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An innovative approach for the design of cryogenic electrical and process control systems at CERN: the cryogenic Continuous Integration project

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Abstract. Designing, building, commissioning, operating and maintaining multiple complex cryogenics process control systems involves many challenges. For several years, CERN has developed various solutions to help with the whole lifecycle of a cryogenic process control system. This has allowed the production of quality and highly reliable cryogenic control and electrical systems. This paper will present the use of these innovative and automated tools and their evolution; focusing in the first part on continuous integration practices applied to the production of Programmable Logic Controller (PLC) software. The second part will develop the practical applications for software upgrades implemented for the cryogenics processes of non-LHC detectors and test facilities at CERN. Finally, a detailed description of the approach to a standardized generation of electrical drawing for cryogenic systems will be presented along with concrete solutions already successfully implemented in operation.

1. Introduction

The European Organization for Nuclear Research (CERN) has achieved already two Physic Runs (several-years each) with its powerful, and complex particle accelerator, the Large Hadron Collider (LHC). The cryogenic control system of the LHC [1] is based on the highest technological standards and is capable of collecting information from instrumentation distributed over long distances, interacting with several process logics of thousand variables and loops, as well as communicating in different control layers with operators and on-call maintenance technicians. The CERN cryogenics control system architecture uses various CERN frameworks (including the UNIfied Industrial Control: UNICOS). An important step in improving the control system production has been the association of high-level continuous integration practice allowing for a more reliable and versatile process control system [2]. Recent improvements and applications of continuous integration practices for the development of cryogenics control systems will be showed by detailing the driving force in its approach for a high-level automation. This paper will then focus on the electrical layer, detailing a recently designed innovative approach to improve the electrical design phase dedicated to cryogenics process systems. Obtained results and some future possible improvements will be presented.

2. Continuous integration applied to Cryogenics PLC software development

2.1. What is continuous integration?
Continuous integration (CI) is a standard practice of software development where a project is built and tested with every change committed to a shared project's version control repository. The process is triggered by a new version on the repository, then an automated build script executes automatically all the necessary steps to build the new project, including testing of the new code. Finally, the CI provides a feedback mechanism to inform the user about the result of the process. CERN has applied this method successfully to the LHC tunnel cryogenics control system since 2015 allowing for efficient and reliable development, updates, and redeployment of PLC-based industrial applications [2]. Other benefits that this method provides is a better code quality by creating stable builds more frequently, reducing the time for code review by automatically testing the new modifications, and increasing transparency and visibility by the creation of reports. Usage of CI for PLC applications also means that all the process logic is implemented in Python templates directly in the control framework to guarantee a complete software generation after the continuous integration process. Usage of templates enables us to share and duplicate similar process logics or calculations to multiple applications in an easy and efficient manner.

2.2. Need of CI for cryogenics PLC software development
The lifecycle of a control system in general involves many updates and modifications whether a project is in development or in production. Looking at recent cryogenics control system development at CERN (i.e. new helium liquefier plant in the CERN's SM18 test benches facility), 3 to 5 deployments of the PLC software with significant process modifications are necessary to produce an operational plant well integrated into CERN infrastructure.

On the other hand, maintenance of the LHC tunnel cryogenics control system is done almost yearly to take into account process improvements [3], mandatory commercial software upgrades or patches for detected bugs. Other applications usually need major updates every 2 to 3 years due to cryogenics process optimizations, control framework evolutions or electrical cabinet refurbishments.

Using CI in all of those situations allows for a quick and consistent update of whole control systems even with major process logic modifications. Therefore, in recent years, CERN has applied the IT tools and CI expertise created for the LHC tunnel control system to other cryogenics applications for non-LHC cryogenics System and LHC detectors. While those systems do not have the repetition inherent to the LHC Tunnel control system, the introduction of CI has been very beneficial to deal with the various needed modifications and has allowed the release of numerous operational control systems. Across LHC tunnel, LHC detectors and Non LHC, more than 80% of our cryogenics applications are now managed with Continuous Integration (Figure 1).

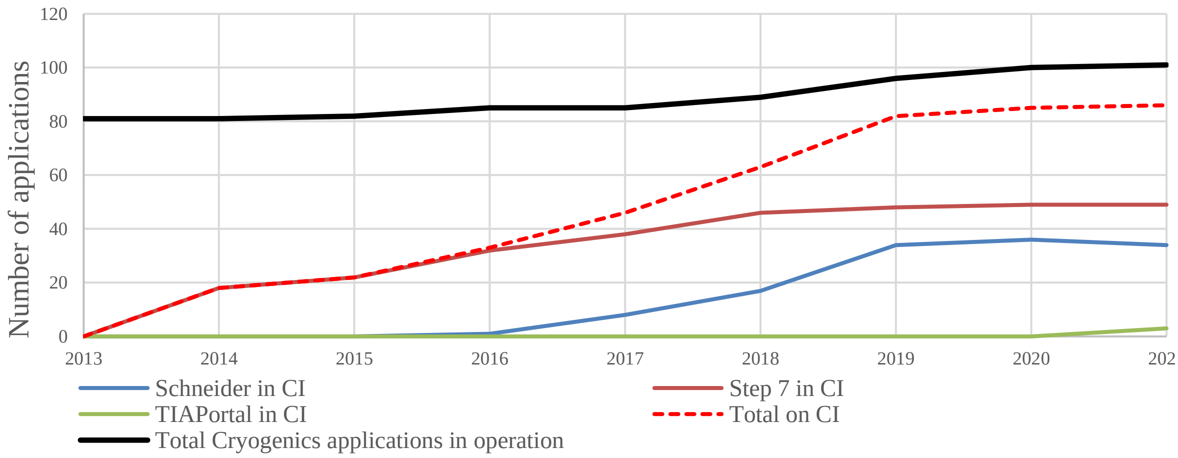

Figure 1: Cryogenics PLC summary (LHC cryoplants excluded)

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2.3. Continuous integration: concrete applications

CI has been particularly helpful in the recent cryogenics process update of the magnet horizontal test benches at the main cryogenics test facility at CERN (SM18). Those 10 identical test benches were used to test the ~1800 superconducting LHC magnets [4]. Due to the new constraint of a strict temperature gradient control during the HL-LHC Nb3Sn magnet cooldown and warm up, the proven cryogenics control process previously developed for HFM and Cluster D test benches [5] was quickly adapted and deployed on selected benches. CI also made it possible to cope with the urgent request for many additional instruments added to closely monitor the cooldown of the magnet halving development time.

Another good example of the benefit of CI is the recent updates of 8 older helium cryoplants used mainly to cooldown CERN non LHC detectors that were previously controlled with an obsolete version of the framework. With the use of CI, it was possible to quickly re-adapt the cryogenics control process to each of the plant specificities while keeping a similar and consistent operation.

Lastly, figure 1 shows an increase of about 25% in the number of applications supported by CERN cryogenics group in the last 8 years. This is mainly due to several projects such as the test facility for the FAIR magnets [6], Neutrino Platform [7], Cryolab refurbishment [8] and CERN main test benches facility infrastructure upgrade [9]. Such a substantial increase is managed with constant manpower mainly thanks to all the tasks that are automatically handled with continuous integration.

3. Electrical diagram generation

Electrical diagram is a critical element of a control system, essential to insure flawless commissioning, easy fault diagnostics and an efficient maintenance campaign. For this reason, the CERN cryogenics electrical team has always put a lot of effort into the development and update of this documentation. Over the last years, the overall quality and clarity of our electrical diagrams has increased thanks to an important investment in the software environment (i), symbols (ii), general rules and organization (iii).

(i) Software environment and methods were cleaned up and developed to use all features given by the software: Use of cabinet layout for construction, correct affectation of types of wires, link symbols with actual manufacturer references to generate part lists for procurement.

(ii) The symbol library was upgraded to improve how objects are shown and wired

(iii) General rules and electrical diagram organization review: devices are now grouped by subset and not per type, follow Piping and Instrumentation Diagram (P&ID) numbering and every wire and component shall be drawn once and once only.

Generally, the conception of the electrical diagram is performed in manual way. A trained electrical designer uses the physical position of the devices to define the electrical architecture of the project (position, size and number of cabinets and field boxes) following usual standards. After this phase, a long manual process creates the electrical diagram itself to start the procurement and construction of the electrical equipment. This conception phase is repetitive, involves a lot of copy / paste and manual entry, and imposes tedious work to check the standard way of treating every specific device which could differ between designers and result in dissimilar electrical diagrams.

Standardization and acceleration of the conception process was possible with the concept of blocks (see figure 2). The user can define a block and duplicate it as many times as needed, bringing an object oriented approach to the electrical diagram. However, it was impractical to use due to the quantity of detailed information (called block parameters) such as equipment location, names, Input / Output numbering or links that needed to be manually modified by the technician.

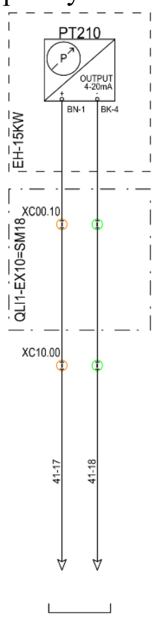

Figure 2: Block example : 4..20mA pressure sensor

3.1. Automatic diagram generation strategy

In view of an optimal utilisation of manpower, CERN has given itself an initial goal to generate a minimum of 50% of the final electrical diagram using high level IT tools. In order to succeed in its strategy CERN has recently acquired a newly introduced functionality of the software used for electrical design (called ADG), that allows a generation of the electrical diagram using the concept of blocks and filling all block parameters through an Microsoft Excel © file. Associating this tool with the standard methods of the electrical software, it is possible to generate most of the electrical diagram through an external file.

This functionality enables the application of the successful methodology used to develop the control system to the electrical drawing. The main drawback is that all block parameters must be manually enter in the file instead of in the electrical diagram software. This leads to the creation of the Cryogenics Automatic Electrical Diagram Generator (CAEDG) to solve this issue and automatically fill in the ADG import file.

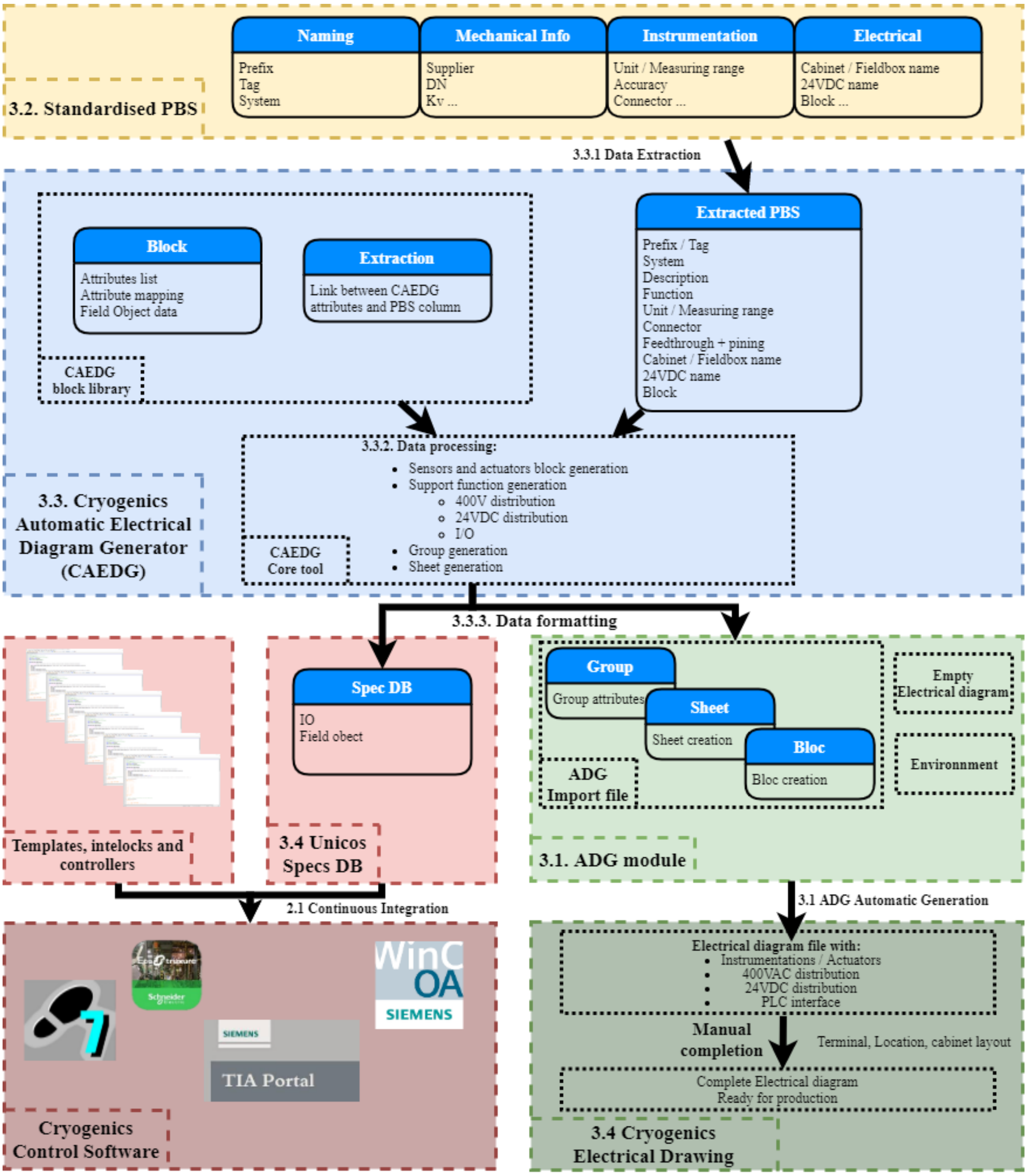

Figure 3: CAEDG workflow

Figure 3 describes the workflow for the generation of the cryogenics electrical diagram and control software. Numbers in the figure correspond to document subsections where the purpose of each block and the link between them is detailed.

3.2. Standardized Product Breakdown Structure (PBS)

In the definition of every project, a PBS is created and gathers all the technical detailed data about sensors and actuators (name, range, failsafe position, feed through definition etc.) around a cryogenic functionality. This Microsoft Excel © file is the main input for electrical designers to create the electrical drawing, consequently, CAEDG is designed to extract all relevant data from the PBS.

Of course, the PBS is strongly dependant on the life of the project and evolves during the mechanical conception. In the past, an early start of electrical design resulted in many modifications due to several input changes. A feature of CAEDG is to allow a faster electrical schema design conception, thus giving more time to the project team to consolidate the PBS before starting to design the electrical drawing.

3.3. Cryogenics Automatic Electrical Diagram Generator - CAEDG

The main task of the CAEDG is to interface the PBS and the ADG module. The concept behind this tool is to exploit a library of generic blocks at the device level (meaning valves, pressure sensors, etc.) that brings standardisation and capitalization of the know-how and good practices. CAEDG builds on the clear set of rules and our enhanced symbol library and environment to produce quality electrical diagrams.

If we compare with the control layer, one of the main complexities is that electrical equipment is highly heterogeneous. For example, an analog object in the control framework can be transcribed in the field layer as a control valve with Profibus, 4..20mA, needing an external power supply installed with different connectors and so on. At the control layer, this is either transparent or can be configured so one object is sufficient. However, for electrical diagrams the creation of a different object in the library is required as one needs a clear and complete description of the hardware in the electrical drawing. To solve this, the generation is based on a block library (called CAEDG block library) and its block parameter definition. Electrical designers can modify, adapt or add a block in the library if necessary. The configuration of each block is extracted during the generation process and therefore the addition or modification of a block does not require an update of CAEDG core.

3.3.1. Step 1: Data extraction. CAEDG opens the requested PBS and extracts all necessary columns. The extract is done based on a configuration inside the CAEDG block library. Consequently, column names can be adapted to fit within a specific PBS and are automatically selected.

3.3.2. Step 2: Data processing. At this step, data is treated in relation to block parameters and the PBS. CAEDG creates the sheets of the skeleton of the electrical diagram. This includes the main power supply, low and very low voltage power supplies and the IO interface blocks. All actuators and sensors are grouped by subset, ordered by P&ID number, and arranged on each sheet.

3.3.3. Step 3: Data formatting. Empty templates from the ADG file and Unicos Specs database are an input for the generator. Consequently, the last step is to format the data to fit with existing ADG and Unicos templates. This allows CAEDG to be independent from ADG and Unicos versions. After this last step, the generation of ADG module can be processed and can generate the electrical drawing.

3.4. Electrical diagram & Unicos Specs DB

After the ADG module generation, a manual completion is still required to check and finish the electrical drawing. A generic list of tasks is provided to designers to define the work to be performed in order to obtain an electrical drawing ready for the production of electrical cabinets.

As CAEDG manages PLC Input / Output configuration and all the device details, it can generate the first UNICOS Specs database that configures the control system. The software developer thus avoids manual data entry for input from either the PBS or the electrical diagram. The generator pre-fills data for every physical Input / Output object and every field object removing human errors in this process and efficiently linking the control system to the electrical diagram.

3.5. *Result*

CAEDG was used for the first time to generate the electrical diagram of the SM18 HL-LHC IT-String Proximity Cryogenics Distribution System (PCDS) currently under construction at CERN. This project was also used to evaluate the performance and efficiency of the workflow. Some new blocks had to be created but it was efficiently done using the CAEDG block library. The generation of the skeleton of the electrical diagram was performed satisfactorily and the ADG module proved to be very robust. In total, 56 sheets (Figure 4) were generated with around 60 Input / Output. This electrical diagram also includes Profibus DP, Profibus PA and Profinet slaves. It was estimated that around 70% of the electrical diagram was generated with CAEDG, hence reducing conception time by half.

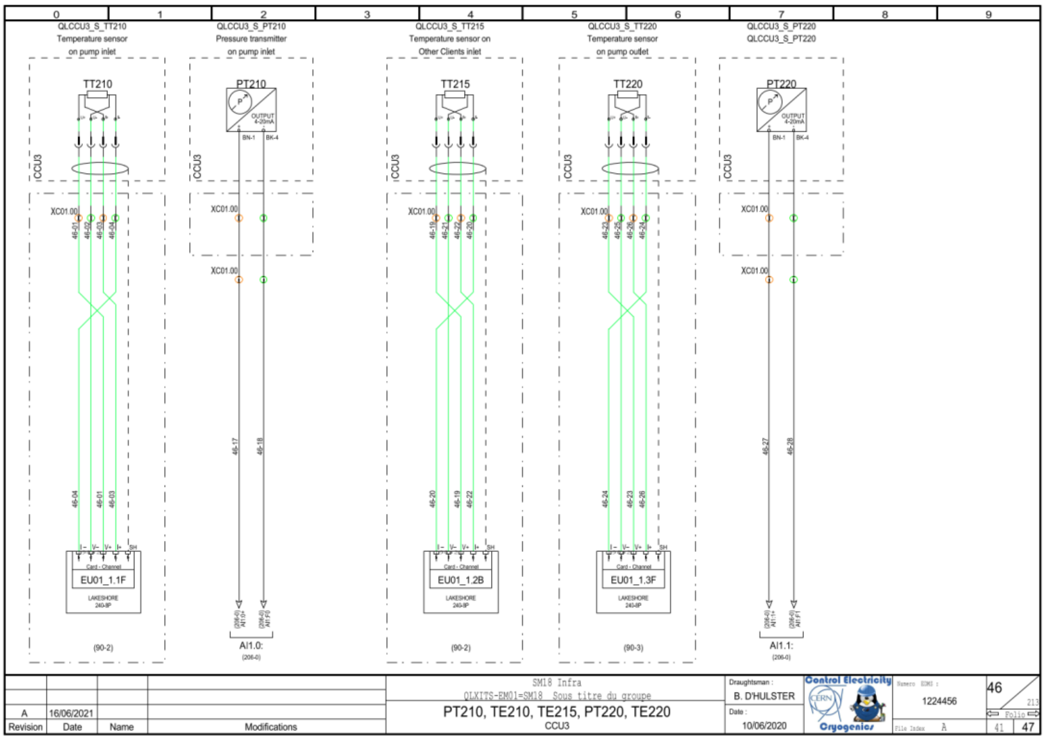

Figure 4: *CAEDG* sheet

3.6. *Evolution*

The tool developed is a proof of concept that already sped up electrical diagram conception for the SM18 HL-LHC PCDS project and the Super Conducting Link test. After generation, some manual tasks still had to be performed to finish the electrical drawing. For example, CAEDG names the terminals but designers still need to number them manually. In the future we need to think about how much effort we want to put in this tool to increase or not the proportion of generated diagrams.

For now CAEDG only generates "simple" electrical architecture, i.e. only one main cabinet with the PLC and several field boxes on the field. It is not yet suited to more complex architecture with remote input/output architecture. A refactoring of the code to improve maintainability and an improvement of the succinct existing user interface could also be necessary.

CAEDG is a Microsoft Excel VBA © macro as it was easier to develop and maintain. An evolution could lead to a development of this as a Python or Java application with an improved User Interface.

4. Conclusion

At the control layer, many tools and the expertise acquired by the CERN cryogenics team during the LHC Tunnel control process development, were applied to other plants and systems across CERN. This has allowed us to deal with the ongoing development of several new projects and deploy many major process updates while providing reliable and consistent cryogenics control systems.

At the field level, recent improvements with the development of CAEDG are paving the way for a faster and more standardized design of cryogenics electrical diagrams. This brings confidence to our ability to streamline new developments and to cope with future challenges while maintaining high quality equipment and documentation.

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