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CONCEPTUAL DESIGN OF THE MATTER IN EXTREME CONDITIONS UPGRADE (MEC-U) REP-RATED CONTROL SYSTEM

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Abstract

The Lawrence Livermore National Laboratory (LLNL) is delivering the Dual-mode Energetic Laser for Plasma and High Intensity Science (DELPHI) system to SLAC as part of the MEC-U project to create an unprecedented platform for high energy density experiments. The DELPHI control system is required to deliver short and/or long pulses at a 10 Hz firing rate with femto/pico-second accuracy sustained over fourteen 12-hour operator shifts to a common shared target chamber. The MEC-U system requires the integration of the control system with SLAC provided controls related to personnel safety, machine safety, precision timing, data analysis and visualization, amongst others. To meet these needs along with the system's reliability, availability, and maintainability requirements, LLNL is delivering an EPICS based control system leveraging proven SLAC technology. This paper presents the conceptual design of the DELPHI control system and the methods planned to ensure its successful commissioning and delivery to SLAC.

INTRODUCTION

As part of the MEC-U project at SLAC, LLNL is developing DELPHI, a dual-mode rep-rated laser that provides short-pulse lasers to a target chamber (TCX) shared with the Linac Coherent Light Source (LCLS) X-ray Free Electron Laser (XFEL). The combination of these two systems, plus a third system being provided by the Laboratory for Laser Energetics (LLE) provides a leading experimental platform for high energy density (HED) plasmas under extreme environments [1]. The current project scope for DELPHI is a single Petawatt beamline. We have deferred or do not preclude requirements for a 2nd beamline, plus the addition of a long-pulse rep-rate laser (Fig. 1).

There's a total of 628 laser control points in the conceptual design, with an additional 213 control points in the utility systems. The system is expected to fire at a fixed enumerated rates up to 10Hz delivering optical pulses to the beam transport treaty point with a timing jitter of less than 200fs rms. Experiments are expected to run across multiple 12-hour shifts, which emphasizes the need for high reliability, availability, and maintainability (RAM). To help meet these requirements, LLNL is prioritizing the re-use of LCLS' EPICS based control system software, controllers, devices, and instrumentation in the DELPHI control system design.

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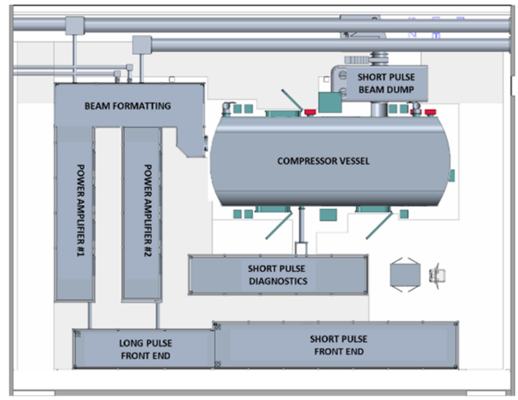

Figure 1: Conceptual Layout of DELPHI.

ENGINEERING PROCESS

The original proposal for the DELPHI control system included the use of the National Ignition Facility (NIF) & Photon Science (PS) Photon Control System (PSC) framework. This technology is based on NI LabVIEW and relies heavily on NI cRIO hardware and other related technologies. It allows for the rapid development of scalable distributed control systems, including the addition of new device level controls including common control system features such as configuration user sets, configuration locking, etc. The introduction of this technology into SLAC's disparate control system ecosystem presented significant RAM challenges. SLAC, LLNL, and LLE agreed to take a unified approach to the MEC-U control system and adopted LCLS' EPICS baseline. To address the lack of in-house expertise with EPICS and LCLS hardware, we placed the engineering agency Cosylab, on contract. Cosylab is an active member of the SLAC control system engineering team and has been responsible for the development and deployment of several of their systems. Given their level of knowledge of EPICS based control systems and SLAC technology, they have been given responsibility for the hardware detailed design and controller/PLC level software engineering through LLNL's final design review (FDR). Part of their mandate is to work with SLAC to identify hardware already in production use to avoid introducing new or unique hardware as part of the DELPHI system. This reduces the overall software and hardware engineering effort, eases maintenance by deploying familiar hardware, and helps with an overall hardware sparing strategy at MEC-U.

The DELPHI control system recently completed its conceptual design review (CDR) that included

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representation from several international scientific laboratories. As part of the NIF&PS structured engineering process, the CDR provided valuable insight and recommendations from organizations experienced with EPICS based control systems. During the 6-hour review, 69 actions were recorded and are being addressed during our engineering design process.

The commissioning of DELPHI involves a factory acceptance test (FAT) at LLNL, followed by system teardown and rebuild at SLAC for the site acceptance testing (SAT). SLAC is providing LLNL with surrogate systems to verify integration of these critical systems needed for DELPHI operation. These are discussed in subsequent sections. LLNL is planning on a controls testbed, separate from the primary DELPHI testbed to aid in control system prototyping and system integration at a supervisory level. This testbed will take advantage of EPICS emulation capabilities and virtualization options to build a full representation of DELPHI for control system integration testing.

The software engineering effort has multiple organizations contributing to the code base. We are leveraging SLAC's GitHub and Jira instances and are expecting to move to their Github enterprise edition which is under evaluation. Cosylab is tasked with containerizing and delivering a build environment to LLNL for installation on local virtualized machines. Production source code will be downloaded to this build environment and compiled locally to generate executable code to be pushed to targets.

During the hardware detailed design phase, we are using LCLS' neo-CAPTAR database for cable management. This cable database will store the cables planned for both the LLNL testbed as well as the final build-out at SLAC, with a subset of cables used at both locations. A process for the QA of this cable database is being defined by SLAC. This cable database will be used during design through to procurement, assembly, installation and commissioning. Additionally, automated tools that integrate with our mechanical engineering drawings of facility infrastructure such as cable trays are under evaluation to aid in automatic cable routing and load monitoring.

ARCHITECTURE

The control system architecture is hierarchical, with EPICS providing the core communication framework, and controller software. At the top level of the architecture are the supervisory processes and user interfaces for coordinating activities across the system. These processes will be written in Python, with PyDM used for the graphical user interfaces (GUI).

At the highest level, a shot sequencer process runs a state machine designed around the Unified Modelling Language (UML) definition. A framework to support this process is under development by SLAC and LLNL that will leverage the features of EPICS, along with best practices at NIF for the safe setup and execution of laser shots. This framework will support the definition and execution of custom state machines, along with automated sequence of operations across multiple subsystems and devices. This framework is intended for use on DELPHI, LLE's high-energy long pulse (HE-LP) system, and the overarching MEC-U control system.

Where feasible, photon system devices are managed by a standard Input/Output Controller (IOC) as shown in Fig. 2. These systems are diskless and require a runtime environment for acquiring their OS, drivers, EPICS libraries, etc. Cosylab has been tasked to build this runtime environment that will be deployed at LLNL to support integration testing and FAT.

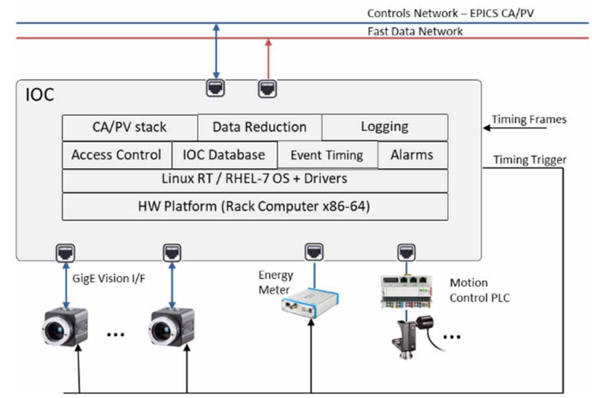

Figure 2: IOC architecture and interfaces.

ATCA crates are another host type used for high-speed and/or highly reliable computing [2]. Although the detailed design phase is only ramping up at the time this paper is written, it is anticipated that the ATCA crates will support timing distribution to DELPHI, as well as high-speed digitization.

Beckhoff PLCs are used for a variety of subsystems as described in the next section. They are tied together on an EtherCAT ring network to provide reliable and predictable communications. An IOC process provides the EPICS communication needed for basic I/O including calls for command and control.

SUBSYSTEM CONTROL CONCEPTS

Personnel Safety System

LLNL and SLAC are providing their own personnel safety systems for mitigating laser hazards within the DELPHI laboratory for their own respective sites. LLNL provides the necessary devices, interfaces etc. to tie into the room interlock system at MEC-U, and qualify them as part of FAT. LLNL will use their own Safety Interlock System (SIS) that follows LLNL engineering safety standards [3] for controlling laser hazards, but the system itself is not a project deliverable. The interfaces related to personnel safety are managed through an Interface Control Document (ICD) currently in draft form.

Machine Protection System

The role of the machine protection system (MPS) is to be able to rapidly process machine protection alarms to stop the next laser pulse. At a 10 Hz rate this requires

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better than 100 ms response time that includes the end-to-end processing time from when a diagnostic receives input, to the time that the MPS removes firing permissives. In response to an alarm, the MPS system removes firing permissives to the short-pulse front-end via a pulse picker at its output and stops the firing triggers to the pulsers which flash the power amplifier diode arrays.

We are leveraging the photon MPS (PMPS) system developed by the LCLS control system team which uses a PLC within an EtherCAT network to process input and manage permissives. Measurements have been taken to show that PMPS can respond to an alarm within 2ms, which provides a significant margin. To inhibit triggers, options include a Stanford Research Systems DG645 or TL distribution unit such as a Pulse Research Lab PRL-4110. Ideally the trigger output halts when the permissive signal falls low, however both the DG645 [4] and PRL-4110 [5] require these signals to be high to halt trigger output which in itself does not support a failsafe design.

To address the deferred and not to preclude scope, we will need to segment the PMPS system to support shutdown of system segments. As an example, an active long pulse system should remain active if a machine safety alarm is raised for the short-pulse system.

Utilities

The DELPHI system will require access to multiple SLAC provided utility systems including process cooling water, rough vacuum, helium, clean dry air (CDA), as examples. LLNL provides the local control system to monitor and control utilities within the DELPHI laboratory. These systems run on Beckhoff PLCs tied together with the machine protection system over an EtherCAT network. Command sequences and I/O are provided over their EPICS interface to a Utility IOC process. Due to the anticipated extended cable lengths between the sensors and PLC chassis, we are prioritizing 4-20 mA connections as the preferred interface for the sensors.

Timing

The ability to meet the timing requirements for MEC-U is the focus of a joint SLAC and LLNL working group. The upper limit of 200fs jitter on photon arrival time at the treaty point located beyond output of DELPHI, coupled with the ability to adjust the delay by +/- 100 ps relative to the x-ray arrival time from XFEL at TCX, are challenging. The system concept involves locking the short-pulse seed laser to the LCLS-II 1300 MHz reference clock, along with SLAC's Timing Pattern Receiver (TPR) cards present within the DELPHI Timing ATCA crate. As part of FAT, SLAC will be providing a populated ATCA crate and surrogate RF signal to allow LLNL to verify the system against our timing requirements at LLNL during FAT.

The event timing system provides low precision timing for diagnostics and other instruments within DELPHI. An estimated 197 timing channels are required by DELPHI. Some of these channels can be grouped together or spliced from a single timing channel as the receiving instruments do not require independent control of their hardware timing. The instrument timing signals are supplied either by an external TTL distribution unit, or directly from a TPR installed within the IOC host. If the latter, the TPR does support timestamping collected data from the host's instruments. The hardware design process in this next phase of the project will determine whether an IOC host TPR, DG645, or some other distribution unit will be used to supply timing.

Motion Control

The standard controller for motion control is a Beckhoff PLC as shown in Fig. 3. SLAC has a range of stepper and servo motors in production use with this configuration. We have identified that a motor manufacturer commonly used within NIF&PS laser projects is not readily supported via direct PLC control. As our priority is not to introduce any unique or new technology into SLAC, we are looking at replacing these motors with another that is compatible and in use at SLAC. LCLS prefers a local installation of their motor controllers collocated to the motors in their laser hall. NIF&PS mounts controllers within racks that are often located outside of the laser hall. Our investigation shows that cable lengths up to 30m are supported, however additional prototype testing is necessary, as well as an emphasis on cable shielding to protect against electromagnetic interference (EMI).

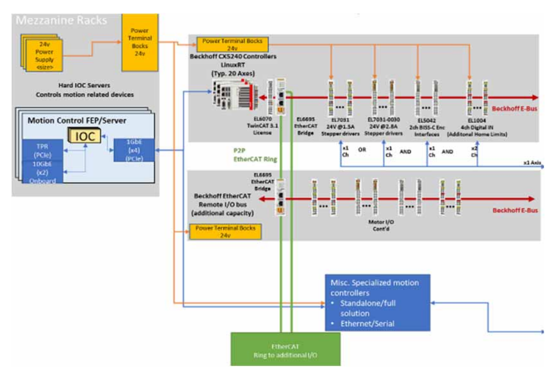

Figure 3: Motion control design.

Vision

Our standard cameras are Gigabit Ethernet (GigE) cameras. These run on a standard IOC host as described earlier in this paper. Camera data is streamed to clients and to archive systems over a separate high-bandwidth network dedicated to large data sets. This is currently planned as a 10 GigE link from the host computer. The standard LCLS vision software/however solution is planned however upgrades are likely necessary to support the alignment requirements for DELPHI, which are currently under review. Additionally, there are runtime image analysis routines necessary for damage detection using darkfield and brightfield images. If damage or misalignment is detected, we require the ability to immediately halt lasing via PMPS. The current LCLS vision solution does not support this level of image processing therefore solutions are under evaluation.

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Pulsed Power

The pulser crates are responsible for delivering power to the diode arrays that energize our gain media in the main amplifier. The pulser crates have internal printed circuit boards (PCB) that provide their own internal machine protection capabilities to prevent electrical anomalies from propagating to the diodes, an example being an over current condition. Additionally, the pulser crates have hardware limits in place to restrict the power delivery to the diodes.

The architecture for controlling the pulser crates is shown in Fig. 4. Within each pulser crate is an NI cRIO running LabVIEW. Due to the tight coupling of the pulser crate design to the software and diode array designs, the source code and detailed design information for the pulsers are not currently planned for delivery to SLAC. There is an expectation that LLNL will be involved in a sparing strategy and/or support contract if needed to ensure the pulser crates are available for the lifetime of the project.

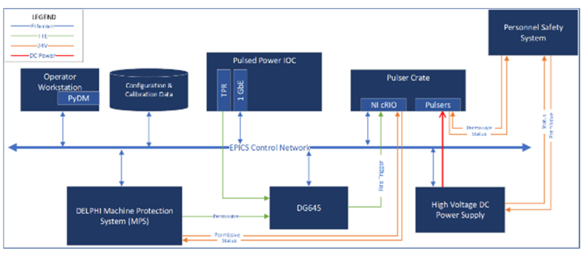

Figure 4: Pulser crate control.

The pulser crate controller uses the Simple Messaging Protocol [6] to communicate with the upper layer EPICS controller. Cosylab is currently evaluating the port of this library to C++ for inclusion in the EPICS framework. This allows the pulsers to be integrated into EPICS without a LabVIEW based translation layer using a proprietary protocol which would add the burden of supporting this language during control system maintenance.

SUMMARY

The MEC-U project offers LLNL, SLAC, and LLE a unique collaboration opportunity to allow us to build on our own technology bases to ensure robust control systems on MEC-U and the future. The conceptual design for DELPHI is largely dependent on existing LCLS system, and through prototyping and detailed design we will flush out and address additional issues necessary to meet the system requirements and support the system's use cases. Our next steps involve the start of the hardware detailed design and software design, which is dependent on the maturation of the DELPHI subsystems including selection of device models and requirements.

ACKNOWLEDGMENT

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