CRANEBot: Teleoperated Crane-Suspended Robotic System for Inspection and Manipulation in Harsh Environments

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Abstract: The need to perform operations from above has become one of the primary challenges that robotics must address in recent times. At CERN, high-intensity hadron colliders and fixed target experiments increasingly require robotic telemanipulation to prevent human personnel from being exposed to radioactive environments. In this article, we propose a modular robotic system called CRANEBot, which is transported by cranes. This system enables operations from above, allowing for extended sessions of inspection, manipulation, and remote handling at variable heights with minimal impact on the external environment. The system operates using a robotic framework that enables communication with its hardware components and is controlled by a teleoperator through a graphical interface. The proposed functionalities have been tested and validated in multiple robotic interventions.

1 INTRODUCTION

The development and deployment of robotic technology in hostile environments has received considerable attention in recent years. Key applications include space exploration, nuclear inspection and decommissioning, offshore energy maintenance, underwater inspection and deep mining (Bellingham and Rajan, 2007), (Trevelyan et al., 2016). In all these application areas, the robot is the ideal candidate to replace skilled personnel, both to eliminate the risk related to human health and to increase productivity. At the European Organization for Nuclear Research (CERN), the world's largest high-energy physics laboratory, robotics fits exactly into this context. At CERN there are more than 70 km of underground tunnels and multiple fixed target experiments, with thousands of items that need to be inspected, monitored and maintained. The radiation from particle collisions and the high magnetic field are major risk factors for human operators. The use of robots in CERN's semi-structured and unstructured environments is particularly challenging (Di Castro, 2019): the specific environments in which robots have to operate led to the need to design ad-hoc solutions with high level of dexterity that are not available on the market. Maintenance and inspection work at CERN can require both ground (Di Castro et al., 2017), (D'Ago et al., 2022) and overhead operations (Di Castro et al., 2018b), (Gamper et al., 2021), (D'Ago et al., 2024).

The necessity of conducting operations from above is one of the primary challenges that robotics is increasingly being called upon to address. Examples include the inspection and maintenance of difficult-to-access sites and structures, such as bridges (Dorafshan and Maguire, 2018), (Ivanovic et al., 2021), power lines (Cacace et al., 2021), and pipe arrays in chemical plants (Suarez et al., 2020a). A solution to these challenges is provided by the expanding field of Unmanned Aerial Manipulators (UAM) (Ruggiero et al., 2018), (Ollero et al., 2021). This field combines aerial vehicles, such as drones, with manipulators, enabling not only visual inspection but also the execution of manipulation tasks at significant heights and over extended distances. Other examples of robotic activities from above include the inspection and dismantling of nuclear sites, for which the most com-

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Figure 1: CRANEBot, crane-suspended robotic system in its dual-arm configuration.

monly used solutions are once again drones (Jiang et al., 2018) or robotic systems suspended from above using cable systems (Yokokohji, 2021). Overhead operations are also a fundamental aspect in the latest installations for nuclear fusion research, where it is necessary to perform remote handling operations in highly radioactive zones. In this case, the most commonly used solutions consist of long-reach manipulators (Ribeiro et al., 2011), or industrial manipulators connected to telescopic structures extending from the ceiling (Haines et al., 2014).

However, the robotic solutions presented are inadequate when the following conditions occur simultaneously:

- The operating environments are unstructured, and the height of operation is variable;
- There is a requirement to perform not only visual inspections but also heavy remote manipulation tasks;
- The total operation time can be considerably high;
- It is essential to minimize environmental contamination, especially in areas with radioactive dust.

Furthermore, the presented systems typically suffer from the disadvantage of having a limited workload capacity. As a result, they are unable to perform handling, installation, and dismantling tasks through a single robotic system in one operational phase.

We propose the mechatronic design and control architecture of a modular robotic system named CRANEBot, shown in Fig. 1, which allows operations from above and extensive inspection, manipulation and remote handling sessions at varying heights with minimal impact on the unknown external environment.

2 RELATED WORKS

This section aims to present the state of the art in robotic systems for inspection and manipulation from above. Robotic systems can be categorised into two primary classes based on their operational environments: (i) systems designed for structured or semi-structured environments, where environmental knowledge can be utilised to grant the robot a high degree of autonomy, and where the robot often integrates seamlessly with its surroundings; (ii) systems intended for unstructured environments, where the robot does not inherently integrate with its surroundings from a design perspective.

The first category includes numerous robotic systems designed for operations from above, commonly used in big science facilities. In (Di Castro et al., 2018b), a robotic system employed at CERN, known as the Train Inspection Monorail (TIM), is presented. This system entails a train that moves along an overhead monorail within the Large Hadron Collider (LHC) tunnel, which comprises several modules including a wagon designed for overhead manipulation, equipped with robotic arms for handling and measurement tasks from above, as illustrated in Fig. 2a. In (Gamper, 2024), a study is presented on the development and deployment of a robotic system within the 100 km-long tunnel of the Future Circular Collider (FCC) at CERN. This system comprises a trolley mounted on a double rail, capable of bidirectional movement. Attached to the trolley is a 9-degree-of-freedom robotic arm, enabling inspection and manipulation tasks from above. These functionalities are crucial for reducing human intervention in such an extensive workspace. In (Graves and Dayton, 2011) and (Haines et al., 2014), the robotic system utilised at the Spallation Neutron Source (SNS), a nuclear fusion facility characterised by high radiation levels, is presented. This system, depicted in Fig. 2b, is meant to handle and place experimental samples within the SNS instrumentation. The system is a telerobotic dual-arm servomanipulator mounted at the end of a vertical telescoping boom, which is in turn attached to a traversing gantry. The system at the European Spallation Source (ESS) (Gahl, 2015) is used instead for remote handling within the Active Cells Facility. It consists of a dual-arm system suspended on rails at an approximate height of 7 meters from the ground and connected via a telescopic boom. However, all the presented systems are closely tied to their operational environment both in terms of functionality and design, which limits their use in an unknown environment.

To overcome this limitation, one possibility is offered by aerial platforms such as drones, which are ideal for working in unknown and unstructured environments. These systems are capable of being positioned throughout the whole three-dimensional space. They are well-suited for outdoor visual inspection (Falorca et al., 2021), and recent research allows their use even in GNSS-denied environments (Mostafa et al., 2018). When interaction with the environment is needed, manipulators can be installed underneath the aerial platform (Ollero et al., 2021). However, the rigid coupling of manipulators with drones may prove inadequate for maintaining a safe distance between the rotors and the area to be inspected. Therefore, the trend is to separate the manipulation structure from the transport structure using rigid rods (Suarez et al., 2020b) or cables (Miyazaki et al., 2019), (Lee et al., 2020). An example of this type of solution is provided in Fig. 2c. Despite being an excellent solution for inspection and manipulation tasks in unknown environments, these systems encounter three significant limitations: (i) their inability to execute heavy manipulation tasks (such as screwing, sewing, bolting, etc.) due to the presence of an unconstrained floating suspension platform; (ii) diminished operation times due to the restricted space for batteries within the aircraft and the energy expended in flight management; (iii) the potential dispersal of contaminating particles if radioactive dust is present in the environment, facilitated by the airflow generated by the rotors.

The limitations outlined are partially addressed by solutions conceptually akin to the one devised for the dismantling of the chimneys of Units 1/2 exhaust stack at the Fukushima nuclear reactor (Yokokohji, 2021), as depicted in Fig. 2d. This system consists of a large lifting beam containing all the electronics to power and control multiple Staubli industrial manipulators capable of cutting the chimney. In this scenario, the benefits associated with the capability to operate in an unfamiliar environment despite the absence of inherent integration with the surroundings are facilitated by the option to link the system to a standard crane. This crane then positions and lowers the system to the desired height. Nonetheless, the system presented is oversized for the requirements of indoor facilities necessitating narrow spaces.

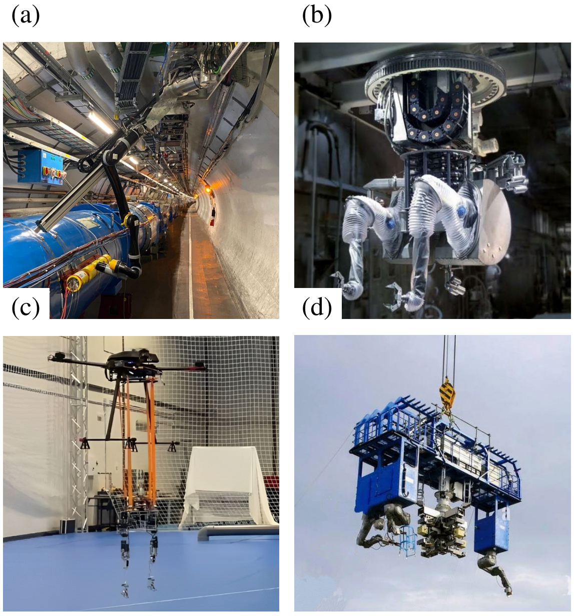

Figure 2: (a) Long-reach robotic arm mounted on the Train Inspection Monorail inside CERN's LHC tunnel. (b) Telerobotic dual-arm servomanipulator mounted on a telescopic boom at SNS[1]. (c) UAM for bird-diverter installation on power lines, with drone and dual-arm system connected via four ropes. (d) Multi-arm system mounted on lifting beam hoisted by cranes for decommissioning of Fukushima nuclear site[2].

To date there is no robotic system in the literature capable of performing both inspection tasks and time-consuming heavy manipulation tasks in unstructured environments (indoors and outdoors), with the need to access narrow spaces with variable heights and with minimal impact on the external environment.

3 ROBOT DESCRIPTION

This section is intended to provide the functional and mechatronic specification of the CRANEBot robotic platform.

3.1 Functional Specifications

This robotic system allows the execution of tasks at considerable heights by leveraging lifting systems (e.g. overhead and tower cranes), hence being capable of tackling all those manipulation and inspection tasks in areas inaccessible to ground robots (wheeled and legged). In the specific setting of CERN, where

[1]Courtesy of Oak Ridge National Laboratory
[2]Source: Tokyo Electric Power Company Holdings

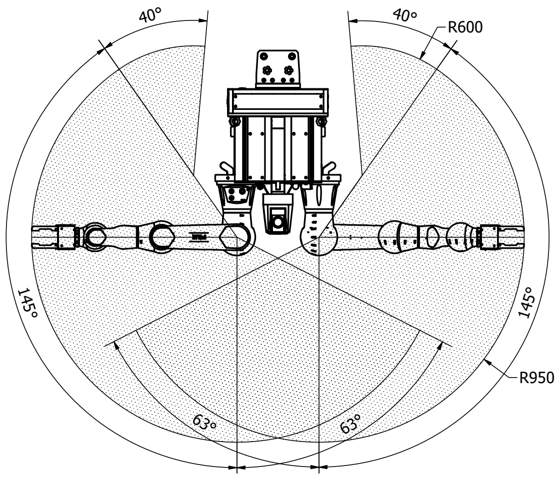

Figure 3: Robot workspace with grippers installed on the end-effectors.

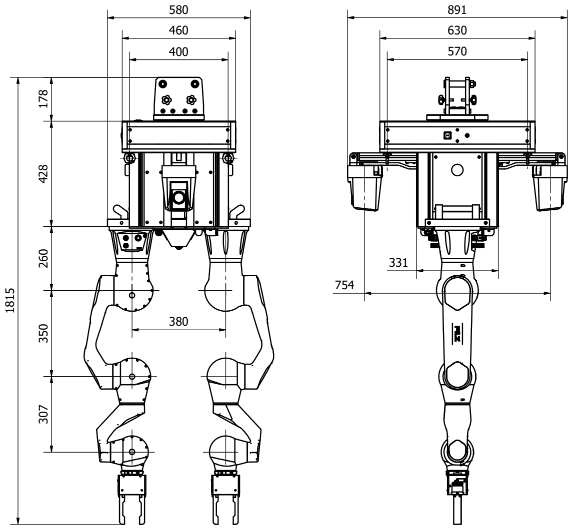

Figure 4: CRANEBot dimensions.

the system is currently deployed, the robot's activities primarily occur within hazardous areas. This hazard stems from the radioactivity generated by the particle accelerator, as well as the complex nature of the manipulation and inspection tasks, which pose risks to human intervention.

The tasks encompassed by the robot include object recognition, machinery monitoring, and defect detection, thanks to its on-board camera system. Additionally, manipulation, positioning, and object insertion are enabled by the presence of two robotic manipulators. Furthermore, by equipping the robotic arms with various mechatronic tools, the robot can undertake assembly, disassembly, screwing, centring, measuring, and maintenance tasks. Robot's large workspace and overall compact dimensions, shown in Fig. 3 and Fig. 4 respectively, make it a device capable of accessing relatively confined spaces while ensuring high dexterity.

Another important innovative feature is the possibility of using the robot as a rotating lifting beam for the remote transport of loads up to 300 kg. Objects to be transported can be hooked/released using special hooks/lifting components handled by the manipulators, slung and lifted via the 4 eye nuts installed under the platform, and eventually rotated for accurate positioning.

3.2 Mechatronic Design

The robot's key component is its central platform, i.e. an aluminium frame that plays a multiple role: (i) allows the connection with the crane hook; (ii) offers an additional degree of freedom allowing the robot to rotate around a vertical axis; (iii) supports the two robotic manipulators; (iv) incorporates the on-board camera system; (v) contains all the essential electronics for powering, actuating and controlling the connected systems; (vi) plays the role of lifting beam for remote transport of additional loads. The following will give more details on the above-mentioned points.

In its top part the robot features an adapter designed to accommodate double hooks (adhering to DIN15402 or UNI 9470/1 standards) that serves as a safe and solid attachment point, allowing the system to be lifted vertically and handled by the crane (see Fig. 6). The hook adapter comprises three plates arranged in a U-shaped configuration and affixed to the top of the platform. Upon inserting the crane hook between the two vertical plates, it is securely held in place by lifting pins equipped locking nuts. Additionally, four threaded knobs are provided to ensure the hook is correctly centred and its lateral movement is restricted. Currently a set of four adapters is available to accommodate four different DIN15402 hook sizes: 4, 6, 8, and 10. When dealing with larger hooks, it is necessary to harness the platform by attaching two slings to the lifting pins. The crane hook adapter is attached to a rotational actuated joint that allows a 360-degree rotation around a vertical axis at a speed of 4 revolutions per minute. To utilise this capability, it is imperative to lock the rotation of the crane hook. Thanks to this joint it is possible to rotate the platform, and therefore the load it carries, to enable a precise orientation positioning.

On its left and right lateral sides, the system is equipped with two lightweight robotic arms, as shown in Fig. 5. Currently, the system can accommodate two manipulator models, namely PRBT6 arms man-

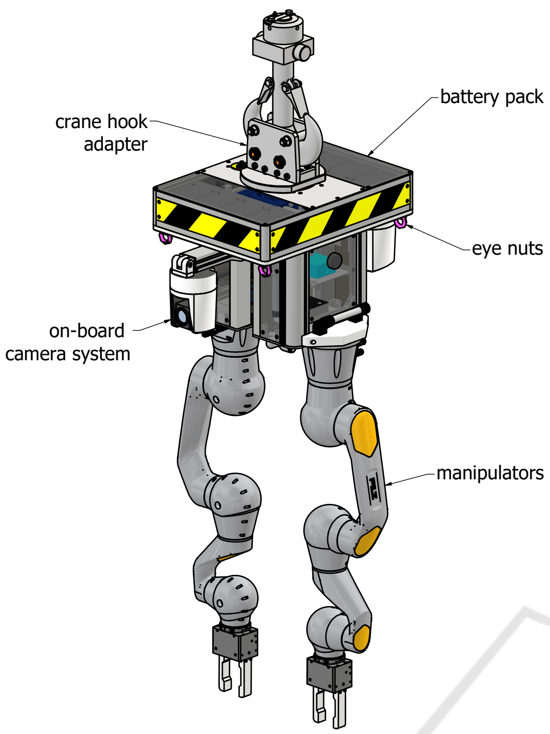

Figure 5: Overview of CRANEBot mechanical design.

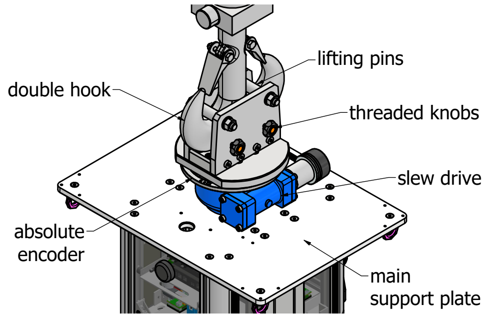

Figure 6: Detail on the hook system and the rotational actuator with vertical axis positioned below the adapter.

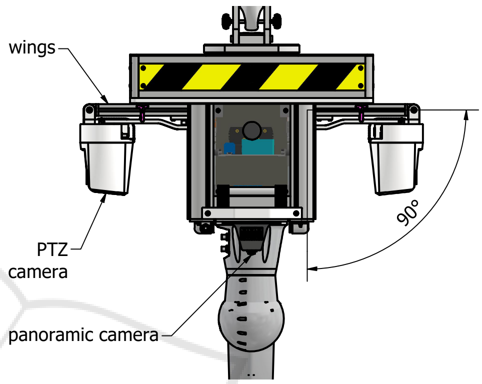

Figure 7: Detail on the camera system and the wings opening/closing feature.

ufactured by PILZ and LWA4P arms manufactured by Schunk. Both models are driven by three pairs of actuators with perpendicular axes, named ERB modules, located at the shoulder, elbow and wrist respectively, for a total of 6 revolute joints. Each ERB module is endowed with zero-backlash Harmonic Drives which allow precise positioning of manipulator joint. These arms are also notably lightweight (maximum of 19 kg per arm) and compact, and have a maximum payload of 6 kg, allowing for high versatility with respect to the mentioned tasks. The arms are also powered 24 V DC power, so they do not require an external large inverter. The choice of this manipulator, besides its construction characteristics, is also due to the possibility of not necessarily having to use a proprietary control system and external control box, but of being able to write open-source code and interface with the firmware via the CANopen protocol.

Additionally, the central platform houses the on-board camera system, as shown in Fig. 7. This set of vision sensors is meant to provide a visual feedback during inspection and teleoperation. It comprises a panoramic camera, specifically an AXIS F1035-E Sensor Unit, located in the lower central portion of the frame pointing down, and two Pan-Tilt-Zoom (PTZ) cameras, denoted as AXIS V5925, positioned on the front and back sides of the platform. Moreover, with the aim of enhancing the operator's perspective and visibility, a wings system enables independent movement of the PTZ cameras on the sides of the platform. The system is also pre-wired for the installation of three additional cameras, in particular AXIS F1005-E Sensor Units, which can serve as additional points-of-view for observing the manipulator end-effectors.

All mentioned electromechanical devices are internally connected to each other via the platform and are powered by 8 lead-gel 24 V batteries, which guarantee a total operating time of up to 8 hours, in most situations sufficient to complete a robotic task. The central structure houses an on-board controller PC, a Inertial Measurement Unit for on-line pose estimation, and a router for connecting the robot via 4G/5G and WiFi.

Finally, four eye nuts are available in the corners of the central platform facing downwards, allowing an external suspended load of up to 300 kg to be tied to the robot and thus transport simultaneously the robotic system and additional object via overhead crane. The combined handling of the two systems (robot and load) is of fundamental importance because: (i) it allows, via the robot, to have an easy visual feedback on the handling of the load suspended by the overhead crane, which is important when, for example, the load has to be centred with respect to

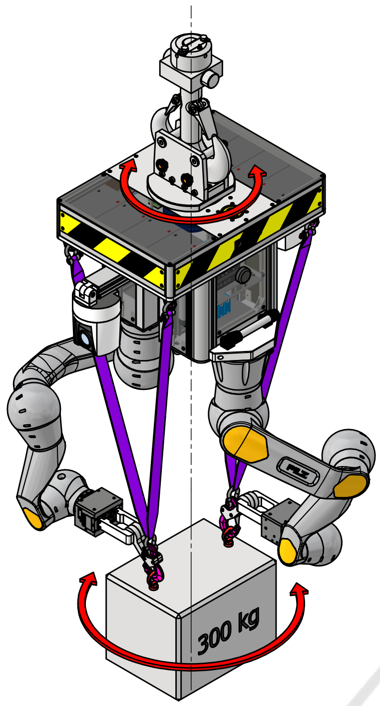

Figure 8: Robot handling an external load (max. 300 kg), with the manipulators in the configuration to hook/release the load.

fixed supports; (ii) once it has been positioned in the space via the overhead crane, it allows immediate manipulation on the load (e.g. screwing it onto a support) in the same operational phase, without the need to separate the two handling actions.

4 CONTROL

The robot operates in a remote, hazardous area, controlled through its on-board computer, which interfaces with all physical components, including motor drivers, cameras, and sensors. This computer runs a robotic framework that processes sensory data and manages both control functions and communications. Operators interact with the robot through a Graphical User Interface (GUI) connected over available networks. There are two types of interfaces developed for use at CERN: a 2D GUI and a 3D Mixed Reality GUI (Szczurek et al., 2023), both created with Unity and C#. Depending on the specific setup, communication between the robot and the GUIs can occur via a 4G network, WiFi, or a wired network connection.

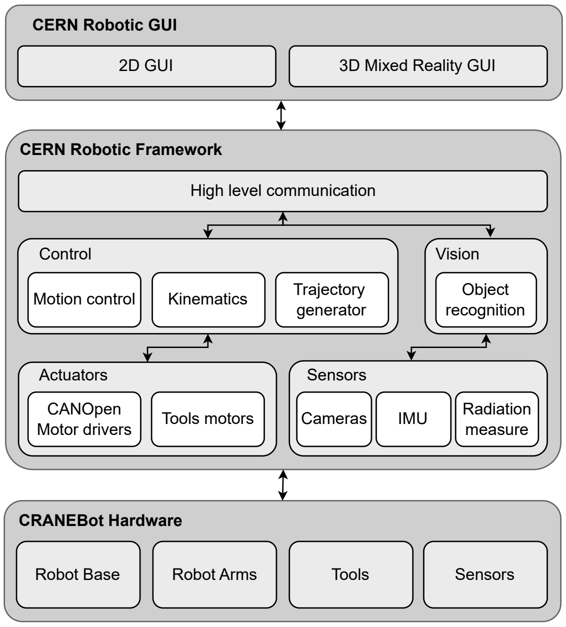

Figure 9: Overview of control architecture.

4.1 Control Architecture

The CERN Robotic Framework, abbreviated as CRF (Di Castro et al., 2018a), is a modular software architecture developed at CERN for supervised teleoperation and autonomous inspection in hazardous environments. It is a fully in-house solution essential for controlling CERN's pool of robots. The CRF covers all the software aspects required for using a robot, ranging from low-level driver implementations, through middleware communication, to communication with the user interface for teleoperations. The framework is written in standard C++17 and uses CMake as its building tool. The framework is currently ran and tested on Ubuntu 20.04 and Ubuntu 22.04 distributions. As shown in Fig. 9, the CERN Robotic Framework decomposes into a set of interconnected modules. These include modules for low-level communication with actuators and sensors, modules for control, kinematics management, and trajectory generation, modules for vision algorithms, and modules for data exchange with user interfaces.

4.2 Graphical User Interface

At the top of the control architecture is the Graphical User Interface (GUI), which allows the teleoperator to control all the main components of the robot and be informed about its current status. To enable remote operations, the user connects via 4G or WiFi to the same network as the robot. This setup allows the initiation of the so-called communication points, which

(a) (b) (c)

Figure 10: Robotic interventions and tests conducted at CERN with CRANEBot.

are software modules developed within the CRF that establish the connection between the robot and the GUI. For this purpose, the Transmission Control Protocol (TCP) is used. The communication points also initiate the control loops for the central platform and the arms, ensuring that command signals can be transmitted from the interface to the robot's joints. In the specific case of the CRANEBot, the teleoperator can control the central platform, which includes the rotational joint with vertical axis and the wings, the robotic arms, and the tools. Video information from the on-board camera system is streamed in real-time to the interface.

The interface also provides a visualisation of a three-dimensional model of the robot, i.e. a graphical representation of the system's current state. This is crucial for the operator to understand the robot's configuration, offering an external view that complements the on-board camera views.

5 VALIDATION: ROBOTIC OPERATIONS

The robot's functionalities and control architecture have been validated in real operations within CERN facilities, as demonstrated by the examples shown in Fig. 10. As mentioned in Section 3.2, the robot can be integrated with different types of cranes and can be equipped with different types of arms and tools. In Fig. 10a the CRANEBot is shown equipped with Schunk LWA4P manipulators and grippers, transporting a vacuum module connected to the platform via slings. The module is to be installed on a fixed support and aligned with the beamline within the Compact Muon Solenoid (CMS) experiment. The devices required for the installation are shown in Fig. 10b, where one of the two manipulators, in this case PILZ PRBT6, is equipped with a screwdriver for tightening the vacuum connections. Finally, in Fig. 10c, the robot is shown tightening a vacuum tank flange using an impact driver.

6 CONCLUSIONS

This study presents an innovative robotic system developed at CERN, called CRANEBot, capable of performing remote operations in harsh environments where access from above is required. Its design allows the use of different robotic arms and different tools, making it capable of long inspection sessions and heavy manipulation. Finally, the robot is also configured as a mechanical interface, i.e., lifting beam, with respect to another load to be transported, allowing components to be placed and installed easily and effectively. The system has been validated in numerous tests and robotic interventions, successfully performing the required tasks.

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