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Section A

The experimental physics and industrial control system architecture: past, present, and future +

Leo R. Dalesio [a,*], Jeffrey O. Hill [a], Martin Kraimer [b], Stephen Lewis [c], Douglas Murray, Stephan Hunt [d], William Watson [e], Matthias Clausen [f], John Dalesio [g]

[a] *Los Alamos National Laboratory (LANL), Los Alamos, NM, Mexico*
[b] *Argonne National Laboratory (ANL), Argonne, IL, USA*
[c] *Lawrence Berkeley Laboratory (LBL), Berkeley, CA, USA*
[d] *Superconducting Super Collider Laboratory (SSCL), Dallas, TX, USA*
[e] *Continuous Electron Beam Accelerator Facility (CEBAF), Newport News, VA, USA*
[f] *Deutches Elektronen-Synchrontron (DESY), Hamburg, Germany*
[g] *Tate Integrated Systems (TIS), Baltimore, MD, USA*

The Experimental Physics and Industrial Control System (EPICS), has been used at a number of sites for performing data acquisition, supervisory control, closed-loop control, sequential control, and operational optimization. The EPICS architecture was originally developed by a group with diverse backgrounds in physics and industrial control. The current architecture represents one instance of the "standard model". It provides distributed processing and communication from any local area network (LAN) device to the front end controllers. This paper presents the current architecture, performance envelope, current installations, and planned extensions for requirements not met by the current architecture.

1. Introduction

The Experimental Physics and Industrial Control System (EPICS), has been used at a number of sites for performing data acquisition, supervisory control, closed-loop control, sequential control, and operational optimization. The current EPICS collaboration consists of five U.S. laboratories: Los Alamos National Laboratory, Argonne National Laboratory, Lawrence Berkeley Laboratory, the Superconducting Super Collider Laboratory, and the Continuous Electron Beam Accelerator Facility. In addition, there are three industrial partners and a number of other scientific labs and universities using EPICS. Details of these and the history of the design of EPICS are given in a companion paper [1]. This paper will present the genealogy, current architecture, performance envelope, current installations, and planned extensions for requirements not met by the current architecture.

* Corresponding author.

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2. Design history

EPICS was developed by a group with experience in control of various complex physics processes and industrial control. Three programs preceding the EPICS development were high order beam optics control, single shot laser physics research, and isotopic refinery process control. These systems were all developed between 1984 and 1987. The three programs embodied different aspects of data acquisition, control and automation. They used equipment and methods most appropriate for the time and scope of their respective problems. The Ground Test Accelerator project, where EPICS development began as GTACS [2] required fully automated remote control in a flexible and extensible environment. These requirements encompassed aspects from all of the previous control system experience. The design group combined the best features of their past, like distributed control, real-time front-end computers, interactive configuration tools, and workstation based operator consoles, while taking advantage of the latest technology, like VME, VXI, X-windows, MOTIF, and the latest processors (Table 1). Since the collaboration began, major steps have been made in portability between sites, extensibility in database and driver support, and added functionality

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Table 1
Architectural history

	One shot laser physics	High order beam optics	Isotopic refinery process control	GTACS/EPICS
Architecture	hierarchical	distributed	distributed	distributed
Signal count	~ 4000	~ 300	~ 3000	~ 30000
Field bus	STD/CAMAC	CAMAC	Industrial	VME/VXI/ GPIB/Industrial Bitbus/CAMAC
OPI/front end	VAX/VAX	VAX/VAX	6800/6800	680x0/ workstation
Network	DecNet/RS232	DecNet	MAP	TCP/IP
Data transfer	polled	polled/ notification	polled	polled/ notification
Special I/O	200 TDRs positioning	Video diagnostic positioning	High rep rate closed-loop control	full complement
Offline configuration tools	none	displays	displays, alarms, I/O, control, and archive requests	displays, alarms I/O, control, and archive requests

like the alarm manager, knob manager and the Motif based operator interface. The EPICS name was adopted after the present multi-lab collaboration began. The key to the design strength has always been the ability of the design engineers to explore and evaluate new ideas.

3. Current architecture

The EPICS architecture [3] represents an instance of the "standard model" [4,5]. There are distributed workstations for operator interfaces, archiving alarm management, sequencing, and global data analysis. There is a local area network for communicating peer-to-peer and a set of single board computers for supporting I/O interfaces, closed-loop control, and sequential control.

The software design incorporates a collection of extensible tools interconnected through the channel-access communication protocol [6–8] (Fig. 1). The software architecture allows the users to implement control and data acquisition strategies, to create state notation programs, and to implement sequential control in a single board computer called the Input/Output Controller (IOC). All data is passed through the channel-access protocol using *gets*, *puts*, or *monitors* (notification on change). One can extend the basic EPICS system in the IOC by creating new database record types, calling 'C' subroutines from the database, extending the driver support and creating independent VxWorks task (Fig. 2). Some of the larger extensions include video sampling, video analysis [9] and support for a 4 kHz closed-loop control distributed over multiple IOCs [10]. Workstation-based tools are frequently developed to accommodate unique operator requirements, to integrate physics codes or to take advantage of some commercial package. Some examples are an adaptive neural network for optimizing a small angle ion source [11], WingZ, PV-Wave, and Mathmatica. The EPICS software architecture provides a flexible environment for resolving problems that extend beyond its present capabilities.

4. Performance

The IOC provides the physical interface to a portion of a machine. The limiting factors in the perfor-

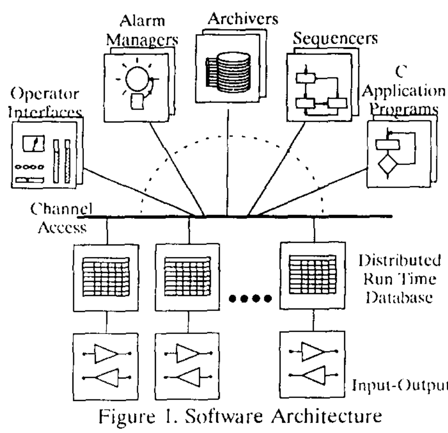

Fig. 1. Software architecture.

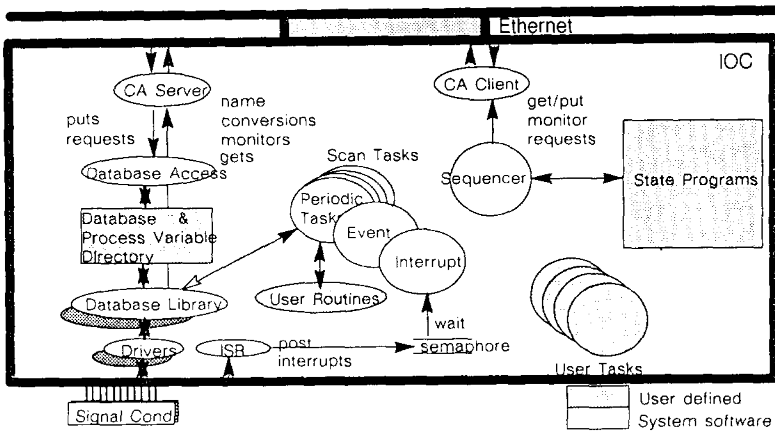

Fig. 2. IOC Dataflow diagram with user defined areas shown.

mance of the IOC are the CPU bandwidth and memory. Table 2 shows the measured performance for analog inputs, binary inputs, and monitors. If channel-access notification is required, an additional 100 μs is incurred. It is important to note that most signals are not monitored by channel-access clients and that monitors are only sent on change of state or excursion outside a dead-band. In the average case, a signal being processed will not post monitors. Periodic scan rates vary from 10 Hz to one per minute, but can be modified to range from 60 Hz to once every several hours. In addition, records can be processed on end-of-conversion and change-of-state. For analog inputs, scanning on end-of-conversion significantly reduces the latency between gating a signal and processing the record. This is useful for pulse-to-pulse closed loop control. The scheduling and dead-bands should be selected to fit the situation. The database scanning is flexible to provide optimum performance and minimum overhead.

Communication performance is bounded by the channel-access protocol, TCP/IP packet overhead, and the physical communication media. Channel-access makes efficient use of the communications overhead by combining multiple requests or responses. For a point to point connection, 1000 monitors per second (~ 30 bytes per monitor) will use about 3% of the 10 Mbit Ethernet band-width. To avoid collisions and therefore avoid non-determinism, the Ethernet load is kept under 30% [12]. At this level, we can issue 10000 monitors per second. The use of LAN bandwidth can reduced by 50–80% by changing the channel-access protocol to variable command format and compressing the monitor response data (~ 6–15 bytes per packet). LAN bandwidth can also be expanded by using commercially available hardware. By isolating subnetworks with bridges or an Etherswitch, the bandwidth can easily be tripled. Going to a 100 Mbit Ethernet yields a 10 times performance improvement. Using a 100 Mbit FDDI provides a 10 times faster medium with twice the available bandwidth since it is a token-based scheme. The Ground Test Accelerator, with 2500 physical connections and 10000 database records, distributed among 14 IOCs and interfaced to 8 workstations, used only between 5–7% of our 10 Mbit Ethernet during operation. Using the GTA measurements as a basis a 10 Mbit Ethernet and the current system will support around 20000 physical connections is estimated that networks using bridges, Etherswitches, 100 Mbit Ethernet, and 100 Mbit FDDI will be able to support systems with between 60000 and 400000 physical connections on a local area network.

Table 2
IOC measured performance and memory consumption [13]

	Number of bytes per instance	instances to use 1.5 M B	μs each 68040 (MV167)	CPU Usage at 1000/s
A/D Conversions	576	2600	61	6.1%
Binary Inputs	480	3100	52	5.2%
Monitors	32,000/client	46 clients	100	10.0%

Table 3
Installations of EPICS

	Signals implemented	IOCs Installed	Workstations Installed	Signals on completion
Ground Test Accelerator	2500	14	8	15000
Advanced Photon Source	400	3	3	30000
Gammasphere	150	8	6	3000
Superconducting Super Collider	200	3	1	1000000
CEBAF	0	0	0	50000
Duke Mark III IR FEL	380	1	2	380
St. Louis Water System	7200	4	6	7200

Table 4
Configuration tool extensions for EPICS

	Solution	Work in progress
Graphical database configuration	Use Objectviews as basis for tool	ANL, SSCL
	Use schematic capture program	LANL, CEBAF
Graphical state notation language	Use Objectviews as basis for tool	SSCL
Extend Graphical Display Configuration	Motif based	ANL
	X-based	LANL
Graphical Alarm Configuration	Motif-based	ANL
System Configuration	Use a relational database	
	D-BASE	Tate
	INGRES	CEBAF
Graphical Archive Configuration	Use Alarm Configuration tool as basis	None

Table 5
Channel access extensions

	Solution	Work in progress
Need dedicated point to point communication	Add an option to use a name server	Tate, SSCL,
	Add drivers for serial and T1	LANL
Access protection	Add access control based on user, location, channel, and machine mode	ANL, LANL
Need closed-loop control across the network	Add multi-priority channel access connections	LANL
Connect to alternate data stores	Port the channel access server to different data stores	DESY, LANL
Support a multitude of operator interfaces	Create a data gateway to clients that are able to withstand a single point of failure and the added latency	LANL
IOC memory limitations	Size server queues according to need	LANL
Socket and task limitations in the IOC	Take advantage of the newly working Vx Works Select	Tate, LANL
Long time-outs on disconnect	Add a time-out heartbeat when there's no traffic on a connection	Tate, LANL

5. Installations

EPICS is in use at a number of scientific laboratories, universities and commercial installations. Table 3 presents a summary of some of these installations, the number of signals, IOCs, and workstations installed and the projected number of signals on completion. The EPICS software is typically used in systems between 200 and 50000 signals. The SSC is a unique case with 1000000 signals projected. Although we have run a number of tests to characterize the operating parameters for EPICS, the largest installation that has been operated has only 2500 physical connections and 10000 database records. EPICS extensibility will be demonstrated on CEBAF, APS, and GTA installations in the next 12 months, as each of these installations are commissioning large portions of their respective accelerators.

6. Extensions

There are a number of extensions required to meet the needs of the laboratories currently specifying EPICS. The major shortcomings in the EPICS environment revolve around configuration tools, communication support issues, and some general system functions.

There are a number of significant development and tool integration efforts going on at several sites to bring the configuration tools up to modern standards. Most of these efforts are directed at graphical configuration tools as shown in Table 4.

The communication support issues are just being addressed, as the channel-access protocol is the basis for all compatibility. We have run the same version of the channel-access protocol for the past three years. The requirements forcing us to revise channel-access are to provide support for serial communication media, for user facilities, and for the integration of other data sources (Table 5). We are maintaining compatibility at the subroutine interface level so that all of the current channel-access clients and servers will only require recompilation and relinking.

Other system-wide functions needed are: the ability to add and delete signals during operation, redundant IOCs for critical processes, higher level physics objects as database records, a general save and restore of operating parameters and a support group to reintegrate, test, and distribute these new versions. We are currently exploring options for providing this support function. In the past, we integrated extensions and supported the EPICS installations through direct program funding. As the collaboration has grown, this has proved to be more difficult.

There are significant pieces of development required to make EPICS a complete solution for experimental physics. Most of the tasks are currently under development at the collaborating laboratories or the industrial partners. We are exploring options for providing good user support for the EPICS community. The functional specifications and design for these added tasks have been reviewed by the collaboration members and have been approved. The collaboration works as a single group to specify and design additions to EPICS, using the combined resources and knowledge of the collaboration.

7. Conclusion

The EPICS toolkit provides an environment for implementing systems that range from small test stands requiring several hundred points per second to large distributed systems with tens of thousands of physical connections. The application of EPICS requires a minimum amount of programming. The EPICS environment supports system extensions at all levels, enabling the user to integrate other systems or extend the system for their needs. Work is underway to provide a more integrated application development environment. The base software is also being extended to support some of the fundamental needs of the projects that are controlling user facilities. Through the modular software design which supports extensions at all levels, we are able to provide an upgrade path to the future as well as an interface to an installed base. With the addition of a user support group, we will be able to provide a stable starting point complete with an upgrade path, for those projects choosing to use the EPICS toolkit.

Acknowledgements

There are now several chapters in the EPICS story with close to one hundred colleagues contributing thus far. The decision to collaborate with others brings the responsibilities to support one's low collaborators as you would your own programs. This responsibility has received the necessary managerial support from each of the five member laboratories to provide the environment for a successful collaboration. The ability to develop system software in a collaborative manner requires a real dedication to finding the best solution. The system designers that have been involved in this collaboration have been "egoless" in their search for the best answer resulting in consensus design. Finally, there are the application engineers who have continually provided suggestions for upgrades and extensions and have supported our efforts even through some challenging times. All of the teams at Los Alamos National Laboratory, Argonne National Laboratory,

Lawrence Berkeley Laboratory, the Superconducting Super Collider Laboratory, and the Continuous Electron Beam Accelerator Facility have contributed to this success in co-developing software. It is certainly rewarding to work with such a wide range of experience and knowledge.

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