technische universität dortmund

Communication Networks Institute

Master Thesis

Teleoperation and Coordination of Collaborative Robots Using Digital Twins and XR Interfaces

Motivation

In the era of Industry 4.0, the use of collaborative and mobile robots is rapidly transforming modern manufacturing environments by enhancing flexibility, adaptability, and productivity. The integration of such systems into factory networks, however, poses challenges in terms of coordination, communication, and real-time responsiveness [1]. A particularly promising direction involves the teleoperation of real robotic arms using immersive Virtual and Extended Reality (VR/XR) interfaces. This approach enables human operators to intuitively control robotic systems in dynamic environments while being physically remote. At the heart of this teleoperated control lies the concept of the Digital Twin—a virtual representation of physical robotic systems that allows for real-time monitoring, simulation, and interaction. Digital twins have become foundational technologies in Industry 4.0, enabling predictive capabilities, performance optimization, and system transparency [3]. When combined with XR technologies, they offer a highly interactive and immersive control environment for human-robot collaboration. Collaborative robotics itself is evolving rapidly, driven by advances in AI, sensing, control algorithms, and communication protocols. As highlighted in recent reviews, key trends include adaptive task sharing, human-in-the-loop systems, and robust cooperation under uncertainty [2]. These innovations are particularly relevant when systems must function over communication networks with unpredictable quality. This master's thesis focuses on developing a VR/XR-based teleoperation system for two real robotic arms operating collaboratively within a digital twin framework. A major research goal is to investigate how network quality factors—such as latency, jitter, and bandwidth—affect collaboration and control, and to explore strategies to maintain performance under suboptimal conditions. These findings aim to contribute to the design of resilient, adaptive communication and control architectures for collaborative robotic systems in real-world industrial settings.

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Potential Goals

A master's thesis in this area spans several exciting research topics, including teleoperation, digital twin technology, intent-based communication, and adaptive control in the context of real-world collaborative robotics. Your thesis may explore, but is not limited to, the following objectives:

- **Development of a Digital Twin Framework for XR-Based Teleoperation**
  Create an immersive digital twin system that represents two real robotic arms:
  - Familiarize yourself with simulation and robotics frameworks such as ROS2, Gazebo, RViz, unity or NVIDIA Isaac Sim
  - Integrate VR/XR interfaces (e.g., Meta Ques 3t) to enable intuitive teleoperation.
  - Demonstrate the framework through collaborative task scenarios performed by the real robotic arms under human control.
- **Optimization of Collaborative Task Execution Under Network Constraints**
  Develop and analyze coordination strategies to ensure reliable collaboration despite unstable network conditions:
  - Research shared control techniques for distributed manipulation tasks.
  - Implement adaptive algorithms that allow the robotic system to compensate for network degradation in real time.
  - Evaluate performance differences in collaborative execution with and without network impairments.
- **Investigation of Network Quality Impact on Human-Robot Collaboration**
  Explore how mobile or remote connectivity (e.g. 5G, WLAN) affects the efficiency of teleoperated robotic arms:
  - Measure the influence of latency, bandwidth, jitter, and signal quality on task performance.
  - Identify critical thresholds for network parameters necessary to maintain functional collaboration.
  - Propose and evaluate methods (e.g., prediction, buffering, semantic compression) to mitigate performance drops under poor connectivity.
  - Build upon recent studies such as [4], which explore predictive scheduling and digital twins for real-time robot control over mobile networks.
  - Leverage [5] which introduces proactive bitrate control mechanisms and multi-link communication protocols to minimize latency and ensure reliability in teleoperation systems.

Requirements

- Interest in 5G/6G communications, robotics, collaboration tasks between robots
- Basic knowledge on Machine Learning
- Good Python, LaTeX and presentation skills
- successful participation in CNI courses are beneficial
- Good English skills; highly desirable: Willingness to write thesis in English

References

[1] K. Aliev, D. Antonelli, A. Awouda, and P. Chiabert, "Key Performance Indicators Integrating Collaborative and Mobile Robots in the Factory Networks," *IFIP International Conference on Advances in Production Management Systems*, pp. 457–464, 2019. doi: 10.1007/978-3-030-28464-0_56

[2] S. Patil, V. Vasu, and K. V. S. Srinadh, "Advances and perspectives in collaborative robotics: a review of key technologies and emerging trends," *Discover Mechanical Engineering*, vol. 2, no. 13, 2023. doi: 10.1007/s44245-023-00021-8.

[3] M. Javaid, A. Haleem, and R. Suman, "Digital Twin applications toward Industry 4.0: A Review", *Cognitive Robotics*, vol. 3, 2023. doi: 10.1016/j.cogr.2023.04.003.

[4] H. Schippers, T. Gebauer, K. Heimann, C. Wietfeld, "RISE: Multi-Link Proactive Low-Latency Video Streaming for Teleoperation in Fading Channels," in *IEEE 101st Vehicular Technology Conference (VTC-Spring)*, Oslo, Norway, June 2025. (*Accepted for Presentation.*)

[5] N. A. Wagner, J. Eßer, I. F. Priyanta, F. Kurtz, M. Roidl, C. Wietfeld, "Real-Time Predictive Scheduling for Networked Robot Control Using Digital Twins and OpenRAN," in *IEEE Globecom Workshops (GC Wkshps): Workshop on Digital Twins over NextG Wireless Networks*, Cape Town, South Africa, December 2024. (Forthcoming.)

– References to external related works can be made available to interested students upon contact. –

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