Mechanical Engineering Dissertation Defense

Software Architectures for Enhanced Physical Human-Robot Interaction and Mixed Reality-based Robotic Rehabilitation

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Abstract

Physical human-robot interaction (pHRI) and mixed reality (MR)-based robotic rehabilitation impose stringent requirements on software systems: safety-critical real-time execution, integration of heterogeneous sensors, and support for collaborative multi-user workflows. Yet conventional research prototypes, typically monolithic and single-threaded, lack the reliability and extensibility required for large-scale experimental studies. This dissertation develops and validates software architectures that advance pHRI and MR-based robotic rehabilitation, guided by two software design principles: (1) parallel architectures that deliver real-time and robust performance through non-blocking execution, and (2) modular architectures that enable scalable development through clear functional separation and decoupled communication.

For pHRI, these principles are instantiated in a shoulder exoskeleton robot employing lock-free multi-threaded pipelines, a wearable upper-limb exoskeleton built on a layered ROS-based architecture, and a robotic arm manipulator using a message-driven distributed framework. The principles are further extended to MR-based robotic rehabilitation, where resource-constrained head-mounted displays and multi-user collaboration introduce additional constraints and challenges. A multi-user MR robot-aided rehabilitation platform formalizes visualization-control separation through policy-based configuration, enabling flexible onsite-remote collaboration while maintaining spatially synchronized shared interaction across users.

Validation across these systems demonstrates the effectiveness of the proposed architectures. The shoulder exoskeleton achieves real-time control at 250 Hz with high impedance estimation reliability ($R^2 > 0.97$) in a biomechanics study. The wearable exoskeleton attains 500 Hz control with high reliability in simulating impedances (>99.2% VAF). The robotic arm manipulator reduces interaction energy by 45% through a distributed task scheduler enabling continuous user-specific parameter optimization across sessions. The multi-user MR platform maintains real-time state synchronization across distributed head-mounted displays via cloud networking, enabling spatially synchronized multi-user interaction across on-site and remote participants.

Together, these architectures provide a foundation for transforming prototype-level pHRI and MR-based robotic rehabilitation systems into reliable research platforms capable of supporting robust long-term, large-scale experiments and multi-site collaborative studies.

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