# MAINTAINING AN EFFECTIVE AND EFFICIENT CONTROL SYSTEM FOR THE ELECTROMAGNETIC CALORIMETER OF THE COMPACT MUON SOLENOID EXPERIMENT DURING LONG-TERM OPERATIONS OF CERN'S LARGE HADRON COLLIDER*

O. Holme, D. Di Calafiori, G. Dissertori, W. Lustermann, ETH Zurich, Switzerland
S. Zelepoukine, ETH Zurich, Switzerland and University of Wisconsin-Madison, U.S.A.

*Abstract*

The sub-detectors of the Compact Muon Solenoid (CMS) multi-purpose particle detector at the CERN Large Hadron Collider (LHC) have been collecting physics data from particle collisions for almost three years. During this period, the CMS Electromagnetic Calorimeter (ECAL) Detector Control System (DCS) has contributed to the high level of availability of the experiment. This paper presents the current architecture of this distributed and heterogeneous control system alongside plans and developments for future improvements. To ensure that the system can efficiently operate and adapt to changes throughout the required operation lifetime of more than a decade, the potential legacy aspects of this kind of control system must be carefully managed. Such issues include evolving system requirements, turnover of staff members, potential benefits from new technologies and the need to follow release schedules of external software dependencies. The techniques and results of the work to continually maintain, improve and streamline the control system are presented, including the use of metrics to evaluate the impact of this effort.

## INTRODUCTION

The CMS ECAL consists of three partitions: the barrel (EB), the endcaps (EE) and the preshower (ES). The EB and EE are based on lead tungstate scintillator crystals, with the generated light being measured by Avalanche Photo Diodes (APDs) and Vacuum Photo Triodes (VPTs) respectively. The ES uses reversed biased silicon sensors as the detection devices. The differing technologies of the three partitions imply specific control system needs; however there are common features such as the requirement for low voltage (LV) to power the data acquisition (DAQ) electronics and bias voltage (BV) to bias the particular type of sensor. All CMS ECAL partitions are vulnerable to overheating and require constant cooling during operation. Additionally, the humidity level of the air in the detector can provide further important information. For these reasons, the cooling systems and environmental conditions inside each of the partitions must be carefully monitored.

The prevention of damage to the detector is delegated to Programmable Logic Controller (PLC) based safety systems [1], which monitor detector conditions and can act by interlocking the powering devices and the cooling systems. The DCS monitors the same data as used by the safety PLCs and can take pre-emptive actions before safety actions would be required. Importantly, this enables less abrupt actions to be performed, reducing risks of hardware damage and in some cases speeding up recovery to a fully operational state.

## ARCHITECTURE

The CMS ECAL DCS consists of both software and hardware elements. The architecture was implemented with existing designs and technology where possible, either from commercial vendors or from high energy physics collaborations. This approach accelerated and simplified the implementation and continues to have a positive impact on the maintenance load of the system.

The role of the hardware is to host the software and to gather or send the data required to operate and monitor the detector. Currently one DELL PE2950 and 14 DELL PE1950 servers running Windows XP are used to execute the DCS software. The readout of data is performed using Ethernet and Controller Area Network (CAN) bus, according to the supported interfaces of existing hardware. In order to connect the CAN buses with the server PCs a suitable interfacing device must be chosen, with the existing solution being a CAN to USB adapter.

The BV and LV power supplies used in the CMS ECAL DCS are provided by commercial vendors together with Open Platform Communications Data Access (OPC DA) servers for monitoring and controlling the devices. The safety systems are based on Siemens PLCs and the standard S7 readout over Ethernet is used. For the remaining monitoring systems, custom electronics have been developed to read out several types of sensor inside the detector, such as the negative temperature coefficient (NTC) probes used to precisely monitor the EB and EE environmental temperature. Where possible, development of completely custom electronics was avoided by making use of the Embedded Local Monitor Board (ELMB) [2] which is an input/output electronics board equipped with a CAN transceiver. Use of the ELMB enabled a considerable simplification in the DCS electronics design.

The software layer is used to combine data from all the sources and handle it according to the requirements. This data handling includes:

- Filtering and smoothing.
- Archiving.
- Generating alarms on abnormal conditions.
- Visualisation of the data in user interfaces panels, including graphical representations and plots.

*Work supported by the Swiss National Science Foundation

ISBN 978-3-95450-124-3

The software is built with the commercial Supervisory Control and Data Acquisition (SCADA) toolkit called Simatic WinCC Open Architecture (WinCC OA) 3.8 SP2 developed by ETM Professional Control [3]. In addition, a framework of tools, called the Joint COntrols Project FrameWork (JCOP FW) [4] and developed by CERN in collaboration with LHC experiments, was used to assist the development with WinCC OA in the high-energy physics domain.

The CMS ECAL DCS software is divided into several applications, with each focussed primarily on one system or device type. For example, separate applications are provided for interacting with the BV, LV, safety system PLCs and the cooling system. This concept of modular applications enables parts of the DCS to be developed independently, giving flexibility in allocation of tasks to developers as well as simplifying the testing procedures.

## CONSOLIDATION PHASE

The CMS ECAL DCS was developed over several years in parallel with detector construction activities. Early prototypes were essential for testing all detector components before installation in CMS and experience from these prototypes was incorporated into later versions. Due to the length of the development period and the fact that several of the team members were involved for only short periods, there was a large turnover of developers. As the project moved from a development to maintenance phase when the LHC started physics operations in 2009, the number of developers was reduced, leading to a significant support load that had to be lessened in order to be sustainable in the long term.

The applications, developed in parallel by different developers, had evolved to varying levels of maturity and were based on distinct programming styles and development philosophies. As a result, it was apparent that a phase of consolidation could produce a more homogenous, higher quality software that was simpler to maintain and more robust to failure while still providing the same level of functionality.

The consolidation of the software was initiated by a software analysis project [5], aimed at homogenising the application implementations, factoring out common functionality into reusable modules and removing features that were no longer relevant. This process yielded a significantly smaller code base with considerably fewer differences in design and development style between the individual applications of the ECAL DCS.

The control system requirements continue to develop and grow with time as the system is methodically improved in response to operational experience. For this reason, there is continual development of new software and measures had to be put into place to ensure that these new developments did not counteract the gains made with the software consolidation. To achieve this, a continuous quality assessment methodology was introduced with the code quality regularly being measured in terms of specified metrics.

### *Code Quality Assessment*

The tool chosen to perform this evaluation was the Continuous Quality Assessment Toolkit (ConQAT) [6]. ConQAT analyses code against defined metrics and produces visual representations of the results, making it easy for developers to identify and resolve issues where code does not meet the required standards. A new component was developed by the CMS ECAL DCS team to enable ConQAT to assess software developed with WinCC OA and the JCOP FW. As an additional benefit of this integration between ConQAT and WinCC OA, it became possible to precisely quantify the DCS software in terms of physical source lines of code (SLOC).

The following metrics were chosen to assess the quality of the code and indicate areas to improve:

- SLOC in segments of code that are duplicated.
- Functions exceeding a given number of source lines.
- Files with code block nesting level over a threshold.

The acceptable thresholds to determine these values were initially chosen based on the existing state of the code in order to ensure that a significant, but not overwhelming, number of potential improvements would be identified. As the code quality improved, the thresholds were adjusted to be more demanding and to continue to drive the improvement in code quality.

Using the latest thresholds, it is possible to reanalyse previous software versions stored in the CMS ECAL DCS Subversion software repository to chart the software quantity and quality over time, as shown in Table 1.

Table 1: Evolution of ECAL DCS Code Metrics with Time

| Metric | January 2011 | October 2011 | April 2012 | October 2012 |
|---|---|---|---|---|
| Total SLOC | 67,532 | 59,665 | 39,044 | 37,124 |
| Duplicated SLOC | 31,237 | 26,328 | 7,386 | 6,623 |
| Long functions | 183 | 127 | 81 | 54 |
| Files with high nested block level | 40 | 33 | 25 | 18 |

It is interesting to observe that before the introduction of ConQAT in November 2011, a significant reduction in code quantity and duplication had occurred, which was due to the consolidation of the code based on manual inspection. However, a large amount of duplicated code had not been detected and ConQAT enabled the discovery, visualisation and resolution of these issues.

The process of improving the code quality is an ongoing task that is performed in parallel to maintenance, operation and development work. While removing duplicated segments of code, it was noted several times that bugs had been fixed in one place in the code but not in a duplicated segment elsewhere in the software. This type of issue highlights the importance of the continuous

ISBN 978-3-95450-124-3

quality approach in reducing the number of bugs and making the code easier to maintain in the future.

## CHANGING REQUIREMENTS

During the operation of the CMS ECAL DCS, there has been significant learning about the behaviour of the detector. This knowledge has been used to extend the control system to get further knowledge of the detector characteristics and to enable easier operation. For instance, more detailed monitoring of the EE and ES BV distribution has been added since the start of LHC operations. Additionally, the original humidity monitoring of the EB and EE is being upgraded to improve the readout range.

This evolution of the DCS scope is a significant driver for change and has to be carefully managed to ensure that the system remains maintainable. The approach to deal with this is to encourage the reuse of known hardware technologies and to adopt communication protocols that are supported by WinCC OA as standard. By enforcing this strategy, the CMS ECAL DCS team can extend the functionality while making maximum benefit of existing knowledge and ensuring that the system does not become increasingly heterogeneous and difficult to support.

As an example, ELMBs, which were already used in the EB and EE temperature monitoring, were chosen for the BV distribution monitoring systems. However, for the improved humidity readout hardware, a fully custom electronic front end was necessary. To make sure that the software could easily access this system, the standard MODBUS protocol was specified, as this is supported by WinCC OA and could easily be implemented on the microcontroller in the front end electronics.

## NEW TECHNOLOGIES

A major challenge in 2012 has been to prepare for the next generation of computers, selected by CMS, to host the DCS. Due to the significant increase in memory and processing power of these DELL M610 blade servers, it will be possible to run the complete CMS ECAL DCS on four machines. The new computers will run Windows 7 and it is anticipated that a new version of WinCC OA will be adopted in the near future. These software upgrades are essential in order to avoid running with commercial software versions that are no longer supported.

In addition to the obvious need for testing and revalidation associated with the new hardware and software platform, this change also requires the merging of applications onto fewer machines. In turn, this requires that the applications are compatible to run side-by-side with each other. This was not a requirement in the past development of the software and investigations exposed several incompatibilities, mostly relating to object name clashes, which had to be resolved.

Another significant improvement planned for the CMS DCS is the move to a redundant WinCC OA configuration where each application runs simultaneously on two machines. With two running instances, a failure of a single host PC will no longer degrade functionality. The most significant impact of this new technology is that all DCS data communication must be via Ethernet so that either of the redundant instances can access all devices when required. This has a particular impact on the current CAN bus interface, which is based on USB. Work is under way to evaluate a suitable interface that enables CAN readout via Ethernet [1].

To keep pace with the opportunities and challenges associated with new technologies, a policy of active research and development has been a priority in order to discover and resolve issues well before the planned deployment in CMS. A replica laboratory setup of the new computer platform has been purchased and configured to develop, test and certify future software versions and hardware interfaces. Previous experience has proven that this methodology minimises problems and downtime following new DCS component deployments.

## CONCLUSION

From the initial design phase of the CMS ECAL DCS, the system has made optimal use of pre-existing hardware implementations, software frameworks and commercial products. The success of this decision has been demonstrated by the excellent performance during more than four years of LHC operations. As new requirements emerge, the same approach is adopted to reuse existing technologies to take maximum benefit from experience and prevent increasing heterogeneity of the system.

To ensure the software remains maintainable, a continuous quality control approach has been implemented and the resolution of existing quality issues is a persistent background development task.

With these approaches and active research and development into new technologies, the maintenance load is controlled and the benefits of new technologies can be gained without compromising the robustness and effectiveness of the system.

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ISBN 978-3-95450-124-3