

ABSTRACT

The engineering requirement to enforce physical, multi-directional motion constraints within highly restricted operational volumes is critical across advanced collaborative robotics and micromanipulation applications. Historically, collaborative robots, or cobots, have delivered safe, mechanically compliant, and adaptively constrained interactions through large-scale steerable transmissions [1, 2]. However, downscaling these architectures to a finger-scale footprint introduces distinct mechanical and kinematic challenges. Conventional joint-localized micro-actuators are often challenged at these scales by adverse payload-to-weight scaling, internal structural friction, and elevated reflected rotor inertia.

To address these limitations, this dissertation introduces a novel 2-DOF finger-scale parallel cobot transmission architecture driven by a centralized drive cylinder and independently steered dual-carriage rollers. This work shifts active power transmission away from moving components by implementing a network of continuously variable transmissions (CVTs) that enforce programmable nonholonomic rolling constraints to regulate spatial coordinate velocities while preserving mechanical transparency. While the comprehensive theoretical framework maps a future multi-link planar transmission and thimble-gimbal end-effector, the physical benchtop testbed isolates and evaluates the core transmission mechanics directly at the carriage level.

The evaluation framework shifts from human-centric perception to objective mechatronic characterization of system performance. This work systematically evaluates the agreement and behavioral consistency between theoretical models and measured system responses under representative simulated interaction-force profiles. Through numerical simulations and hardware-in-the-loop (HIL) benchtop experiments, workspace boundaries, joint-space kinematic accuracy, transmission-steering tracking, and constraint-enforcement behavior are characterized. The results indicate that the physical system behavior is consistent with the developed multi-body control framework under representative operating conditions, supporting accurate trajectory regulation and effective constraint enforcement. This research establishes a predictive and empirical foundation for the downscaling and coordination of multi-axis nonholonomic parallel transmission networks within highly constrained volumetric footprints.