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CRYOGENIC CONTROLS TODAY AND TOMORROW

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Abstract

The CERN cryogenic facilities demand a versatile, distributed, homogeneous and highly reliable control system. For this purpose, CERN conceived and developed several frameworks (JCOP, UNICOS, FESA, CMW), based on current industrial technologies and COTS equipment, such as PC, PLC and SCADA systems complying with the requested constraints. The cryogenic control system nowadays uses these frameworks and allows the joint development of supervision and control layers by defining a common structure for specifications and code documentation. Such a system is capable of sharing control variables from all accelerator apparatus. The first implementation of this control architecture started in 2000 for the Large Hadron Collider (LHC). Since then, CERN continued developing the hardware and software components of the cryogenic control system, based on the exploitation of the experience gained. These developments are always aimed to increase the safety while improving, at the same time, the performance. The final part will present the evolution of the cryogenic control toward an integrated control system SOA based, using the Reference Architectural Model Industrie 4.0 (RAMI 4.0).

INTRODUCTION

The CERN cryogenic infrastructures for accelerators, detectors and test systems include large and complex facilities able to cool the equipment down to 80 K with liquid nitrogen (LN_2), to 4.5 K with liquid Helium (*LHe*) and to 1.9 K with super fluid helium. These facilities are placed in dedicated test facilities, experimental areas and around the 27 km LHC. The complexity of the cryogenic facility requires an automated and homogeneous control system that must be flexible, reliable and distributed around the entire CERN LHC cryogenic line QRL [1]. Today, for the High luminosity (HL-LHC), era some adaptions will be applied to fully automate the control development and to prepare the integration of the control system with the existing Maintenance Management Software (MMS) and the operational support environment from the conception stage to the daily operation. Tomorrow, a new generation of large accelerators is forecasted, making the story far from finished. Hence this article will also present additional thoughts and potential developments proposals.

CRYOGENIC CONTROL SYSTEM TODAY

Currently, the cryogenic control system follows the standard automation pyramidal structure of the International Electrotechnical Commission (IEC-62264) and is based on industrial components deployed in all control layers (see Fig. 1):

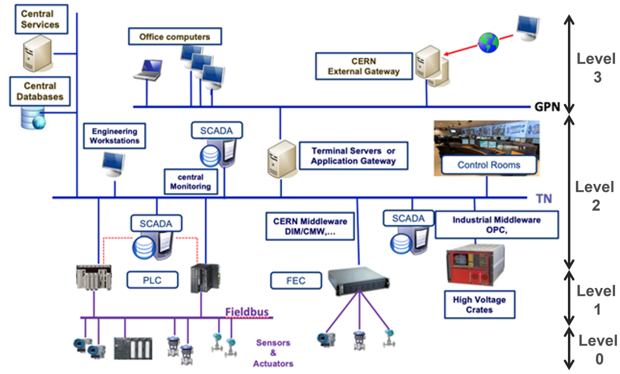

Figure 1: CERN Industrial Control Ecosystem.

- Instrumentation layer (IL): The cryogenic instrumentation needs a significant number of industrial sensors to collect data, electronic conditioning units and actuators to execute commands. To ensure the correct communication with the devices, both copper cable connections and a protected and dedicated Ethernet network or industrial field-buses are used. In the LHC, where the environment is hostile, radiation resistant instruments and fieldbuses were chosen.
- Control layer (CL): The control duties are executed within PLC, with safety interlocks either cabled in the electrical cabinets or programmed in local protection PLCs. In radiation exposed area radiation tolerant crates and field-bus are used, coupled with standard CERN Front End Computer (FEC). The long-distance integration site to site or toward the supervision layer, relies on the CERN Ethernet Technical Network (TN) whereas the local ones (internal to a cryogenic site) are implemented on field-buses using both fibres and copper cables or direct cabled to the cabinets.
- Supervision layer (SL): All cryogenics systems are supervised through Data Servers (DS) running the WinCC-OA® SCADA system within off-the-shelf's Linux machines. The Human-Machine Interface (HMI) clients allows operators to monitor and act on the cryogenics facilities using Linux PC deployed within the control rooms. In addition to the classical SCADA features, several functionalities have been added in the last decade: visualisation of the process hierarchy, access to the interlocks per devices, control loop auto tuning, direct access to device documentation, etc. This layer provides also interfaces to the Management Layer, and a dedicated connections toward the CERN central alarm system and the LHC experiments control systems.
- Maintenance & Operation Management System layer (ML): The central long-term logging database (NXCALS), the CERN CMMS (Infor-EAM) and the Accelerator Fault Track application (AFT) are parts of this

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layer. They monitor the whole process and integrate it into the campus environment. These applications are currently being integrated with the present cryogenic control system and the next run will be a good opportunity to validate them.
- The Company Overall Management layer (CL): At CERN, this level is filled with Administrative Information Services (AIS) applications. Up to now there are few ad-hoc integrations with ML components for specific CERN groups. However, the complete vision is lacking and there is not yet a well coordinated development.

Cryogenic Control Applications

The cryogenic process control system uses the first implementation of the UNified Industrial Control System (UNICOS), a CERN-made framework to develop of industrial control applications that integrates the development the SL and the CL in PLC and SCADA as it's done in a Distributed Control System (DCS). The main benefit of UCPC applications (UNICOS coupled with the Continuous Process Control package) [2, 3] is to ease the operator's ability to follow the evolution of the process and to understand the dynamics of a situation as well as the role of each physical component. It also helps to identify the origin of a failure, predict what could happen in the near future, etc. To achieve these duties, operation teams have access to classical SCADA tools (process synoptics, time stamped alarms, events lists, trend curves with long term storage, etc.), but also to the visualisation of the process hierarchy, the interlocks per devices, the control loop auto tuning, and the device documentation, etc.

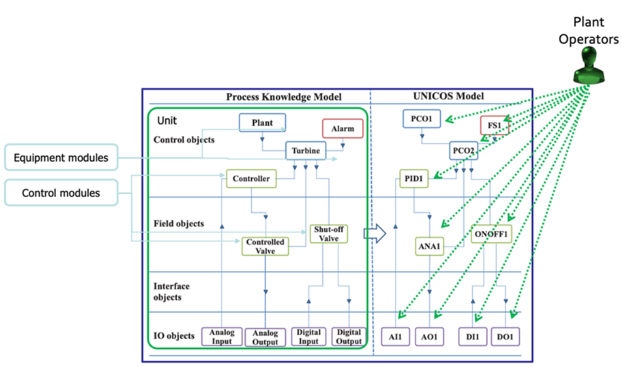

Figure 2: cryogenic device hierarchy according to IEC61512-1 decomposition and its equivalence in UCPC.

The UCPC model is based on the IEC61512-1 model that decomposes (see Fig. 2) the cryogenic plant in smaller components (Equipment Modules (EM) or Process Control Object (PCO) for UCPC) down to the smallest possible equipment module. These EM are structured in Control Modules (CM) representing the sensors and actuators or regulators and alarms connected to the process through inputs and outputs. The UCPC device model permits the concurrent access from the supervision and process control hierarchy to the devices with the mechanism as exposed in Fig. 3. It allows the operators to intervene at the right place without side effects to the other components.

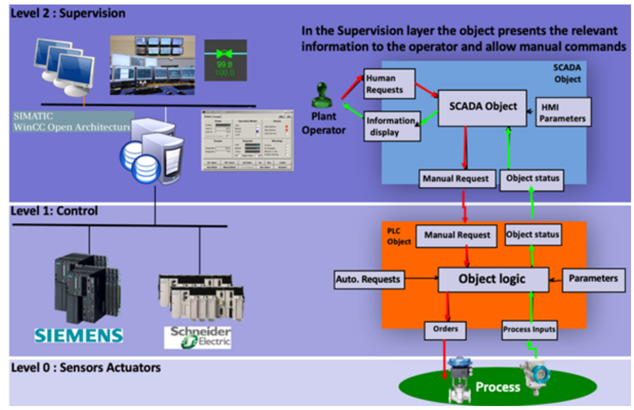

Figure 3: UCPC Control & supervision layer integration.

Application Development

To achieve the delivery of high-quality control system applications within a certain cost and time constraints, a generator, using a step-wise development methodology (as shown in Fig. 4), has been elaborated by CERN. This 5 part process makes the development team's life easier:

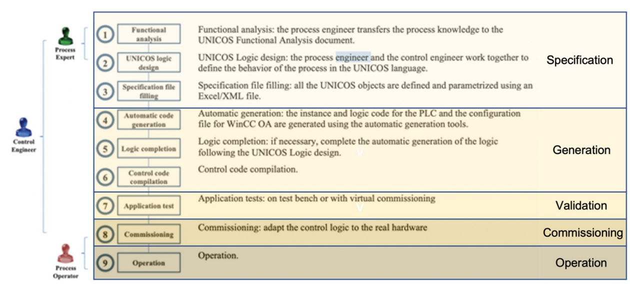

Figure 4: UCPC development methodology.

a) Specification: To produce the initial specification (step 1, 2, 3 in Fig. 4) the process experts use a common set of basic documentation elaborated during the design phase of the project:
   - The electrical schemas, the Process & Instrumentation Diagrams (P&ID) and the instruments lists together with their associated data to validate the conformity with the cryogenic group prescription for construction and protection principles;
   - The P&ID to elaborate the Process Flow Diagram (PFD), to identify the functions and the completeness of the proposed instrumentation to ensure the requested duties. They permit also to validate if the tag names proposed are in conformity with CERN required standards;
   - The instruments lists to identify the conformity with the prescriptions of the components choices and to validate the availability of the necessary process data.

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From these documents it is possible, in collaboration with a control expert, to prepare either manually or automatically:

- The devices description specifications as XML format sheets to describe all devices to be used within an application;
- The functional and logic specifications based on text templates used to code the needed PLC function placeholders in a standardised way using predefined templates;
- The supervision configuration data and synoptics that can be either drawn manually or generated using standardised templates.

A quality testing of the data validity can then be conducted to maintain the maximum reproducibility and to reduce the commissioning time (comparison of the parameters stored in the databases together with the parameters extracted from the production system). Today the non LHC cryogenic systems and the LHC cryoplants are manually developed whereas the cryogenic tunnel applications are automatically generated.

b) Generation: When generating the applications (step 4, 5, 6 in Fig. 4), the XML inputs files describing the devices as well as their properties and the python templates for PLC codes and SCADA panel, are processed and combined by the UNICOS Application Builder (UAB). Its internal plugins follow semantic rules to produce the application files to be loaded directly in PLCs and SCADA. If at this stage templates are missing, the control expert must either manually complete the control logic placeholder in the PLC or draw the process synoptics with the SCADA drag & drop tool.

c) Application Validation or Virtual Commissioning (step 7 in Fig. 4) can be performed to validate the implemented logic:

- Application validation : A mirror PLC with automated or semimanual features, to control the different thresholds for the interlocks logical transitions, is used [4];
- Virtual commissioning : A cryogenic model using a dynamic simulation model based on EcosimPro® and a Cryogenic library developed at CERN is exploited to validate the control loops through the UCPC decomposition, allowing a complete virtual commissioning of the system.

d) Final Cryogenic Commissioning (step 8 in Fig. 4): After the completion of the previous validation tests, process experts can proceed to the actual commissioning to adapt the application to the process.

e) Operation: In this last step the operators use the SCADA User Interface (UI) to take over normal operation. In case of failure, they can obtain detailed information about the entire process and controlled devices. For instance, they have the access to diagnostic panels to investigate the origin of interlocks (mechanical, electrical, hardware, control software, etc.) in order to take quick corrective actions to overcome problems and reduce potential downtime.

Automation of the Application Generation

The complexity of the cryogenic control system and the frequent updates carried out for optimisation or regular maintenance have made the follow-up of the control software complicated and time-consuming with high demand for complex Information Technology (IT) tools. To elaborate automatically the UAB inputs files and improve the quality of the cryogenic control applications, an adapted generator using the design principle of the "Continuous Integration" model has been developed [5]. This generation process uses a shared project control repository, with the XML devices fill, the process logics and generic panels implemented in Python templates easing the replication and automates all the steps to build new projects including the new code testing. Hence, since it's implementation the applications controlling the LHC tunnel, have been regularly updated, with excellent results in terms of efficiency and reliability such as the reduction of the necessary time for the code review. The different languages semantic and the lack of inter-operability between PLC brands and the integration of PLC-SCADA with common protocols were the main limitations of industrial control systems. The use of UCPC solved a large part of these limitations. Applications generation for the various brand of PLC are homogeneous since they are based on a common control model. The PLC-SCADA communication configuration is automated and the communication from PLC to SCADA uses a Time Stamped Push Protocol (TSPP) adapted to the PLC brand. All the application generation processes have been automated and implemented.

CRYOGENIC CONTROL SYSTEM EVOLUTION IN THE NEAR FUTURE

Beside the process control applications needs continuos to be update in both the supervision and control levels to follow the operation requested evolution (synoptic evolution, new trends, new alarms, etc.), to implement the logic modifications related to the hardware protection evolution,to follow the evolution of the requested logic & presentation and to develop additional process operation features. The goal is to facilitate the operators duties to improve the application software productivity, to reduce the critically of several components improving the hardware availability, and to simplify the preventive maintenance reducing the costs [1].

Supervision Level Evolution to Facilitate the Operator's Duties

A new version of WinCC-OA® and the UCPC SCADA framework package will be introduced [6], in addition to a new archiving technology compatible with the NXCALS storage and a new alarm list with additional functionalities. The new version offers a large integration with ML layer

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information tools from each device (e.g., CMMS data, Control Logic, Electrical Drawing) that will be extended in the coming years.

Improving Application Software Productivity

A recent extraction of the control devices has shown that around 280000 UCPC devices are already deployed and used for the various cryogenic controls systems at CERN. This gives a total of more than 13 million fields to be maintained. Since in the specification phase of UCPC, technical documents contain all the technical information needed to develop the cryogenic control system applications. Therefore, the needed evolution is to make the complete set of technical data contained in those documents available. Thereby, the various stakeholders will be able to access all necessary information to develop, operate or maintain the cryogenic system [7]. Besides this work, a Control Specification Generator including a new database as well as a set of generic software components to extract the information to produce the XML input files for UAB will have to be developed [7, 8]. An official request to the CERN Industrial Control group to prepare the generation database and develop the tool has been filled, accepted and noted in the Road-Map. However, the development is presently on hold.

Other Generators

With a similar approach, an evolution of UAB and the development of adapted python templates and rules should be generated for new projects or renovation of existing ones:

- EcosimPro® & CryoLib, cryogenic simulation models;
- Cryogenic Maintenance plan for MMS (procedure, frequency, checklist, etc.);
- Data driven schematics;
- Intelligent electrical schemas;
- Intelligent mechanicals P&ID

Improving the Control and Instrumentation Availability

To enhance the availability of the control and instrumentation hardware there is a need to eradicate the root causes of failures, to reduce the fault diagnostic time and to minimize the equipment variability, eliminating at the same time unnecessary equipment to limit the annual maintenance costs. This goal will be achieved by using industrial fieldbus, standard cabinets and removing outdated plugs and installing push terminals:

- The PROFIBUS® communication will be updated with the migration to Ethernet-based technology for PROFIBUS® DP long distance Network, and the replacement of PROFIBUS® PA I/O board to introduce additional redundancy.
- The 400 V distribution design will be modified to simplify the distribution and protection. Main maintenance switches will be installed on the cabinets to facilitate and accelerate the recovery in case of failure.
- The 24 V devices will be supplied with a bus to enhance the flexibility, ease the diagnostic and improve the availability in case of a component failure.

Radiation Tolerance Consolidation

The LHC cryogenic system has operate during 2 physics Runs without radiation induced failures. However, in the coming years, with the increment of the luminosity in the frame of the HL-LHC, this aspect must be considered to avoid failures that will lead to unplanned downtime. Several solutions have been explored (i.e. transfer the cryoplants to a surface building or to existing underground protected locations or creation of a new service caverns) The most suitable solution seems to shield by a wall between the source of the radiation and the sensitive equipment, in order to reduce the numbers of events [9]. The problem of this installation is the crowded environment and the thickness of the wall to achieve the right reduction of radiations as an attenuation by a factor of 5 is the goal to achieve when the luminosity will rises to $50\,fb^{-1}/y$.

CRYOGENIC CONTROL SYSTEM TOMORROW

This chapter is based on real concepts studied and, for a part of them, already in practice in the contemporary control community. First of all, the groups do agree with many assertions presented in the [10] (chapter 5.10) and in particular with those going in a direction, particularly true and necessary for the control systems, to make the choice of homogeneous solutions for the various control systems (infrastructures, accelerators & detectors) and to open large cooperation with industrial, research and institutional partners. Strong partnership with industrial providers can be a key to the success of a project. Indeed, specific requirements that drastically differ from those of industry (scale of the applications, integration with external or exotic systems, flow control and ultra-fast real time constraint) have to be offered. For the evolution of the control systems, the cryogenic group preference, is to remain as compatible as possible with its present implementation and follow the state-of-the-art. Then, many components or services will have to be developed and maintained by the appropriate entities: IT department, controls groups. The plan is to collaborate as much as possible to develop the most adapted solutions.

Architecture Evolution

Today the buzzwords for the future of industrial automation are Internet of Things (IoT) and Service Oriented Architecture (SOA). Internet of things applies to the devices/components found in the control system [11]. With IoT the control devices are no longer at the lowest level of the control pyramid but they are the node of interactions with several services across the levels such as presented in Fig. 5:

- Service-oriented automation : The application domain is the source of knowledge. Several techniques can be used to describe the available information (e.g. the use

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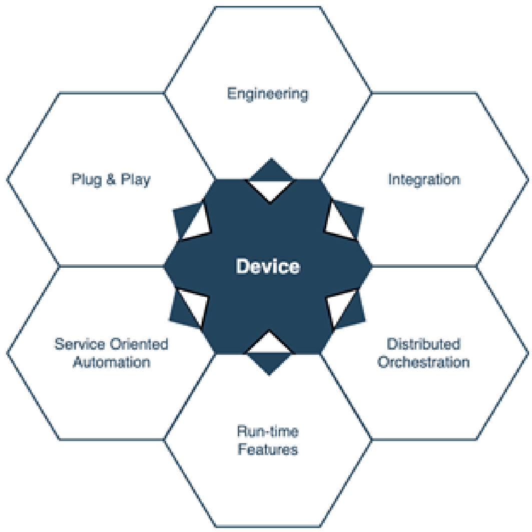

Figure 5: IoT Device model.

of semantics, ontology), besides the intrinsic capabilities provided by web service technologies to capture them in an automated way;

- Plug & play is the ability to connect devices to a network with minimal need of configuration as they are able to integrate themselves and will be ready to work. It uses dynamic discovery, dynamic configuration, uniform description of the device functions and use of standard interfaces;
- Engineering represents the methodologies and tools to make the controlled system run and behave in accordance to what is expected. Services engineering covers every aspect from the initial analysis phase to the operation & maintenance phase;
- Integration covers not only the integration of devices with others, but also their interaction with other levels (e.g., entire production systems, Business);
- Distributed orchestration, since the coordination of activities is not viewed in a central manner, the collaboration between separated units need the use of complex interactions such as orchestration and composition of control to achieve the global objectives.
- Run-time features: When the system is running, there is a continuous monitoring of several useful features to automatize the process to improve the maintenance and to take actions as soon as possible failures occur. The distinctive features are considered to be re-configurable, adaptable, intelligence, auto-sustainable.

In Service Oriented Architecture (Fig. 6), the hierarchical communication of the classical layered architecture, is replaced by a flat exchange of information. The services used in the process can be easily modified with a cross layer integration to improve the inter-operability. The embedded services incorporated in the system operate independently [12]. For this reason, adding or modifying new services and processes will become easier. As result, the process is no longer constrained in a specific platform, but it can be considered as a component of a wider process and therefore reused or modified.

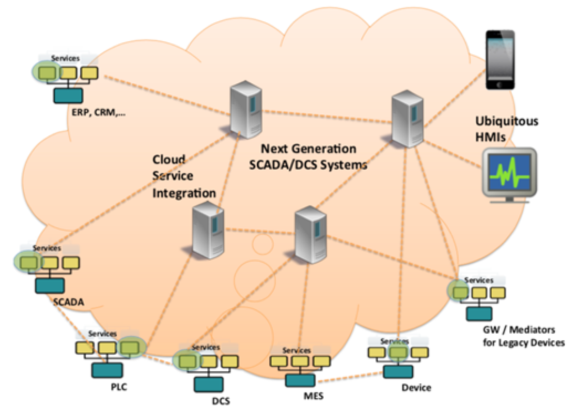

Figure 6: Next generation of industrial control system, service based, and flat information driven interaction [12].

Evolution of the Control Architecture

The transition to SOA technology has already been implemented in the highest layer of the enterprise system (CL) for many years. It is also used for the integration between CL and ML with solutions available on the market. The downward spread to SL, CL and IL is progressing today thanks to some initiatives such in Industry 4.0 and existing industrial protocols covering a large part of the necessary services such as OPC-UA (Fig. 7).

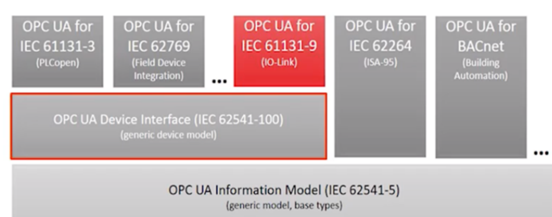

Figure 7: OPC-UA information model that can already be used as generic middleware for slow control systems.

To develop a SOA based control system, the Reference Architectural Model Industries 4.0 (RAMI 4.0) presented in Fig. 8 could be considered. The hierarchy level axis may integrate the accelerators and detectors equipment (field devices and control devices) with the system levels (connected world, enterprise, workcentre, station). Consequently, services, interfaces and integration guidelines shall be used to allow the aforementioned components to interact with the different functional levels (business, functional, information, communication, integration and asset). Ultimately, the life cycle management framework shall be used by the development process to span from concept over requirements, design, implementation/procurement, transition to operation, maintenance and retirement.

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This model is an ideal reference to establish the control and data acquisition architecture for an entire project, limiting internal project developments to the only parts that cannot be covered by existing products, services, standards and guidelines.

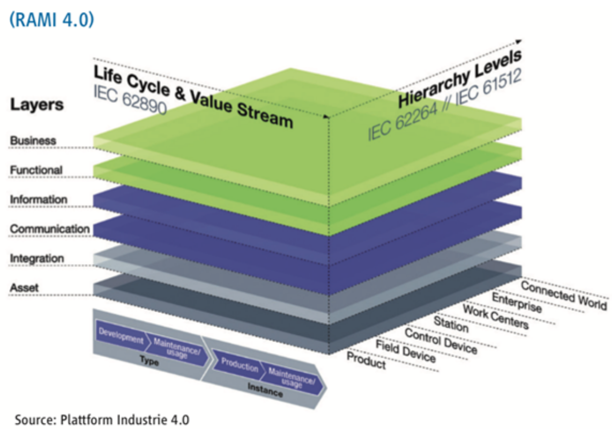

Figure 8: Reference Architectural Model Industrie 4.0.

Migration from the UCPC Cryogenic Control System

To adapt the cryogenic control layer to the SOA architecture, the following challenges must be faced [13]:

- One of the strengths of the cryogenic control architecture is the tight link between the HMI and the control execution with the operator's intervention restricted to the chosen devices. Hence, further break down of the hierarchy shall not affect the functional integration. In addition, the choice of an adapted middleware such as OPC-UA will offer additional features.
- Group the devices: Within a given system, it must be determined which device can be migrated to SOA as devices and which devices shall be grouped together and then migrated to SOA as a group.
- For process control execution the present architecture allows an excellent integration between devices if the expected behaviour by the process expert has been implemented. However, in case of unexpected event, adapted behaviour will have to be automatically initiated from the lowest level possible and propagated with automation services (such as OPC-UA for IEC61131.3).
- Preserve real-time control: The real time control execution, which, in the legacy system, is secured in the controllers, must be preserved [14]: As example, a subsystem using feedback and regulation might require legacy interfaces due to real-time needs. For such a group of devices the SOA interface will be implemented using a Mediator for the entire group and this part of the system will be handled as a black-box.

Hardware Evolution from High Luminosity LHC to Future Circular Collider (FCC)

Hardware for the cryogenic control systems should be able to support the software evolution towards IoT and SOA. At the low level of the pyramid, PLCs were the best choice for systems such as cryogenics, cooling, ventilation, vacuum, etc. because they are simple, with an efficient programming language, high level of availability and reliability. However, they lack the capabilities to run parallel equation solving algorithms or high level programming languages necessary to implement the IoT and SOA complex capabilities such as dynamic discovery and configuration adaption with process conditions typical of IoT devices or the interconnection of services (configuration, maintenance data exchange, etc.) necessary for SOA. Even though the features just mentioned can be obtained thanks the LHC Front End Computer (FEC), their reliability is not as high as that of the PLC. New solutions, such as the Beckoff Twincat PLC, must be investigated to obtain a product compatible with the new concepts with a very high reliability. Today the low-level devices used in cryogenic systems do not integrate complex capabilities such as dynamic discovery and configuration adaption with process conditions typical of IoT devices. However, some of IoT compatible devices already exist (such as IO-link compatible devices). In addition, Industrial Control Middleware such as OPC-UA proposes a mediator for the interconnection of services (configuration, maintenance data exchange, etc.). For the communication to the process interface at the lowest level of the pyramid, the main concerns are related to the electronic control components located inside the accelerator tunnel, due to the harsh conditions. For the FCC, a FLUKA model of the collider arc has been created. The results obtained, show increment factors of about 500 time compared to the LHC for the stochastic and the cumulative effect respectively. But the same model shows that shielded alcoves radiation levels are such that they can host electronics devices with a proper lifetime and with stochastic effects reduced to an acceptable rate. However, some electronic components will have to be implemented close to the accelerator. As a consequence, the major concerns of the cryogenic control system for this level, will be the data acquisition and the powering means between the sensors/actuators located in the vicinity of the beams and the processing/driving activities that will be in the alcoves. The FCC design report proposes to study the hardening of a cabled Ethernet based solution by applying the recommended "The FCC-hh Radiation Hardening Availability (RHA)", founded on a full-availability approach based on moving the processing tasks away from the equipment under control, introducing functionalities for self-diagnosis of failure, online hot swapping, remote control and remote handling.

A potential solution could be to use a CERN custom-made module, the Distributed I/O Tier (DI/OT). In this solution, a generic low cost customisable and reusable communication intermodule is deployed (see Fig. 9) to achieve the needed for radiation-exposed and radiation-free areas. This platform

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is based on compact PCI serial communication. It allows the designers to use standard elements and standard voltages. The hardware kit includes different interchangeable modules (”1” for radiation-exposed ares and ”2” for the free radiation areas) [15]:

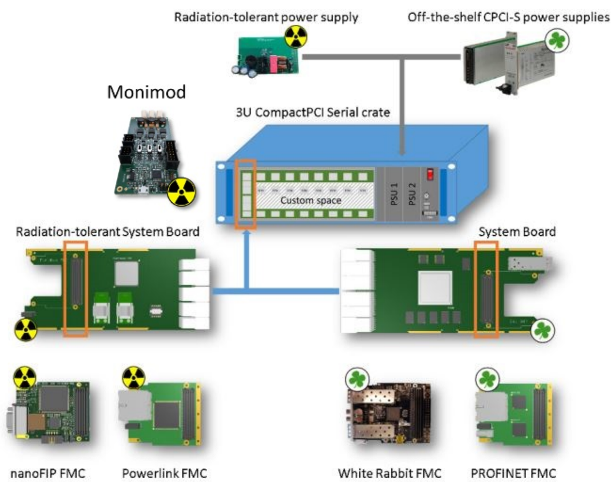

Figure 9: Distributed I/O Tier hardware [15].

- Power supply:
  - ”1” RaToPUS: hardened 100 W AC/DC switched mode power supply ;
  - ”2” Off-the-shelf CPCI-S power supply: 300 W switched-mode power supply.
- Monitoring module Monimod to monitor simple functionalities such as voltage, current, temperature or the control of an additional fan tray temperature and speed in radiation exposed area ;
- FPGA based system board with replaceable fieldbus communication mezzanines to allow different communication protocols:
  - ”1” WorldFIP and Ethernet-POWERLINK
  - ”2” White Rabbit and PROFINET

In addition, considering the burden (resources, planning and costs) faced by the LHC cabling campaigns for each LS, wireless communication and power supply from the alcoves to the sensors/actuators, would be an excellent solution. It has been proposed in the FCC week 2015 [16] and since then, two initiatives WADAPT [17] and The “Smart Diagnostics” from the FuSuMaTech project [18] have presented the same type of proposal based on 60 GHz wireless CMOS Chips including IoT features for the second one

Responsibility Sharing for Future Large Projects

For future projects, the sharing of responsibilities must be organized at the laboratory level. Hence, the CERN control community will be able to address the challenges proposed by the evolution of technologies. To achieve this goal the project need to profit of the experience at CERN labs or within successful control collaborations and last but not least to setup large collaboration frameworks for hardware and software.

CONCLUSION

The LHC cryogenic control is the result of years of experience with this highly demanding process that can induce very long accelerator downtime in case of failure. To achieve the present availability, an automated and continuously updated cryogenic process was considered and implemented thanks to a good synergy between the cryogenic group and the accelerator controls groups.

Today, the ongoing CERN HL-LHC upgrade project requests the cryogenic system to be more reliable, versatile, and still easy to implement. These goals will be achieved with the collaboration of a large part of CERN control community spread in at least 5 CERN departments.

This evolution must start with a serious consciousness of the experience within successful control collaborations (e.g. Tango, EPICS), the integration of versatile procedures and protocols in parallel with several open and active collaboration frameworks (for hardware and software parts). It will be crucial to set the right balance between open solutions, solutions based on open standards, off the shelf’s components and proprietary solutions. Special attention must be given to keep strategical domains under control, avoiding vendor lock-in issues and allowing a fair knowledge transfer between partners. This new architecture shall cover all the levels of the ancient control pyramid and offers all necessary services proposed by the SOA approach.

To integrate the presented technological breakthrough and not miss any technological rupture the CERN (infrastructures, accelerators systems, experimental physic, and the information technology) control community shall be included together with CERN research partners and partnership with the industry to federate the efforts. Our recommendation for the needed collaboration frameworks is to start as soon as possible (I.e., the hardened hardware components) with a strong management support.

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