

THE EVOLUTION OF THE CONTROL SYSTEM FOR THE ELECTROMAGNETIC CALORIMETER OF THE COMPACT MUON SOLENOID EXPERIMENT AT THE LARGE HADRON COLLIDER*

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Abstract

This paper discusses the evolution of the Detector Control System (DCS) designed and implemented for the Electromagnetic Calorimeter (ECAL) of the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC) as well as the operational experience acquired during the LHC physics data taking periods of 2010 and 2011. The current implementation in terms of functionality and planned hardware upgrades are presented. Furthermore, a project for reducing the long-term software maintenance, including a year-long detailed analysis of the existing applications, is put forward and the current outcomes which have informed the design decisions for the next CMS ECAL DCS software generation are described. The main goals for the new version are to minimize external dependencies enabling smooth migration to new hardware and software platforms and to maintain the existing functionality whilst substantially reducing support and maintenance effort through homogenization, simplification and standardization of the control system software.

INTRODUCTION

The CMS ECAL DCS monitors the environmental conditions and provides control and supervision over the powering systems of the ECAL detector which forms part of the CMS experiment at CERN. The ECAL detector consists of three partitions: Barrel, Endcaps and Preshower. In total, the system comprises 972 temperature sensors, 180 humidity probes and it provides control of over 1400 bias voltage and 1000 low voltage channels. The details of the control system architecture and the operating status have been reported previously [1,2].

The CMS ECAL DCS software is built upon the supervisory control software called WinCC Open Architecture (WinCC OA) [3], formerly Prozess Visualisierung und Steuerungs System (PVSS), from ETM professional control. The CERN developed JCOP (Joint Controls Project) Framework [4] provides extensions to WinCC OA for the high energy physics domain and was used to facilitate the development process. The system was built over a period of more than seven years. During that time, there have been contributions from nine software developers and four hardware developers.

The CMS ECAL DCS models each piece of hardware as a separate device object. Using the JCOP Framework, the devices are organised in hierarchies, which provide views of the system in terms of off-detector hardware

layout or on-detector location. One particular hierarchy includes a Finite State Machine (FSM) implemented with SMI++ [5] which provides a way to summarise the state of the whole detector and to disseminate high level actions such as power switching. The FSM is also used to sequence actions and to perform automatic protection actions when conditions of the detector deviate from the normal range.

The JCOP Framework provides several other useful features, including a Configuration Database (ConfigDB) which is used to store details of the device configuration and of groups of hardware settings, known as recipes. These features were used in parts of the control system and the application of this tool is being extended throughout the system.

The CMS ECAL DCS runs on 14 computers with all WinCC OA applications being linked together in a distributed system. The CMS ECAL DCS is integrated into the CMS DCS [6], which aggregates all sub-detector control systems.

EXPERIENCE FROM LHC DATA TAKING

Throughout the 2010 LHC data taking period and so far during 2011, the CMS ECAL DCS has shown high levels of availability and has proven to be capable of taking protective actions based on anticipated safety hazards. A 24/7 expert on-call service has ensured that requests for actions on the detector and fixing of problems are carried out promptly. All of these factors have contributed to a high level of readiness for data taking.

Statistics from October 2010 to August 2011 from CMS DCS indicate that the ECAL had a readiness of 97.8% during periods when LHC was delivering stable colliding beams. These data represent a combination of all services such as the DCS, the bias voltage, the low voltage and cooling. The predominant factors contributing to the 2.2% of non-ready time include failures of power supplies and problems with external infrastructure such as delivery of chilled water. The DCS itself was responsible for almost no downtime.

Outside LHC data taking periods, the CMS ECAL DCS continues to monitor the conditions of the detector and enables parts of the detector to be powered on and off as required. This means that the control system software must be available all of the time. Experience shows that the DCS applications have high availability and that most down time is due to planned software upgrades as well as planned and unplanned cuts of power to the DCS computers. In 2010, there was a period of degradation in a temperature monitoring system that forms part of the

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DCS. This was due to a single fault in the power distribution that meant that all temperature probes from one of the monitoring systems could not be read out. Work to overcome this issue is ongoing and will be discussed in the next section.

Records have been kept of the activity of the on-call service for a period of more than 12 months. The on-call activities are two-fold; detector operation during development phases and fast trouble shooting in LHC data taking periods. The data show that the frequency of trouble shooting requests has considerably dropped in the past year. This demonstrates that the software improvements, based on the feedback from the operators, combined with an increase in overall operating experience have lead to a smoother operation of the ECAL detector.

HARDWARE UPGRADES

Changes to the hardware were performed during 2011 in order to further improve the control system robustness as well as to lower its recovery time in case of faults.

The first change was a modernisation of the Controller Area Network (CAN) bus [7] interfaces. PCI-based CAN cards installed in the DCS computers have been replaced by external USB-CAN interfaces from SYS TEC Electronic GmbH [8]. These allow readout of CAN based devices via USB ports and this will save time if a faulty CAN-equipped computer needs to be replaced because there will be no need to transfer the PCI card between machines. Instead, the only step required is to connect the USB-CAN interface box and install the necessary drivers. A software library [9] from the CERN Industrial Controls & Electronics (ICE) group enabled a transparent migration between PCI-CAN and USB-CAN interfaces.

From the experience in 2010 with the fault in the temperature monitoring system, it was decided that the power distribution for this system should be improved. This involved sourcing new power supplies and constructing new power distribution blocks that allow individual switching of power to each CAN-based readout device. The system was divided into two independent parts, limiting the impact of a single fault and allowing independent power interlocks.

Further upgrades are under development. One of them aims to provide relative humidity measurements below 60% using the installed humidity probes, which is presently not possible. This system will use custom readout electronics communicating with WinCC OA via Modbus [10]. The system is being developed and manufactured at the University of Belgrade, Serbia. The Modbus data channel will be converted to Modbus TCP with a Modbus RTU-TCP adapter such that the data can be read via the standard CMS Ethernet network.

Finally, an upgrade of the Preshower bias voltage distribution system is foreseen. In the Preshower, each power supply bias voltage channel is distributed to multiple detector elements. The extension presently developed will provide greater granularity for the monitoring of currents drawn by the Preshower detector elements. While not solely a DCS issue, this additional

monitoring system will require both software and hardware changes by the CMS ECAL DCS team.

SOFTWARE ANALYSIS PROJECT

Due to a reduction in the number of people working on the CMS ECAL DCS project after CMS commissioning it was essential to focus on the long term maintainability of the system.

The system functionality can be divided into monitoring applications and combined monitoring and control applications. These applications were originally assigned to individuals who then developed the software to achieve the control and monitoring goals of that application. This approach enabled the system to be delivered on time and with sufficient functionality to operate the detector.

In the current phase of the project the approach is different, with a central team of three developers being responsible for the whole DCS. This has required a large shift of information from the original developers to this new core team. During the process of centralising the detailed information about the software, certain aspects were identified that could be improved upon or standardised between applications.

As the software met all the operational requirements, the team was able to concentrate efforts on investigating ways to streamline and standardise the software. This led to the creation of the CMS ECAL DCS Software Analysis Project which took place throughout 2010. The goals of the project were to evaluate the existing software and identify ways in which the support and maintenance load over the next years of LHC operation could be reduced. This involved discovering potential simplifications, identifying areas of weakness and revisiting the original design assumptions that were embedded in the code during the original development. As the control system must run for several years, it is unavoidable that its operating environment will change. For example, operating system versions and WinCC OA versions will continue to evolve. Plans are already in place to upgrade the computers with considerably different hardware. So the analysis project considered the preparedness of the software to handle transitions such as these.

The analysis project delivered a detailed investigation of each application. This consisted of both static code analysis and dynamic analysis of the running application. The following aspects were evaluated:

- Security.
- Use of JCOP Framework and CMS DCS tools.
- Efficiency of architecture and implementation.
- Dependencies on software versions.
- Interfaces to external systems.
- FSM logic and hierarchy.
- User interface functionality and look and feel.

As an additional benefit, the analysis project produced detailed written documentation of the internal workings of the system. Previously, the documentation was focussed more on operating the software rather than how to

maintain it. As the original developers began to leave the project, detailed maintenance documentation became a high priority.

The final stage of the system analysis was the summarising and integration of the individual application analyses. This stage provided particularly good findings regarding features that could be factored out and made into generic components. Also, the compatibility amongst applications was studied to evaluate the feasibility of running multiple applications on the same machine. This would enable the number of computers to be reduced and allow more efficient use of the new generation of powerful computers.

SOFTWARE ANALYSIS OUTCOMES

Results

The process of analysing the software was successfully completed by October 2010.

The metric of lines of code (LOC) is useful to indicate the effort required to understand and maintain a code base in the long term. The total LOC of the CMS ECAL DCS is 200,000. The code required for installation and core monitoring and control functionality accounts for 40,000 LOC. The remaining 160,000 LOC are dedicated to user interface code and graphical widget configuration.

The FSM was analysed and found to have around 4,000 low-level objects to model hardware devices. There were an additional 1,000 high-level objects that summarise the device data into a hierarchical structure. A total of 61 object classes are used to instantiate all 5,000 FSM objects. It was found that a reduction in the number of classes could be achieved by combining similar classes.

The analysis detected several bugs, highlighted some deficiencies in functionality and discovered security issues that had not been identified from the experience of using the software in the CMS environment. One particular area of concern was the installation process, which ideally should be fully automatic, but in many cases was seen to fail certain steps or require additional manual configuration after installation.

In terms of consistency between components, it was noticeable that each application was developed by a different developer. Where common interfaces were required between applications, these interfaces had been defined and adhered to. Internally, architectural concepts, naming conventions, coding styles and the amount of use of the JCOP Framework varied between applications.

Planning

With the qualitative and quantitative results of the software analysis, it was possible to take informed decisions about how to reduce the maintenance effort of the system. Due to the proven stability of the existing software, it was essential that any plan for developments should not compromise the current reliability. On the other hand, there were several changes that could clearly provide benefits by reducing the complexity and heterogeneity of the software.

Two possible strategies were considered for the renewal of the CMS ECAL DCS applications. The first was to take a radical approach and re-write complete or significant parts of the existing applications. The alternative strategy was to focus on specific elements of the applications and to substitute relatively small functional blocks with newly improved elements. The former approach offered the possibility to start from scratch and re-develop a system with the advantage of the considerable knowledge acquired in the development of the existing software version. The latter piece-by-piece method provided a more cautious way to target specific problematic areas while preserving the remaining structure and code of the application.

A decision was taken to follow the piece-by-piece approach to resolve a series of issues throughout 2011. This strategy minimized the risks of altering the source code while still providing a way to significantly improve the software. With this approach, goals such as the global standardisation of function names and data object names are immediately out of scope as these would require a complete overhaul of the software. However, the benefits of a broad code cleanup did not outweigh the risks, so it was decided to keep the majority of the existing code, including its known imperfections.

The piece-by-piece approach made it possible to deploy the improvements into the production environment with minimal delay. The LHC has regular technical stops throughout the year, roughly every two months, providing opportunities to update systems without compromising LHC data taking. A laboratory setup was available for testing and validation of the software. This setup has recently been upgraded to include a computer of the new type foreseen to be introduced in CMS DCS, enabling realistic performance tests to be undertaken.

The analysis project highlighted areas in the user interface where improvements or standardisations could be made. However, operators are used to the existing screens, so only a small set of important changes were put in the software development plan.

MAJOR DEVELOPMENTS

Essential Modifications

The first priority in terms of development was to fix the security issues. These were resolved by following the CERN security team guidance [11].

The second priority of development was to ensure that the applications of CMS ECAL DCS could be installed with a completely unattended process. This is important to reduce downtime that occurs when a computer fails and the application has to be installed on a new computer. As a short term measure, work was done to improve the existing installation procedures for each application. These changes were tested in December 2010 during a long shutdown of CMS where a complete re-installation of the CMS ECAL DCS software was performed. The results showed that the installations could be completed

with almost no user interaction, although some work remained to achieve a completely unattended installation.

Configuration Database

In early 2011, emphasis was placed on moving hardware and software configuration data and hardware setting recipes into the ConfigDB. Some applications used the ConfigDB previously, but none made use of the full range of possibilities available.

One desirable feature was the facility to apply and verify hardware settings each time before switching on the low voltage and bias voltage channels. This approach ensures that all settings are correct before switching on the voltages and was previously available in the low voltage application only. In order to deploy this functionality across the whole CMS ECAL DCS, a new generic component was written that was capable of interacting with the FSM and the ConfigDB to apply recipes on demand and then verify that these have been correctly applied. In addition, the software checks to see if there is any spontaneous change of hardware settings that deviate from the stored recipe values. This component was based on development already undertaken by the CMS Tracker DCS team [12], which in turn was inspired by a tool provided by JCOP. A new generic component was designed and implemented for the CMS ECAL DCS with a view to it being used elsewhere in the CMS DCS. This component was first deployed in the CMS DCS in April 2011 and the component was integrated into all the CMS ECAL DCS applications that control low voltage and bias voltage power supplies.

Installation Mechanism

The installation procedures of the individual CMS ECAL DCS applications were all developed individually and although they all performed similar steps, the approaches were very different. From the analysis of the installation procedures, it was noted that there was a considerable mixing of code and data. As a result, each application was tuned to perform the required installation but the code to execute these steps was not generic. Based on the work performed to concentrate the configuration data in the ConfigDB, there was an opportunity to standardise and streamline the installation process.

A new data driven installation method was developed, where a single generic installation mechanism can install any application. To achieve this, a custom data object was defined that contains the data required to drive the installation process. A common piece of code interprets this data at installation time to perform all the necessary steps to setup the system. The first unattended application installation using this method was in July 2011.

SOFTWARE STATUS

The changes in the CMS ECAL DCS software so far have yielded a reduction of around 20% in the number of lines of code, when excluding the user interface. This equates to around 8,000 lines of code and has been achieved with no loss of functionality. In fact additional

functionality has been added including a new application displaying the status of equipment racks.

Further developments are planned to factor out common functionality and reduce the overall software complexity. An associated reduction in LOC is anticipated. Particularly in light of the upcoming hardware changes to some CMS ECAL DCS monitoring applications, the option to make a more radical redevelopment of certain applications will be reassessed.

Changes to some applications are required to ensure that multiple applications can run together on a single computer. Performance tests are also required to test that such combinations are feasible.

CONCLUSIONS

Experience from 2010 and 2011 shows that the CMS ECAL DCS meets the required standards and has matured into an extremely reliable system. Changes have been made to the software and hardware to ensure reliability of operation and reduction of the maintenance load. The changes were implemented in a piece-by-piece way to minimize the risk associated with modifying a working system. This strategy also enabled deployment during regular technical stops of the LHC. The control system now has greater functionality even though the code base of the project has been significantly reduced. As a result of changes to both the hardware and software, the system is more robust for LHC data taking periods and better prepared for future hardware and software changes.

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