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The IFMIF-DONES remote handling control system: Experimental setup for OPC UA integration

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A R T I C L E I N F O

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A B S T R A C T

The devices used to carry out Remote Handling (RH) manipulation tasks in radiation environments address requirements that are significantly different from common robotic and industrial systems due to the lack of repetitive operations and incompletely specified control actions. This imposes the need of control with human-in-the-loop operations. These RH systems are used on facilities such PRIDE, CERN, ESS, ITER or IFMIF-DONES, the reference used for this work.

For the RH system is crucial to provide high availability, robustness against radiation, haptic devices for teleoperation and dexterous operation, and smooth coordination and integration with the centralized control room. To achieve this purpose is necessary to find the best approach towards a standard control framework capable of providing a standard set of functionalities, tools, interfaces, communications, and data formats to the different types of mechatronic devices that are usually considered for Remote Handling tasks. This previous phase of homogenization is not considered in most facilities, which leads towards a costly integration process during the commissioning phase of the facility.

In this paper, an approach to the IFMIF-DONES RH Control framework with strong standard support based on protocols such as OPC UA has been described and validated through an experimental setup. This test bench includes a set of physical devices (PLC, conveyor belt and computers) and a set of OPC UA compatible software tools, configured and operable from any node of the University of Granada network. This proof-of-concept mockup provides flexibility to modify the dimension and complexity of the setup by using new virtual or physical devices connected to a unique backbone. Besides, it will be used to test different aspects such as control schemes, failure injection, network modeling, predictive maintenance studies, operator training on simulated/real scenarios, usability or ergonomics of the user interfaces before the deployment. In this contribution, the results are described and illustrated using a conveyor belt set-up, a small but representative reference used to validate the RH control concepts here proposed.

1. Survey of existing RH systems

The use of remote handling equipment is common within environments such as nuclear power plants, space missions, underwater environments, mines, or medicine. The application on each of these environments entails certain peculiarities related to the use case, so the study will be focused on the concept adopted by nuclear power plants. In this case, RH systems are conceived to carry out maintenance, handling and inspection tasks within the so-called 'hot cell' (radiation environment). The devices are controlled and operated from a control room located within the facility following the man-in-the-loop concept [1].

The literature is extensive in this field, especially about operation logistics [2], telemanipulation systems [3], the design of control systems for specific mechatronic devices [4] and integration with virtual reality environments [5,6]. However, there are few articles dedicated to offering an overview of the control architecture used to integrate the different remote handling devices from a high-level perspective, focused

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on the integration in a single control room. This will be the focus of this article.

In most cases, each RH device comes from a different supplier, and each one will use different controllers and tools for the development of control systems. This ends up resulting in each operator having to deal with a different set of tools, the modifications and updates will depend on experts that will involve external contracts (it will not be possible to create a team of in-house engineers) and therefore a worse use of the systems. To illustrate the variety of approaches and problems, we will summarize the solutions implemented in different scientific facilities as key references.

1.1. PRIDE (PyRoprocess integrated inactive demonstration) facility

The purpose of PRIDE is to test processes regarding unit process performance, remote operation of equipment, integration of unit processes, scale-up of process, process monitoring, argon environment system operation, and safeguards-related activities. The test of PRIDE will be promising for further pyroprocessing technology development.

PRIDE facility combines three different devices to operate inside the argon cell facility: single arms, a dual manipulator and a bridge transport system (crane). The dual manipulator and the crane are operated remotely using a set of cameras installed on board, while the single arms are mechanically linked through the wall and can be operated using window vision [7]. The interfaces used by the operators are shown in Fig. 1. Despite the dexterous manipulators and the different cameras used inside the Process Cell, the operators experienced difficulties in operating these systems because of several ergonomic issues, such as the lack of strategies to handle the cameras, eye/hand alignment or the correct estimation of the gripper pose and surroundings.

1.2. ESS (European spalation source) active cells control system

ESS is a spallation source to test neutron beams for many different applications [8]. RH Systems on ESS are located at the Active Cells facility and controlled from the local control room placed in the basement of the technical galleries. The most important devices designed for RH are an industrial crane, the Shaft Cutting Station, the Machining Station and the Robotic Handling System (crane bridge with telescopic mast carrying two manipulators). The control system shown in Fig. 2 is called ProgrESS, and is focused on Augmented Reality, Virtual Reality and Synthetic Viewing. The use of these techniques will improve the operator perception of the remote environment, providing the feeling of presence and improving the execution of RH operations. In this approach, windows are excluded from the day-to-day operation, reducing the illumination requirements inside the Active Cell and opening new possibilities for the location of the control room.

1.3. ITER RH core system

ITER purpose is to build the world's largest tokamak, a magnetic fusion device that has been designed to prove the feasibility of fusion as

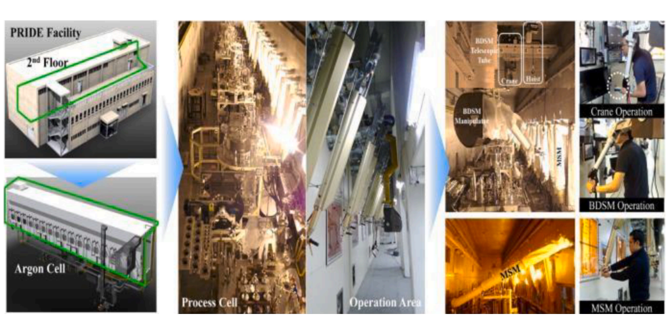

Fig. 1. PRIDE facility and remote handling devices.

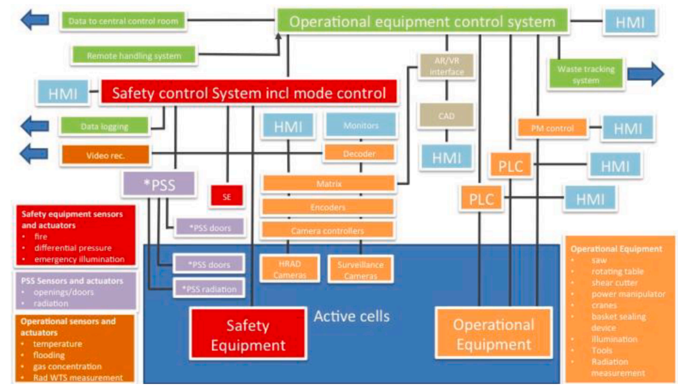

Fig. 2. Schematic layout of progress.

a large-scale and carbon-free source of energy. This project demands great capabilities in terms of remote handling. The RH systems have been designed to be bound together by a common control room. All of them will need to cooperate, be synchronized, share data and resources [9,10]. DONES and ITER RH have many similarities, which translates into a conceptual design that shares many aspects but have significant differences as described in chapter II section D.

Due to the great complexity of this project is necessary to limit the heterogeneity of software tools, control hardware and user interfaces of all devices RH. A set of standard functionalities has been defined and mapped into a standard architecture to avoid these issues. The higher level covers the top-level functions and matches with the interfaces presented to the operator in the RH control room Fig. 3, while the lower one defines the standard structure of the control cubicles. On the software side, GENROBOT provides a common interface between the different low-level controllers and the High-Level Control System.

1.4. CERNTAURO robotic framework at CERN

CERN goal is to probe the fundamental structure of particles that make up everything around us by means of using the most advanced scientific instruments. The remote handling needs at CERN are slightly different from the previous facilities. The size of the building is much bigger and does not contain a hot cell, but instead, a huge quantity of tunnels and corridors needs to be inspected and maintained regularly. This approach does not require such advanced capabilities for telemanipulation considering that the radiation level will be much lower and human intervention is allowed in most cases. However, the capability to perform regular autonomous inspections is a key point to reduce the workload of operators and the accumulated radiation dose received by them.

A new robotic framework is presented in [11] to cover all aspects of a robotic intervention, from the specification and operator training, the choice of the robot and its material under possible radiological contamination risks, to the realization of the intervention, including procedures and recovery scenarios. The level of reliability required by these devices is lower than in previous examples considering the radiation levels (in case of device failure, human intervention is allowed).

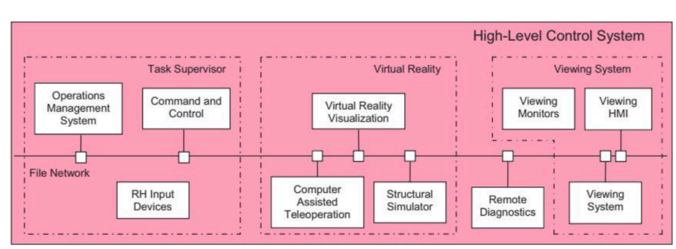

Fig. 3. RH high level control system of ITER.

This allows CERNTAURO to increase the automation degree and reduce the involvement of operators in the control loop by making use of techniques such as autonomous navigation or artificial intelligence, as shown in Fig. 4.

2. Remote handling control system for IFMIF- DONES

The IFMIF-DONES Project aims to create a high energy – high current neutron source like that expected inside a fusion reactor. This radiation will be applied to different samples of materials and will allow their characterization to choose those that offer the best performance for the construction of future nuclear fusion reactors.

Due to the expected radioactivity that will be present in these areas of DONES facility, it will be required RH techniques to manipulate the specimens, maintain the devices inside the restricted areas and perform reparations. The RH methodology to operate in hazardous environments of DONES plant was described in [12].

According to [13], 3 plant systems will require remote intervention: the Lithium System, the Test System and the Accelerator system. Around 35 RH devices are considered to perform such tasks, including cranes, camera systems, manipulators, cleaning tools and transportation platforms. All of them must be unified under a single control architecture that must provide all the tools and functionalities required by the operators. The most important recommendations and requirements that have been considered in the design of the control system are listed below:

- RH Operations will be directed from a dedicated RH Control Room.
- RH Local Instrumentation and Control System (LICS) is one of the DONES LICS, so it must interface with the Central Instrumentation and Control System (CICS) and its architecture must conform to the three-tier I&C system (CODAC System, Interlock Control System, Safety Control System).
- RH Operations may require the presence of a man-in-the-loop for their execution.
- The control of RH equipment, in addition to classical GUIs, may require special Input Devices (3D joystick, Master Arm Device to control a master/slave arm, …).
- The RH CICS must be able to perform scheduled and unscheduled RH activities.
- Remote Handling Equipment (RHE) must be designed to be retrievable, safe, and feasible for recovery and rescue.
- RHE must be designed to perform the maintenance tasks within a set time limits defined by the short (3 days) and long (20 days) maintenance periods foreseen during the yearly schedule.
- RH System must support the parallel operation of different devices in different areas to optimize time consumption.
- The RH System is a system of systems and should be flexible enough to deal with reasonable upgrades to the facility.
- To use of Rad Hard components is recommended in a highly activated environment.
- Visual interaction is a key feature for manipulation and maintenance tasks.

2.1. Two different control systems

Mechatronic systems that allow remote manipulation tasks differ significantly in terms of control requirements for the rest of the subsystems that are controlled by CICS.

In the case of CICS, the devices to be controlled are mainly scientific instrumentation devices that seek to collect data in a coordinated way and industrial (typically PLC, FPGA cards and CPU crates) based systems that execute automated control strategies. In this approach, the engineers of the control system will define the behavior of the system based on events that will trigger actions in a fixed sequence, and the operators will participate by setting parameters and triggering some of these events. Therefore, the interaction between operators and systems will be done using discrete events that will trigger automatic sequences that only require setup points and parameter configuration from the operators being most of the action is fully automated.

On the contrary, for the operation of RH devices, the operator will be an active part of the control loop. The different devices will be used as remote tools controlled or supervised by the operators. This man-in-the-loop approach means that sometimes the operator will take control in real-time (by using haptic devices) of the devices or, at least, will be actively supervising the automated tasks due to the criticality and lack of predetermined structure of the environment. The use of robotic systems implies the need for additional features that cannot be covered by CICS (based on EPICS or similar frameworks for scientific instrumentation) such as visual guidance, virtual reality environment, haptic feedback, motion planning or teach pendant.

This leads towards a framework oriented to the control of mechatronic systems tightly coupled with human interaction. In that way, CICS will perform coarse-grained control tasks (systems coordination at the plant level), and RH LICS will perform fine-grained control (RH device operation).

2.2. Integration within CICS

The core of DONES CICS is the CODAC system, which is in control of

Fig. 4. Central Operating System of CERNTAURO.

the different plant systems and coordinates them. It is currently based on EPICS control framework.

Fig. 5 represents the application of the standard architecture defined by CICS to RH. According to the general approach for DONES subsystems, CODAC shall oversee the following functions:

- Overall monitoring of the LICS.
- Downloading the configuration parameters to the LICS.
- Perform manual operations.
- Perform diagnostics.
- Automated execution of sequences.

RH LICS will be an exception to this general approach due to the limitations of EPICS to control these types of devices. RH LICS shall be considered a semi-autonomous element with a high degree of independence from the rest of the DONES facility. The main reasons are the following:

- The devices used for Remote Handling are mechatronic systems.
- Tasks are not always repetitive, being difficult to apply fully automated sequences due to the continued need for human interaction and supervision.
- These mechatronic systems are complex elements requiring advanced control strategies considering kinematics, pose estimation or collision avoidance.
- RH equipment shall be specially designed for recoverability.
- Mechatronic systems used for RH tasks require in some cases specific interfaces (3d joysticks, master arms, haptic devices) to allow the operator to execute the control in real-time.
- RH operations will be carried out from a dedicated control room. The operations will be coordinated from this room, where the different subsystems shall be arranged creating different work cells that will ease operator interaction to perform complex tasks.
- Visual interaction is vital for manipulation and maintenance tasks.

For these reasons, the proposal is to define an RH LICS with the required specificities to fulfill the previously mentioned requirements.

2.3. Conceptual description of the proposed control system

Considering the prerequisites and the tasks defined in the DONES Maintenance Plan [2], an architecture has been designed to represent the different hierarchy levels in the control system as well as their integration at the plant level:

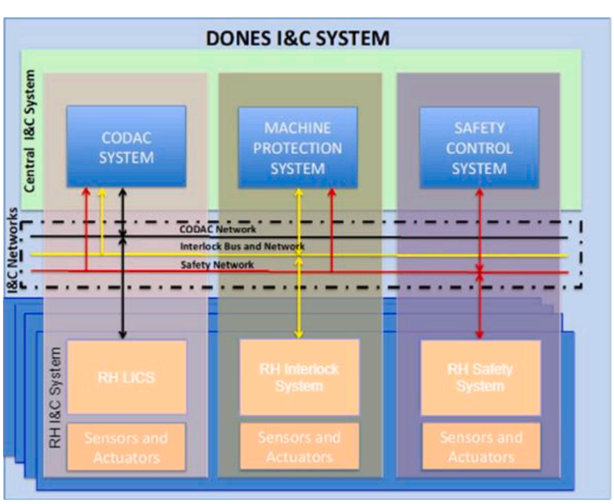

Fig. 5. CICS and RH LICS.

- The lowest level corresponds to the mechatronic devices themselves (manipulators, cranes, AGVs...). At this level, no control electronics are included, only sensors and actuators. They will be in areas with radiation and therefore rad-tolerant / rad-hard components could be required.
- The Cubicle Level contains the control units, electronics for signal conditioning and power supplies. This level also contains specific input devices (i.e., master arm) that are considered part of the control electronics but will be physically located inside the RH Control Room with no radiation.
- The Operational Level allows the implementation of the additional functionality necessary for the operation of the RH systems. It can be mapped to the advanced features required by RH Operators, and will be implemented on dedicated servers or by software tools executed on operator workstations.
- The top level corresponds to the Central Instrumentation and Control System of DONES, which controls and coordinates all the processes in DONES facility. A data flow will be established to allow monitoring and recording of events from the RH LICS on the upstream, as well as sending information with the state of the plant and the necessary maintenance campaigns on the downstream.

Fig. 6 represents the different levels and components for each one. It is necessary to point out that different institutes and companies develop RH devices independently, and each one will use controllers and electronics from different manufacturers. That is why the Operational Level shall provide a set of standard features to all the operators independently of the RH device. These modules represent the different functionalities required in black boxes, and each of them is briefly described below:

- Integration Device: provides a standard interface and communication protocol to all control devices, regardless of the type of device they control or the manufacturer. This will allow using only one tool to develop and standardize the Graphic User Interfaces (GUIs), to use standard commands and provide a homogeneous data format to the other modules.

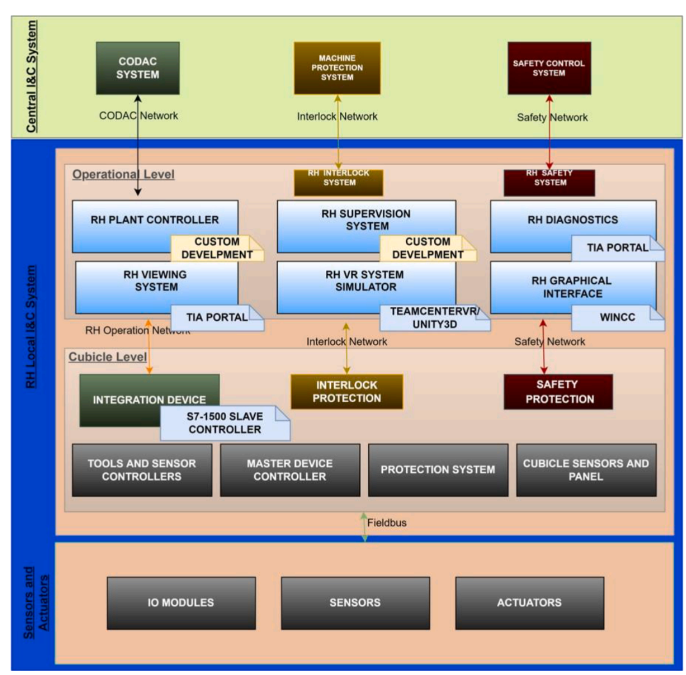

Fig. 6. Control hierarchy of RH LICS.

- Plant Controller: it is the gateway that connects CODAC with the RH Operational Network and exchanges information with CICS by using EPICS CA.
- Diagnostics: it collects monitoring information from device controllers to evaluate the performance of individual device components and raise alarms. This functionality can be accessed by any user from RH Control Room.
- Supervision: it manages the Maintenance Campaigns, checks the RH equipment that can be assigned to the operators and locks the devices to each operator.
- Graphical interface: it contains all the OPIs (OPerator Interfaces) configuration files. This allows the provision of the same version of the GUIs to all the users in the RH Control Room and will ease the maintenance and updating.
- Viewing System: it will receive the video streaming of the cameras from a separate physical network. This video network will be designed according to the bandwidth required to transport the video streaming generated by all the cameras simultaneously. The system shall also provide the user interfaces necessary to select and position the cameras and adjust the different parameters and image visualization.
- VR Simulator: it provides a virtual environment of the operation scenario. It shall be capable of providing offline simulation to prepare and validate operations before the execution. During operation, it shall receive the position in real time of all the devices to represent the virtual scenario and help operators. It shall also provide the user interface required to navigate and configure the required parameters.
- Safety System: It is connected to the Central Safety Control System (SCS) through the Central Safety Network, and to the single RH protection modules through the RH Safety Network. No interface is required with the RH Control Room, in case of activation of any function the CICS will send a notification through CODAC.
- Interlock System: It is connected to the Central Machine Protection System (MPS) through the Interlock Bus and Network, and to the single RH protection modules through the RH Interlock Network. No interface is required for the RH Control Room, in case of activation of any function the CICS will send a notification through CODAC.

2.4. Differences with ITER approach

The proposed architecture exhibits significant conceptual similarity with the ITER one, as the required functionality in both installations is quite similar. However, there is a scale factor that affects not only the facility itself but also the overall project approach:

- Machine complexity: ITER is a more complex installation than DONES [13,14], requiring a greater number of RH devices, many of which have been designed ad hoc. In the case of DONES, most devices have been adapted from industrial solutions to be used in activated environments. This makes it easier to develop control logic based on COST controllers and develop control strategies using agile and well-known commercial tools.
- ITER Organization has the financial capacity and human resources to develop new technologies, while DONES resources are more limited. For this reason, the design of DONES RHCS seeks to reduce integration and development processes by using standard (industrial) technologies.
- DONES RH devices will be "in-kind" contributions from the various countries participating in the project development. The ITER approach implies the use of new technologies and tools that few experts know about nowadays. This would represent an additional overhead to adapt the devices before commissioning, which would be carried out by an in-house team of specially trained engineers or outsourced to external companies.

For these reasons, it has been decided to adapt the ITER control architecture to offer similar functionality and architecture but using technologies and components based on industrial standards, a more cost-effective approach with a limited set of resources.

3. Candidate control frameworks for RH LICS

The main goal of this proposal is to develop an architecture for RH control systems as mature as possible focusing on aspects like interoperability, standardization, reusability and maintainability instead of providing fully custom solutions as it is done in other facilities requiring RH. These features can be improved by defining a set of standard components and tools for the control system together with creating a team of resident engineers capable of updating and upgrading the system. This combination provides the best automation with the best flexibility (provided by humans) and reduces the total costs during the project lifetime.

The seamless integration of the different control cubicles within a common set of software tools at the Operational Level is a key aspect of this RH control system architecture. Four different candidates have been considered for this task: EPICS, GENROBOT, SIEMENS and OPC UA. Table 1 summarizes the main contribution of each of them.

3.1. EPICS

It is the control framework currently proposed for CICS level to interact with the plant systems. EPICS (Experimental Physics and

Table 1
Summary of candidates for RH Control framework.

	Target	*Benefits*	*Drawback*
EPICS	Distributed control for scientific instrumentation (LICS -> CICS)	-Open-source -Real-time - Proposed for CICS	-Outdated base technologies -Not applicable for robotics and industrial control - Reduced community
GENROBOT	Generic robotic controller (Sensors/actuators -> Cubicle)	- Provides a common interface for RH equipment -Designed for RH and telemanipulation	-Still under development -License cost -No community
SIEMENS	Proprietary industrial automation (Cubicle -> CICS)	-Widely used and reliable -Efficient tools for development -Extended community and technical support -Is the base of MPS and SCS	-License cost -Robotics is starting to be considered - Not for customization
OPCUA	Standard industrial automation (Cubicle -> CICS)	-Open standard -Natively implemented in many controllers -Information models for robotics	-Robotics is starting to be considered

Industrial Control System) [15] is a set of open-source tools, developed to create distributed control systems with critical real-time requirements based on a client/server scheme specially designed to be used in facilities such as particle accelerators, telescopes and similar scientific instruments. EPICS also provides SCADA capabilities. Its design is focused on helping to develop systems that often have a large number of networked devices that provide control and feedback to the system. EPICS is designed for controlling automated instrumentation elements but does not provide all the functions required to operate mechatronic devices with highly coupled telemanipulation tasks.

3.2. GENROBOT

The singularity of ITER in terms of RH devices motivates the creation of their own control framework, GENROBOT. It is the ITER generic software controller [14] that offers a common development environment for all RH controllers. It provides a common interface between RH equipment and the upper layers utilizing CIP(Controller Interface Protocol).

This software runs on cPCI controllers and includes libraries for Linux and Windows to interface with the applications of the upper level. It has been specially conceived for use with RH systems, offering great flexibility for integration and tools oriented to telemanipulation. However, it is under development and is not a fully mature solution yet.

3.3. TIA portal

This is the industrial alternative, widely used for the automation of power plants, manufacturing or material handling. The integration device required to make use of Siemens ecosystem should be a PLC from S7–1500 or S7–1200 family. This device can be used directly as the control unit for custom RH devices by adding the required IO peripherals, or as a gateway to interact with others COTS controllers from different vendors. The standard fieldbus used by SIEMENS and natively supported in all controllers is Profinet. TIA Portal is the core of the framework, providing functionality to configure, program, test and diagnose the controllers.

3.4. OPC UA

OPC UA is the interoperability standard for the secure and reliable exchange of data in the industrial automation space and in other industries. It is platform-independent and ensures the seamless flow of information among devices from multiple vendors. As an open standard, OPC UA is based on standard internet technologies like TCP/IP, HTTP and Web Sockets. It also provides a set of services and a basic information model. The OPC Foundation is responsible for the development and maintenance of this standard. Its purpose is to abstract PLC/controller-specific protocols (such as Modbus, Profibus, etc.) into a standardized interface allowing HMI/SCADA systems to interface with a “middle-man” that convert generic- OPC read/write requests into device-specific requests and vice- versa [16].

4. Experimental setup

In our path towards an industrial-like RH control system, the previous analysis shows that two of the frameworks are suitable for the DONES RH use case, SIEMENS and OPC UA. Taking them as a reference, a conceptual design has been made combining both in a modular test bench with two different objectives. First, to test the correct interaction between the previously described modules allowing to increase the dimension and functionalities offered according to the development of the IFMIF-DONES project. Second, to provide a suitable platform to execute remote manipulation tasks, verify their feasibility and train operators. This experiment will provide clear evidences about the interoperability and benefits of using both systems for the RH control.

4.1. Description of the implemented modules

The hardware used, OS and software tools used are briefly described below. Fig. 7 describes the experimental setup, where the modules shaded in blue will be connected to the same LAN (representing the local control system), and those marked in green will be connected to another LAN (representing the central control system of the plant).

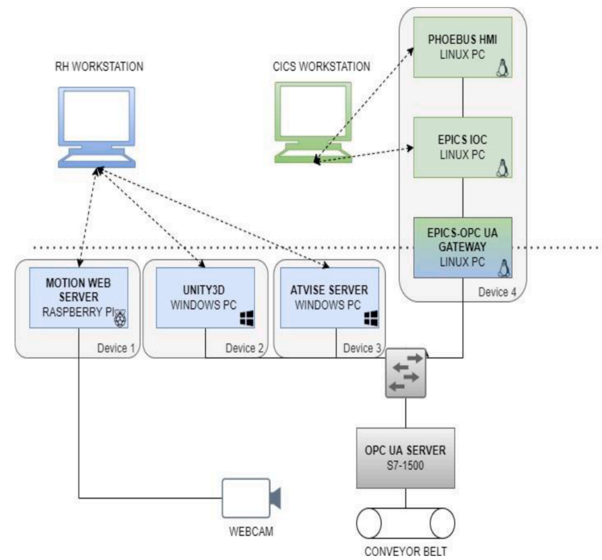

Fig. 7. Experimental setup. Blue boxes represent RH LICS (OPC UA based) and green boxes CICS (EPICS based).

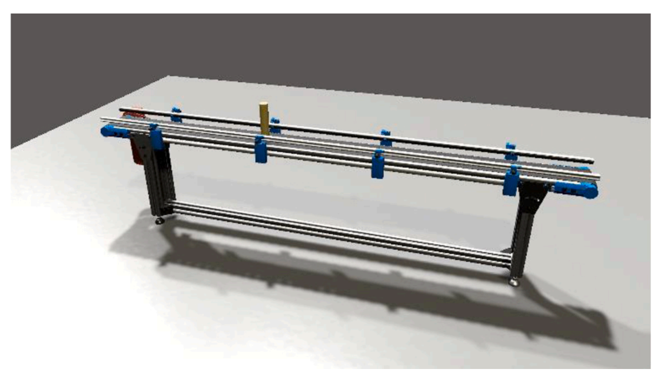

Fig. 8. Unity3D scene representing the real-time status of the belt.

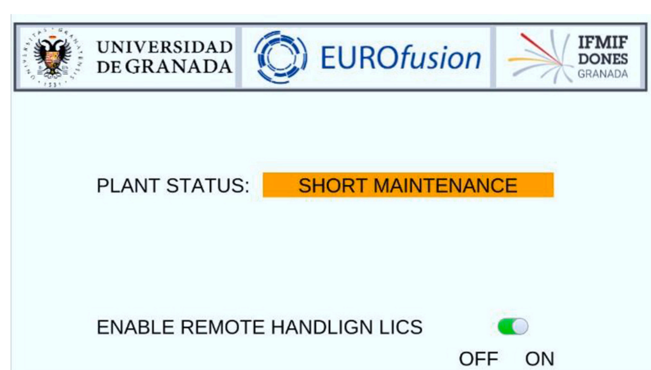

Fig. 9. EPIC HMI mockup for CICS workstation.

A conveyor belt will be the physical device. This device is controlled by a single axis of movement with a Siemens S7 1500 PLC containing an integrated OPC UA server. Each module provides the following:

- Viewing system: video stream provided by TCP/IP Motion Web Server running on a RaspberryPi 3B+ (device 1). Two different cameras can be selected.
- VR Environment (Fig. 8): virtual scene created on Unity3D containing the CAD model of the conveyor belt running on a Windows 10 PC (device 2).
- EPICS-OPC UA gateway: custom made program running on Linux PC (device 4) to connect the top control level (EPICS based) and the low control level (OPC UA based).
- EPICS IOC: it enables Channel Access and manages the input/output of Process Variables (PVs). Running on a Linux PC (device 4).
- EPICS HMI (Fig. 9): it provides a panel to the user to enable/disable operations on the low control level. Running on Linux PC (device 4).
- SCADA (Fig. 10): OPC UA server from Atvise [17] running on a Windows 10 PC (device 3). Enables HMIs, Alarms, Events, Historical Data Access and Access Control configuration based on OPC UA specifications. The interfaces are HTML based, making it possible to access from any device with a web browser.

4.2. Latency estimation

The glass-to-glass (G2G) latency is the amount of time it takes for a single frame of video to transfer from the camera to the display.To assess G2G latency, a setup proposed in [18] was employed. A USB webcam Logitech C505 was connected to a Raspberry Pi 4B running Motion 4.3.2 software. Motion was configured to capture a maximum video streaming of 1280 × 720 and 25 frames per second, with all pre-processing capabilities disabled. Additionally, a Windows 10 Pro laptop was prepared with the Arduino IDE 1.8.5, as well as a workstation with the same operating system running a Google Chrome web browser version 111. An Ethernet connection was established between the workstation and a Huawei AX3 router, which was also connected to the RPi. The webcam video stream could be displayed on the workstation by knowing the RPi IP address and the Motion TCP port.

An Arduino Mega 2560 was prepared using the components illustrated in Fig. 11. The white LED was positioned in front of the webcam at a distance of 30 cm, while the phototransistor (PT) was positioned perpendicularly in front of the workstation display at a distance of 1 cm, just in front of the screen area displaying the LED. The Arduino software turns the LED on and attempts to detect it. The only modification was the inclusion of a 2 ms delay between the PT readings due to the PT's high-speed sampling. If the PT could not detect the LED brightness after 3 s, a new iteration was initiated. A total of 750 samples were recorded. As a reference, the latency between the LED and the PT was also measured with no intermediaries or added delay, resulting in a mean value of 16 microseconds.

5. Results

The development of this demonstrator has proven the benefits of using an industrial standard and commercial tools for Remote Handling tasks. The compatibility of all the modules has been provided by the use of OPC UA, and the integration between them has been reduced to configuring basic parameters (server IP and credentials). In addition to simplifying the communication layer and simplifying integration, OPC UA provides a series of services that have been very useful for the development of the SCADA shown in Fig. 10 (management of users, sessions, alarms and conditions, historical data...).

In addition, some metrics on the network and communications have been obtained. To characterize the local network, the G2G latency has been measured and represented in Fig. 12. The average latency measured for the video traffic (encapsulated over HTTP) is 141,859 ms (standard deviation of 17,96).

It is important to remark that our setup was based on non-real-time OS (Win10 for the laptop and the workstation, and Debian-based Linux for the RPi), so it is not possible to guarantee a latency maximum threshold. Anyway, latency requirements are closely linked to the task to perform. For instance, for teleoperation tasks involving object placement, grasping, tracking and 3D tracking, latency is not a problem, but the frame rate [19]. However, for surgical telemanipulation, the latency is a notable metric, covering from a maximum threshold of 105 ms (laparoscopy surgery) to a more relaxed limit of 300 ms (cutting, stitching and knotting) [20,21]. For robotic telepresence, however, 125 ms is considered the maximum acceptable delay [22]. The current G2G measured values are slightly above so future work may require some optimizations. In contrast with those values, people are capable of detecting latencies as low as 15–20 ms [23].

Apart from that, bandwidth has been analyzed using Wireshark to monitor the traffic between a simulated OPC UA server and Unity3D. Reading a double variable (8 bytes) requires sending a ReadRequest of 190 bytes and a ReadResponse of 140 bytes. Fig. 13 shows the bandwidth occupied by subscribing to 6 doubles variables in Unity3D at a

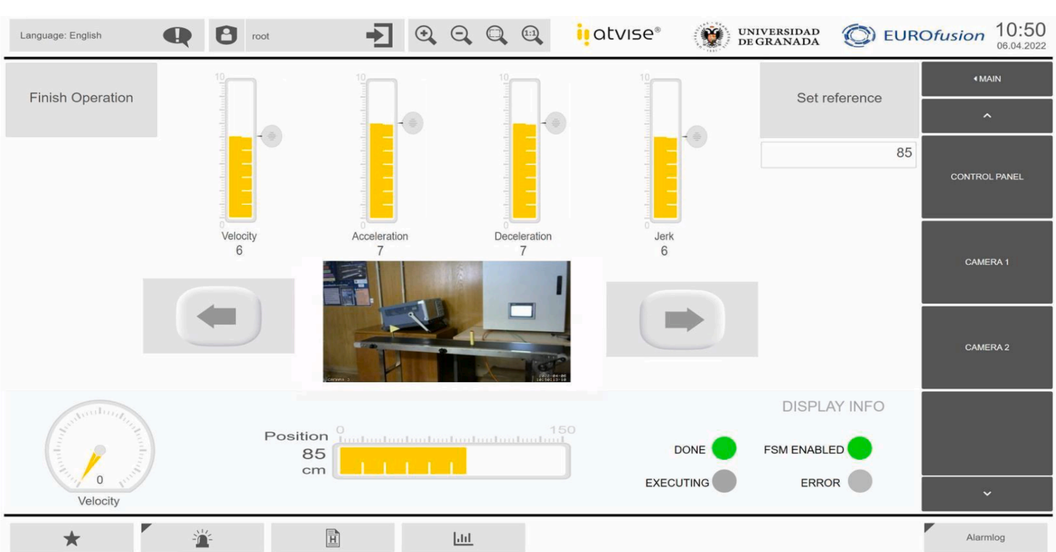

Fig. 10. Atvise SCADA for real time operation of the belt.

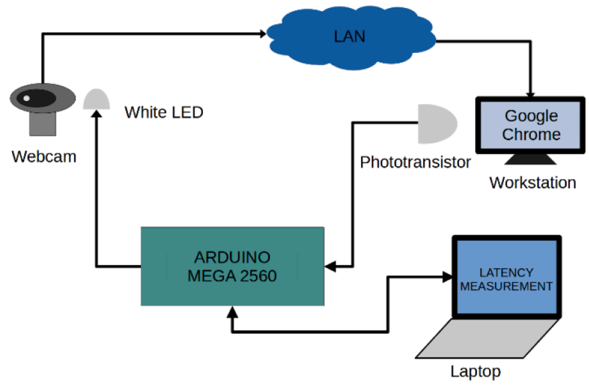

Fig. 11. Diagram for Glass-to-glass latency measurement system.

rate of 60fps (each variable is requested every 16 ms).

Based on these data, we can estimate that for a 1 Gbps network where we leave a 30% network overhead, we could accommodate up to 4375 double-type variables @ 60 Hz. Considering the 35 RH devices estimated for DONES project, and a worse case of 10 DoF for each device, the estimated bandwidth for real-time synchronization of the VR is 55,44 Mbps, all values that perfectly fits on the proposed technologies capabilities and that demonstrate the large scalability of the current technical solution.

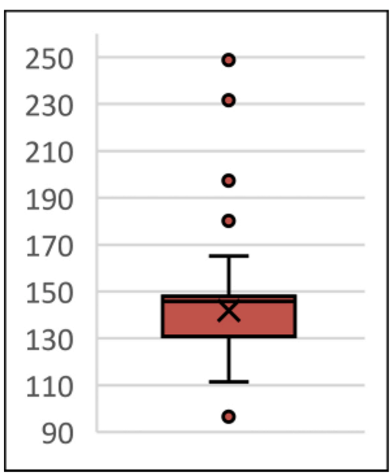

Fig. 12. Box and whiskers diagram for G2G latency in milliseconds (750 samples).

6. Future work

The next steps require clarifying many operational aspects of DONES RH. Through the definition of use cases, high-level requirements can be inferred to serve as a basis for the definition of networks, communication protocols, roles, control room design, etc... This topic has been identified by the project organization as a critical point that will be addressed on the next year of the IFMIF-DONES activities.

The control system shall provide tools to schedule and plan maintenance campaigns, define the operation sequences, coordinate parallel operations, assign resources, and report the progress of the RH tasks. Structured languages could be highly beneficial for this task as shown in [24] and will be studied and included in future demonstrator upgrades.

OPC Foundation is working on the definition of new specifications in close collaboration with leading companies from the industry. Some examples are the OPC UA Field eXchange (UAFX) Specifications [25], which lay the groundwork for using OPC UA at the field level, or the OPC UA Robotics Companion Specification [26], which defines an OPC UA information model for robotics communication. These advances combined with Pus/Sub or other technologies such as TSN will extend the applicability of OPC UA from higher control levels (the main focus of this publication) down to the low level control.

7. Conclusion

In this paper, the different RH concepts adopted in relevant scientific facilities have been analyzed, showing that there is no common approach and that most of them are custom-made to suit facility needs.

An analysis of the use case of IFMIF-DONES has been carried out, proposing the main requirements of the installation and identifying possible frameworks capable of satisfying them, reducing integration efforts and allowing the high-level control system to be homogenized.

RH control architecture has been defined with the focus of using as much as possible industrial and well-proven standards that can be properly integrated with the human-in-the-loop RH requirement. Different middleware control communication frameworks have been analyzed as one of the key goals to achieving practical implementation of such architecture.

Finally, an evaluation setup has been implemented based on OPC UA

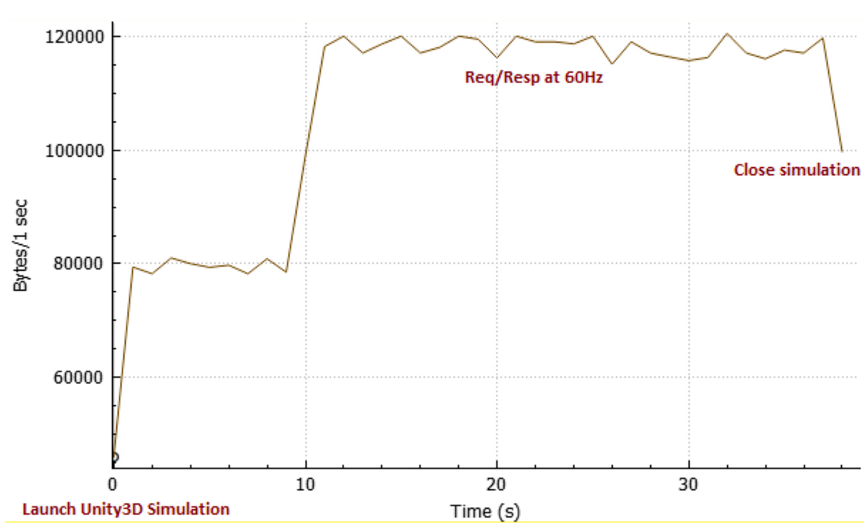

Fig. 13. Bandwith consumption for 6 double @60 Hz over OPC UA.

as the central decision to evaluate. This technology has been validated by implementing an experimental setup that will be extended with different physical machines and new modules. The result shows very positive features of OPC UA for interoperability reasons, support of industrial devices, scalability and simplicity. Furthermore, as already stated, there is significant ongoing work (at the industrial and scientific level) to extend this protocol and include robotics features. The setup here proposed allows concluding that OPC UA is a clear target element toward a much more industrial RH control system realization and that it should be incorporated into IFMIF- DONES control elements.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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