A Teleoperation Testbed for Resilient Wireless Industrial Collaborative Robotics Evaluations

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***Abstract*—Robotics and teleoperation have become pivotal in modern industrial settings, offering robust solutions for enhancing operational flexibility and safety. By leveraging telerobotics, the presented real-world test environment investigates the intersection of resilient wireless communications and collaborative robotics, emphasizing the necessity of reliable, low-latency data transmission for real-time control and feedback. The test environment features two collaborative robots (cobots), a high-precision Motion Capture (MoCap) system for position tracking and localization, and a Digital Twin (DT) for collision prevention and visualization. Based on Robot Operating System 2 (ROS 2) and Docker, the system is highly customizable, providing a foundation for comprehensive digital twinning, Artificial Intelligence (AI) training, and evaluation of flexible multipath networking. The inherent demands of robotic teleoperation make it particularly suited for exploring resilience, security, and adaptability of wireless communication technologies and advanced (multipath) protocols in real-time and safety-critical applications. Integration and extensive testing of 5G and emerging 6G approaches, such as a decentralized Ultra-Reliable Low Latency Communication (dURLLC) system, demonstrate the environment's capability to evaluate advanced wireless communication strategies under real-world conditions.**

***Index Terms*—Cobotics, Robotics, Beyond 5G, 6G, Teleoperation, Industrial Communication, Digital Twin**

Please note: This work is a preprint.

I. Overview

Robotics is rapidly evolving, with the advent of Large Action Models (LAMs) offering transformative potential to transform industrial automation and everyday tasks. LAM are pivotal in enabling robots to learn complex, multi-step actions autonomously by leveraging advanced Artificial Intelligence (AI) techniques, significantly enhancing robotic versatility and efficiency [1]. Still, the development of comprehensive test environments remains a key objective.

To support this, a robotic test environment is presented, designed for end-to-end multipath communication, digital twinning, precise localisation testing, AI training and LAM integration. The demonstrator setup is illustrated in Fig. 1. The test environment features two Franka Research 3 collaborative robots (cobots) in a leader-follower configuration, where one cobot serves as the executing unit (4), while the other cobot is the controlling instance (2). The follower not only mirrors the leader's motion, but also transmits externally applied forces back to the leader, enabling direct force feedback and enhancing intuitive teleoperation. The setup is implemented within Robot Operating System 2 (ROS 2), a flexible framework for robotic applications that utilizes Data Distribution Service (DDS) for reliable and scalable communication. The entire laboratory area is scanned by a precise Motion Capture (MoCap) system (5), enabling position tracking of the cobots, assets and additional controllers to be located with sub-mm accuracy.

The communication between the cobots can be dynamically switched between various wired and wireless transmission technologies (1). Leveraging the ROS 2-based infrastructure, the system supports multipath communication, enabling comparative analysis of different wireless technologies and the investigation of symbiotic communication structures. This approach ensures seamless integration of diverse communication methods and higher-level systems. Building on this foundation, all processes and communications are mirrored in a Digital Twin (DT) (3), which extends the system's capabilities by providing parameter monitoring and a three-dimensional visualization of the entire laboratory space. Complementing the leader-follower teleoperation, the environment also includes a specialized wireless motion controller (6) with optical-active

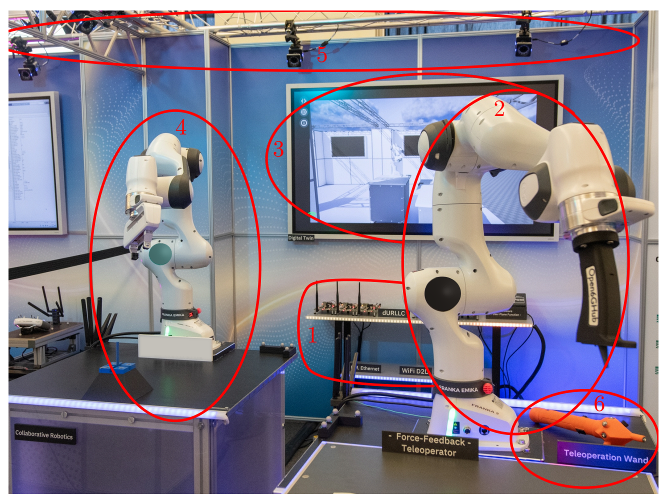

Fig. 1: Image of the collaborative robotic test environment, as presented at Berlin 6G Conference 2024.

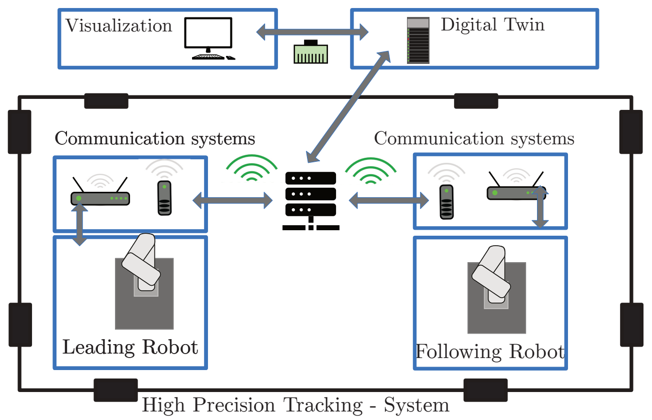

Fig. 2: Overview of the teleoperation test environment and laboratory space.

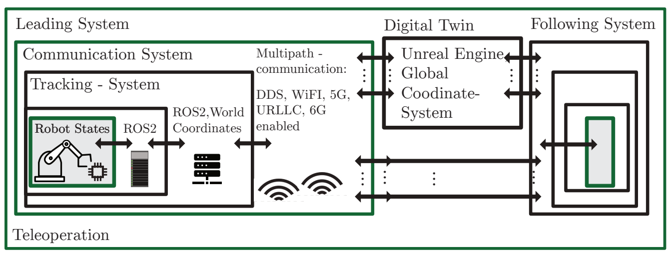

Fig. 3: Infrastructure and communication within the teleoperation test bed.

tracking via the MoCap system and wireless transmission of control commands via ESP-NOW. This controller offers an alternative teleoperation mode, enabling precise and intuitive control of the cobots in scenarios requiring greater mobility and freedom of movement.

While aspects of this test environment have been explored individually in other robotic platforms, their integration into a unified, modular environment is novel. Together, these components establish a versatile and scalable framework for comprehensive experimentation on fault tolerance, resilience, latency and real-time capability under realistic operational conditions—not only of various networking strategies, but also for bringing LAMs into application.

The following section outlines the main components of the test environment; more detailed descriptions will be published separately.

II. Main Components

The test environment is structured around three core components, which are illustrated in Fig. 2. First, the teleoperation setup is outlined, describing its implementation and functionality. Next, the communication architecture is detailed, highlighting the underlying infrastructure that enables analysis across various network technologies. Finally, the DT environment is presented, demonstrating the integration of sensor data from multiple subsystems to enhance not only monitoring, and analysis, but also enables the integration of LAMs for automated robotic training.

A. Teleoperation Setup

The teleoperation system is an enhanced ROS 2 version of [2]. Each cobot is mounted on a mobile machinery table, representing local (leader) and remote (follower) stations. Utilizing a modified joint impedance control approach, the follower replicates the motion of the leader cobot, which is hand-guided by a user. As external forces are applied to the follower, these are transmitted back to the leader, thereby generating direct force feedback. To evaluate the real-time capabilities of communication technologies, the control loop operates at an update rate of 1 kHz. Originally based on Franka Robotics' ROS implementation, the teleoperation code is divided into separate controller instances for leader and follower, as described in [2]. For better real-time performance of the underlying framework, the architecture of the teleoperation system is adapted to ROS 2 Humble.

Each cobot is controlled by a dedicated computer running a preemptive real-time kernel (v6.1.0-27-rt) to guarantee precise and deterministic timing. To enhance portability and flexibility, the setup is containerized using Docker, with Debian 12.8 as host OS and Ubuntu 22.04 containers for running ROS 2 processes.

B. Communication Architecture

The communication infrastructure is depicted in Fig. 3 and built upon the Fast-DDS middleware implemented within ROS 2 Humble, which manages teleoperation logic and data exchange at the application layer. Data exchange for the teleoperation relies on ROS 2 topics, with measured data rates of 1.2 Mbit/s from leader to follower and 0.7 Mbit/s in the reverse direction at 1 kHz for raw ROS 2 messages. At DDS level, these rates increase to approximately 4 Mbit/s and 3.5 Mbit/s, respectively. The teleoperation platform offers two distinct methods for integrating communication systems:

a) Integration via Linux Network Stack: Managing standard IP-based connections via NetworkManager, ideal for UDP-compatible technologies like Wi-Fi or 5G. Fast-DDS profiles restrict communication to designated network interfaces for efficient data transmission within the ROS 2 environment.

b) ROS 2 node-based integration: This method provides greater flexibility for specialized systems like a decentralized Ultra-Reliable Low Latency Communication (dURLLC) system [3]. To ensure compatibility with the external communication system, a custom ROS 2 node can adapt message handling as needed, such as serializing data into a UDP stream. This enables seamless integration by accommodating various communication requirements without imposing rigid constraints.

The test environment is designed to handle duplicate messages from redundant communication systems or other integrations, ensuring that only the first received message is processed. This approach enhances reliability and reduces latency, with implementations possible both at DDS and ROS 2 level. Such functionality is essential for robust teleoperation in dynamic environments where multiple communication paths may be available.

C. Digital Twin

The DT is implemented using Unreal Engine, which provides a robust and feature-rich pipeline for photorealistic rendering. It integrates the models of both the leader and follower as .gltf files, which are converted from URDF using Phobos. To accurately represent the cobot poses, joint states are applied to the corresponding link meshes according to defined rotation axes. Data exchange between the physical system and the DT is facilitated through a UDP-based communication architecture, where ROS 2 messages are serialized and transmitted to the DT environment. Data sent to the cobots is converted back from serialized data streams to ROS 2 messages. To enhance situational awareness, the cobot stations are equipped with individual tracking markers, enabling motion capture-based localization. This allows the DT to dynamically adapt to positional and environmental changes, enabling collision prevention through automated corrective actions when prohibited zones are breached.

ACKNOWLEDGMENT

This work has been supported by the Federal Ministry of Education and Research of the Federal Republic of Germany (Förderkennzeichen 16KISK003K, Open6GHub). The authors alone are responsible for the content of the paper.

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