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STATUS OF THE CLARA CONTROL SYSTEM

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Abstract

CLARA (Compact Linear Accelerator for Research and Applications) is a test facility for Free Electron Laser (FEL) research and other applications at STFC's Daresbury Laboratory [1]. The control system for CLARA is a distributed control system based upon the EPICS [2] software framework. The control system builds on experience gained from previous EPICS based facilities at Daresbury including ALICE (formerly ERLP) [3] and VELA [4].

This paper presents the current status of the CLARA control system, experiences during beam exploitation and developments and future plans for the next phases of the facility.

INTRODUCTION

The build of the CLARA facility is currently staged to run across 3 main phases. Phase 1, the CLARA Front-End, Phase 2 the main accelerator and Phase 3 the FEL.

The installation and commissioning of Phase 1 comprising of the photo-injector, RF gun and the first linac was completed during 2018. Subsequent machine development and beam exploitation took place during late 2018/early 2019. Phase 2, the main accelerator is now being installed along with design and development of a Full Energy Beam Exploitation (FEBE) line for 250MeV beam experiments. Phase 3 is currently on hold awaiting funding.

The control system for CLARA is an evolution of the control system developed for VELA. It retains the use of the EPICS software toolkit and Input/ Output controllers (IOCs) running the Linux operating system. In fact, with the deployment of CLARA Phase 1, and due to VELA and CLARA sharing the same common infrastructure, the control system of VELA has effectively been absorbed into CLARA and can now be considered as a single system.

This paper gives an overview of the current status of the major sub-systems of the control system. Experience gained during machine development and exploitation of Phase 1 along with future plans for satisfying the requirements of Phase 2 is discussed.

MOTION CONTROL

Operational experience of the motion control system during Phase 1 has proven the Beckhoff EtherCAT based system to be reliable and robust. Additional experience has also been gained with the Beckhoff closed loop stepper motor control; this has resulted in smoother operation of axes that had previously been problematic.

For Phase 2 the motion control system which comprises Beckhoff TwinCAT 3, CX5020 embedded PCs and EtherCAT modular I/O terminals, has been extended to control the 5-axis Variable Bunch Compressor.[1] This includes co-ordinated movement of collimating jaws at narrow gap, and logic for collision avoidance during homing.

Additionally, for Phases 2 and 3 of CLARA the Beckhoff system is being developed to control an 8-axis de-chirper module. This will use absolute-encoder feedback for precise positioning of quartz plates, both parallel to, and at known angles to the electron beam.

RF CONTROL

The CLARA photo-injector gun shares the RF (Radio Frequency) infrastructure from the VELA photo-injector with an RF switch controllable through EPICS. The switch transfers power between the existing VELA RF gun (10Hz) and the new high repetition rate RF gun of CLARA (400Hz).

The low-level RF (LLRF) is provided by Libera, a system from Instrumentation Technologies [5]. These systems implement an EPICS IOC on board. One Libera system is shared between the 2 RF guns of CLARA and VELA and a second is dedicated to linac 1. Our experience with these systems during operation of Phase 1 has been positive, with Instrumentation Technologies supporting us with development of features to enable the pulse-to-pulse acquisition and processing of RF data through the control system at 100Hz.

The ScandiNova RF modulator for the VELA and CLARA guns is integrated into the control system via the manufacturer’s proprietary ASCII protocol over TCP/IP using StreamDevice and Asyn EPICS support modules.

High-power RF for linac 1 is provided by a Diversified Technologies modulator which provides a Modbus TCP interface via its internal Beckhoff EtherCAT control system. It is integrated into the control system via this interface using Asyn & Modbus EPICS support modules. Further higher powered modulators for the 3 linacs of Phase 2 will be provided by Diversified Technologies and integrated with the control system via the same method.

Unmanned Conditioning

To facilitate faster RF conditioning a system was developed, in close cooperation with RF scientists and the accelerator physics group, to allow safe unmanned operation of the CLARA RF systems [6]. This was implemented using the EPICS Sequencer to monitor all the relevant safety and machine interlocks for failures, log the failures when they occurred, and then to reset the RF systems to bring them back online. This was improved by checking the error log to ensure that certain failures were only allowed to happen a certain number of times in a given time period before the

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system would shut down the RF and notify the appropriate personnel via email. This new development was successfully used alongside software that automatically adjusts power levels of the RF to utilise the evenings and nights of CLARA's exploitation period for conditioning the high repetition rate RF gun, time which otherwise wouldn't have been used. This system has the potential to save weeks of conditioning time for the linacs of Phase 2.

TIMING SYSTEM

The event timing system used on CLARA to distribute triggers to various sub-systems is provided by Micro Research Finland (MRF) [7]. The system comprises 300DC series devices with VME form factor. Electron beam diagnostic cameras use a PCIe Event Receiver (EVR). The VME EVM (Event Master) and EVR devices are controlled by EPICS IOCs running on IOxOS IFC1210 VME single board computers. The timing system is currently using the PSI branch of the EPICS support module mrfioc2 3.0.5 [8].

The timing system is currently only used to distribute triggers. Accurate time is not currently distributed but this is planned before the end of the year. The timestamp latched when an event at the machine rep-rate is received by an EVR will be used to timestamp data acquired by devices attached to that EVR. This will allow data from a single shot of the accelerator to be easily correlated across multiple devices and sub-systems. A machine pulse ID is also deterministically distributed across the timing system to allow all endpoints to stamp beam-synchronous data with a unique ID allowing easier cross-correlation and retrieval of data for post-processing.

Preliminary work on embedding EVRs in devices that don't have native support has been carried out. The MRF Open EVR [9] has been deployed on a Xilinx Zynq development board and an interface written to monitor operation. The open source firmware from MRF was straightforward to utilise, but is unsurprisingly very hardware specific. Xilinx 7 Series DCM and Kintex-7 GTX transceivers are both required.

Our future plans for the timing system also include migration of the whole system from EPICS Base 3.14 to V7 and potential use of uTCA form-factor hardware within future phases of the project. With the assistance of the community it's hoped that standardisation of the various branches of the EPICS mrfioc2 support module can be achieved. Different branches maintained by different institutions are diverging and not all MRF hardware is supported.

Our experience during the exploitation of Phase 1 showed us that it is essential for the timing system to be flexible in-terms of delivering triggers for users. It is essential to have spare capacity to deliver triggers to various locations on the facility and to be able to tune the timing of these triggers to suit user's requirements which can differ significantly from the normal accelerator operational requirements. For example pre-triggering gas jets, gating particular numbers of triggers and counting triggers to provide a specific integrated beam charge all required changes to the timing system to provide custom behaviour to exploitation users.

BEAM DIAGNOSTICS

Data Acquisition

Data from Faraday Cups, Integrating Current Transformers, an Optical Beam Loss Monitor (oBLM) [10], and a Wall Current Monitor along with other diagnostic signals previously determined from oscilloscope traces are now acquired using dedicated data acquisition hardware. Waveforms and parameters are acquired at the full machine repetition rate of up to 100Hz.

Two different systems are used, one based on hardware from IOxOS which gives us integration with the MRF event timing system, and another based on the DRS4 [11] evaluation board from Paul Scherrer Institute (PSI) which provides the high sample rate needed to acquire waveforms for the oBLM. Both systems are controlled using EPICS and transmit their data over the gigabit network using Channel Access. Parameters are archived using the EPICS Archiver Appliance at the machine repetition rate [12]. Data acquired using this system can be correlated easily and has been used in studies of beam stability across many diagnostics [13], RF breakdown [6], laser diagnostics, charge scans and long term monitoring of machine performance. Data is currently timestamped using the local clocks synchronised with NTP (Network Timing Protocol) [14].

Problems have been observed with software running on IOxOS hardware crashing and it's suspected that this is the same problem previously identified by PSI caused by issues with the Linux kernel driver for the PCIe-VME bridge [15]. The Tosca kernel driver written for PSI by DENX will be used instead in the near future and it is hoped that this will address the problem.

Cameras

Very low noise cameras with 5.5 megapixel resolution and a pixel pitch of 6.5um manufactured by PCO have been installed for viewing diagnostic screens. They are capable of operating at 100fps via their fibre optic Camera Link High Speed (CLHS) interface. These are used alongside lower resolution GigE cameras.

The PCO cameras are integrated into the EPICS control system via x64 Linux IOCs with a dedicated fibre optic PCIe frame-grabber per camera. Due to the requirement to only operate a single camera at one time; multiple cameras can be interfaced to a single IOC by populating with several frame-grabbers. The areaDetector [16] driver pcocam2 [17] from Diamond Light Source has been ported to work with the new PCO SDK for Linux and modified to operate with the fibre optic CLHS interface and now operates routinely.

A dedicated Gigabit Ethernet network between the camera IOCs and a dedicated NAS RAID storage device allows images to be streamed at full machine repetition-rate off local IOC storage. Machine operators can then access the images without overloading the IOCs. To improve overall

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performance with the large volumes of data options are being considered for streaming to local M.2 solid state disk and longer term archival.

Accelerator physicists have developed algorithms to calculate beam centroid and size information from the camera images. These utilise mean vector and covariance matrices, allow various corrections and run in real-time at the full frame rate of the cameras. The algorithms have been written in C++ and fully integrated into the EPICS control system as an areaDetector plug-in.

Extensive use of the areaDetector framework and plugins has been made in the overall system implementation with multiple outputs to cover user requirements, see Fig 1. The analysis plug-in continues to be developed based on user experience and feedback from exploitation beamtime. A HDF5 plug-in was written to allow saving of images for later analysis. Masking of the image can be performed at source or via a region of interest plug-in providing data directly for further user analysis. A separate support module groups the features and requirements for individual cameras to be integrated into specific IOCs. The same features are being rolled out across all camera IOCs.

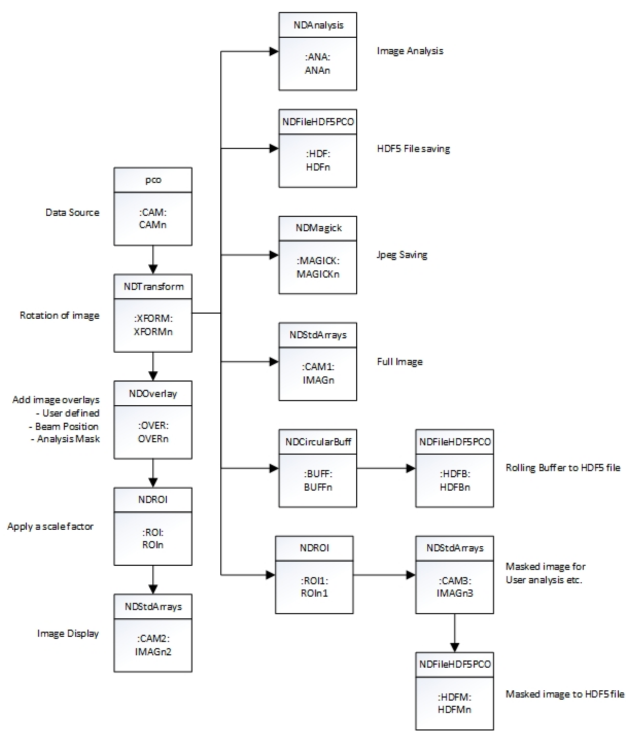

Figure 1: Overview of AreaDetector plugins for image analysis implemented in CLARA control system.

Accelerator physicists develop their own applications in Python that run in parallel with and use data from IOCs, see Fig 2. Events determined in these analysis applications can be used to trigger storage of data from circular buffer plug-ins. As experience grows in the area of analysis and feedback control consideration will be given to migrating the core of these into areaDetector plugins, EPICS database structures or firmware on the frame-grabbers as appropriate to achieve the required performance.

Whilst no direct use of pvAccess features is being made yet, current releases of camera EPICS systems are now being built against EPICS V7. Development of these camera systems will continue providing one of the core requirements for successful exploitation and development of CLARA.

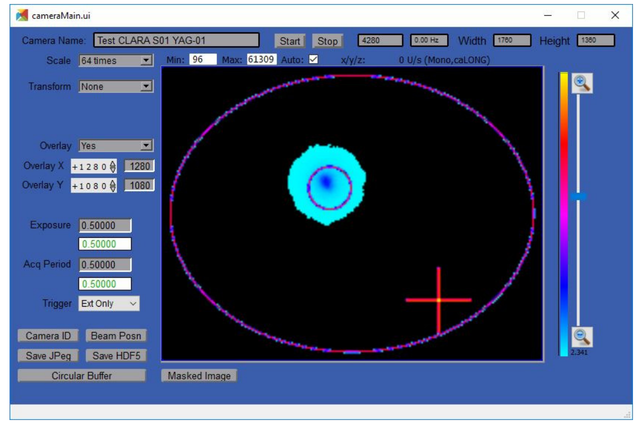

Figure 2: User interface for camera image processing. The centre of the beam is shown in the inner circle. The red cross marks the middle of the image.

PERSONNEL SAFTEY SYSTEM

The CLARA Personnel Safety System (PSS) controls the generation of ionising radiation by enabling the operation of the electron gun and RF cavities. The gun and RF cavities may only be operated when the appropriate accelerator areas have been searched and interlocked. The CLARA PSS uses SIL 3 (Safety Integrity Level) rated Omron Safety Network Controllers and DST1 series safety I/O terminals to construct a safety control network, providing safety logic operations and a DeviceNet safety protocol (PSI, 2019). A master-slave relationship is established for each connection on the DeviceNet Safety Network and the status of the safety I/O data in the Safety Network Controller is mapped to the memory of an Omron CJ2M standard PLC, in order to integrate the PSS into CLARA's EPICS based control system. This enables real-time monitoring of all PSS interlocks by the CLARA operations team.

Phase 1 of the CLARA PSS was successfully implemented in 2017 and Phase 2 commissioning has just started. Recent changes to the CLARA accelerator room shielding has necessitated the reconfiguration of the search path and associated search points, emergency beam off buttons and warning signs. The PSS logic has also been modified to enable two distinct 'designated laser areas' to be created inside the accelerator rooms. This allows alignment of the photo-injector laser transport system and TW (terra watt) laser alignment to take place simultaneously, maximising accelerator running time. Additional I/O modules have also been added to provide the capacity required to permit the operation of RF systems associated with new accelerating cavities to be installed for CLARA Phase 2.

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VIRTUALISATION

During the development of the control system simulation it was noted that virtualising the real CLARA infrastructure could provide several benefits. Currently, the infrastructure relies on IOCs running on individual servers and a number of servers providing file-systems and centralised services. Virtualisation can be used to harden the controls network against server failure by distributing file-systems and services across different server nodes. This would allow easy replication and provision of IOCSs and reduce their rack space footprint. Elements of the EPICS system and controls infrastructure can also be sandboxed before live deployment. [18]

Virtualisation has been achieved using a combination Kernel-based Virtual Machine (KVM), and Linux container (LXC), see Fig 3. KVM simulates a server but requires the full memory of that server. LXC uses the kernel to simulate a full Linux OS but only requires the memory used by the application. Both systems have been shown to use CPU and memory within only a few percent difference to a native server.

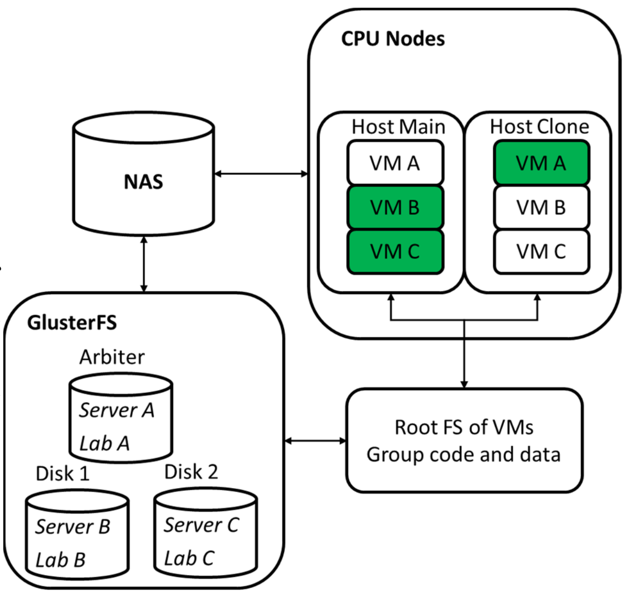

Figure 3: Diagram of virtualisation showing redundancy. Green VM's are connected to the network.

KVM has been used to replace and replicate physical servers. This has been used successfully to clone, upgrade and maintain live servers. LXC is used for extremely low memory footprint applications such as IOCs. Many racks of native servers can be replaced by LXC in these cases. LXC is also more efficient than a full VM instance on KVM in these cases. It has been tested with IOCs, services, EPICS simulations and Archiver Appliance instances all running on a single hosts.

These systems will allow us to supply novel new services such as "Archiving-on-Demand". The Archiver Appliance proved remarkably successful during the last exploitation period but required a lot of set up on individual servers. Virtualising the archiver will allow a live management of data storage, CPU and memory resources. It will allow isolation of critical archiver services and to rapidly 'spin up' custom archivers for end users.

FUTURE PLANS

As the construction of CLARA continues with phase 2 and eventually phase 3 the control system continues to evolve. As more IOCs are built against EPICS version 7 it's hoped that some of the features of pvAcess can be exploited.

Developments to the timing system will include implementing pulse numbering for diagnostic data and distributing time. RF systems will be tested for operation at 400Hz by running at 10Hz but with asymmetric triggers. Work will also be carried out to investigate running diagnostic systems at up to 1KHz repetition rate.

Upgrades are planned to the existing Beam Position Monitor (BPM) electronics and readout system. This will involve sampling filtered responses from BPMs with 1Gsps ADCs provided by IOxOS. The samples will then be interpolated to find maximums of peaks in the waveform whose magnitude is proportional to position. A similar method has been implemented with sampled waveforms from other diagnostic devices such as the Wall Current Monitor. This ADC will also be used to sample the output of a Beam Arrival monitor (BAM).

Signals from laser diagnostics will also be sampled and parameters exposed in the controls system. One EPICS support module provides a common data acquisition interface for various different sampling devices. As well as the diagnostics described here it will be used for user experiments on an ad hoc basis.

Diagnostics systems from Instrumentation Technologies will be used for Cavity BPMs and the BPMs on FEBE. Both will have event receivers embedded in them for triggering and pulse numbering of data. Support for distribution of data on a dedicated network will be developed on these devices with the aim of implementing control loops with corrector magnets.

User interface screens are continually being migrated from EDM to windows .NET applications. iOS apps are also being prototyped.

CONCLUSION

The CLARA control system continues to develop, integrating more third party systems and making updates to existing systems developed for previous facilities at the laboratory. While third party systems like those used for LLRF and timing system enabled rapid progress, integration between them has often required modification.

The control system proved reliable and flexible throughout exploitation phase. New features required for particular experiments were easily added due to the scalable nature of support modules like AreaDetector and the flexibility of the timing system. Virtualisation of the accelerator and the hardware running the control system has allowed for offline development of IOCs and other services.

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Work continues to develop systems that reduce the importance of skilled operators on the performance of the machine. This includes developing feedback loops for various subsystems of the accelerator. Unmanned operation has been successfully trailed for the CLARA 400Hz gun.

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