may require improved performance. The upgrade of the LEP narrow-band orbit measurement electronics is just one example [6]. At the same facility, a new operating mode using bunch trains impactson nearly all instrumentation systems [7]. The same modularity that was beneficial during the design phase can provide similar benefits in these situations.

III. STANDARDS FROM THE TEST AND MEASUREMENT INDUSTRY.

As opposed to the industrial instrumentation and controls products, products from test and measurement companies are most similar to accelerator instrumentation electronics. However, their target market is predominantly benchtop test systems and not distributed instrumentation. The standards described in this section are used extensively during the development phase of instrumentation systems. Commercial instruments based on these standards also show up in the operational environment when their performance and flexibility justifies the typically high capital cost.

GPIB

To this day, virtually all rack and stack instruments sport an IEEE 488 port. With it’s 8 data lines, 8 control signals, and bulky connector, this port looks fairly archaic, and the following timeline shows the reason.

1965 - Hewlett Packard defines its HP-IB interface for instruments

1975 - IEEE 488 standard is ratified. Defines physical interface based on HP-IB

1987 - IEEE 488.1 is ratified [8]. Evolutionary step from 1975 standard. Commonly called GPIB.

1987 - IEEE 488.2 is ratified [9]. Defines higher level command structure. Revised in 1992.

Because the 1975 standard did not define status reporting, data formats and other software protocols, manufacturers each invented their own implementations. The resulting mess is partially responsible for GPIB’s poor reputation with system integrators. IEEE 488.2 defined the command structures that all instruments and controllers should support. In 1990, the Standard Commands for Programmable Instruments (SCPI) Consortium defined an extensible set of instrument specific commands.

Although some instruments allow for binary data transfers, all of the standard commands are ASCII that must be parsed in real time. Thus, a one shot request for a small data block incurs significant latency and overhead. The typical raw transfer rate for a GPIB connection is over 1 MByte/s for long blocks. The bus can have up to 15 devices, each separated by about 1 meter with a total electrical bus length of 15 meters.

As an example of real world system performance, a recent test at Fermilab was performed to evaluate oscilloscopes. The test consisted of digitizing a series of 8 bit samples at 2 Gsamples/s and reading them in through GPIB to a LabVIEW application running on a Macintosh Quadra. With the fastest scope, a 2000 point series was digitized and transferred 10 times in 270 milliseconds. With a 100,000 point series, the same scope digitized and transferred 100 times in 59 seconds.

VXI

VME Extensions for Instrumentation (VXI) is now the card/backplane standard for the test and measurement industry. The VME Handbook [10] provides a very readable overview complete with comparisons to VME. A brief summary is included here.

There are four VXI card sizes, but by far the most popular is the C-size card (6U high by 340mm deep) so this will be the assumed format in the following discussion. To provide room for electromagnetic shielding, the cards are spaced on 1.2 inch centers rather than the 0.8 inch centers defined by VME. P1 and P2 carry the bus signals defined by revision C.1 of the VME specification. The outer two rows of P2 carry the following signals:

- 10 MHz clock
- Bussed TTL and ECL triggers
- 12 pin local bus
- Analog summing bus
- Module Identification bus
- Additional power distribution

The Module ID bus, along with configuration registers defined in A16 space, allow some level of system self-initialization. Two broad classifications of VXI instruments can be defined by their adherence to VXI software standards:

1. Message Based: Usually produced by a test and measurement company that ports its GPIB instruments to VXI. Typically they will use a word-serial protocol similar to GPIB SCPI commands. The company's customer base is usually downsizing a rack and stack test system and also increasing throughput. For example, converting an oscilloscope-based digitizing system to VXI will result in a 1 to 3 increase in channel density [11].
2. Register Based: Usually produced by a data acquisition company that moves functionality from CAMAC, VME, etc., to the VXI format. Register-based devices keep the efficient memory-mapped access to data and control/status registers. To an accelerator control system, VXI register-based devices are accessed like any other memory-mapped VME card. Many modern control systems provide VME-based real time systems. In these cases, the VXI address space can be transparently bridged to the VME address space. At Brookhaven, the AGS to RHIC transfer line position monitor electronics reside in a VXI crate that is transparently bridged to the control system VME crate [4].

Message based commercial equipment is not conveniently integrated with most control systems. The messaging architecture of this equipment has a long history in the single user, bench-top test environment. A modern control system provides its own messaging standard to solve the problem of distributed control over relatively slow LANs for multiple users. With its large library of instrument drivers, LabVIEW has been used as an integration tool at several laboratories. Two examples illustrate two different approaches. The Sampled Bunch Display system at Fermilab acts as a local front end for the Tevatron control system [14]. The GUI provided by LabVIEW is not present on the control consoles. A small set of parameters is provided on the network and displayed in a laboratory standard parameter page.

A tune meter at the Berkeley ALS provides another integration example. Here, LabVIEW is again communicating with a message-based single user instrument, but the interface to the control system happens at the application layer. With this access to the control system on-line database, the technique could be extended to provide a data acquisition system with the LabVIEW graphical interface and rapid turnaround development environment [15]. A system with a similar architecture is in the prototype stage at RHIC and might be used for instrumentation-related machine studies.

IV. ADDITIONAL STANDARDS

The test and measurement standards described above are currently in use at virtually every accelerator facility. However, two points were mentioned earlier:

1. In the development and upgrade phases of an instrumentation system, fine-grained modularity (below the VXI module level) can increase testability and reduce costs in the event of a change. Since Industry Packs are used for this purpose at several accelerator labs, the standard will be summarized here.
2. Register-based VXI cards can present an efficient memory-mapped interface to the control system. However, it is sometimes necessary to distribute the modules in a topology that does not allow cost effective use of VXI packaging. This could happen when the analog functions cannot fit into the VXI format, or when performance could be increased by placing the digitizers close to distributed signal sources. In either case, it is desirable to keep the efficient memory-mapped access even though the instrumentation modules are not confined to a physical backplane. A standard under consideration at RHIC is the IEEE P1394 Serial Bus [16].

Industry Pack (IP)

A summary of features:

- slightly larger than a business card
- 2 connectors for each single wide Industry Pack
- 50 pin user connector simply wired to a header
- 50 pin logic connector memory-mapped to one port of the DSP
- 16 bit synchronous logic interface for single wide packs
- option of 32 bit interface for double wide packs
- standard 8 MHz interface or preliminary 32 MHz interface
- Many available commercially
- very simple to develop in-house for special functions
- dozens of competitors, but IP seems to have the broadest market penetration
- Other market winner will surely be the PCI mezzanine standard, PMC. But it is a larger format with demanding design requirements.

Real world performance with the RHIC Beam Instrumentation Section DSP board is quite reasonable. At 8Mhz, a 5.3Mbytes/s throughput from IP to DSP is achieved. This can be doubled to 10.6Mbytes/s with a double wide industry pack. The Industry Pack specifications also specifies (preliminary) a 32 Mhz interface, which has been implemented giving a throughput of 12.8Mbytes/s or 25.6Mbytes/s for double width Industry Pack.

IEEE P1394 Serial Bus

Some comments on this standard:

- IEEE 1212 Command and Status Register (CSR) standard with a 64 bit address space
- 100, 200, or 400 Mbits/s bandwidth
- memory-mappe- like architecture is well matched to load-store architecture of current processors.
- real world performance should be comparable to VXI backplane performance. Any standard based on RS-485, Universal Serial Bus (USB), ethernet, etc. will be significantly slower.
- LAN/WAN technologies would introduce complex protocol stacks and driver software. This is a high price to pay for simply moving modules off the backplane.
- asynchronous and isochronous (guaranteed bandwidth and latency) data transfers are supported

- maximum of 4.5 meters between nodes is standard, but work is in progress to extend to much longer distances with cable upgrades and/or bridges
- cheap ($50/node in 1995)

An Industry Pack that contains a 100 Mb/s Serial Bus interface has been developed at RHIC. Several of these devices will be used to evaluate possible applications in the collider ring position monitor and loss monitor systems. Results of this study will be reported in the near future.

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