EXTREME LIGHT INFRASTRUCTURE, BEAMLINES – CONTROL SYSTEM ARCHITECTURE FOR THE L1 LASER*

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Abstract

The ELI-Beamlines facility aims to provide a selection of high-energy and high repetition-rate TW-PW femtosecond lasers driving high intensity XUV/X-ray and accelerated particle secondary sources for applications in materials, medical, nuclear and high-field physics sectors. The highest repetition rate laser in the facility will be the L1 laser, producing 1 kHz, 20 fs laser pulses of 200 mJ energy. This laser is based entirely on picosecond chirped-pulse parametric amplification and solid-state pump lasers. The high repetition rate combined with kW pump powers and advanced technologies calls for a highly automated, reliable and flexible control system. Current progress on the L1 control system is discussed, focussing on the architecture, software and hardware choices. Special attention is given to the LabVIEW-EPICS framework that was developed for the ELI Beamlines lasers. This framework offers comprehensive and scalable EPICS integration while allowing the full range of LabVIEW real-time and FPGA embedded targets to be leveraged in order to provide adaptable, high-performance control and rapid development.

INTRODUCTION

The four laser sources (L1-L4) are currently under development and will be installed in the facility in time for a ‘first light’ demonstration in 2016-17. The L1 laser’s high repetition rate, 5 TW peak power and excellent beam quality is aimed at experiments based on high-harmonic generation (XUV), X-ray and keV betatron radiation in the molecular, biomedical and materials sciences [1].

The resulting L1 control system architecture and design is currently in a fairly final state with most hardware and software components operational and tested as part of an integrated solution. The aim of this paper is to summarise the chosen architecture and highlight some of its advantages for similar control system projects.

ARCHITECTURE DEVELOPMENT

At the start of control system development, the type and quantity of I/O was estimated by reference to similar laser systems. Requirements were also collected regularly from the laser scientists. The estimate of the scale of the I/O requirements was the basis of the architecture:

Table 1: L1 Control System Scale

Device	**Parameters**	**Approx. qty**
Cameras	20 Hz, 2 M pixel	60
High speed cameras	1 kHz 0.5 M pixel	6
Stepper motors	Simple, open loop	100
Piezo actuators	Small, open loop	20
Piezo steppers	Mostly open loop	20
Laser relative energy	*e.g.*, photodiode, kHz	40
Digital I/O channels	Mostly 24 V logic	30
General analogue I/O	≤kHz, 16 or 24-bit	30
Temperature sensors	RTDs	20
Flow sensors	Cooling water, pulse	20
Complex instruments	Serial, USB, Ethernet	6
Simple devices	Serial, Modbus, *etc.*	15

Over the course of development other project-specific factors have also been significant in determining the final choice of implementation:

- The high laser repetition rate and expense of key laser optics necessitates a real-time control system with sufficient intelligence to provide machine protection;
- Some laser instruments are highly specific and available from few vendors. Generally the only integration for these is via LabVIEW;
- The laser is based on new and cutting-edge technology, so control system requirements change frequently;
- The budget, time and effort required for laser control systems are often underestimated;
- Human resources, particularly software developers, are limited due in part to competition from the rapidly growing IT sector locally;
- Being a new facility there is little established experience. Any solution must be easy and quick for new staff to learn and work with;
- Strict tendering rules and laws restrict procurement; therefore reliance on a few key suppliers for most of the control system components justifies the time and expense of preparing a framework contract.

EPICS was chosen as the integration framework as it is widely used, stable and requires minimal programming. Use of LabVIEW was essential and is fast, flexible and easy to learn. This was chosen to be the sole software development language for reasons of maintainability and to streamline training. The resulting structure of the control system (Fig. 1) is based on a simple 3-layer scheme appropriate to the scale and suitable for an industrial/machine-control system.

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* Work supported by the European Regional Development Fund and the European Social Fund under Operational Programs ECOP and RDIOP. The project is hosted by Fyzikální ústav AVČR, v.v.i.

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The services layer provides database-driven configuration and data archival. A flexible HMI server supports flexible configurations of in-lab displays and centralised status panels. A hierarchical state machine model governed by a top-level sequencer ensures subsystem modularity and facilitates integration and automation. Finally, the interface gateway provides network security and integration to the rest of ELI-BL.

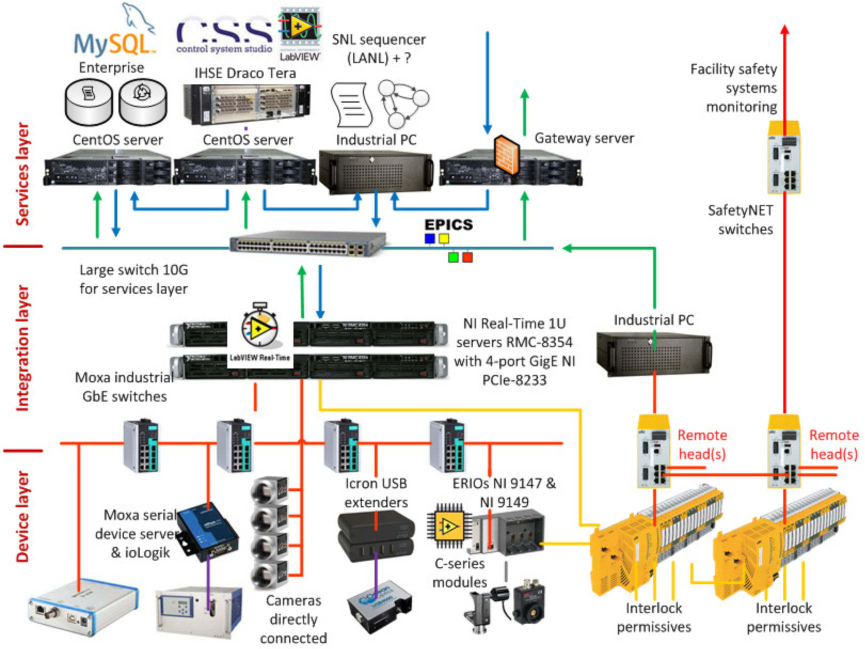

Figure 1: Control system architecture for the L1 laser – implementation view.

ARCHITECTURE IMPLEMENTATION

Selection of hardware and software solutions to implement this control architecture is now largely finalised. Advice from National Instruments and from Lawrence Livermore National Laboratory (contractors for the L3 laser at ELI-BL) was instrumental in selecting an implementation. Ongoing collaboration with LLNL on the High-Repetition-Rate Advanced Petawatt Laser System (HAPLS) [2] and with National Energetics-EKSPLA on the 10 PW L4 laser [3] has resulted in the standardisation of much of this control system architecture across all of the laser beamlines – a major achievement for integration and assurance of the future maintainability of the facility.

Due to the large number of cameras the NI RMC-8354 controller was chosen. This product is normally marketed as a remote PXIe chassis master. It is based on a 1U server-class computer with NI's Pharlap-based operating system. The one x16 PCIe slot is suitable for mounting a 4-port frame grabber (NI PCIe-8233), and the powerful platform is useful for image processing at the 20 Hz framerate. Each IOC has a dedicated link to the MSS via its serial port; modem lines are used as a deterministic digital interface to signalise faults and trigger a safe-state. The RMC-8354 has limited I/O options; therefore the device layer was restricted to Ethernet with the use of Ethernet-to-serial (Moxa NPort) and USB-over-Ethernet (Icron RG2304GE-LAN) interface adapters. This has the advantage that IOCs can be largely hardware-independent, supporting virtualisation.

The machine safety system (MSS) and personnel safety system (PSS) are controlled by a SIL-3 rated (IEC 61508) PLCs (Pilz PSS 4000) offering reliability and flexibility at reasonable cost. Although SIL-3 is not required for machine safety, use of the same platform for both systems simplifies training and improves maintainability.

The MSS is interfaced via Modbus to EPICS integration layer using Base records on Linux. Standard records are used to interface most simple support devices such as chillers and PSUs. PSUs with analogue control such as those for Pockels Cells are controlled using simple remote I/O modules (Moxa ioLogik) using Base records. This approach avoids unnecessary LabVIEW development when the application is straightforward.

More complex low-level I/O is handled by NI C-series modules on a programmable FPGA expansion platform (Ethernet RIO). The C-series range is sufficient for all of the analogue and digital I/O requirements of the L1 laser. This solution was chosen as it is more modular, cheaper, and easier to use than higher-density platforms such as MicroTCA or PXIe which are better suited to higher performance I/O and/or higher channel counts. The Artix-7 FPGA is flexible to handle changing laser requirements and powerful enough for sophisticated feedback systems (such as laser power stabilisation, fast beam-pointing correction and temporal jitter cancellation).

NI provides two other RIO expansion systems, MXIe and EtherCAT. An expansion system is appropriate because the RMC-8354 is the real-time host. ERIO is the lowest cost interface for C-series modules. For 'hard-real-time transfer of data at sub-ms rates only EtherCAT RIO and MXIe RIO are suitable. However, trials showed that ERIOs have sufficient determinism to guarantee 1-2 ms transfers over the device layer network with an RMC-8354 host. This is sufficient for all applications in L1.

ISBN 978-3-95450-148-9

SOFTWARE IMPLEMENTATION

A LabVIEW framework was established to support the integration of ERIO controls, instrument drivers and camera image processing. The architecture is simple and robust, well-suited to machine-safety-centric design and real-time software (Fig. 2).

At its heart is a hierarchical state machine model. Each IOC has its own state machine definition to abstract its component processes. Below this, every hardware device driver, feedback algorithm, analysis task, *etc.,* is contained within a process, based on a queued state machine. Messages are strictly produced only by a single central sequencer. When the IOC is sent an external state transition request (via a PV), the sequencer translates this into process messages executed in the appropriate order. Failure of a process causes the sequencer to revert all steps in the transition, returning the IOC to a known state. Laser automation is therefore handled by distributing state transition requests to IOCs; this can be done without detailed knowledge of all IOC processes.

Processes inter-communicate via notifier references only. All upward data flow is via a hierarchical current value table implemented using variant attributes. The LabVIEW IOC core is designed so that multiple instances can run on the same RMC-8354 server independently. This facilitates the modularisation of software IOCs as a reusable functional unit.

This architecture is simple and fairly inflexible, yet is easy and quick to use. LabVIEW object orientated programming (LVOOP) is avoided in this framework. Much more sophisticated frameworks exist, such as the GSI CS-Framework based on the Actor Framework [4], but these were considered too complex for this application and difficult for novice LabVIEW developers to learn and use. One benefit of inflexibility here is that it forces processes to be well-designed and self-sufficient. Since individual processes are easy to unit-test, this lends greater confidence to IOC integration.

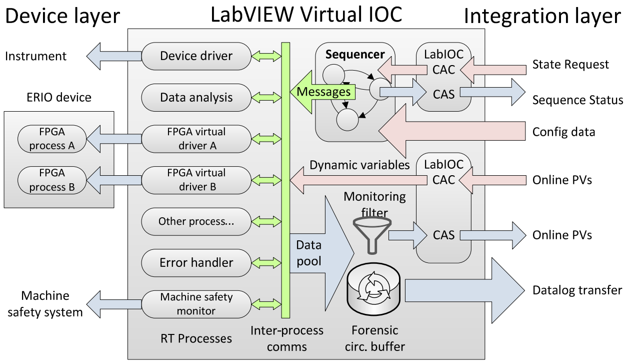

Figure 2: Block diagram of the LabVIEW-based IOC framework.

LABVIEW-NATIVE CHANNEL ACCESS SERVER AND CLIENT - LABIOC

A vital component of the control system is an EPICS channel access client (CAC) and server (CAS) that is compatible with the RMC-8354 platform. It was decided that the only acceptable implementation would be in native LabVIEW to ensure the longevity and ease of integration of the solution, regardless of any later upgrades to the Real-Time OS or server platform.

Many solutions for LabVIEW-EPICS interface have been developed previously [5]. The majority are incompatible with Pharlap and are not LabVIEW-native. Initially, NI's built-in solution was considered. However, this requires Network Shared Variables to be used. These have been found by us to be slow, unstable and have poor scalability and are avoided in our control system. Furthermore, the server only implements a partial record that does not have many important fields. In early testing this caused problems for Control System Studio clients. There were also concerns about the longevity of the solution and that the solution is not open-source.

Due to the critical nature of this package we opted for a commercial open-source solution. Observatory Sciences Ltd. (OSL) [6] were approached to deliver a LabVIEW-native server and client package. This LabIOC package is based on an existing LabVIEW client for EPICS developed by OSL. As well as L1, the package will be used in the other laser systems, particularly L4, making it key to the successful integration of the ELI-BL's lasers.

The package was released in May 2015 and is now undergoing comprehensive testing and bug fixes in collaboration with National Energetics. The package implements a LabVIEW-native CAC and CAS and supports standard record types (ai/ao, bi/bo, longin/longout, mbbi/mbbo, stringin/stringout, and waveform). On the LabVIEW side, automatic type conversion to I8, I16, I32, SGL, DBL, STR, Boolean, and arrays of these types is handled automatically via convenient polymorphic VIs.

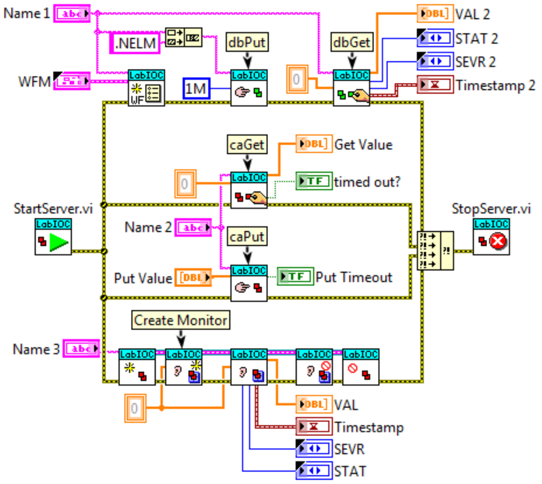

Figure 3: Example of the LabIOC LabVIEW interface.

A major advantage of the package is that multiple software can IOCs run in parallel. Instances share a single UDP port on the NI run-time engine by setting the flag "SocketSetReuseAddr=TRUE" to the LabVIEW .ini file options. However, this feature has the consequence of

ISBN 978-3-95450-148-9

making the library take up rather a lot of memory on the server – possibly limiting its use on smaller real-time targets such as cRIOs. We are working with OSL to streamline and optimise the package.

LABIOC PERFORMANCE ANALYSIS

To evaluate the performance of the LabIOC package, two RMC-8354 servers were connected by a 1 GbE Moxa switch. Identical versions of LabIOC were run on both and a variety of measurements performed. Access times were analysed (Fig. 4) to verify the determinism of the software on the real-time system.

The analysis shows that server-local variable access is quick and fairly deterministic, as expected. Access time decreases exponentially and appears bounded at no more than three times the median vales of 60 and 330 microseconds for Get and Put, respectively.

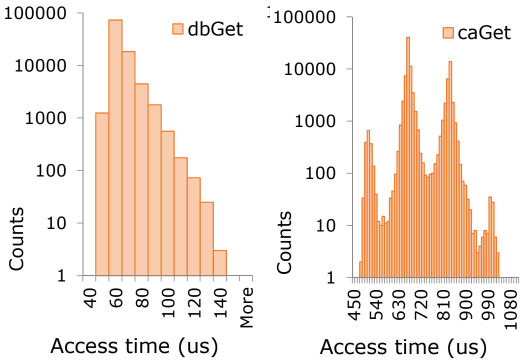

Figure 4: Server and client access time histograms for a single, local PV of DBL type (ai record).

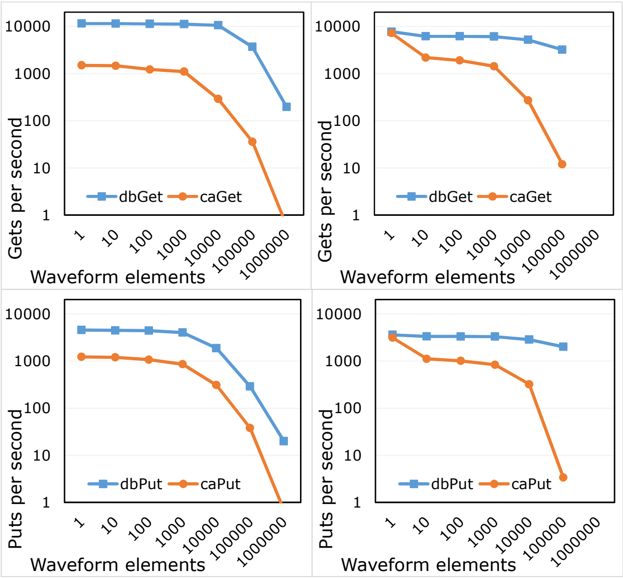

Figure 5: Server and client access frequencies. Top right: Gets per second for a single waveform; top left: Gets per second for 1000 channels of waveforms; bottom left Puts per second for a single waveform; bottom right Puts per second for 1000 channels of waveforms. All PVs are DBL/ai type.

Measurements of maximum read/write frequencies (Fig. 5) show that LabIOC is slightly slower than typical figures for CA (~2k caGets/sec for single element). Results for single-channel and 1000-channel are similar below 1M elements – showing library to be robust and scalable.

Generally these measurements show that the overhead associated with the LabIOC library is reasonable and meets the requirements for the ELI-BL lasers. Tests are ongoing.

CONCLUSION

Control system requirements, architecture and implementation for the L1 beamline have been discussed. Central to the control system was the development of a LabVIEW-native EPICS server on the Real-Time RMC-8354. The package has been tested and found to be a satisfactory solution for the integration challenge.

Future development will focus on integration of LabIOC into the software framework. This will provide integration of the hierarchical state machine within each IOC with the top-level sequence engine to enable laser automation. Laser diagnostics can also be displayed via CSS panels, archived, and plotted using existing tools – removing a significant software development burden.

Currently, the main drawback of the solution is that it does not support the transfer of camera image data with the required frequency and fidelity (smaller ‘preview’ images can still be transferred). Laser beamlines have highly camera-focussed control systems and a LabVIEW-EPICS integrated solution for high-performance camera image transfer would be a welcome future development.

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