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OPERATIONAL CONTROLS FOR ROBOTS INTEGRATED IN ACCELERATOR COMPLEXES

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Abstract

The fourth industrial revolution, the current trend of automation and data interconnection in industrial technologies, is becoming an essential tool to boost maintenance and availability for space applications, warehouse logistics, particle accelerators and for harsh environments in general. The main pillars of Industry 4.0 are the Internet of Things (IoT), Wireless Sensors, Cloud Computing, Artificial Intelligence (AI) and Machine Learning. We are finding more and more ways to interconnect existing processes using technology as a connector between machines, operations, equipment and people. Facility maintenance and operation is becoming more streamlined with earlier notifications, simplifying the control and monitor of the operations. Core to success and future growth in this field is the use of robots to perform various tasks, particularly those that are repetitive, unplanned or dangerous, which humans either prefer to avoid or are unable to carry out due to hazards, size constraints, or the extreme environments in which they take place. To be operated in a reliable way within particle accelerator complexes, robot controls and interfaces need to be included in the accelerator control frameworks, which is not obvious when movable systems are operating within a harsh environment. In this paper, the operational controls for robots, integrated in accelerator complexes at the European Organization for Nuclear Research (CERN), is presented. Current robot controls at CERN will be detailed and the use case of the Train Inspection Monorail (TIM) robot control will be presented.

INTRODUCTION

Maintenance and availability for space applications, warehouse logistics, particle accelerators, and harsh environments in general, increasingly rely on automation and data interconnection thanks to advancements in technology and the Industry 4.0 revolution [1]. Nuclear plants like Fukushima [2], fusion reactors like ITER [3], and particle accelerator facilities [4], such as the European Organization for Nuclear Research (CERN) [5], the European X-ray free-electron laser (XFEL) [6], or FERMILAB [7], present harsh environments, several kilometers of underground and semi-structured accelerator areas with thousands of different items of equipment which need to be inspected and maintained often through remote interventions to decrease human exposure to hazards and reduce intervention time.

Mechatronics and robotics have undergone several evolutionary steps over the past years [8], but particle accelerator environments present particular constraints, such as accessibility, long distances, communication possibilities with installed equipment, unknown objects and occlusions in

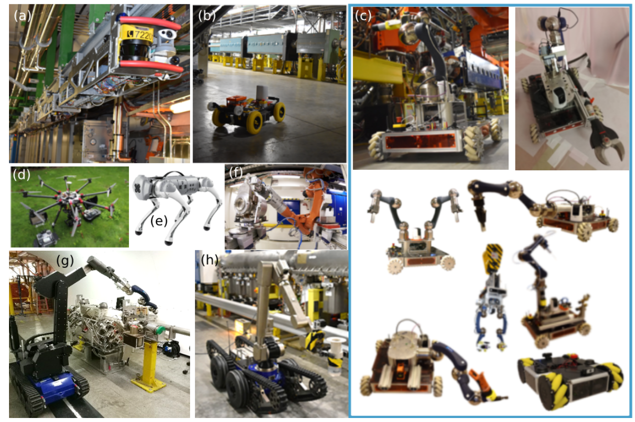

Figure 1: Overview of CERN's robots: (a) Train Inspection Monorail (CERN-made), (b) EXTRM robot (CERN-controlled), (c) CERNBot in different configurations (CERN-made), (d) drone for tele-op support, (e) quadrupeds for challenging terrain, (f) high-payload industrial arm for milling and repetitive tasks, (g)TEODOR robot, (h) Telemax robot.

cluttered areas. In addition, the equipment is delicate and expensive, thus in most cases, equipment owners and/or machine experts must operate the robots. This aspect requires a remote robotic system with a user-friendly Human-Robot Interface (HRI) that augments the proprioception [9] of the person assigned to its control and/or monitoring, sometimes also needed for autonomous systems. To improve their awareness a robot's environment, operators should have seamless information of the robot's environment, position, joint angles, velocities, torques and forces fundamental to teleoperation tasks.

Industrial robotic solutions are assigned to repetitive work without much modularity or intelligence and are not adapted to harsh or semi-structured environments. Operating robots for maintenance in dangerous environments on costly machines requires skilled and well trained, dedicated shift operators [10] and specific controls infrastructures. To be operated in a reliable way robot controls and interfaces need to be included in the accelerator control frameworks, which is not obvious when movable systems are operating within a harsh environment [11, 12]. Human robot communication is a fundamental aspect for the success of remote missions, and the communication channels used (e.g. WiFi, 4G, radio etc.) are key points to be addressed when designing robotic controls [13]. Table 1 shows possible connection types between a robot and the operator's computer, while Table 2 indicates the bandwidth and standard deviation, round-trip time, and jitter for all connection types.

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Table 1: Connection Types Between a Robot and Operator

Network connection type	Robot side's connection	Interconnection	Operator's computer
Ethernet cable directly	Ethernet cable connector	Single cable	Ethernet cable connector
Ethernet over CERN GPN	Ethernet cable connection to CERN General Purpose Network	CERN General Purpose Network cabled indrastructure	Ethernet cable connection to CERN General Purpose Network
VPN 4G modem in the LHC tunnel	4G modem	Network operator 4G connection in the LHC tunnel, VPN connection to CERN General Purpose Network cabled infrastructure	Ethernet cable connection to CERN General Purpose Network
Wi-Fi over CERN GPN	Wi-Fi connection to CERN General Purpose Network Wi-Fi infrastuture	CERN General Purpose Network cabled infrastructure	Wi-Fi connection to CERN General Purpose Network Wi-Fi infrastructure

Table 2: Bandwidth and Standard Deviation, Round-Trip Time, and Jitter Measurements for All Connection Types

Network connection type	Downlink bandwidth [Mbps]	Round-trip time [ms]		Jitter [ms]	Bandwidth standard deviation [Mbps]
		Bandwidth usage = 0%	Bandwidth usage = 100%		
VPN with 4G modem	11.99	43.4	131.5	26.00	0.61
Wi-Fi over CERN GPN	73.95	20.33	30.3	5.64	17.88
Ethernet over CERN GPN	885.8	0.04	1.61	0.19	38.1
Ethernet cable directly	941.8	0.24	1.47	0.28	0.42

Although progress has been made, there is much work left in deploying mobile manipulators in harsh and semi-structured environments. In the following sections, the operational robotic controls which are integrated into the accelerator infrastructure at CERN is presented, and a use case on the TIM robot [14] control will be shown.

ROBOTIC OPERATION AND CONTROL AT PARTICLE ACCELERATORS

Remote interventions in particle accelerators are used to ensure safety and increase accelerator up-time through punctual or preventive maintenance. At CERN, robots for remote inspection and maintenance are designed and controlled using our CERNTAURO framework [15], a novel in-house solution based on a core-periphery design, guaranteeing modular interfaces [16]. Figure 1 shows an overview of the robots under the responsibility of the robotics service at CERN [17, 18].

This service has carried out more than 1000 robotic operations over the last 8 years, operating robots for more than 1500 hours. Figure 2 shows the architecture of the robot control framework, which provides control and monitoring capabilities to expert operators and equipment experts, including perception [19–21] and multi-robot controls [22]. Many in-situ, challenging tasks, like cutting, screwing, sewing etc. have been performed, significantly reducing the radiation dose to personnel, and improving accelerator availability (Figure 3). However, this framework it is not suitable for accelerator operators as is not integrated in the accelerator control infrastructure [23, 24], for example not providing the possibility of logging key data [25].

CONTROL DESIGN AND INTEGRATION

Figure 4 shows the control scheme for the robots integrated in the accelerator controls infrastructure. Embedded control solutions are managing the robot low-level control, status and missions performed in the tunnel. The tunnel-surface communication is guaranteed using a 4G router that,

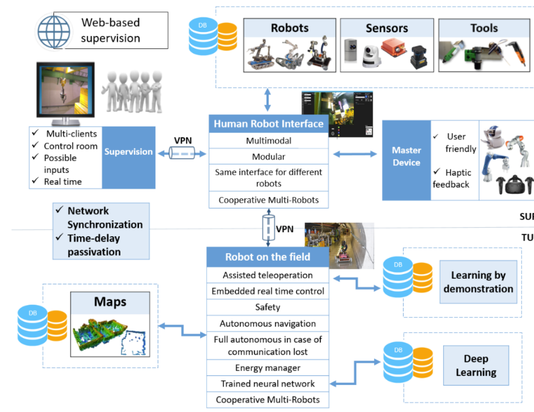

Figure 2: CERNTAURO framework architecture. The robot has an onboard intelligent control featuring capabilities like autonomous navigation and energy management.

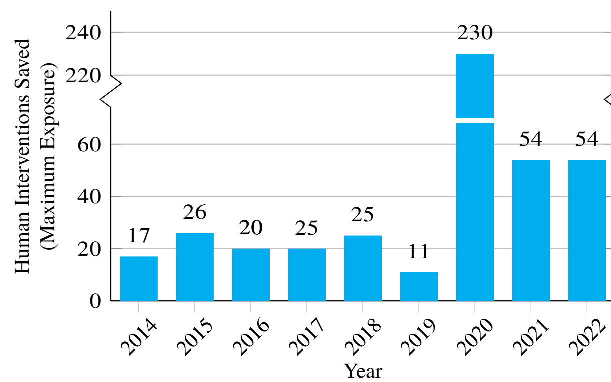

Figure 3: The equivalent number of human interventions saved with robotic interventions assuming maximum annual exposure.

through a VPN, is made visible from the CERN technical network. In case of 4G communication interruptions a LoRa connection is used as backup to send low-bandwidth commands and any hardware restart procedures. Front End Computers (FECs) and expert-operator computers join the robot's VPN to access and connect services hosted on the robot's local-network. FECs display and log robot parameters and forward services such as video or audio streams to make them available from the CERN middleware on the CERN Technical Network (TN).

OpenVPN clients are running for user interfaces and FECs, and display and log relevant parameters in the CERN central database NXCals. The back-end of web-applications are hosted in containers running in a trusted Kubernetees (PaaS) cluster hosted on the CERN General Purpose Network (GPN) that has elevated privileges to access CERN middleware services available on the CERN TN.

To lower the bandwidth load on the robot's local-network and on resource constrained up-links such as 4G networks, a dedicated camera streaming service has been designed and implemented. Its main purpose is to reduce and con-

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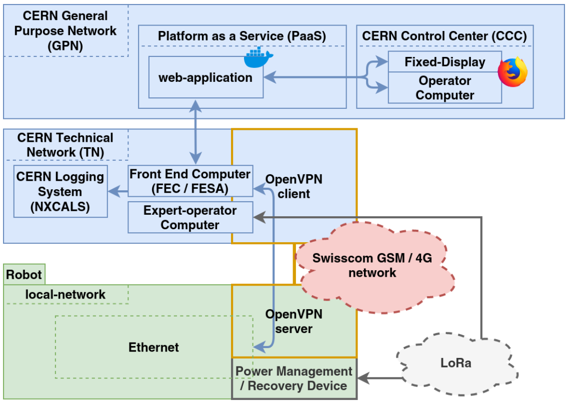

Figure 4: Control scheme for the robots integrated in accelerator controls infrastructure.

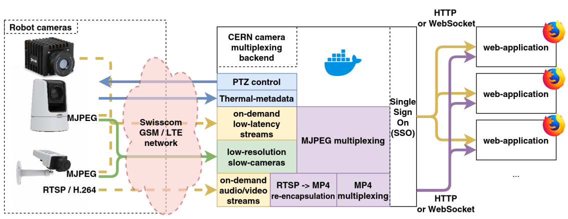

Figure 5: Novel framework developed for camera images streaming from the TIM robot.

trol the number of connections made to the field network, prioritizing and multiplexing the streams to the browser-based client applications. This multiplexing service has been implemented to support both low-latency streams using MJPEG, and multi-media streams using RTSP / H.264. It includes advanced features such as Pan Tilt Zoom (PTZ) control, augmented streams with thermal-metadata, vision-depth, and more. The multiplexing service is hosted as a containerized service on the Kubernetees infrastructure (PaaS) providing additional security by separating the field-network devices and managing device authentication. It nevertheless still provides a flexible security mechanism by protecting its own interface through the CERN Single Sign On (SSO) authentication. Figure 5 shows the architecture for the novel video streams framework.

OPERATIONAL CONTROLS OF TIM

The TIM robot system is a battery-powered vehicle [26] that runs on a monorail in the Large Hadron Collider (LHC). TIM is composed of multiple wagons (Figure 6), each with a length of 180 cm that can be adapted to different needs. Due to the dimensions of the LHC ventilation and sector doors apertures in which TIM has to pass, the TIM cross section is limited to 30 x 30 cm. Different mechatronic systems are deployed from TIM according to the needs of the mission. Figure 7 shows the TIM operator control scheme. Embedded PLC-based control solutions and compact PCs running Ubuntu manage the robot control, status and missions performed in the LHC tunnel. Figure 8a shows the web based HRI with information related to the robot status

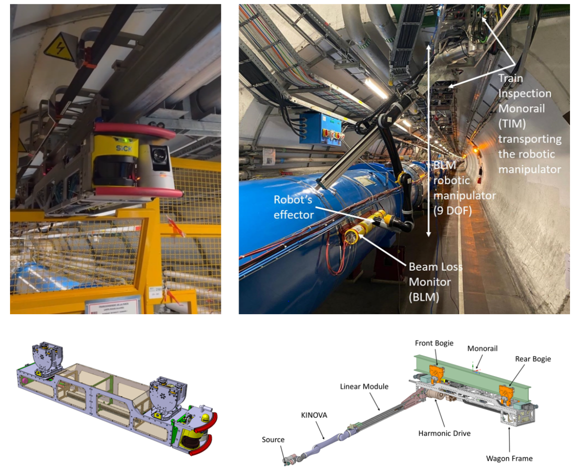

Figure 6: TIM robot passing the LHC sector doors (top left), 3D view of a TIM wagon (bottom left), 9 degrees of freedom robotic wagon (top right), 3D view of the robotic wagon (bottom right).

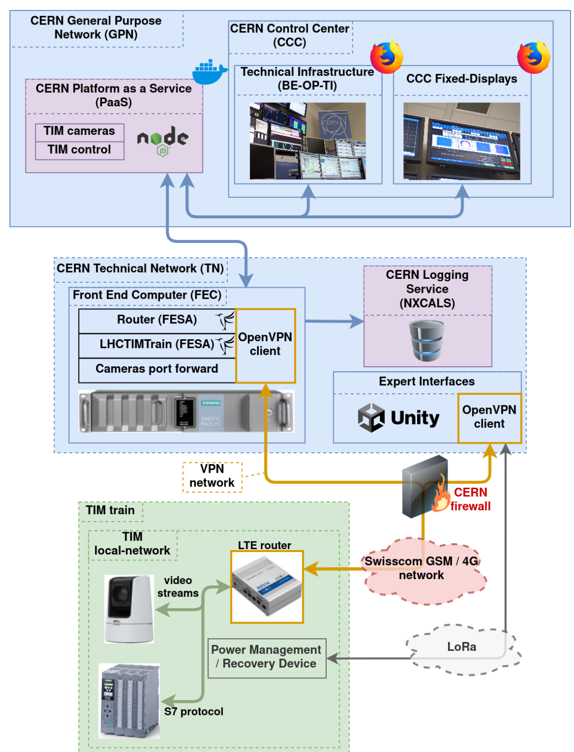

Figure 7: TIM operation general overview.

and communication coverage, including the current position of the TIM robot in the LHC.

Figure 8b shows a tab of the HRI showing the live cameras from the TIM installed in the tunnel, while Figure 8c shows the four TIM localization interface tab, that indicates the position of the four TIM in the tunnel including their battery charging status.

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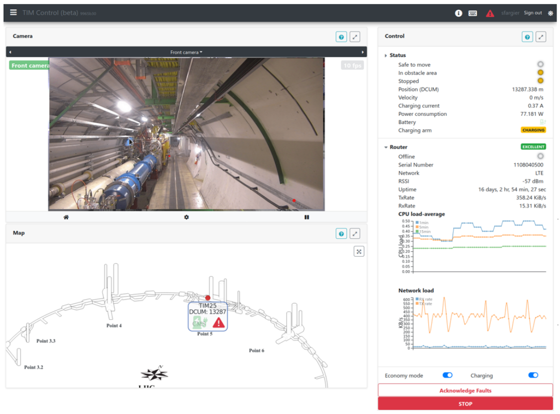
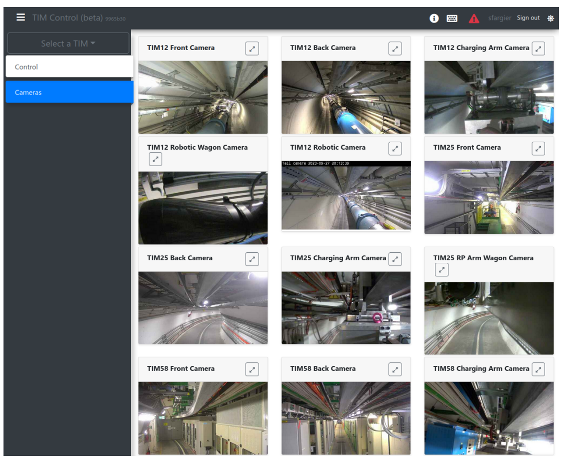


(a)



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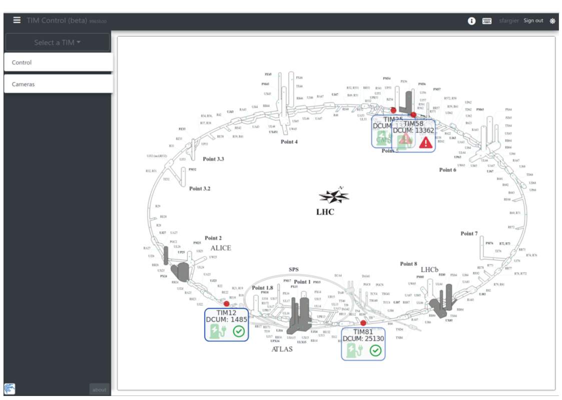
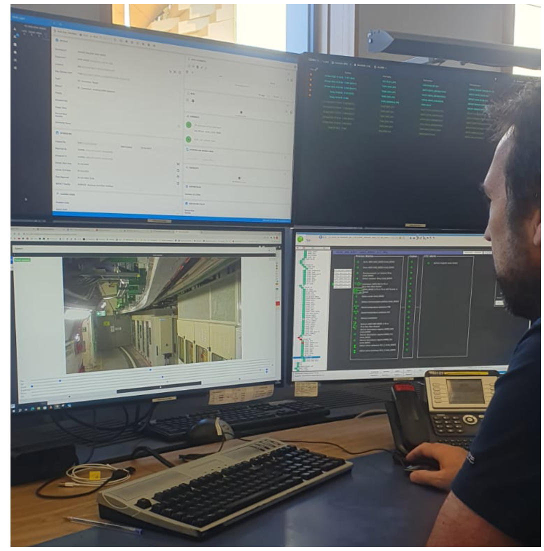


(c)

Figure 8: TIM GUI examples: (a) HRI main tab showing one camera, robot position in the LHC and live robot information, (b) TIM operator tab showing feed from integrated TIM camera, and (c) TIM operator tab showing the position of the four TIM robots operational in the LHC.

SUMMARY

A novel robotic framework integrated within accelerator controls for the inspection and maintenance of particle accelerators has been developed and is currently in operation at CERN on four TIM robots within the LHC (Fig. 9).



(a)

(b)

Figure 9: Robotic operators: (a) using the TIM web interface integrated within the LHC technical island of the CERN control center, and (b) wearing enhanced reality devices controlling the TIM robot with the 3D Mixed reality interface [12] in the CERN Control Centre.

The control chain and the operator interface have proven to be operationally ready at Technical Readiness Level 8, and was validated through successful demonstration in single and multi-user missions. In the future additional robots could be controlled by accelerator operators for remote inspection and environmental measurements [27]. In addition, tele-operation tasks [28, 29] for remote maintenance that are currently performed by expert robotic operators could in future be driven and/or supervised by accelerator operators by integrating advanced robotic algorithms and shared controls. The project will profit from the return of experience for the rest of LHC RUN3 to drive possible future robots designs targeted for accelerators maintenance needs [30, 31].

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