15 YEARS OF ALICE DCS

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Abstract

The ALICE experiment studies ultrarelativistic heavy-ion collisions at the Large Hadron Collider at CERN. Its Detector Control System (DCS) has been ensuring the experiment safety and stability of data collection since 2008. A small central team at CERN coordinated the developments with collaborating institutes and defined the operational principles and tools. Although the basic architecture of the system remains valid, it has had to adapt to the changes and evolution of its components.

The introduction of new detectors into ALICE has required the redesign of several parts of the system, especially the front-end electronics control, which triggered new developments.

Now, the DCS enters the domain of data acquisition, and the controls data is interleaved with the physics data stream, sharing the same optical links. The processing of conditions data has moved from batch collection at the end of data-taking to constant streaming. The growing complexity of the system has led to a big focus on the operator environment, with efforts to minimize the risk of human errors.

This presentation describes the evolution of the ALICE control system over the past 15 years and highlights the significant improvements made to its architecture. We discuss how the challenges of integrating components developed in tens of institutes worldwide have been mastered in ALICE.

THE ALICE DCS ARCHITECTURE

The ALICE Experiment

The ALICE experiment [1] involves the deployment of a massive detector system at the Large Hadron Collider (LHC), positioned approximately 65 meters beneath the Earth's surface. With dimensions measuring 15x15x20 m^3 and a total weight of 11,000 tons, it stands as a remarkable feat of engineering, posing formidable operational challenges.

ALICE has been designed as a modular device, comprising 15 subdetectors employing diverse technologies to cover the entire spectrum from solid-state silicon modules to gaseous detectors. The operation of these subdetectors is notably demanding, given the distinct operational conditions within the rigorous ALICE environment. For instance, the TPC field cage, housing 90 cubic meters of gas, must maintain a stable temperature of 20 degrees Celsius with a precision of 0.1 degrees Celsius, even in proximity to electronics modules emitting several kilowatts of thermal energy and adjacent to lead crystals held at -22 degrees Celsius.

The majority of ALICE's detectors are installed within a 9,000-ton solenoid magnet, necessitating their operation within a strong magnetic field. During LHC operations, the cavern housing ALICE remains sealed, with access for maintenance being granted only under exceptional circumstances.

ALICE Distributed Control System Architecture

The initiation of ALICE DCS traces back to 2008, coinciding with the first delivery of particle beams by the LHC to experimental setups. This milestone marked the conclusion of nearly seven years of preparatory work and testing [2]. Since then, an uninterrupted DCS service has been responsible for upholding the stability and safety of the detectors.

The current DCS architecture is a product of years of experience refined during its operational history. While it has adapted to evolving requirements, the fundamental architectural principles remain steadfast. The design places significant emphasis on the autonomous operation of system components, employs a rigorous hierarchical structure, and incorporates an intuitive user interface equipped with mechanisms to preempt human errors. These fundamental elements are complemented by extensive standardization across all control domains.

At the core of the DCS lies the WINCC OA SCADA system by Siemens [3], a configuration in line with other CERN experiments. It is extended through the JCOP framework, which offers customizations tailored to the CERN environment. Additional framework layers are developed by ALICE teams to introduce ALICE-specific extensions, including detector safety protocols, responses to beam conditions, and user interfaces, among others.

Control System

Each ALICE subdetector is designed as an autonomous unit, capable of independent operation within the DCS. To minimize interdependencies among detectors and to ensure the integrity of hardware modules, such as power supplies and crates, sharing is prohibited. An initial architectural decision was the subdivision of control systems into subsystems, wherein devices with similar functions were grouped and isolated from other subsystems. The specific requirements of various detectors led to physical distinctions among subsystems. For instance, the powering system necessitates finer granularity to differentiate between electronics power and detector power. This separation allows high-voltage power supplies to be located outside the experimental cavern, while low-voltage modules remain in proximity to the detectors to minimize electromagnetic noise generated by long power lines. This approach facilitates the deployment of cost-effective devices not designed to withstand strong magnetic fields or radiation and simplifies their maintenance during LHC operations.

Each WINCC OA project, configured to manage a subsystem, operates on a dedicated server. While simpler subsystems may not fully utilize their assigned servers, this approach ensures that maintenance of one subsystem does not affect others. However, for more complex detectors, the operation of multiple subsystems may be closely interrelated, making it advantageous to run them on the same physical server. Additionally, complex detectors can distribute subsystem control across multiple servers as needed, optimizing load and resource utilization.

The WINCC OA system is constructed as a collection of highly specialized modules known as managers, which execute assigned control tasks in parallel. The type and quantity of managers vary between detectors and subsystems, allowing for flexibility in task allocation. This configuration is particularly beneficial for detectors with numerous channels of the same type.

Individual WINCC OA systems can be integrated into a common distributed system, enabling data and command sharing among participants. At the detector level, these distributed systems are designed to fulfill detector-specific requirements and support autonomous operation.

The central DCS functions as an aggregation of all detector systems. Central servers connect to all subsystems, synchronizing individual detectors, overseeing functionality, managing data flow, and facilitating communication with external services. In total, 82 SCADA systems, comprised of 2613 managers, constitute the ALICE DCS.

The concept of the ALICE distributed system has been in operation since 2008 and has undergone minimal revisions. The introduction of global data exchange addressed the need to eliminate cross-dependencies among detectors. For instance, if the radiation background exceeds tolerable limits during maintenance, operation of sensitive detector modules may need to be restricted. Dedicated detectors produce this information, allowing sensitive systems to subscribe and respond accordingly. However, issues can arise if the source system is restarted, for example due to maintenance, triggering responses in other detectors. Global data exchange servers collect sensitive information from individual systems and redistribute it to consumers, providing greater control over automated actions.

Control Hierarchy

The distributed system is comprehensively designed to ensure control and operation of ALICE, yet the experiment's overall complexity renders centralized actions challenging to implement. Centralized tools must account for the unique characteristics of each detector, making it particularly difficult to manage configurations when portions of the detector are temporarily unavailable.

To address these challenges, a sophisticated SMI++ toolkit [4], integrated within the JCOP framework, has been employed. Each object, whether it be a detector, module, or channel, is represented as a Finite State Machine (FSM). These FSMs can transition between stable states on operator command or automatically in response to changing conditions. In their operation, FSM nodes take into consideration the state of other objects, thereby preventing, for instance, the activation of frontend power when cooling is not operational. Moreover, objects can be organized hierarchically, with commands issued to top-level objects cascading down to subordinate objects, including subsystems, crates, modules, or channels. Each object reports its state to its parent, and the resulting state is calculated at the top level, representing the entire detector. Finally, the resulting state of the experiment is provided as a logical combination of all detector states.

Modules undergoing maintenance can be excluded from operations. In such cases, these modules do not respond to commands, and their state is not factored into the calculation of their parent object's state. Each excluded object can be operated independently, allowing for parallel activities conducted by experts. Currently the ALICE DCS deploys 17000 FSM nodes.

This approach shields the operator or script responsible for operations from implementation details and the current detector configuration, significantly reducing the risk of operational errors.

The FSM mechanism serves as the central logic for ALICE DCS, encapsulating detector operation logic while accommodating individual requirements and conditions. However, the flexibility that allows parts of detectors to be excluded during temporary maintenance introduces safety risks. For example, certain LHC operations, such as injecting new beams, may potentially endanger detectors. To mitigate these risks, a parallel mechanism based on software probes has been introduced. Dedicated scripts monitor critical parameters, irrespective of the FSM state. This ensures that conditions of modules excluded from operations are always considered, enhancing safety.

User Interface

The initial concept of ALICE DCS assumed that all detectors would follow a predefined set of top-level states. For example, the "READY" state indicates that a detector is ready to participate in physics data collection, while "STANDBY" signifies that the detector's power supply crates are active, but individual channels are not providing any output.

Efforts were made to unify all ALICE detector states into five standard top-level states, and during the early years of operation, the FSM served as the primary tool for operators. However, as detector complexity grew and ALICE data-taking requirements evolved, this approach became demanding and led to operator errors.

One major complication arose from variations in detector responses to external conditions. While certain detectors could remain in the "READY" state during beam injections, others needed to transition to "STANDBY" or

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"OFF" states. This variation also depends on different types of beams, frontend configurations, and procedural adjustments based on experience gained during data-taking. As a result, operators were inundated with complex and permanently evolving instructions, negatively impacting response times.

Another concern stemmed from the power of the FSM, which could execute low-level actions on any type of hardware, potentially risking detector damage through incorrect command sequences.

To address these issues, the central team introduced a new operational concept. The operator interface was condensed into two main panels:

1. The Operator UI: This panel provides a graphical interface for all DCS components, enabling control and monitoring of all objects from a single location.
2. Alert Screen: These screen displays all anomalies in one place, allowing the operator to access relevant instructions.

Furthermore, the use of the FSM by the operator was restricted to troubleshooting. During standard operations, actions were encoded in graphical panels, where the operator selects a task, and the script translates it into an orchestrated sequence of FSM commands. The FSM continues to govern ALICE, but its use is safeguarded by expert scripts, providing an additional layer of protection.

The user interface component deployed in this system is highly adaptable and has been uniformly integrated across all detector systems. A tree browser, an integral part of the user interface, facilitates intuitive navigation through the detector hierarchy. Whenever the operator selects an object in the tree browser, the user interface component dynamically presents a corresponding, intuitively designed panel crafted by detector experts.

In routine operations, the operator can efficiently utilize a set of standardized panels that encompass predefined tasks. In the event of an anomaly, an alert screen promptly notifies the operator. This alert text is accompanied by instructions prepared by experts, guiding the operator through the hierarchy to the specific element requiring attention. The uniformity of these tools ensures that the operator can pinpoint the required elements even within a system comprised of thousands of distinct panels.

DCS Infrastructure and Network

The use of a wide range of detector technologies with demanding operational requirements complexifies the selection of control hardware. Given that the experiment is located in an area inaccessible during LHC operation, hardware robustness and stability are prioritized.

Whenever feasible, devices are positioned outside the experimental cavern. Still, several devices need to be installed in close proximity to the detectors. Their locations are meticulously chosen based on magnetic field and radiation level studies. Some devices allow for a hybrid solution, with sensitive components, like control computers, located outside the cavern and communicating with near-detector electronics through a field bus. As most devices are Ethernet-based, the DCS maintains its own network, covering both the ALICE cavern and the surface area, providing approximately 1,200 network ports, many of which feature redundant fallback connections, resulting in a significantly higher number of final physical connections.

The central DCS team played a crucial role in the design phase by analyzing detector requirements and proposing common solutions where possible. Emphasis was placed on the unification of purchased devices, prioritizing those equipped with standardized communication interfaces supported by the JCOP framework. The decision was made to use only devices equipped with CANBus or accessible via Ethernet, with a small fraction of devices, mainly the PLCs, accessed via ProfiBus.

Most of the hardware removed from the cavern is installed in one of the two DCS counting rooms situated near the surface, approximately 50 m above the detectors. One of these rooms contains central servers, including around 200 computers responsible for hosting the DCS systems, with 82 of them running WINCC OA. The remaining servers provide essential services, such as system supervision and network services, including BOOTP servers. The computer infrastructure operates on an isolated network and is designed to function autonomously even in the event of external connectivity loss. Communication with systems external to ALICE DCS is established through a series of secure gateways.

All data acquired by the DCS is stored in an ORACLE database. It is supported by redundant servers with robust storage capacities, directly installed in the server room. Leveraging ORACLE RAC technology, a real-time replica of ALICE ORACLE cluster is also installed in CERN IT. Its primary function is to provide system redundancy, while also serving as a read-only repository of DCS data accessible from the CERN campus network. This architecture allows for the convenient offloading of extensive analysis tasks to IT servers without adding extra loads to the production systems.

Interfaces to Other Systems

For safety and security reasons, the DCS operates on an isolated network and does not rely on external services for uninterrupted operation. The DCS can withstand a complete external network outage for several days.

To facilitate remote access for experts during maintenance, a cluster of remote access gateways, accessible from the CERN campus network, is provided. Authorized users can gain interactive access to detector servers, following a strict authorization hierarchy.

In the context of physics data-taking, ALICE DCS serves as an information exchange point between ALICE and the LHC. Condition data is streamed to event processing farms, and synchronization data is exchanged with trigger and data acquisition systems.

During the Long Shutdown in 2018-2022, ALICE underwent significant modernization to accommodate higher interaction rates, exceeding the original design by two orders of magnitude [5]. A substantial amount of physics data, approximately 3.5 TB/s, is transmitted over

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radiation tolerant links to a farm of 200 First Level Processing servers (FLP). The physics data is then relayed to a farm of 350 Event Processing Nodes (EPN), where events are reconstructed and prepared for analysis. This new approach, called O2 (Combined Online Offline Processing) , as opposed to the traditional methodology of first storing raw data and then processing it, places increased demands on DCS since data processing relies heavily on detector conditions data. The traditional model based on extraction of conditions data from the archive after each period of data taking was replaced with real time streaming of DCS data.

To address this requirement, modifications were made to the dataflow within the DCS. ALICE adopted a new technology from Siemens called the Next Generation Archiver (NGA).

In the traditional WINCC system, one of the managers stored data in the ORACLE database each time a parameter changed its value. To preserve the disk space a value was archived only when this change exceeded predefined thresholds. The new model replaces the archival manager with NGA manager, which acts as a fanout. Data tagged for archival is forwarded by NGA to a software module that writes the data to the database, respecting the predefined thresholds in the same way as it was achieved in the old system. Simultaneously, each value is forwarded by NGA to ADAPOS (ALICE Datapoint Service) [6], which collects data from all systems and streams formatted data blocks to O2. The data suppression based on archival thresholds is not applied, each value change is streamed to the consumer. ADAPOS serves currently about 10 000 different condition parameters from ALICE DCS. The current streaming rate is approximately 1000 updated condition values every 50 milliseconds, while ADAPOS has been tested to withstand a sustainable load of 150,000 changes every second. The ADAPOS architecture allows for load balancing by deployment of additional ADAPOS servers, which makes the system highly scalable. In theory each WINCC OA system can talk to an individual ADAPOS server. Due to data processing limitations on WINCC OA side it is not possible to overload an ADAPOS server by a single WINCC OA instance. This guarantees the sufficient throughput, even under most extreme data load. In addition, ADAPOS servers can operate in parallel mode, providing system redundancy.

The majority of detectors generate their configurations through dedicated calibrations or continuous online data monitoring. These essential parameters are written into the electronics systems and must also be seamlessly transmitted to the O2 processing nodes. This data, however, is not amenable to real-time streaming since it remains constant throughout the data-taking phase. To facilitate the continuous availability of up-to-date configuration data for processing, specialized gateways are employed.

In some instances, specific configurations are computed on external farms and rely on offline analysis. This necessitates the option for reverse transfer of configuration data. The deliberate use of gateways serves to block direct access to the DCS infrastructure from both O2 farms and external institutes, ensuring controlled and secure data flow.

The ALICE upgrade entailed a comprehensive redesign of the frontend electronics, covering all new detectors and a significant portion of the existing ones. A central component of this upgrade involved the implementation of new optical links, primarily responsible for transmitting physics data to the First Line Processing (FLP) units. These optical links serve a dual purpose by enabling both monitoring and control of the detector frontends from the DCS. Control packets are interleaved with physics data, allowing for concurrent operation of the DCS and data acquisition.

The Control and Readout Units (CRU) that oversee the optical links are physically integrated into the FLPs. To provide DCS access, a specialized software module named ALF (Alice Low-Level Frontend Access) is deployed for each CRU. On the DCS side, the ALFs interface with a server module known as FRED (Front End Device) [7, 8]. FRED plays a pivotal role in ensuring seamless communication between ALFs and WINCC OA systems associated with the same detector.

To streamline the development of individual FREDs, a sophisticated software framework was established within the ALICE project. This framework equips detector experts with essential communication interfaces, synchronized thread management, database access tools, and more. The user logic is implemented through a component known as MAPI, which enables the incorporation of C++ code provided by experts into the FRED structure.

FRED was designed as a scalable framework, offering the flexibility to clone and configure instances for load balancing purposes. Typically, one FRED instance suffices for the majority of detectors, given its ample processing power. However, due to its substantial scale, the Time Projection Chamber employs a remarkable 20 FREDs to ensure flawless data processing. This modular and adaptable approach has been instrumental in the successful execution of the ALICE upgrade. Currently 21 FRED instances communicate with 106 subordinate ALF modules. A total number of 7972 optical links is supervised by FREDs.

Operators and experts who are remotely connected to the DCS systems can harness the graphical capabilities of WINCC OA to examine all system data. However, it is not desired to employ production servers for extensive data analysis. To address this concern, two supplementary interfaces have been prepared.

DARMA (Dcs ARchive MAnager) [9] stands as a web-based application that facilitates the extraction of substantial volumes of data. The user specifies the desired datasets and the period of interest before submitting the task to DARMA. Once pulled from the ORACLE databases, the data becomes accessible for download on the server. As previously underscored, the data retrieval process is conducted from the RAC replica of the DCS

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database, a measure instituted to safeguard the integrity of the production systems.

The second system, known as AGRANA (Archive GRAphical NAvigator), furnishes real-time access to DCS data and its web-based representation. AGRANA serves as an interface module that seamlessly bridges the custom ORACLE database and Grafana. Standard GRAFANA dashboards are employed by users to formulate queries, with AGRANA expertly managing the interfacing process with the DCS archive.

The newly developed AGRANA system supersedes the conventional DCS monitoring system that was initially deployed in 2008. The earlier system relied on periodic execution of WINCC panels. Following the construction of graphical representations of the requested data by WINCC OA, screenshots were captured and subsequently transferred to a web server. This method afforded secure access to DCS monitoring while eliminating the risk of compromising the system, as there existed no direct connection between the system and the web page. AGRANA perpetuates this level of security, given that data retrieval transpires exclusively from mirror servers accessible in a read-only mode.

Project Organization and Operation

The ALICE experiment stands as a collective endeavor, involving 170 institutes from 40 countries. The majority of detectors are the product of collaboration among multiple institutes, jointly responsible for their design, production, and ongoing maintenance.

A compact central team consisting of seven people oversees the DCS activities within each detector group. The approach adopted dictates that detector experts develop the control systems, guided by the central team's directives.

This approach presents undeniable advantages, namely that the systems are crafted by experts who possess an in-depth understanding of the detectors' operational requirements. In the short term, this approach results in a swift development cycle, allowing the DCS to evolve alongside the detectors from their initial stages. However, drawbacks also emerge. Experts tend to use their preferred frameworks, often resisting the implementation of standard tools. Stringent deadlines pose the risk of divergence from a common strategy, leading to a proliferation of customized tools. Moreover, the solutions devised by detector experts frequently lack consideration for the challenges posed by the operation of numerous detectors as part of a global system. Consequently, these implemented solutions may disrupt central operations. Finally, experts typically concentrate on their specific tasks, often overlooking the fact that detectors will be operated by non-expert users. As a result, instructions, diagnostic levels, and user-friendliness of the tools frequently fall short of required standards.

To address these challenges, the DCS team carefully integrates individual detector systems into the global system, ensuring that requirements are met. This effort reaches its zenith upon the delivery of the final product and often contends with tight deadlines.

One significant consequence of control systems developed by detector teams is their impact on long-term maintenance. Experiments like ALICE span several decades, and the experts who initially created the systems eventually move on to new challenges. Maintenance duties typically fall to Ph.D. students, whose tenure with the detector is limited. To ensure detector stability, the central team must absorb available knowledge and bridge the gaps during periods when new collaborators are brought on board. Over time, the volume of knowledge to be absorbed and preserved by the central team grows, and any deviations adopted in individual designs become increasingly apparent.

Once delivered to CERN, the systems undergo evaluation by the central team and are subsequently handed over for operational use. During data-taking, a dedicated operator supervises the DCS in a 24/7 mode. These operators are recruited from institutes external to CERN and often possess limited or no prior experience with the DCS. As a result, comprehensive training is provided by the central team. Each operator must complete a class followed by an examination and then engage in three days of training shifts, during which their work is closely monitored by a senior operator. On the final day of the training shift, the new operator assumes control of the experiment, with continuous oversight from the seasoned operator. Each year a pool of more than 200 operators is trained.

To ensure stable operations, considerable efforts have been invested in crafting robust and unambiguous operational procedures. User interfaces undergo constant refinement to offer a clear view of the experiment through intuitive operation panels.

In exceptional circumstances, when the operator encounters anomalies beyond the scope of provided instructions, remote consultation with an expert becomes necessary. Each detector maintains a 24/7 service accessible to the operator. Given the nature of CERN experiments, situations may arise where the remote expert is located a considerable distance away, underscoring the critical importance of a stable and resilient remote access mechanism. Lastly, the central team extends a 24/7 on-call service to assist the shift crew in cases where detector experts are unable to resolve problems promptly or when an intervention on infrastructure provided by the DCS team is required.

CONCLUSION

For the past 15 years, the ALICE DCS (Detector Control System) has been ensuring the stable and secure operation of our experiment. Over time, its architecture has evolved to seamlessly adapt to experiment upgrades, all while staying true to its original design concepts. Furthermore, we have introduced additional features to enhance the safety of our detectors, building on operational experience.

Notably, during the LS2 phase spanning 2019 to 2022, a significant overhaul of the DCS dataflow was undertaken.

This transformation was aimed at enabling real-time publication of detector conditions, a critical advancement in our experiment's capabilities.

In our recent paper, we described the fundamental architectural principles underpinning the ALICE DCS, addressing the key technical challenges that have been encountered along the way. We also emphasize the importance of providing high-quality training for our operators, as their expertise is pivotal to the success of the system.

It is essential to recognize that the ALICE DCS is an example of the collaborative spirit that drives ALICE experiment forward. Through the joint efforts of institutions participating in the project, our DCS serves as an exemplary model of wide cooperation.

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