Design and Performance Analysis of a Non-Standard EPICS Fast Controller

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Abstract—The large scientific projects present new technological challenges, such as the distributed control over a communication network. In particular, the middleware EPICS is the most extended communication standard in particle accelerators. The integration of modern control architectures in these EPICS networks is becoming common, as for example for the PXI/PXIe and xTCA hardware alternatives. In this work, a different integration procedure for PXIe real time controllers from National Instruments is proposed, using LabVIEW as the design tool. This methodology is considered and its performance is analyzed by means of a set of laboratory experiments. This control architecture is proposed for achieving the implementation requirements of the fast controllers, which need an important amount of computational power and signal processing capability, with a tight real-time demand. The present work studies the advantages and drawbacks of this methodology and presents its comprehensive evaluation by means of a laboratory test bench, designed for the application of systematic tests. These tests compare the proposed fast controller performance with a similar system implemented using an standard EPICS IOC provided by the CODAC system.

Index Terms—EPICS middleware, fast controller, PXI/PXIe, LabVIEW.

I. INTRODUCTION

The particle accelerators require a high variety of technologies for a correct operation, both cutting-edge and mature. Therefore, an important effort must be focused on the development of new technologies in order to achieve the high demands in this field. The control tasks in a large scientific facility are fundamental for a correct machine operation and for ensuring the safety of the machine and the personal. The design of those control systems is a challenging problem, which must take into account considerations about the distributed nature of the facility and the variety of present technologies.

Experimental Physics and Industrial Control System (EPICS) middleware is one of the most relevant solutions developed for the implementation of the control solutions in this class of facilities and, in particular, it is very usual as main control technology in particle accelerators. This open source toolkit was initially developed for the control system of the Advanced Photon Source (APS) in the Argonne National Laboratory in collaboration with the Los Alamos National Laboratory, and is a software framework specifically designed for the development and implementation of distributed control systems for scientific facilities. In particular, it is useful for the connection of large number of controllers in a networked environment and gives monitorization, supervision and control utilities, including feedback actions and guaranteeing soft real-time behavior.

The evolution of EPICS over the years in different facilities reflects its capabilities in these environments. EPICS has been evolved and adopted in a large number of facilities due to its power and versatility and, nowadays, it is used in many particle accelerators and other large facilities, including telescopes, and other scientific and industrial facilities. Some of the well known facilities using EPICS are the Spallation Neutron Source in USA, the KEKB Collider in Japan, and the Diamond Light Source in United Kingdom.

Recently, EPICS has been chosen as the key element in the control system for the International Thermonuclear Experimental Reactor (ITER), being the heart of the CODAC (Control, Data Access and Communication) system. In addition to this relevant international center, the international project IFMIF/EVEDA, and the European Spallation Source (ESS AB), have chosen EPICS as their respective control system.

On the other hand, different hardware solutions are used under EPICS for the development of the control systems and the related diagnostics. In this regard, it is worth stressing that one of the most relevant characteristics required in those applications is the high reliability and long lifetime of the selected technology, since the accelerators are designed for an operation of decades. For this reason, the technology involved in the implementation of any particle accelerator must be well known and therefore, has been used along decades. Highlighted examples are hardware elements based on the standards CAMAC and VME.

In particular, control devices based on VME have been a very relevant elements in the last years. Therefore, EPICS has a wide support for hardware based in this standard. However, the technological advance for instrumentation and control has lead to the appearance of new standards such as PXI/PXIe and more recently, xTCA. Hence, following those advances different initiatives are trying to increment the support for this kind of technologies and its integration in EPICS. In fact, the efforts for integrating PXI/PXIe based hardware in EPICS networks is being positively fueled by the impulse received in the last years.

In this sense, the development of standardized solutions for the ITER project using PXI/PXIe platforms is a remarkable fact. The CODAC distribution includes the device and driver support for PXI/PXIe based hardware, in order to develop
standard EPICS IOCs, [9]. In particular, there is an strong interest for providing support for the National Instruments devices which include FPGA cards for data acquisition and control applications. The deployment of the integration of a standard EPICS IOC for a PXI/PXIe based controller is described in [17]. An additional proposal in [17], similar to the one presented in the work, is based on the implementation of an EPICS server in a PXI/PXIe controller under LabVIEW RT. Finally, the use of a LabVIEW based EPICS CA server, which is still under development, is proposed in [18].

The main objective of this work is the description of an architecture appropriate for the integration of NI PXI/PXIe platforms in EPICS networks, extending and complementing the results presented in [19]. The use of this hardware is oriented to the implementation of the so called fast controllers, [20], which in the current case are based on the use of FPGA cards and real time controllers. The graphical design tool LabVIEW is used as the development tool for the development of the control application. This architecture has been successfully applied in a real system, specifically in the control system for the ISHN ion source developed in ESS Bilbao, [19] as well as in [21].

In addition to the details of the proposed architecture and its implementation, a test bench developed for the validation of the proposal is presented. The results obtained from the preliminary tests are also described. Moreover, several laboratory tests have been designed and implemented in order to compare the reliability of the proposed system and compare to a similar hardware which implements a standard EPICS IOC, based on the support provided by CODAC. The initial results show that both systems provide a comparable performance.

In this case, the controller is implemented using LabVIEW-RT and its integration in EPICS networks is based on the use of the LabVIEW EPICS server by means of the Data logging and Supervisory Control module (DSC), with an additional interface to EPICS by means of a new external IOC. The resulting system is equivalent to a standard EPICS IOC, overcoming the limitations present in the LabVIEW EPICS server. This approach has several advantages derived from an easier and flexible implementation thanks to the use of the LabVIEW development environment and the availability of commercial drivers. The use of LabVIEW eases and speeds up the development of control structures, avoids the hardware dependent developing costs and offers a very high compatibility with a large variety of hardware devices used in control and data acquisition systems. These characteristics make the system easily reconfigurable, with a versatile EPICS integration.

On the other hand, several potential drawbacks arise, being the most import one the reliability, which must be assured for those schemes, since its usage in scientific facilities is not extended. In addition, the control of the internal details of the software relays on external companies. Anyway, the performance of this non-standard EPICS implementation is analyzed, and satisfactory results have been obtained.

In addition, the proposed system is compared with a similar hardware, which implements an EPICS IOC controller, developed using the tools provided by the CODAC distribution. This comparison is based on a test bench which simulates a real control system environment, following the scheme proposed in [22]. This system emulates real schemes present in scientific facilities and in particular, a particle accelerator. A large number of process variables are considered, including digital and analog IO signals, monitors and data processing. The work describes the implementation of the test bench and analyzes the results comparing both architectures. The study is focused on the reliability of the configuration, facing the proposed solution and the EPICS standard methodology.

This work is organized as follows. First, the motivation of this work is presented in Section 2. Next, Section III describes the main characteristics of the proposed architecture for PXI based fast controllers and its integration in EPICS networks. In Section IV the laboratory test bench implemented for testing the proposed solution and the obtained results are presented. Finally, the conclusions and future work end this paper.

II. RELIABILITY OF COTS CONTROL SYSTEMS FOR PARTICLE ACCELERATORS

The control system of a particle accelerator must fulfill multiple technological challenges, therefore an efficient design architecture for the control system must be considered, taking into account all of the requirements for the whole facility. In particular, some applications needs stringent requirements: a fast response, precise real-time measurements, fast data acquisition, etc. In those cases, an advanced hardware is needed to cope with the requirements, and to get the so called fast controller, a high performance controller. In order to get the required characteristics, the use of the most advanced and commercial available control hardware is a valuable choice, taking into account the associated costs. In fact, the usage of COTS hardware usually requires a lower cost than home-made ad hoc designs, which involves a time and budget consuming design and development process.

An architecture which is gaining relevance in modern accelerators is the use of control chassis based on PXI/PXIe platforms. Furthermore, National Instruments (NI) company provides this technology and supports a large variety of DAQ and FPGA cards. Among other reasons, this fact has push ITER to select NI company as one of its hardware providers.

However, in the case of being EPICS the main control element in the facility, the key issue for the use of the aforementioned technology provided by NI relies in its integration in EPICS networks. This is the case when designing fast controllers based on NI PXI/PXIe technology. Due to the interest aroused, NI provides tools integrated in its graphical design environment LabVIEW, which allow the creation of EPICS controllers using PXI/PXIe based high performance hardware. However, the currently available solution has limited functionalities regarding EPICS environment and the integration in EPICS networks is basic. The resulting functionalities can be insufficient, depending on the specific necessities for a particular application.

On the other hand, LabVIEW is a versatile and powerful design tool which allows an easy implementation of control
and data acquisition systems. The use of commercial and well tested controllers and cards and the design of custom monitoring tools in an easy way are also valuable characteristics. Those features make LabVIEW an interesting design tool for specific control systems in particle accelerators.

The main advantage of this approach is that the development process is easier and faster compared to other alternatives (usage of embedded C within a real-time Linux for example). Control and monitoring elements are more easily deployed when programming is done using a top-level language such as LabVIEW. In addition, a large variety of robust hardware is available.

Nevertheless, LabVIEW based development is uncommon in scientific facilities. It is used mostly for laboratory developments and diagnostics. In SNS [23], LabVIEW is used mainly for the development of beam diagnostics. A similar path is followed in ISIS [24], where the hardware deployed using LabVIEW is used mainly for beam diagnostics and it is not integrated in the main control system. On the contrary, in ESS Bilbao the use of LabVIEW is more extensive, including the development of the control systems for several subsystems of the accelerator, [19]. In any case, the reliability related issues are not fully tested.

As a consequence of the previously mentioned drawbacks, the use of COTS controllers designed with LabVIEW are not extensively tested in current accelerators and the characteristics needed in this kind of facilities are not conveniently assured. Summarizing, the following characteristics must be fulfilled by any element present in the control system of a particle accelerator:

- **Reliability**: a device including a controller developed using LabVIEW must be carefully tested in realistic experimental environments. Only if the concluding results are positive enough, the device is valid to be used in the facility.
- **Standardization**: due to the characteristics and limitations and the harsh environment the installation and machine maintenance are complicated and resource consuming tasks. For this reason, the use of standard devices is fundamental, based on hardware, procedures and software known by all the developers and operators. The standardization also facilitates the evaluation and fulfillment of the required design and operational rules.
- **Software reuse**: the use of well known and documented code, enhances software reusability and maintenance. In addition, tracing faults and debugging can be performed more easily.

The last two issues can be solved using a modular design architecture and standard hardware, including well structured software libraries and version control tools. Furthermore, the documentation is completely necessary for achieving design goals.

Finally, the reliability of the devices can be assured under an exhaustive test plan. In fact, this is one of the objectives in this work, thus, the experimental test of the proposed methodology for the integration in EPICS networks of fast controllers based on modern and commercial equipment.

### III. Integration of the PXI based Fast Controllers in EPICS Networks

The use of chassis based on the PXI/PXIe bus can be considered a good option for modern accelerators. In particular, the National Instruments company provides this technology including FPGA and data acquisition cards. In addition, NI has developed tools allowing the definition of EPICS servers with LabVIEW, but with limited functionalities. The advantage of this solution is the use of LabVIEW as design tool and very versatile and powerful hardware, with an easy implementation. Also, the solution includes already tested commercial drivers, and the design of monitoring elements is performed in a simple way.

The EPICS solution provided by LabVIEW for the PXI/PXIe controllers only implements a limited EPICS server by means of the Datalogging and Supervisory Control module (DSC). Thus, it is not a complete EPICS environment and, in many cases, it is not enough for control purposes. The lack of features such as alarms and a full EPICS record support is very limiting.

In consequence, some issues must be solved in order to use PXI/PXIe fast controllers in facilities using EPICS control network:

- The EPICS system provided by NI is limited and its integration is not full, which could lead to unmet requirements depending on the specific necessities.
- This kind of solutions using LabVIEW in EPICS networks is not usual in large facilities. As result, the solutions based on LabVIEW have not been tested adequately for being used as control elements in particle accelerators.

The aim of the proposed solution is to deal with these problems.

#### A. Proposed methodology

The proposed solution to overcome the previous issues is based on the use of the EPICS Server provided by the LabVIEW DSC module, filling the gap with the development of a new interface in order to suit the needs of the project.

Initially, the primary interface between the local fast controller and the EPICS control network is based on the tools provided by National Instruments in the LabVIEW DSC module, and runs on the real time system in the PXI controller. This module acts as a plug-in to the Shared Variable Engine and functions as the link between shared variables and the EPICS network. Shared variables are bound to an EPICS Process Variable while the I/O server handles updates to the PVs. The I/O Server then publishes the PVs to the network using the Channel Access Protocol.

This interface is not sufficient, since the library provided by NI lacks some important features (record structure, alarming, etc.) and must be improved.

In order to solve this problem, an enhanced architecture is proposed. It is based on a new IOC implementing a communication gateway between both systems, the standard IOC and the LabVIEW/EPICS server in the PXI controller. The main function of this gateway is to redirect and complete the information...
from the LabVIEW/EPICS server. Hence, a full EPICS IOC is obtained which behaves as a single system with the features of the fast controller and with an EPICS based communication channel.

Accordingly, the most remarkable characteristics that have been added are the following ones:

- Data: Tools for translating the values of the variables of the system to EPICS are provided. The system allows the addition of information regarding alarms, security, and so on.
- Record structure: The specific record structures are mapped between server and IOC. The aim of this mapping is to allow an automatic integration and translation of variables through the proposed gateway.
- Timestamp: Each PV holds the time instant corresponding to its acquisition.
- Data archiving: It is possible to store data with EPICS archiving tools, this facilitates the use of HyperArchiver solution.
- EPICS integration: Since there is a full IOC, the full set of EPICS features is available.

The main idea for a full integration of the fast controllers in EPICS networks is shown in the Figure [1]. There is an EPICS server in the LabVIEW RT system, related with a Shared Variable Engine (SVE), which publishes the required PVs in the network. A full IOC is connected with this server for retrieving PV data, it adds the needed information and fields, as the information related with the alarms, and publishes again the new PVs with a prefix identifying them from the original ones (“NIOC:”). Therefore, the rest of system and applications in the network can use the new published PVs, obtaining information related to the RT application in the fast controller but with all the required services (data archiving, alarm handler, monitorization, etc). The resulting control system is from the point of view of the EPICS network, equivalent to a standard EPICS IOC and, thus, the fast controllers is integrated in the EPICS network in a transparent manner.

The rest of the applications on the network will use those complete PVs in their operation (data archiving, alarming system, operator panel, etc.) provided by the new IOC. The resulting control box can be seen from an EPICS network as an equivalent EPICS IOC, and the final design must be transparent from the point of view of such an EPICS network. This approach also facilitates updates and replacement of PXI hardware without changing the overall system characteristics.

From the point of view of hardware requirements, an external computer is needed for hosting the IOC which implements the gateway. This, usually, does not present any special drawback since an standard control cabinet has enough space for storing an embedded computer. In addition, the cost is not increased in a dramatic way.

The following steps summarize the main rules that have to be fulfilled for implementing a fast controller in the present methodology. The guidelines are split into two main stages:

1) Definition and programming of the record structures for the communication gateway. In this sense, IOC records must be defined to be compatible with the data that LabVIEW publishes. For example, a Double type could be mapped to an analog input/output record and a DBR_FLOAT_EPICS data type, a Boolean corresponds to a binary record and DBR_ENUM, etc. This stage is only done once, unless new functionalities are required.

2) Controller design
   a) Design the control and data acquisition application for the FPGA and the real-time (using LabVIEW design tool).
   b) Define which LabVIEW shared variables will be accessible through EPICS, configure and deploy the required LabVIEW EPICS server in the embedded controller. A custom program generates automatically an EPICS database with the correct data types and links, it only requires the PV list.
   c) User access control, alarm information and other functionalities are added to each record. This step is strongly dependent on the application objectives and decisions of the developer.
   d) Deploy the IOC. Those PVs will be accessible for read and write access in the EPICS network.

The addition and modification of existing features is performed following the second step. If the improvement requires new data types or new functionalities, new records should be added corresponding with the new functionalities, following the rules of the first stage. This approach for the integration of fast controllers into EPICS has been successfully applied to the control system of the ISHN ion source [19].

In conclusion, the strategy allows the use of LabVIEW as design tool for fast controllers, and the drivers developed by National Instruments for their cards. However, the resulting system has the characteristics of a full IOC controller.

This scheme allows variations and alternative architectures, such as an hypervisor based dual boot system, [25].

IV. PERFORMANCE ANALYSIS AND VALIDATION TESTS OF THE PROPOSED METHODOLOGY

The proposed solution for the definition of the fast controllers designed with LabVIEW and integrated in EPICS networks, has some advantages, specially, a fast, flexible and easy development. However, the associated risks must also be considered, specially related to the fulfillment of the requirements requested to the hardware in a particle accelerator, as has been mentioned in Section 2. In consequence, those risks must be characterized and bounded to obtain similar results compared with other technical solutions which are used nowadays in particle accelerators, in order to be able to use the proposed solution in real environments.

A. Laboratory test bench

The test of new control elements is not possible in a real particle accelerator, since the real environment is not usually accessible for those testing purposes. In addition, the real facilities are not flexible and new devices and equipment are not easily introduced into the system. For these reasons, a laboratory test bench has been designed and implemented, with the aim of replicating the characteristics of a control system.
in a particle accelerator, with the appropriate scaling in its dimensions. This strategy has been followed to implement the proposed fast controller and to compare this alternative with another implementation based on the standard EPICS strategy. The latter has been implemented using the tools provided by the CODAC system. In any case, in both cases similar hardware solutions have been considered, in order to get a realistic comparison.

Therefore, the test bench includes two parallel systems which implement two fast controllers to be tested in a long-term experiment. Both systems implement the same functionalities and the typical actions which are habitual in a controller for a subsystem of a particle accelerator, which mainly include data acquisition, feedback control actions and finite state machines. Hence, the first implementation is based on an embedded controller under LabVIEW Real Time, publishing PVs with the method proposed in this work, see Section 3. The second implementation uses an embedded controller under Linux by means of a standard EPICS IOC. This second implementation is equivalent to the solution used in ITER, based in the CODAC system. The basic scheme of the test bench is shown in the Figure 2. In addition, the main characteristics of both implementations is shown in the table 4.11. The proposed fast controller and to compare this alternative with the standard EPICS solution.

Therefore, the reliability of both system can be studied and compared. In this experiment, a novel archiving system, called HyperArchiver, has been used. This archiving system has been developed in ESS Bilbao in collaboration with the Instituto Nazionale di Fisica Nucleare (INFN) research center in Legnano. HyperArchiver allows the use of large data tables with high performance thanks to the usage of Hypertable database and it is considered scalable and reliable. In addition, a pyQT graphical tool has been developed to visualize the archived data (Figure 3).

Reliability test results

All of the results obtained with both systems are analyzed exhaustively and archived using a dedicated database. Therefore, the reliability of both system can be studied and compared. In this experiment, a novel archiving system, called HyperArchiver, has been used. This archiving system has been developed in ESS Bilbao in collaboration with the Instituto Nazionale di Fisica Nucleare (INFN) research center in Legnano. HyperArchiver allows the use of large data tables with high performance thanks to the usage of Hypertable database and it is considered scalable and reliable. In addition, a pyQT graphical tool has been developed to visualize the archived data (Figure 4).
The main parameters under consideration in order to perform comparison analysis are related to the reliability and the repeatability. The tests carried out use 1960 records which have been implemented equally in both systems to compare, and then, the total number of defined process variables is 9600, similar to the number of PVs presented in [28]. Most of the PVs are processed periodically at 1 or 5 seconds. On the contrary, a set of 760 records are event processed. In the data archiving process, as soon as a PV is processed, it is written in a Hyperarchiver buffer and the resulting data sets are batch processed each ten seconds, storing the data in the database.

Figure 5 displays the behavior of two process variables of the type of analog input during a time interval of 24 hours of continuous operation. Each of the two variables corresponds to one of the solutions implemented in this work: the solution based on the use of LabVIEW and the one based on the standard EPICS system. The figures shown the distribution of the processing period around the theoretical period of 1 second for 24 hours. The initial analysis of the obtained data, which is shown in Figure 5, indicate very good performance with a similar jitter in both cases. Moreover, the rest of the signals involved in the comparison experiment behave in a similar way. In the present status of the study the tests have been running continuously for several days, however, a longer time interval is required to fully ensure the adequate performance of the proposed approach for the fast controller integration and to provide more reliable comparison results.

The present test bench is also used for the validation of the archiving system. By using the Hyperarchiver archiving tool, it can be analyzed the time span between consecutive timestamps. This data can be later used to analyze the quality of the archiving process. Thus, the test bench provides an appropriate mechanism for the improvement and adjustment of the parameters of the archiving system, which eventually might help avoiding the data loss.

**Worst case test results**

The main objective of the proposed fast controller is oriented to the systems which require a high performance with a high speed data acquisition and time synchronization. It is not oriented to applications aimed to a high data volume processing. However, in order to test the behavior of the system in different scenarios, the next situations have been considered:
• An increase in the number of access in the EPICS network. The increment of get petitions does not lead to any problem when packets up to 180 PVs are requested at once.

• An increase in the number of records until 16000 in each controller, i.e., the number of PVs is approximately 8 times higher. The results are similar in both cases, showing a good behavior. However, the deployment of the application, that is, the initialization time, is higher using the proposed solution than the standard solution.

• An increase in the number of EPICS monitors. When the number of synchronous EPICS monitors exceeds 80 monitors, the LabVIEW based system presents robustness problems, the controller becomes unstable and randomly hangs on data requests, issue not observed in the standard solution.

The results obtained show that the standard solution is more robust in applications with a large number of PVs. This fact is not a surprise and this configuration is preferable to be used when a large number of PVs is required, including simultaneous monitorization. In any case, this issue is not an important drawback of the proposed solution since it is oriented to control applications with high processing requirements but not with high data volume. Moreover, the election in the tests of the monitors has been done in the worst conditions to detect the limit of the system. In this implementation, the simultaneous monitors get the data directly from the LabVIEW EPICS server (using the DSC module). Nevertheless, the monitors can be redesigned to minimize the problems detected using the LabVIEW/EPICS interface.

V. CONCLUSIONS

In this work a methodology for the design of controllers providing high performance is described. The system is very versatile and powerful thanks to the combination of the use of FPGAs, real time controllers and high performance data acquisition cards. In particular, the methodology is oriented to the field of control systems in particle accelerators, related with the fast controllers, and facilitates the integration in EPICS networks. The main advantages of the proposed methodology are, on one hand, the use of fast, flexible and versatile devices and, on the other hand, those devices are easily obtained, since they are COTS and general purpose hardware. Moreover, an integration methodology in EPICS networks is proposed, which it is transparent from the point of view of the local controller and the EPICS network, simultaneously.

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