ROBOT TELEOPERATIVO: Collaborative Cybernetic Systems for Immersive Remote Teleoperation

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Abstract— **Remote robotic teleoperation is becoming vital in numerous fields, especially in hazardous environments where human safety is critical. In these scenarios, teleoperated robots are deployed to perform tasks, reducing human exposure to potential dangers. The *"Robot Teleoperativo"* project aimed to develop a novel, collaborative teleoperation hardware and software system dedicated to operating in hazard-prone environments, reducing risks to people's safety and well-being. It employed, developed, and integrated advanced technologies in tele-locomotion, tele-manipulation, and remote human-robot interaction. This short paper provides an overview of the latest developments in the project and a preliminary system evaluation. The project has successfully demonstrated a teleoperation system that enables intuitive and immersive tele-locomotion, tele-manipulation, and remote human-robot interaction. The project showcases the potential for enhanced operator control and precision, offering a more natural and effective means of remote interaction in complex and hazardous environments.**

I. INTRODUCTION

State-of-the-art remote robotic teleoperation systems are changing how we tackle complex tasks in the most demanding and hazardous environments [1], [2]. Such systems are pushing the boundaries of what is possible, whether nuclear decommissioning, disaster response, search-and-rescue missions, or surgical procedures, and research in this field shows that it is evident that the optimal approach for telerobotics involves a combination of human-in-the-loop remote guidance and local robotic autonomy: offering superior adaptability and performance in unstructured and cluttered environments and safety. Despite extensive research, teleoperation encounters considerable challenges in complex and unpredictable disaster environments [3], [4]. Rapid changes, debris, and obstacles need continuous adaptation to ensure effective operation. Additionally, damaged communication infrastructure can lead to unreliable control and reduced precision, complicating the task further. These factors shows the need for a robust and highly adaptable robotic system capable of handling and maintaining reliable performance in adversity.

This paper introduces the *"Robot Teleoperativo"* project, which aims to tackle these challenges by advancing telerobotic technologies designed for locomotion and manipulation in demanding environments. This project integrates the robust locomotion capabilities of a quadruped robot with the precision and strength of a newly developed dual-arm robotic system. To further enhance operational effectiveness, the project incorporates immersive virtual reality (VR) visualization and haptic teleoperation interfaces. This integration pushes the limits of remote robotic capabilities, especially for operations in unstructured and rugged terrains, ensuring effective human control. The following sections present the system design, integration, use cases, and results.

II. SYSTEM OVERVIEW

As illustrated in Fig. 1, the project follows a typical teleoperation system, consisting of an operator site (MASTER) and a remote robot site (FIELD) subsystems. At the FIELD site, a quadruped robot (RT-Nav) is used. This robot is designed for effective locomotion across diverse and challenging real-world terrains. Additionally, the FIELD site has multi-degree-of-freedom dual-arm manipulators (RT-Man) mounted on the quadruped robot. These dexterous manipulators, equipped with end-effectors, provide precise and versatile handling capabilities, enabling the effective manipulation of a wide range of objects and tasks. At the MASTER site, a Haptic Arm (RT-Hap) serves as the primary controller for the FIELD robot. This haptic arm integrates a hand exoskeleton with a 6 degrees of freedom (DOF) tactile and force feedback system. Additionally, the MASTER site is equipped with an Immersive Visualization System (RT-UI) that enables the robot operator to control the FIELD robot and receive precise real-time visual feedback. Using virtual reality (VR) technologies, this interface offers an immersive and user-friendly experience, allowing operators to manage complex interventions more efficiently and accurately.

A. *RT-Nav – Legged robot system*

The field robot-legged locomotion platform is based on the HyQReal hydraulic quadruped robot as the base vehicle [5], [6]. This subsystem implemented high-level software and hardware architectures to allow the robot to traverse challenging terrain, including slopes, stairs, or debris, exhibiting mobility beyond wheeled or tracked vehicles. The robot has multiple cameras strategically placed around its body, allowing mono and stereo viewing to facilitate remote scene observation, environment 3D mapping, and motion planning across various terrains. It also has a LiDAR sensor for mapping and localization. Environmental sensors such as

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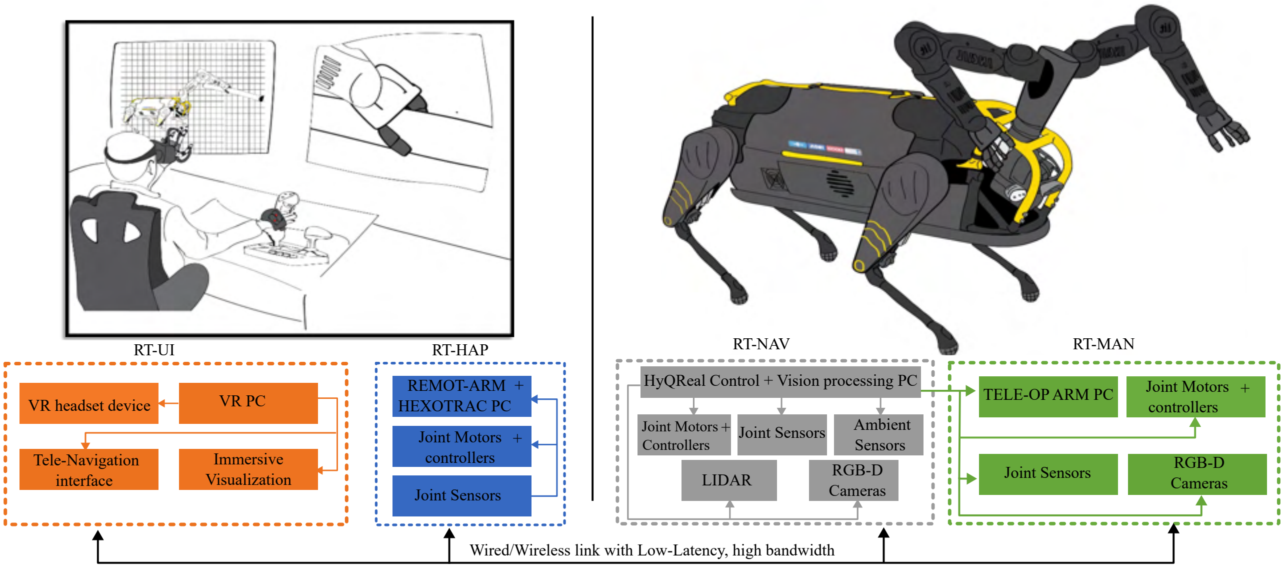


Fig. 1. High- and Low-Level Communication Architecture of *"Robot Teleoperativo"*.

a microphone and thermal sensor can be optionally mounted on the FIELD robot to enhance its environmental perception.

The robot has the following dimensions: 1.32 m in length, 0.67 m in width, and its height ranges from 0.39 to 0.9 m, with a total weight of 140 kg, including onboard batteries. It features 12 DOFs (3 per leg). The joint torques are 175 Nm for the hip abduction-adduction (HAA), 200 Nm for the hip flexion-extension (HFE), and a peak of 300 Nm for the knee flexion-extension (KFE). The range of motion is 65° for HAA, 110° for HFE, and 133° for KFE. The onboard hydraulic system provides 2 x 2 kW of hydraulic output power. It is powered by a Lithium Polymer battery with a capacity of 48.1V and 84Ah, operating with onboard voltages of 48V, 24V, 19V, and 12V. The robot includes two onboard computers: one for real-time control and the other one for onboard perception processing. Knee and hip joints are actuated by Integrated Smart Actuators (ISAs) and Smart Manifolds (couple to custom hydraulic motors), respectively, which are highly integrated systems with electronics and sensors [7] that allow for high-performance joint force control and active impedance [5]. Additionally, the RT-NAV system integrates advanced sensors and computing units, including an Inertial Measurement Unit (IMU) with fiber optic gyros, low-noise accelerometers, and magnetometers for precise motion tracking. Data from these sensors is processed by an embedded Nvidia Jetson AGX Xavier computer, which has multi-core processing chips and a powerful GPU, providing the necessary computational power for real-time processing and efficient data acquisition and transmission.

B. RT-Man – Dual-arm manipulation system

The FIELD robot's dual-arm manipulator system is based on the IIT-INAIL TeleOp Arm [8]. This subsystem has 6 DOFs, with 2 DOFs in the shoulder complex, 1 DOF in the elbow, and 3 DOFs in the wrist. To provide enough workspace around the navigation subsystem, the dual-arms are mounted on the front half of the RT-Nav platform. The positioning of the arms is optimized to enhance the manipulation capabilities of the RT-Man. This configuration allows the arms to extend upwards or reach the ground effectively, facilitated by the RT-Nav robot's ability to raise or crouch. Additionally, it provides sufficient overlapping workspace between the two arms, enhancing bi-manual dexterity.

This subsystem has a universal interface designed for easy attachment/detachment of tools and end-effectors. At present, one of the arms is fitted with the HERI-II hand [9], which uses the universal interface to perform precise manipulation tasks with high accuracy. This hand is ideal for complex operations requiring fine control and agility. On the other arm, custom designed end-effector drill tool is attached for tasks that require substantial power and robustness. Besides the manipulators offer mounting options for additional cameras or sensors.

The RT-Man system's control architecture has several frameworks for precise operation. Cartesian and low-level control are managed using the XBot2 Real-Time Control Architecture [10], the OpenSoT Control Library [11], and the CartesI/O Framework [12]. At the joint level, the system supports both position and torque control, depending on the task and the required Quality of Service (QoS) during teleoperation. This decentralized approach, executed at high frequencies within each joint-servo digital signal processor (DSP), ensures accurate control. The system enables independent or cooperative teleoperation of the 6-DOF arms at the Cartesian level. Operators can directly achieve full three-dimensional control over position and orientation from their inputs. The centralized control, handled by the main arms computer, coordinates these operations.

The subsystem provides two primary control modes: 1) Independent Control Mode: Each arm is controlled separately in terms of position and orientation relative to a base frame. It is suitable for tasks requiring simultaneous yet distinct arm operations, such as opening a shelf while picking up an

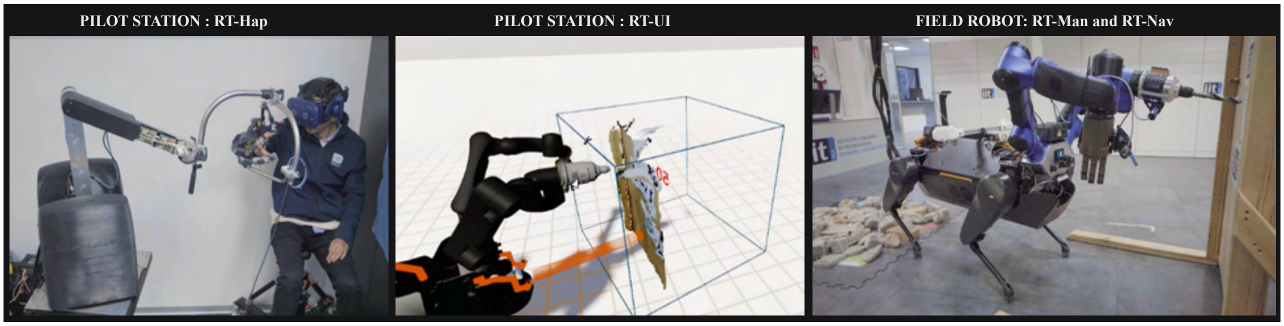


Fig. 2. *"Robot Teleoperativo"* is tested with various use cases. This figure illustrates one such scenario: inspecting a closed door by drilling a hole with a drill in its left hand and using an endoscope camera in its right hand to look inside and carefully open the door.

object. 2) Cooperative Control Mode: One arm functions as the master while the other acts as the slave. The slave arm's position and orientation are controlled relative to the master arm's frame. It is well-suited for high-precision tasks, such as connecting pipes, where coordinated arm movement is essential. Operators can easily switch between these modes based on the specific demands of the task, allowing for flexible manipulation across a wide range of applications.

C. RT-Hap - Dual-arm haptic teleoperation interface

The dual-arm haptic teleoperation device have the HEXOTrAc-Plus hand exoskeleton and the REMOTArm, a desk-mounted, 6-DOF haptic teleoperation device. The REMOTArm tracks the position and orientation of the operator's wrist and provides 3-DOF force feedback at the wrist (greater than 20N). The 3-finger HEXOTrAc-Plus is an ergonomic haptic glove that accurately tracks the operator's gestures during tele-manipulation of the field manipulator [13][14]. It's actuators can display remotely sensed interaction forces (less than 10N) to the user at the robotic hand in real-time. Additionally, this subsystem is controlled by the Teleoperation Master (TOM) software [15]. It is the central unit responsible for integrating all operator input and haptic feedback devices at the haptic master station, managing the manipulation of slave robots, and implementing teleoperation control methods. The software consists of three main layers. 1) A device Layer provides a proxy for each teleoperation device, offering a standard interface to ensure compatibility, including the dual-arm manipulator and the Herri hand. 2) A controller Layer that implements general, high-level control strategies, separated from the Device Layer and 3) state Machine Layer that maintains a state machine to manage controllers and devices and interacts with external interfaces to capture the operator's intentions.

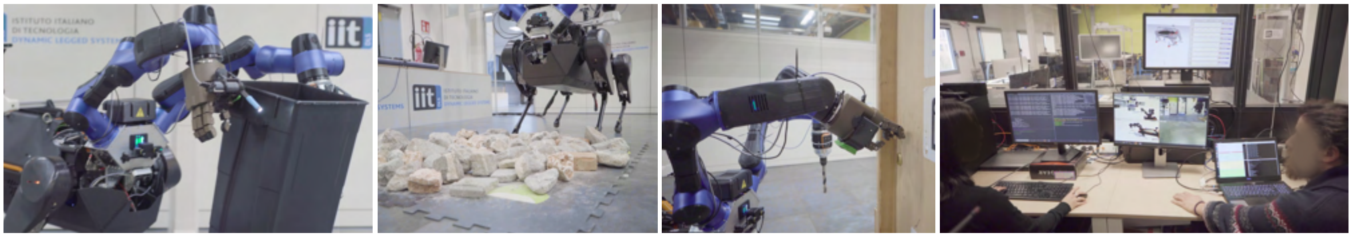
D. RT-UI - VR-based user interface

This subsystem uses the latest computing devices at both the Field and Pilot stations to create immersive visualization. The Field robot subsystems collect and transmit visual and sensor data to the Pilot station. Meanwhile, the Pilot station handles the interaction software, as well as the VR and AR modules, to deliver an immersive visual experience. The visualization interface is based on [16], [17], which offers a fully immersive VR environment and integrates multiple real-time video streams, point clouds, and sensor data. It also offers real-time visualization and control of the field robot and its status to the operator. Operators can select, start, or stop streams based on bandwidth and latency requirements, adjust sensor parameters, and change viewpoints to enhance remote visualization. In addition, this subsystem includes a multi-user visualization interface, which allows multiple users to access, experience, and interact simultaneously. This feature is important for collaborative teleoperation tasks within the same virtual space, facilitating supervision and improving task execution.

While real-time video from monocular or stereoscopic cameras offers visualization and point-cloud data provides depth perception, these methods restrict users to a fixed view. Immersive VR interfaces, on the other hand, provide 6 DOFs, allowing operators to view the environment from any angle and position. This capability supports the integration of the robot's environment through 3D reconstruction and continuously updates the visual information as the robot moves. However, transmitting 3D reconstructed maps can be bandwidth-intensive. To address network latency and throughput challenges with dense 3D maps, the system uses a framework inspired by human visual acuity, which is sharpest at the center and gradually decreases towards the periphery and this is used to sample, process, stream, and render 3D scenes in VR, enhancing immersive visualization [18]. Multiple video streams are handled using FFmpeg with H.264 compression and RTP. In addition, robot control commands are communicated via Rosbridge and UDP sockets to facilitate efficient operations.

III. EXPERIMENTAL DEMONSTRATION

"Robot Teleoperativo" has undergone extended testing with the following use cases shown in Fig. 3: 1) Picking up dangerous objects and relocating them to a safer area; 2) Navigating over rocks and bricks of various sizes arranged randomly; 3) Opening a custom-designed wooden door (105 cm x 205 cm) with a handle height of 100 cm; 4) showing important robot status information for supervisors; and 5) Using a newly designed drill tool to create a hole, then manipulating an endoscopic camera through remote telemanipulation to visualize through the hole and carefully open the door, see Fig. 2.



(1) (2) (3) (4)

Fig. 3. Sample pictures of the following use cases: (1) Picking up dangerous objects and relocating them to a safer area. (2) Navigating over rocks and bricks of various sizes. (3) Opening a door with a handle. (4) Displaying important robot status information for supervisors.

Bandwidth and latency are major challenges when streaming point-cloud and video data over a network. We utilized a latency measurement technique from [17] to assess end-to-end latency, which includes processing times across various stages such as image/point-cloud acquisition, data compression, streaming, data decoding, and display rendering. With video set at HD resolution (1280 x 720) at 30 fps and point clouds at (640 x 480), we measured one-way end-to-end latency from the FIELD to the MASTER station. The video stream averaged 180 ms, while the raw point-cloud stream averaged 500 ms. However, using the technique from [18], we achieved a 50 percent improvement in point-cloud latency, reducing it to 240 ms.

IV. Conclusions and Future Work

This paper presented the framework of the *"Robot Teleoperativo"* project that aims to develop immersive telerobotic technologies for locomotion and manipulation in demanding environments. The project successfully demonstrated efficient terrain navigation, dexterous manipulation, haptic telemanipulation, and an effective data transmission and immersive visualization system that significantly enhances teleoperation performance, as shown in the use case illustrated in Fig. 2. Future investigations will include a comprehensive user study to measure the impact on the quality of experience, teleoperation performance, and engagement in real-world environments.

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