UPGRADE OF THE PROCESS CONTROL SYSTEM FOR THE CRYOGENIC INSTALLATION OF THE CERN LHC ATLAS LIQUID ARGON CALORIMETER

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Abstract

The ATLAS (LHC detector) Liquid Argon Calorimeter is classified as a critical cryogenic system due to its requirement for uninterrupted operation. The system has been in continuous nominal operation since the start-up of the LHC, operating with very high reliability and availability. Over this period, control system maintenance was focused on the most critical hardware and software interventions, without direct impact on the process control system. Consequently, after several years of steady state operation, the process control system became obsolete (reached End of Life), requiring complex support and without the possibility of further improvements. This led to a detailed review towards a complete upgrade of the PLC hardware and process control software. To ensure uninterrupted operation, longer equipment lifecycle, and further system maintainability, the latest technology was chosen.

This paper presents the methodology used for the process control system upgrade during development and testing phases, as well as the experience gained during deployment. It details the architecture of the new system based on a redundant (Hot Standby) PLC solution, the quality assurance protocol used during the hardware validation and software testing phases, and the deployment procedure.

INTRODUCTION

The ATLAS Liquid Argon (LAr) Calorimeter measures the energy and timing of photons, electrons and hadrons produced by proton-proton collisions in the Large Hadron Collider (LHC) [1]. The particles from the collisions are absorbed on particular metal layers, resulting in a shower of new, low-energy particles. The newly formed particles ionize liquid argon between the layers, producing an electric current that is measured by high-voltage electrodes.

The LAr Calorimeter (550 t of cold mass) is housed in three individual cryostats (one barrel and two end-caps) which are filled with a total volume of 80 m^3 of liquid argon at a temperature of 88.4 K. It has been kept in continuous nominal conditions for the past 17 years thanks to a dedicated cryogenic system (the LAr cryogenic installation). Liquid nitrogen, used as cooling medium, is provided to the cryostats (the clients) by a set of back-up supply processes (the infrastructure). In addition, 114 feed-throughs, through which a total of 228,000 wired detector signals are routed to the outside of the cryostats, are kept under vacuum and at a controlled temperature to protect pin-carriers against
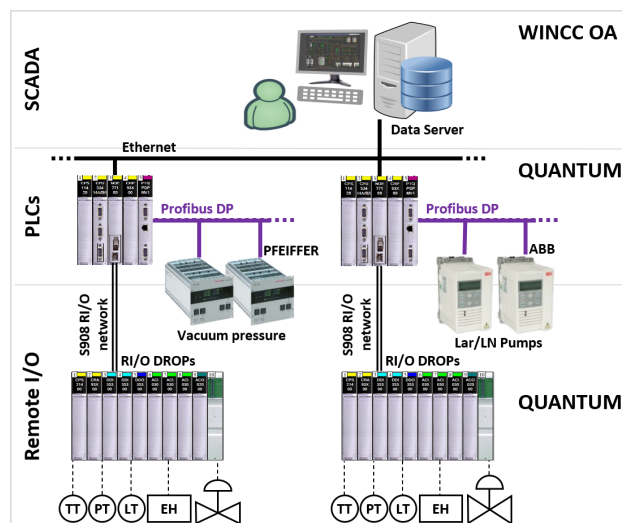

Figure 1: Typical DCS architecture.

humidity damage.

CONTROL SYSTEM OVERVIEW

The LAr cryogenic installation is designed to ensure uninterrupted functioning and safe handling of large quantities of liquid argon in underground areas. Its dedicated LAr control system is classified as critical due to these requirements. In addition to controlling nominal cryogenic conditions and protecting the feed-throughs it also monitors critical insulation vacuum levels. In case of degradation of such vacuum, indicating a potential liquid argon leakage and oxygen deficiency hazard, the control system triggers alarms for personal safety (cavern evacuation, air ventilation system, fire brigade) and for material safety (Detector Safety System interlocks).

Legacy Architecture

To automate the process control of the LAr cryogenic installation, a typical Distributed Control System (DCS) has been implemented (see Fig. 1).

The visualization and operation of the cryogenic process are ensured through Supervisory Control And Data Acquisition (SCADA) based on the WinCC OA® application. One SCADA data server is connected to six autonomous Programmable Logic Controllers (PLCs), which use Modicon M580® and Quantum® technology. Two recently upgraded M580® PLCs are utilized to control a nitrogen refrigerator (cryoplant). Additionally, four old Quantum® PLCs are re-
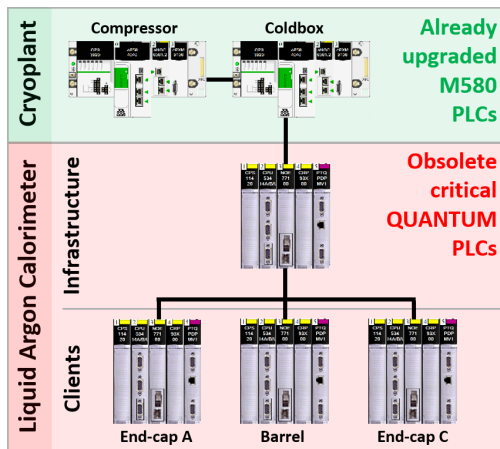
Figure 2: PLCs distribution.

sponsible for controlling the critical infrastructure, as well as the three clients (barrel and two end-caps), as shown in Fig. 2.

Within one DCS, the PLCs share process data to assign cooling resources, control the overall cryogenic process and propagate critical alarms. By using the S908® Remote I/O (RIO) network, each PLC controls its own I/Os that may physically be located inside a surface hall or underground cavern. In total, 27 RIO DROPs (backplanes) made up of 189 I/O cards, with 3140 analog and diGital channels, have been deployed. Additionally, the Profibus DP® field-bus has been used to connect to 16 Pfeiffer® vacuum pressure gauges controllers TPG300 (monitoring 50 vacuum gauges) and 5 ABB® variable frequency drives (VFDs) controlling liquid argon and nitrogen pumps. The LAr control system was developed using an early version of the Unified Industrial Control System (UNICOS) framework, specifically designed for CERN's industrial control applications [2].

CONTROL SYSTEM UPGRADE

Motivation   The upgrade of the LAr control system was the final step of the larger project presented in [3] that aimed to update all cryogenic control systems used by the ATLAS and CMS detectors. The main motivations for upgrading the control systems include several factors. Firstly, Quantum® PLCs have reached their end-of-commercialization phase and are no longer supported. Besides, an increasing number of PLC crashes result in installation failures and downtime. The UNICOS control framework version, which was used for control system development, has become obsolete and is no longer compatible with the new versions of the WinCC OA® application. Furthermore, the maintenance of the process control software has become complex and time-consuming, without the possibility to track the Function Block Diagram (FBD) PLC code changes with any version control tools. More details on the upgrade motivation can be found in [3].

LAr Particularity   Due to the critical nature of the control system and the constraints of the deployment (detailed

in deployment paragraph), the upgrade of the LAr control system required more complex preparation compared to the previously upgraded control systems. Special attention was given to the quality assurance (QA) protocol used during hardware and software offline testing, as all PLCs needed to be replaced in real-time without commissioning, while minimizing downtime and argon losses. The entire control upgrade process was divided into the following four stages: preliminary consolidations, hardware selection and validation, software re-implementation and testing and deployment.

1. Preliminary Consolidations

Before proceeding with the LAr control system upgrade, the initial step involved the identification of all reported non-conformities, system vulnerabilities, and outdated devices. This action was also undertaken to facilitate the deployment of the new control system. Subsequently, numerous system improvements and consolidations were carried out:

- To ensure uninterrupted operation and reinforce the reliability of the control system, **redundant power supplies** of 24 VDC and 230 VAC were implemented for the control system critical devices (i.e.: PLCs, RIOs, TPG300s). The redundant supplies are fed by two separate UPS units and one of the UPS is backed up by a diesel power generator.

- To reduce the dependence on the IT network infrastructure for the transmission of **critical safety alarms** among different PLCs, all critical alarms were hardwired through individual relays. Consequently, in the event of any intervention requiring lockout, the process can now be executed individually for each alarm. This ensures greater control and flexibility, which is necessary for the deployment of the new PLCs.

- After being in service for nearly 20 years, all 16 Pfeiffer® **vacuum pressure gauges controllers** TPG300, which monitor 50 vacuum gauges used to trigger critical safety alarms, were completely replaced. Prior to the replacement, the measurement boards underwent pre-calibration on a dedicated test bench. During the replacement process, several faulty electric connections that were causing spikes were identified and rectified. The old TPG300 was reused to test new PLC hardware.

2. Hardware Selection and Validation

Selection   The selection of the Quantum® PLCs replacement for the LAr control system (see Fig. 2) was guided by several predefined criteria. These criteria included compatibility with used Quantum® Remote I/O technology, assurance of at least a 20-year product life cycle, support from the new CERN UNICOS CPC6 framework (UCPC6), sufficient processing power to accommodate frequent software updates and handle large control applications with thousands of RIO channels. Additionally, the chosen PLCs needed to possess comprehensive diagnostic features, essential for efficient debugging and support.

Due to the criticality of the LAr control system and the potential consequences of a single PLC crash, the upgrade of the control system focused on prioritizing system reliability. To achieve this, the decision was made to replace each old Quantum® PLC by a redundant configuration using two identically configured PLCs. The typical architecture of a redundant PLCs system is illustrated in Fig. 3. Two PLCs are interconnected by a Hot Standby link, connected to the same RIO network via an Ethernet® ring and to the same Profibus DP® network. In the event that one PLC fails, the other PLC seamlessly takes over control of the entire system, ensuring continuous operation without any system downtime.
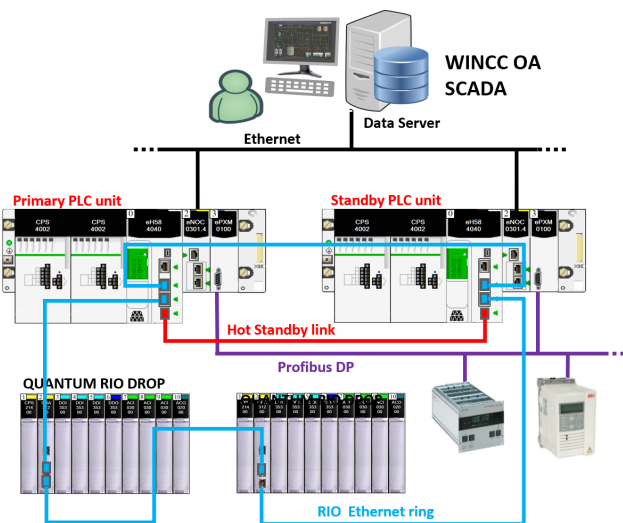

Figure 3: Redundant PLCs system.

The new Modicon M580® Hot Standby System emerged as the ideal solution for replacing the old Quantum® PLCs, meeting all the designated requirements and proposing the high reliability redundancy. Therefore, taking into account the components that have been previously tested and used in past upgrades, such as Ethernet® or Profibus DP® communication processors, the configuration shown in Table 1 was selected for validation tests.

Table 1: Redundant System Hardware Configuration

Function	Model	Firmware
Ethernet rack x 2	BME XBP 0602	1.0
Redundant PS x 4	BMX CPS 4002	1.9
Hot Standby CPU x 2	BME H58 4040	3.1
Ethernet CP x 2	BME NOC 0301.2	2.2
Profibus DP CP x 2	PME PXM0 100	1.001
RIO DROP IM	140 CRA 312 00	2.7

Test Bench   To validate the new redundant configuration, a dedicated modular test bench, allowing to reproduce of the full configuration for each of LAr production PLCs, was setup in the lab. The test bench consists of mobile racks equipped with new redundant PLCs, Remote I/O Drops and

Profibus DP® network with TPG300s and VFDs. Once the lab test was completed, the mobile racks were reused on the production system to test new PLCs together with newly installed cables and optical fibers.

Testing Protocol   The prototype of the new control architecture was successfully validated through a series of tests that involved simulating different types of primary PLC failures and verifying the transparency of PLCs swaps. The configuration for each control system, including infrastructure, barrel, and two end-caps, was tested individually. Before launching all tests, the firmware for all components had to be updated to the most recent version. All new systems were tested with a program execution cycle set as periodic with a time of 100 milliseconds. The average program execution cycle, with the complete configuration, oscillated around a few milliseconds. Even for the largest infrastructure control system, which includes 10 RIO Drops and pump's VFDs on Profibus DP®, no reduction in control system performance was observed.

The following most frequent faulty scenarios were successfully tested: - loss of electrical power on one or both power supplies (PS); - central processing unit (CPU) stopped by command from console, programming error or by removing from the rack; - perturbation of Ethernet® and Profibus DP® communication by unplugging cables or removal cards from the rack. In the final configuration, only one automatic swap from the primary to the secondary unit is allowed. This triggers an alarm and requires a 1st line support intervention. Once the primary unit is restored, the swap back is done manually from the console.

Comments   1. The new redundant system requires two consecutive IP addresses for the PLCs. 2. During early testing, occasional communication losses were observed between the PLCs and SCADA system after PLC swaps. This issue was related to the handling of IP address swapping during the PLCs commutation process, and it was resolved with the new release of the UCPC6 framework. 3. Replacing the Profibus DP® communication processor with the M580® model required redoing the field bus configuration. The newest Prosoft Configurator Builder® and device Derived Data Type (DDT) were used to prepare a new configuration, and a dedicated Profibus DP® diagnostic tool was developed and tested on the SCADA system.

3. Software Re-implementation and Testing

The main objectives of the software engineering phase were to reimplement the LAr process control logic on the new M580® Hot Standby PLCs, based on the new UCPC6 framework and automated software production methodology, while maintaining high system reliability. Most importantly, the entire process had to take into consideration that all PLCs need to be replaced while operations are ongoing (on-the-fly), meaning all preparations and software commissioning must be performed before (offline). Consequently, extremely detailed software simulation and testing had to be performed.

Development The development of the LAr control software was based on the "Unified software production process for CERN's cryogenic control applications", as presented in [4]. Since the software production is fully automated, once the project is configured in GitLab® CI (including the UCPC6 version), the main tasks of the developers, for each PLC, were to provide a tested PLC hardware configuration, complete the UCPC6 objects list (Spec DB), and program code templates in accordance with the process functional specifications (logic specifications) and old PLC program. Each commit to the GitLab® repository triggers CI pipelines that include project generation, checks, builds, and automatic deployment to the PLC-SCADA testing environment. The software engineering workflow is illustrated in Fig. 4.
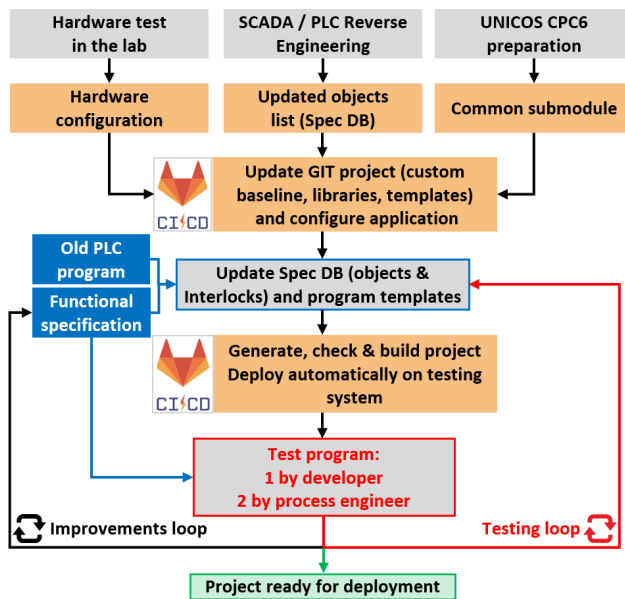

Figure 4: Engineering workflow.

The following principles were used during the development process: - the object specification lists are updated with the current process settings and object properties, extracted from the PLC/SCADA production systems using reverse engineering methods; - the PLC is programmed using the Structural Text (ST) language, which can be easily tracked in a version control system; - whenever possible, use a common template for repetitive process functions, such as the 114 feed-throughs.

During the development of the LAr control software, based on current standards for cryogenic control applications, several improvements to the process logic implementation were made. All unused controller objects, which occupied a significant portion of CPU resources, were identified and removed and at the same time 210 PID controllers were reprogrammed using templates. The number of available spare objects was also revised and readjusted to allow for future software modification. All process alarms (interlocks), including those hard-coded in PLCs, were identified, classified and programmed according to the current UCPC6 classification (diGital or analog alarms). Similarly, all pro-

cess parameters previously hard-coded in the PLCs were implemented as standard parameter objects. Now, all details of over 1700 alarms and 300 process parameters are accessible in the supervision system, facilitating system operation and diagnosis. Since the communication between PLCs plays an important role in the overall process control, the data structures exchanged between all PLCs have been unified and completed. Thanks to the UCPC6 objects implementation and dedicated scripts developed in the supervision system, all exchanged data can be monitored or even frozen in case of a PLC intervention. Due to the extensive use of sequential control in dynamic process phases (60 steppers), sequential function charts (showing each step and transition) were fully animated in the supervision, improving system operability.

In total, the logic for more than 2800 objects including process control objects, regulators, cryogenic valves, electrical heaters, pumps, alarms and interlocks, was programmed.

Testing All tests of the new control software were carried out in the PLC-SCADA testing environment, known colloquially as "mirror." This environment is composed of mobile test benches (built as outlined in point 2) and a dedicated SCADA supervision with a copy of the WinCC OA® production project. When a section of the project related to a specific cryogenic subsystem is ready for testing, the developer starts a CI pipeline that automatically deploys the project to the mirror testing environment, as shown in Fig. 4. Before beginning tests, the process synoptic panels corresponding to the developed subsystem must be converted to the UCPC6 format. Simultaneously, all nonconformities should be rectified, and any anticipated animation improvements in the PLC program should also be implemented.

To ensure software quality assurance, the testing process was performed in three consecutive steps by three different teams. Initially, the preliminary tests were carried out by the developer. This was followed by detailed testing and validation conducted by the cryogenic process engineer responsible for the installation. Finally, the last round of tests was undertaken by the cryogenic operation team. For each subsystem, all process phases and various scenarios were simulated to ensure that the software performs as intended and meets the specified functional requirements. All subsystems, such as feed-throughs, vacuum, nitrogen circulation, etc., were tested individually. Following this, all subsystems were tested together, with particular attention to the propagation of process modes and commands across all subsystems and the communication between PLCs. Several feedback testing loops were typically necessary to fully commission each subsystem. One of these loops usually included a process review and system operability improvements from the cryogenic process engineer. As a result, the entire LAr control system was successfully commissioned offline, ensuring the highest quality of the produced software. At the same time, the logic specifications were updated.

4. Deployment

Deployment Preparation Taking into account the critical nature of the LAr control system and the complex configuration required during deployment, the preparation for deployment was an extremely challenging task for all involved parties. Before preparing the deployment procedure, the cryogenic process engineer conducted a detailed intervention risk analysis. This analysis examined each system function, predicted possible failure modes, evaluated the potential impact of failure on the system, assessed the criticality of failures, identified possible causes of failure, and outlined preventive and protective compensation measures. Then a detailed implementation procedure for the planned PLC upgrade was prepared together with the cryogenic process engineer and validated with cryogenic operation and ATLAS detector teams. This procedure includes: the sequence of PLCs upgrade, a day-by-day plan, mandatory preconditions, the deployment workflow, and step-by-step implementation procedure (checklists) for both clients and infrastructure. Every step in the procedure is detailed, including responsible for each action and the time allocated for its completion.

Strategy The following strategy was adopted for deployment in order to limit risk and time of intervention:

- completely test hardware, code, and implementation procedure on the mirror testing environment;
- install, configure and test (using RIO mobile test bench racks) in parallel to the existing and operating control system, all new control system, including Hot Standby PLCs, SCADA, Ethernet® and Profibus DP® networks;
- prevent co-activity with any other intervention that may interfere with the control upgrade, such as end-cap detector movement, console restarts, emergency stop tests, electrical switchboard maintenance, etc.;
- as a preventive measure, lock-out key cryogenic items (i.e. alarm relays, cryostat drain or vacuum isolation valves);
- limit process interruptions to less than 12 hours, including system restart and a rollback scenario in the event of unexpected problems during deployment;
- implement one PLC at a time. When implementing a client PLC, maintain nominal liquid nitrogen cooling by the infrastructure. When installing the infrastructure PLC, ensure argon pressure control by the clients;
- plan one-week interval between PLC upgrades for feedback from the operations team and to make corrections;
- retain all old PLCs for a certain period for a potential rollback scenario.

The performed risk analysis, the prepared intervention procedure, the adopted strategy, and the implementation of the defined requirements allowed us to limit the most critical part of the intervention to steps illustrated on Fig. 5, where the crucial point is the re-connection of the RIOs from the old to new control system.

The LAr calorimeter control system was successfully upgraded in February 2023. Approximately six hours were
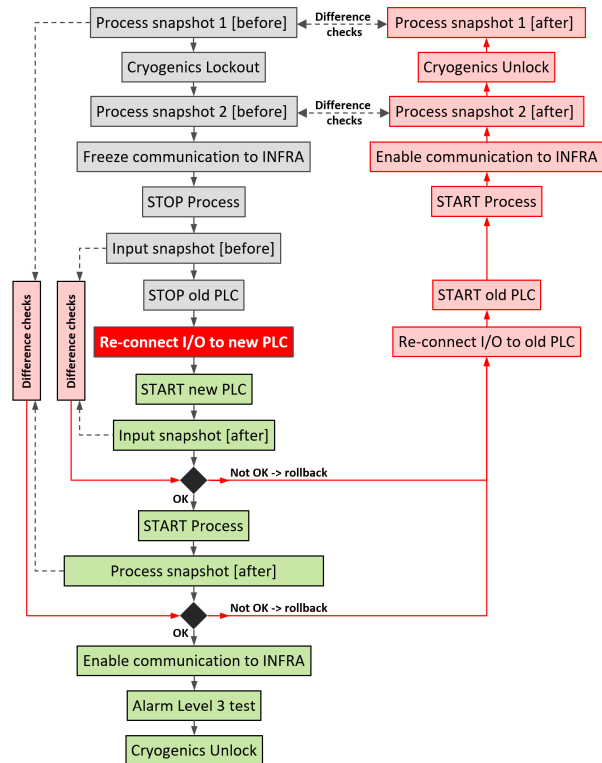
Figure 5: Deployment workflow.

needed to replace each PLC and restore the process. Since then, no issues have been reported, and the old system has been decommissioned.

CONCLUSION

The defined upgrade strategy, along with the substantial effort in all project phases, allowed for a smooth and problem-free upgrade of one of the most critical cryogenic control systems at CERN. Thanks to all the implemented improvements, the LAr control system has become more robust and immune to PLC crashes, simultaneously increasing the overall reliability of the cryogenic system. Any future modifications to the control logic can be easily implemented due to the automation of software production. With the help of UCPC6, control system support and maintenance can be efficiently handled, and operators can benefit from a unified process interface and updated logic specifications.

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