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A DUAL ARM ROBOTIC PLATFORM CONTROL FOR NAVIGATION, INSPECTION AND TELEMANIPULATION

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Abstract

High intensity hadron colliders and fixed target experiments require an increasing amount of robotic tele-manipulation to prevent excessive exposure of maintenance personnel to the radioactive environment. Telemanipulation tasks are often required on old radioactive devices not conceived to be maintained and handled using standard industrial robotic solutions. Robotic platforms with a level of dexterity that often require the use of two robotic arms with a minimum of six degrees of freedom are instead needed for these purposes. In this paper, the control of a novel robust robotic platform able to host and to carry safely a dual robotic arm system is presented. The control of the arms is fully integrated with the vehicle control in order to guarantee simplicity to the operators during the realization of the robotic tasks. A novel high-level control architecture for the new robot is shown, as well as a novel low level safety layer for anti-collision and recovery scenarios. Preliminary results of the system commissioning are presented using CERN accelerator facilities as a use case.

INTRODUCTION

Nowadays, intelligent robotic systems are becoming essential for industrial facilities as for harsh environments, in order to increase equipment availability and safety. In such scenarios, robots should perform repetitive and well-defined tasks as well as unplanned and dangerous tasks, which humans either prefer to avoid or are unable to do because of hazards, size constraints, or the extreme environments in which they take place, such as outer space or radioactive experimental areas. In particular, operating robots for maintenance and inspection in dangerous environments on costly machines requires skilled and well-trained dedicated shift operators. The control of these robots is usually not intuitive and slow: this is mainly caused by the not intuitive human-robot interfaces present on industrial robots and by the lack of adaptability of the standard robots to various intervention scenarios. The European Organization for Nuclear Research (CERN) [1] is the world largest high-energy physics laboratory. At CERN, there are more than 50 km of underground-unstructured accelerators area with thousands of different items of equipment that needs to be monitored and maintained. Due to the presence of human hazards mainly produced by radiation and high magnetic fields, as well as the risks related to an underground facility (e.g. lack of oxygen, fire risks etc.), the accelerators equipment at CERN have the needs to be monitored, inspected and maintained remotely, possibly using robots.

The use of robots in CERN's unstructured environments is particularly challenging: accessing to the equipment is often difficult and time consuming, long distances must be covered, and the equipment to be monitored or manipulated can be in uneven positions.

These aspects require intelligent robotic systems able to travel long distance, equipped with multiple robotic manipulators, possibly with a user-friendly human-robot interface (HRI). The control system of these robotic systems must be designed to overcome the challenges highlighted so far with the following constraints:

- Safe and robust, in order to perform operations without creating any risk for equipment, humans and the robot itself.
- Lightweight and real-time, in order to be deployable on an embedded computer.
- Modular, in order to be adaptable to any kind of robotic configuration.
- Seamlessly connected to a multimodal human-robot interface.

CERNbot (Figure 1), a novel robotic base system has been built at CERN with the goal of guaranteeing autonomous inspection and supervised telemanipulation in the accelerators areas.

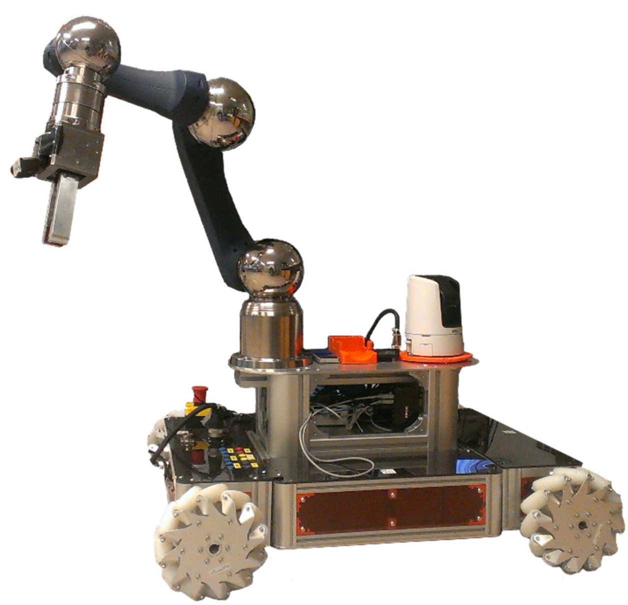

Figure 1: CERNbot.

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The CERNbot control has been designed to let the robot operate in hazardous and unstructured environment and to guarantee the maximum flexibility in term of mechanical and electrical point of view. The structure is divided in subsystems. Each subsystem could be modified separately and adapt to the general use of the robotic platform (Figure 2).

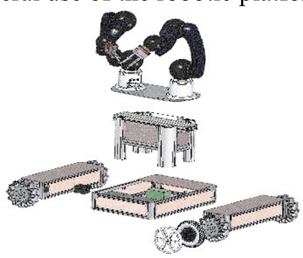

Figure 2: Different CERNbot hardware components.

It is possible to mount up to two robotic arms like in this case, or adapt the space to installation of other different tools or monitors.

In this paper, the control system of the CERNbot is described, highlighting the interconnection between the modules, the division in layers of the control architecture and their functionality. Furthermore, a small description of the operational Human-Robot Interface (HRI) is presented. Finally, the validation of the system is shown in terms of hours of operation and improvements with the previous solutions.

STATE OF THE ART

Modern industrial robots are mainly designed to perform repetitive and structured tasks, without much flexibility or intelligence, and they are not adapted to perform operations in harsh and unstructured environment.

Mobile manipulators are robotic systems consisting of one or more robotic arms deployed on a mobile platform. Starting from 1980s, the development of mobile manipulators has gone through several stages concentrating on different key components in both hardware and software. During this period, many mobile manipulators have been developed: MORO, Rob@Work, Little Helper, PR2, TUM Rosie, KUKA OmniRob and KMR iiwa are the most representative mobile manipulators [2].

Furthermore, robust vehicles were built during the last years for satisfying the demand of demining or explosive manipulation.

The lacking on scalability and adaptability to different scenarios like it is requested in facilities like CERN's ones makes the aforementioned systems not suitable to their direct deployment in accelerators. Therefore, unlike there are many different industrial robots deployed in industrial environments, robots ready to be used in unstructured and hazardous environment are not too common and, in general, they are built for specific needs requiring expert operators to be controlled.

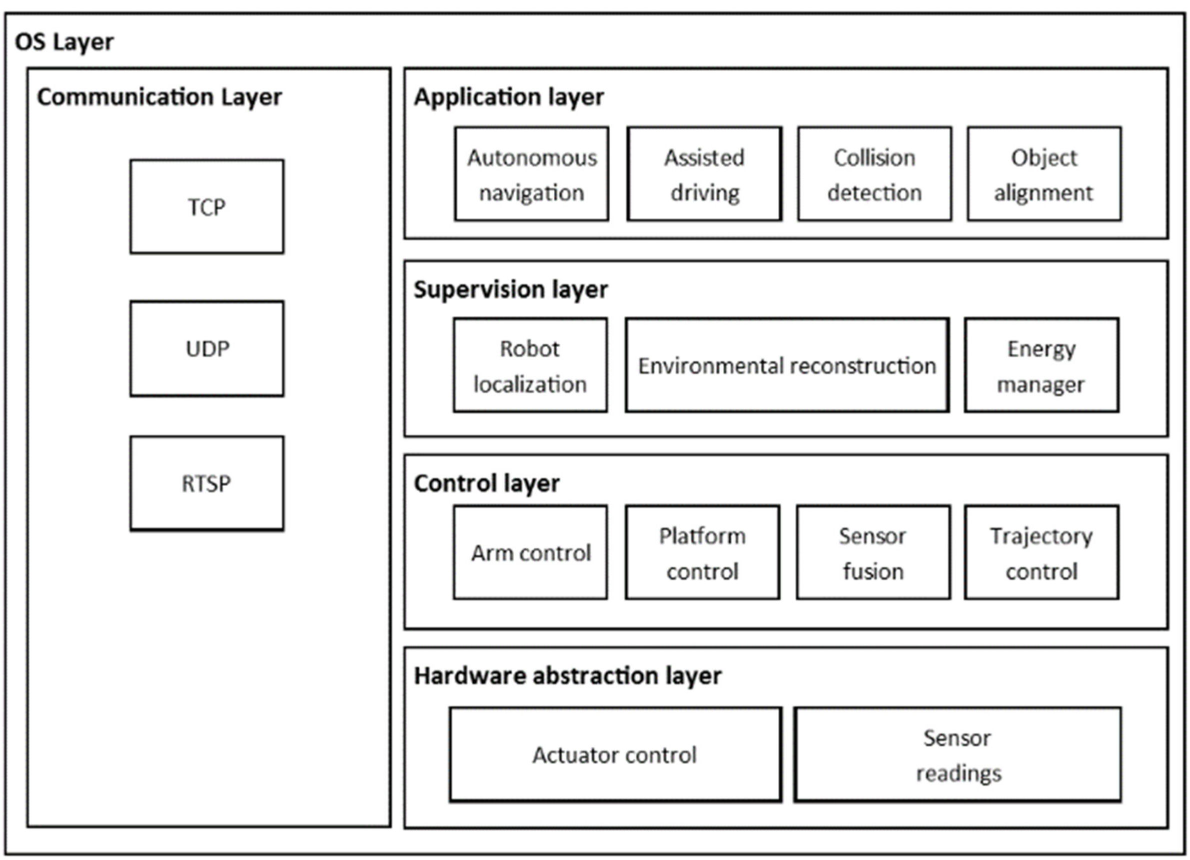

Figure 3: CERNbot control system architecture.

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CONTROL ARCHITECTURE

The control architecture of the CERNbot robot is designed to be modular and safe. The communication link between the operator and the robot is not reliable since is based on 3G/ 4G/WiFi and on standard internet protocols (TCP, UDP). Therefore, to guarantee safety and autonomy, the entire control loop should be closed on the on-board robot control system.

The robot implements two types of control [3]:

- *Supervisory control* in which the closed loop control is entirely on the robot side and the human operator receives feedbacks from the robot (visual, haptics, etc...) and sends controls to it through an HRI;
- *Fully automatic control*, in which the closed loop control is entirely on the robot side and the human operator receives only feedbacks from the robot.

This structure provides a major functional specification for the design of the control system, in which all modules must be perfectly interconnected. The control system must be always capable to provide safe commands to the actuators, no matter which is the state of the connection with the operator.

The CERNbot control system has been entirely written in C++ and does not use any commercial or open source control systems like ROS [4] that are not real-time compliant. This control design decision has been taken because the CERNbot control must run entirely on-board doing parallel computation like SLAM, obstacle avoidance, 3D mapping, vision, etc. This design choice guarantees also the compatibility of the CERNbot control with real-time controllers.

The proposed control system is portable and modular and it is divided in different layers (Figure 3):

- Hardware Abstraction layer
- Control layer
- Supervision layer
- Application layer
- Communication layer
- OS layer

The Hardware Abstraction Layer provides an interface between the system and the hardware. This layer is fundamental for the development of a modular and adaptable system [5], since it provides an abstraction interface between the hardware and the upper layers. Furthermore, the Hardware Abstraction Layer allows also to use and test modules belonging to upper layers by the use of simulated hardware. This is extremely important for the system validation, operational procedures, recovery scenarios and for the operators' training, who can operate a simulated robot in advance as a preparation to the real intervention.

The control layer provides all the control strategies for the actuators. In the control layer, there are the robotic arm controls (e.g. position control, trajectory control, kinematic control, torque control) and the robotic platform control

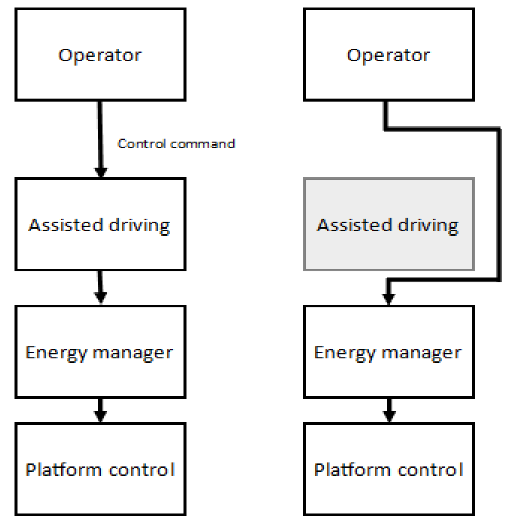

Figure 4: Automatic IPC redirection after suspension of assisted driving module.

(e.g. speed regulation, omnidirectional control). The control layer implements as well all the sensor fusion modules, in which data coming from the sensors in the hardware abstraction layer are filtered and merged together in order to provide proper data to the upper layers.

The supervision layer contains all those modules that are responsible for determining the complete state of the system in each moment. It contains therefore the robot localization, environmental reconstruction, the battery management, the communication optimization etc.

The application layer, finally, contains all the applications that the robot can provide such:

- Assisted navigation
- Autonomous navigation [6]
- Assisted grasping
- Autonomous grasping
- Collision avoidance [7]
- Object recognition
- Object alignment [8]
- Sequencer of multiple operation.

Aside of these layers there are two *special layers* which are broad wise the entire system: the communication layer and the OS layer.

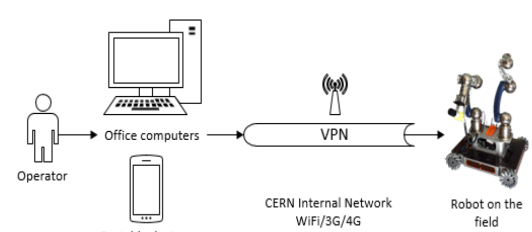

Figure 5: CERNbot basic communication scheme.

The communication layer provides:

- All the communication methods with the Human-Robot Interface.

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- Methods for timestamp synchronization between the HRI and the robot.
- Communication compression methods.
- Communication optimization methods.

The communication layer is connected with all the modules, since each module can provide and receive, if requested, data to and from the HRI.

Table 1: Harsh environments challenges

Challenge	CERNbot control feature
Limited intervention time in very long distances	Variable speeds according to the time needs
Unexpected obstacles	Autonomous navigation andobstacle avoidance
Precision localization during environmental measurement	Precise on board odometry
Delicate equipment	Anti-collision systems and recovery scenarios
Loss of communication signal	Control through SMS, notifications/alarms via SMS, autonomy
Robot autonomy	Energy management system

Above all, the OS layer provide all the functionalities in order to maintain all the modules properly active and interconnected. All the modules communicate together through Inter Process Communication (IPC) but not all the modules are active at the same moment and modules can be activated or deactivated automatically or by the operator according to the needs. When a new module is activated or deactivated the OS layer manages the reconnection and the redirection of the IPC. For example (Figure 4), the operator can choose to drive the robotic platform by sending direct commands or by the use of the assisted driving module in the application layer.

The driving commands pass as well through the energy management to optimize the power consumption of the system. Therefore, when the operator chooses to use the assisted driving, the OS layer automatically modify all the affected IPC connection in order to adapt to the new control configuration.

The OS layer provides also watchdog functionalities, each module has its own priority and its own criticality. According to its criticality and priority, if the module suddenly stops, the watchdog detects this stop and manages it by restarting it or by interrupting other modules in order to maintain the system in a safe state.

HUMAN-ROBOT INTERFACE

Even though the control system allows the robot to operate in a safe and robust way, it is important that the operator sends the proper commands to the robot through a communication channel (Figure 5). Therefore, a deep study for the creation of a usable, learnable and multi-modal Human-Robot Interface have been done [9]. The interface provides a comfortable and uniform environment for the control of different robots, for the analysis of the collected data [10], for the training through simulation etc. Studies on the stress of the operator during an intervention were performed in order to design a HRI which optimize the mental workload for the operator and the maximum telepresence in the environment.

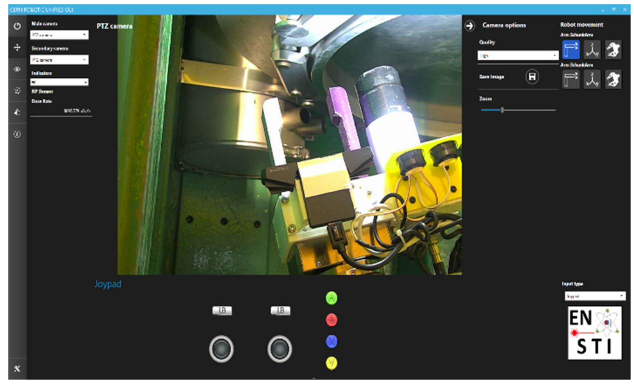

Figure 6: CERNbot HRI.

The multimodality is achieved by the integration in the HRI of different ways for interacting with the robotic system. Several control methods using different input devices are integrated including standard input devices such as keyboard, mouse and joysticks, together with more complex devices such as haptic devices for master slave telemanipulation and RGB-D cameras for body tracking. The operator, then, can choose at any time the input device that finds more comfortable with according to the skills, the type of operation that has to be performed, the mental status and so on.

Furthermore, the HRI adapts itself to the robot configuration, displaying only relevant information without filling the working memory of the operator (Figure 6). The HRI is highly learnable and the procedures are well defined in order to reduce slips and lapses.

Since the HRI is able to control different robots, the operator has always the same experience while operating them, receiving always the same feedbacks and applying always the same actuation commands.

Two focal points is its usability and its user-friendliness. These aspects are very important in order to reduce the learning time of the operator and the stress that he or she could receive from it. Reducing the learning time means also enlarging the operators' pool of a company, which, instead of having few and very well-trained operators which operate in all the situations, it could provide the robotic system directly to the facility expert, who has more knowledge of the environment and everything that is in it.

SYSTEM VALIDATION

The CERNbot and its control system has been validated since September 2016 through several real operations in the CERN accelerators facilities. Before the construction of the CERNbot, remote inspection and manipulation were

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performed by the use of commercial ROVs, reliable and robust but difficult to use and not customizable according to the needs. The first operations performed with CERNbot were as visual support to the tele-manipulation operation of the other two commercial robots, in order to initially validate the communication framework and the basic control system. Since then, CERNbot has been used for many different interventions, from inspection of restricted access areas, to radiation mapping and survey of entire accelerators (more than 7 km covered in one intervention), as well as manipulation of complex devices which required above all unscrewing and cutting. Figure 7 shows the total number of interventions performed in CERN accelerator's facilities with all the robots available. Before the first usage of CERNbot, starting since July 2014 and with the use of the two commercial robots, 27 interventions were performed for a total amount of 80 hours of operation and an average of 40 hours of intervention per year. Since September 2016, with the first usage of the CERNbot, 30 interventions were performed for a total of amount 80 hours of intervention. In particular, from January to September 2017, 27 interventions were performed. During these 80 hours, the control system did not encounter any operational failure, the robot always accomplished the requested tasks and always recovered without problems at the end of the intervention.

Nevertheless, this data is not fully representative of the real success of the CERNbot for teleoperation in CERN's facilities. The modularity of the system allowed operations that were simply not possible with the commercial robots already owned, fully closed and not customizable. Therefore, the integration of proper radiation sensors coupled with a RGB-D camera allowed to make precise radiation mapping of the equipment, the on-board localization system allowed to make surveys of entire accelerators, the dual arm configuration allowed the handling of radioactive sources etc. The possibility to connect the robot to the CERN 4G internal network allowed controlling the robot from any network location at CERN, without the need of human access to an underground area, mandatory with the commercial robots equipped with a point-to-point radio communication. The modularity of the robot allows also faster preparation and reaction time. On a new request, the robot can be configured with different hardware configurations easily and the control system can be adapted to the new hardware configuration in few steps (Figure 8).

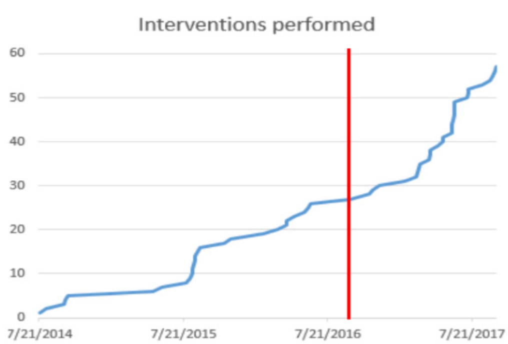

Figure 7: Timeline of the interventions performed during the last years. From the red bar CERNbot was used.

Figure 8: CERNbot core in dual-arms configuration integrated on a crane for accessing complicated areas.

CONCLUSION

This paper showed, based on CERN experience, how the design of a control system is fundamental when developing a modular robot. The control system must be well organized not only for making easier the development, but for increasing as well the safety and the robustness of the system, allowing to define layers, priorities and criticalities. The work has been successfully validated through several hours of operation in harsh environments.

Future work will focus both on extending the control system with more modules such as machine learning as well as modules for assisting more the operator during the operation in order to obtain a fully usable robot by any non-trained operator.

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