ISBN: 978-3-95450-209-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2019-WEPHA050

STATUS OF THE PROCESS CONTROL SYSTEMS UPGRADE FOR THE CRYOGENIC INSTALLATIONS OF THE LHC BASED ATLAS AND CMS DETECTORS

C. Fluder*, M. Pezzetti, A. Tovar-Gonzalez, CERN, Geneva, Switzerland
K. Mastyna, P. Peksa, T. Wolak, AGH University of Science and Technology, Kraków, Poland

Abstract

The ATLAS and CMS cryogenic control systems have been operational for more than a decade. Over this period, the number of PLCs faults increased due to equipment ageing, leading to systems failures. Maintenance of the systems started to be problematic due to the unavailability of some PLC hardware components, which had become obsolete. This led to a review of the hardware architecture and its upgrade to the latest technology, ensuring a longer equipment life cycle and facilitating the implementation of modifications to the process logic.

The change of the hardware provided an opportunity to upgrade the process control applications using the most recent CERN frameworks and commercial engineering software, improving the in-house software production methods and tools. Integration of all software production tasks and technologies using the Continuous Integration practice allows us to prepare and implement more robust software while reducing the required time and effort.

The publication presents the current status of the project, the strategy for hardware migration, enhanced software production methodology as well as the experience already gained from the first implementations.

INTRODUCTION

The CMS and ATLAS experiments installed in the Large Hadron Collider at CERN, have both been equipped with cryogenic installations. For the CMS experiment this installation cools a large superconducting solenoid magnet, while for the ATLAS experiment the installations are used for cooling of three superconducting toroid magnets, a superconducting central solenoid magnet and three liquid argon calorimeters.

The cryogenic system for cooling down the solenoid magnet of CMS consists of one helium refrigeration plant specified to cool down respectively the magnet's cold mass, the shield and the current leads. The cryogenic system to cool down the superconducting magnets of ATLAS is composed of two independent helium refrigeration plants (the Main Refrigerator and the Shield Refrigerator) and two Proximity Cryogenic Systems (PCS), one for each magnet system (the toroids and the solenoid). The cryogenic system of the ATLAS liquid argon calorimeters consists of the barrel and two end-cap detectors housed in three independent cryostats, filled with liquid argon. To maintain the calorimeters at the nominal temperature a complex cryogenic infrastructure and Nitrogen Refrigerating plant are required.

CONTROLS SYSTEM ARCHITECTURE

To automatize the control process of the ATLAS and CMS cryogenic installations three Distributed Control Systems (DCS) have been designed and implemented: CMS magnet, ATLAS magnets and ATLAS calorimeters. For each DCS the visualization and operation of cryogenic processes is ensured through Supervisory Control And Data Acquisition (SCADA) based on the WINCC OA® applications. Typically, one SCADA data server is connected to several autonomous Programmable Logic Controllers (PLCs), based on Schneider Quantum® technology (see Fig.1). In total 16 PLCs have been distributed throughout the cryogenic installations. Within one DCS, the PLCs share process data to coordinate the overall cryogenic process. Using the S908 Remote IO (RIO) network, each PLC is controlling I/O that are physically located in different areas: surface hall or technical or experimental caverns. In total 71 Remote IO DROPs made up of 669 I/O cards, with 7856 analog and digital RIO channels have been deployed. In addition, for some systems, the Profibus DP field-bus has been used to connect to SIEMENS S7® PLCs protecting turbines and to electronics supervising vacuum pressure gauges.

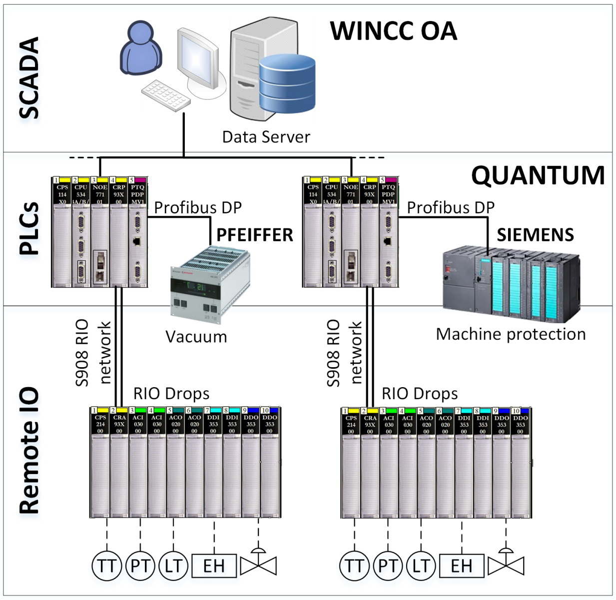

Figure 1: Typical control system architecture.

---

[*] czeslaw.fluder@cern.ch

ISBN: 978-3-95450-209-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2019-WEPHA050

HARDWARE UPGRADE

The control systems (together with the corresponding cryogenic installation) were designed and tested between the years 2000 and 2005 [1]. For most of the individual control systems, the final installation and commissioning phases were launched in 2005 [2] [3] [4]. All control systems were fully operational for the first LHC beam on the 10th of September 2008. From that moment, the control systems were ensuring availability of the cryogenic infrastructure over the first two LHC runs, which means until 2018.

After over ten years of control systems exploitation, the number of PLCs-related faults started to have a tendency to increase. In 2015 the first PLC crash, causing cryogenic installation failures and a significant downtime, was reported. Typically, a crash occurs when a PLC program stops functioning properly (due to PLC hardware problem) and exits the RUN mode. During the following years, three different PLC crashes were reported along with more than ten communication connection losses in particular with PLCs or with remote I/O DROPs. Despite the detailed fault analysis and help from Schneider support, it was not possible to reproduce these events in laboratory conditions and to determinate the causes.

Meanwhile, the life cycle of the Quantum products entered the end-of-commercialization phase. The commercialization of Quantum CPU stopped in 2018 while Remote IO cards ends in 2021 and after-sales support ends in 2026 and 2029 respectively [5]. These events and the fact that the control systems of the ATLAS and CMS cryogenic installation must operate reliably for **the next 20 years**, lead to the review of the long term maintenance strategy. Firstly, the faulty equipment has been systematically replaced by spare parts from an internal stock. In the second stage, two phases of the long-term hardware upgrade plan were defined: 1st for the PLC Upgrade and 2nd for the Remote IO Upgrade (see Fig.2).

Phase 1 - PLC Upgrade

During the Phase 1, taking into consideration hardware obsolescence as well as faults statistics and the potential consequence of a single component fault, the priority was set to upgrade the most critical control systems parts: 16 PLC main racks with CPUs, Ethernet CPs and Profibus DP interface cards. The selection of replacement technology was based on predefined criteria:

- compatible with QUANTUM Remote IO technology and providing a solution to integrate both technologies,
- recently developed (using current state-of-the-art) with more than 20 years of remaining product life cycle,
- supported by the CERN control software frameworks used for development of industrial control applications i.e.: UNified Industrial Control System (UNICOS) [6],
- equipped with enforced cyber security with features like: access control, password protection, memory and firmware integrity checks mechanism,
- powerful enough (in terms of memory size and program execution cycle time) to follow frequent process control software evolution as well as UNICOS framework upgrades,
- equipped with diagnostic features required by 1st line support for debugging,
- able to operate large control applications, with thousands of remote IO channels, without performance reduction.

The new Schneider M580® PLCs fulfil all requirements and became a natural choice for the QUANTUM® replacements. In the new architecture (see Fig.2), the S908 Remote IO network with sensitive mechanical coax cables connections, was replaced by a redundant Ethernet IO (EIO) network with ring topology. The use of the redundant EIO standard improves system reliability (fever connections and devices) and simplifies maintenance. The replacement of Ethernet cable is easy and without the risk of causing a system failure during intervention. The EIO network is connected directly to the new M580 CPU, which allows the Communication Remote Processor (CRP) previously used in the legacy system to be eliminated. On the side of the Remote IO DROP, the Communication Remote Adapters (CRA) were replaced by similar adapters, supporting EIO network. The M580 CPU together with the Ethernet communication processor (CP) and Profibus DP interface are mounted on an Ethernet switch - the main rack ensuring data exchange between all mounted components. The Ethernet CP provides a connection with the WINCC OA® SCADA data server, not concerned by this upgrade. This configuration allows the EIO network to be completely isolated from external systems, guaranteeing IO network cybersecurity. The material references are available in the Table 1.

Table 1: Detailed M580 Hardware Configuration

Function	Model	Firmware
Ethernet rack	BME XBP 0400	1.0
Power supply	BMX CPS 3020	n/a
CPU	BME P58 4040	2.8
Ethernet CP	BME NOC 0301.2	2.07
Profibus interface	PME PXM0 100	1.001
DROP CRA	140 CRA 312 00	2.4

A prototype of the new control architecture was successfully tested in laboratory conditions using a mirror setup (production system reproduced in the laboratory). The compatibility between the old and the new hardware components and the performance of the new hardware and Remote IO Ethernet network was fully validated. Consequently, this allowed upgrade campaigns at the beginning of 2017 to be launched, starting from the smaller and less critical control systems. During the following two years another six control systems for ATLAS and CMS cryogenics were successfully upgraded and put into service. Typically, the hardware upgrade for one control system with 5 RIO DROPs can be performed in a few hours and does not require complete recommissioning. Usually the installation restart can be done within 24 hours.

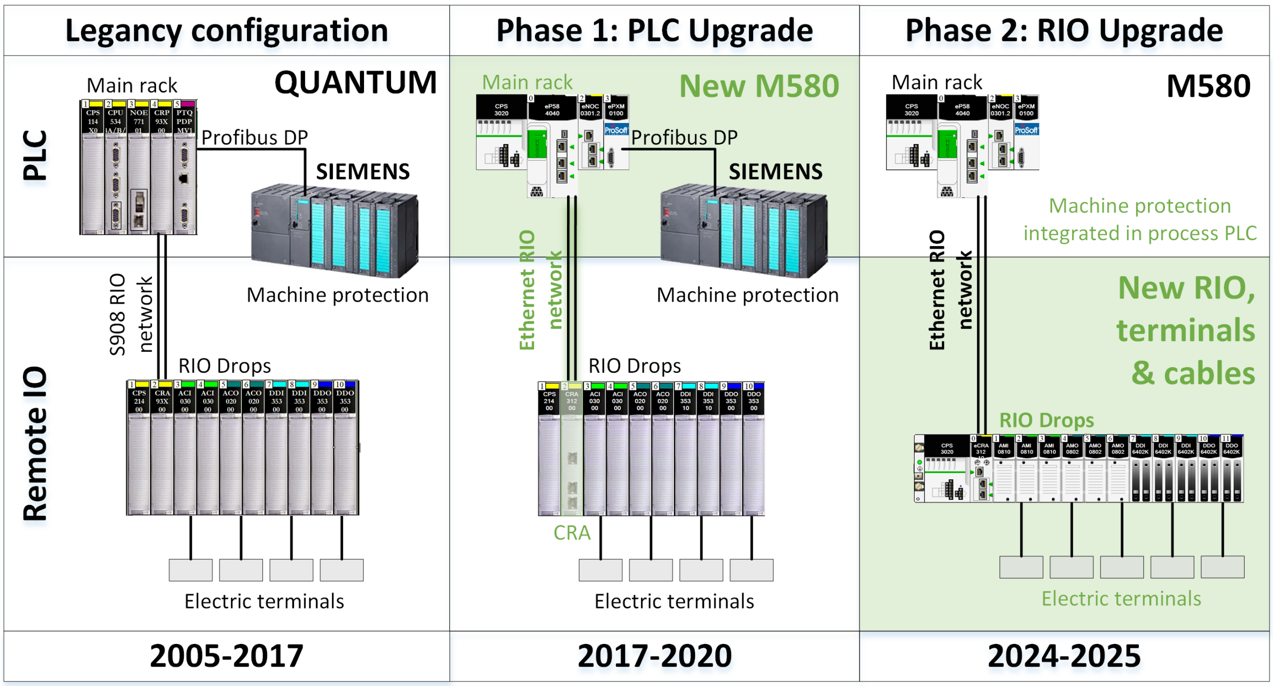

Figure 2: Hardware migration plan.

Two faults of the RIO Ethernet interfaces (CRA) were reported within the first two years of experience with the new systems (M580 CPU with QUANTUM RIO on the Ethernet). Following a detailed investigation, a nonconformity of a grounding connection on RIO DROP was identified as the cause of the CRA malfunction. This led to a review of all of the grounding connections. All discontinuous connections have been identified and consolidated according to the current electromagnetic compatibility standards given by the manufacturer. Besides, the upgrade procedure was updated accordingly.

Phase 2 - Remote IO Upgrade

Due to the few years of the life cycle for the QUANTUM IO cards remaining and nearly fault-free statistics, the second phase has been considered as less urgent. The replacement of the 669 QUANTUM IO cards by the new M580 cards has been scheduled between the years 2024 and 2025, during the next LHC long shutdown. At the same time, all electric terminals and cables have to be adapted to the M580 IO standard. Consequently, new terminals and cables have been developed and have become a new standard for cryogenic installation based on M580 components. To fulfil the LHC cryo-plants standard, the machine protection functionalities provided by the Siemens PLCs will be integrated into the process PLCs and the Siemens PLCs will be dismounted. Therefore, the second phase will require much more effort, time and a complete re-commissioning of all cryogenic installations. Currently, a prototype upgrade is under preparation.

SOFTWARE UPGRADE

The replacement of the existing PLC components by the new M580 standard has provided an opportunity to upgrade the process control software, using the most recent frameworks, commercial engineering software and to improve the in-house software production methods and tools. Since its initial release, the software development of control systems for the ATLAS and CMS cryogenic installations has benefited from the UNICOS framework which has been extensively used at CERN in control applications in many different areas e.g. cooling, ventilation and cryogenics [7]. The framework abstracts the real devices into a set of well-defined software objects and formalizes relationships between them. It eases and simplifies the development of industrial control systems by helping to define the system independently of control system type and providing an automatic source code generation for PLCs.

Although the framework itself is an immense advancement for developing control systems software, it is still very time-consuming and an error-prone task especially when a lot of offline and online changes are made during the development and maintenance. Taking software production of cryogenic control applications for the LHC Tunnel [8] as an example, major improvements were introduced in software development for the ATLAS and CMS cryogenic applications by implementing a continuous integration (CI) approach.

Continuous Integration Although, the principle of CI approach is analogous in both cases, characteristics of the systems differ. In the case of the LHC Tunnel control system,

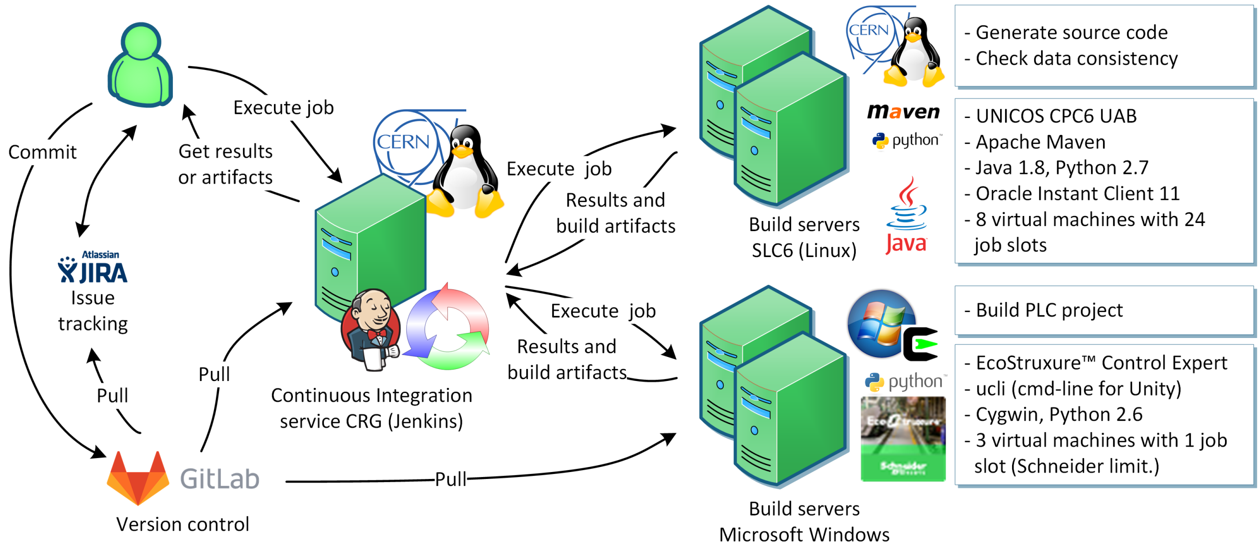

Figure 3: Overall architecture of the CI system for the ATLAS and CMS detectors cryogenic systems.

there are eight similar sectors, consisting of two PLCs per sector. Generating and compiling the control system code can be considered as one parameterized task that depends on which sector is being built. In the case of control systems for ATLAS and CMS each of them comprises 16 independent applications. Another major difference is that the LHC control system employs Siemens PLCs whereas the ATLAS and CMS cryogenic control systems operate with new Schneider M580 PLCs. Consequently, different methods and tools had to be developed to make it possible to implement the CI.

The CI service was built using Jenkins® [9] – an open source automation server, which has already been used to automate the building process of many LHC accelerator control systems. Therefore, it has been a preferred choice due to previous experience with it and because of its reliability so far. Building control applications with the UNICOS comprises two major steps: generation and code compilation, which are mapped directly into Jenkins' jobs (see Fig.3).The Jenkins' service is integrated with: a Git® server (used to store built system input files), Atlassian JIRA® (issue tracking tool) and a number of virtual machines (build servers). The virtual machines are worker nodes to which the Jenkins server delegates tasks of code generation and compilation.

Code generation without CI service is done using the UNICOS Application Builder (UAB), an application provided by the UNICOS framework. It has been automated using Apache Maven, which is a project management and comprehension tool, allowing code generation with different parameters to run easily. Code compilation, in the case of the LHC tunnel control system, is possible thanks to the SIMATIC Step7® command line interface (s7cli). Similarly, in the case of the Schneider M580 PLCs, there was a need for a command line interface, allowing CI to interact with Unity Pro® and later with EcoStruxure Control Expert®. Therefore, the existing command line interface (ucli) had to be extended to easily integrate it with the CI infrastructure.

Building a PLC project (importing and compiling the generated code) is the most time-consuming stage for developers. It requires a lot of manual work, while compilation itself takes a large amount of time, especially in the case of big projects. To manage the entire process, all logical phases of the code generation and compilation were organized into smaller tasks and executed using GNU Make.

Repository After establishing the process of compilation in Jenkins, the first approach to automatize was to organize a repository with one master branch being the template that contains all the files and directory structure, common to cryogenic control applications. This way, one branch corresponded to one application and each application, upon creation, needed to be inherited from the master branch. This approach obviously had its drawbacks as well. Having one application with different UNICOS versions was not possible unless it was done on different branches. This implied many unnecessary Jenkins jobs creations. Consequently, an extension for this solution has been developed (see Fig.4). The base directory structure and common files required by the build configuration is kept to one dedicated repository called the project template. This repository has a master branch, which contains all files not related to the version of the UNICOS framework, such as common scripts and configurations. Other branches that inherit from the master branch correspond to specific UNICOS versions. Creating a new application means creating a new repository project based on the project template repository. This approach gives a lot of flexibility. It allows to have multiple versions of the project, not only regarding UNICOS framework versions, but also versions of the project during the development. Moreover, any functionality developed for one application can be easy propagated to other applications through the template repository.

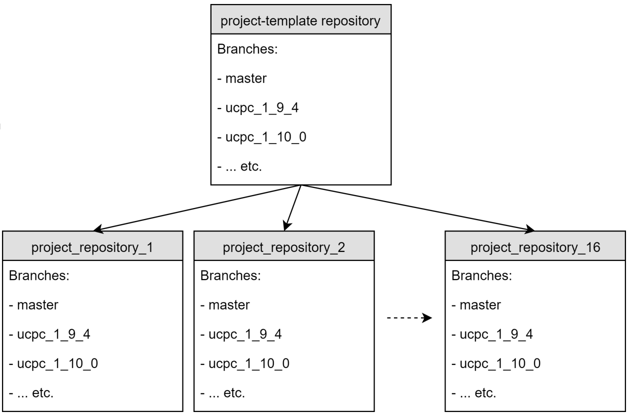

Figure 4: Repository structure.

Elastic CI Using an elastic CI service makes it possible to easily replace single components of it i.e. commercial software used for development. The upgrade of Profibus DP cards was the main reason for the upgrade Unity Pro to EcoStruxure Control Expert software. Thanks to the flexible CI system the only change that had to be made was creating new virtual machines with the new software and connecting them to the Jenkins server and minor reconfiguration of the jobs so that they were executed on proper worker nodes.

Archiving Optimization Redeployment of the control applications has been an opportunity to introduce a standard for archiving and filtering values from the sensors in the database. Arbitrary archiving and filtering rules are the reason for the overflow of the SCADA database used to store historical data points. A dedicated check of the archiving parameters has been developed and integrated to the generation procedure, preventing incorrect configurations. A practical benefit of setting these standards is the reduction of the time needed to load the trends of particular sensors.

Parameters Recovery During exploitation of the installations, operators adjust the process parameters (i.e. parameters of PID controllers). Depending on the UNICOS version the active process parameters can be saved as default values. To manually recover those parameters from the production system for the next system redeployment is a very time-consuming process. A control script executable in the WinCC OA SCADA environment has been developed to automatically extract adjustable parameters into a JavaScript Object Notation (JSON) file. The parameters obtained (active and default) are compared with offline parameters and later correct values are applied to the current control system configuration file (in format of Microsoft Excel®). That is achieved with dedicated Python scripts using openpyxl and xlwings libraries.

Future Plans

The CI have been configured for all of the ATLAS and CMS cryogenic projects. While this is already helpful for the software development of seven upgraded M580 applications, further developments for automating some stages of the process and supporting tools are necessary for replacing the remaining manual tasks. The development of the tool converting static PLC source code previously implemented in Function Block Diagram (FBD) to Structured Text (ST) programming language (easy to track in GIT) is already well advanced. Most likely the next step will be focused on the tool facilitating the ATLAS liquid argon calorimeters UNICOS upgrade, converting and optimizing ST code between two different UNICOS versions.

CONCLUSIONS

The hardware upgrade strategy described as well as improvements in software production methodology permitted us to prepare and to implement seven control system upgrades. Development of the remaining nine control system upgrades are very well advanced. The upgraded system benefits from the newest technology and the most recent versions of CERN frameworks (for developing industrial control applications) and commercial software. The PLC equipment life cycle was extended by another 20 years, which made the systems more reliable and easier to maintain. Thanks to the continuous integration system, the implementation of process logic modifications requires less time and effort, and the code produced is more robust.

REFERENCES

[1] J. Casas-Cubillos *et al.*, “Application of Object-Based Industrial Controls for Cryogenics", in *Proc. EPAC '02*, Paris, France, 2002.

[2] N. Delruelle *et al.*, “Commissioning of the Cryogenic System for the ATLAS Superconducting Magnets”, in *Proc. Advances in Cryogenic Engineering 2006,* vol. 51B, New York, USA, 2006, pp. 2018–2025.

[3] G. Perinić *et al.*, “Installation and commissioning of the helium refrigeration system for the CMS Magnet”, in *IEEE Transactions on Applied Superconductivity,* vol. 14, August 2004, pp. 1708-1710.

[4] C. Fabre *et al.*, “Design Principles and Operational Results of the Cryogenic System for the ATLAS Liquid Argon Calorimeter”, in *ICEC22-ICMC2008,* vol. 14, Seoul, Republic of Korea, Jul 2008, pp.787-792.

[5] Schneider Electric, "La continuité de votre exploitation", `https://www.se.com/fr/fr/download/document/ZZ4199/`

[6] CERN, "UNified Industrial Control System (UNICOS)", `http://unicos.web.cern.ch/`

[7] E. Blanco Vinuela *et al.*, "UNICOS EVOLUTION: CPC VERSION 6", in *Proc. ICALEPCS 2011*, Grenoble, France, 2016, paper WEPKS006.

[8] C. Fluder *et al.*, "Automation of the Software Production Process for Multiple Cryogenic Control Applications", in *Proc. ICALEPCS'17*, Barcelona, Spain, 2017, paper TUPHA006.

[9] "Jenkins, An extendable open source continuous integration server", `https://jenkins.io/`