Doctoral Dissertation
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Modeling, Control and Evaluation of the quasi-Spherical Parallel Manipulator

A master device for telesurgery and teleproctoring

By

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Abstract

This dissertation investigates a quasi-Spherical Parallel Manipulator (qSPM) designed as a haptic master device for telesurgery applications. The device, a fully parallel mechanism with three actuated legs (2RRR-1URU), provides haptic feedback through its end-effector handle to facilitate minimally invasive procedures. Its purpose is to mirror the tool orientation of a slave robotic arm in a bilaterally teleoperated system, complying to a remote center of motion rule as to minimize surgical incision.

The study focuses on the formulation of the qSPM's Inverse Kinematics, linking the Euler *zxz* angles related to the tool orientation to the actuated joint angles of the master device, and derives the Jacobian across the workspace. Dexterity and self-collision evaluation establish the optimal working mode among the eight possible ones, enabling the determination of the actual reachable workspace. Updated Statics and Forward Kinematics are thus analyzed for this mode.

A robust control architecture is thus developed within the Robot Operating System (ROS) and its visualization framework (RViz) featuring: (a) the bilateral teleoperation core architecture, for master-slave communication; (b) an avoidance control algorithm, generating guiding forces/torques when the EE exceeds workspace boundaries, following a segmented spring-like rule; (c) an assistive control algorithm, implementing a hapto-visual Digital Twin for telementoring and teleproctoring, ensuring trajectory adherence while preventing boundary trespassing through haptic and damping feedback; (d) a joint-path planning algorithm, able to smoothly reset the end effector to the workspace center or between arbitrary points.

Preliminary results confirm the efficacy of the avoidance and assistive algorithms in guiding the user and maintaining precision within the operational workspace. The path planning algorithm demonstrated smooth, reliable resets across non-convex

operative workspace. Statics analysis revealed significant friction and clearance impacts, while workspace modeling was preliminary validated through testing.

Future work will focus on integrating axial actuation for complete Remote Center of Motion (RCM) control, refining control algorithms for efficiency and adaptability, and optimizing user-specific parameter tuning via AI-based calibration. Additionally, improvements to the gearbox will reduce friction, enhancing overall performance. Comprehensive testing campaigns are planned to validate these advancements and solidify the qSPM as a robust tool for telesurgery.