Task-Space Path-Velocity Control for Torque-Limited Redundant Manipulators

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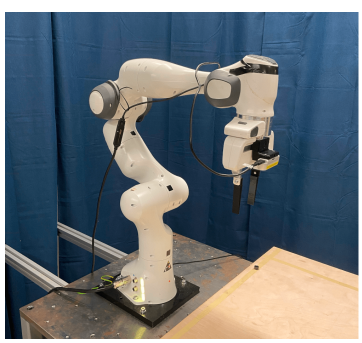
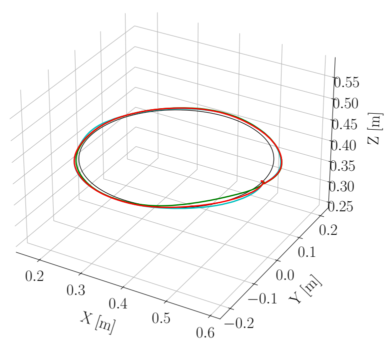
Abstract

This presentation addresses the time-optimal path-tracking problem for redundant manipulators. By integrating path-velocity control into existing task-space robot controllers, the task-space motion can be dynamically scaled to satisfy the torque constraint under both kinematic and dynamic uncertainties. Numerical simulations and experiments demonstrate that trajectory feasibility and path-tracking accuracy of the task-space controllers can be significantly improved by integrating path-velocity control. In addition, the nullspace motion of redundant manipulators can be used to further improve the performance by tracking the approximate time-optimal joint trajectory associated with the tasks in nullspace.

Accurate and fast movement of the robot end-effector can be achieved by controlling the manipulator to follow the desired joint angles as quickly as possible. However, when a robot operates while grasping a tool with approximate dimensions and an uncertain position, and the control objective is focused on the tool rather than the gripper or flange, kinematic uncertainty arises. Task-space control with workspace sensing addresses the challenge of accurate movement in the presence of kinematic uncertainty. However, the movement speed of manipulators is always constrained by the torque limits of the actuators. Kinematic or dynamic uncertainties may cause the planned fast motions to be unrealizable by the task-space controller. In applications where a desired path in task space is prescribed, violation of the torque constraint implies degraded performance of feedback control and path deviation.



(a) Panda in experiments

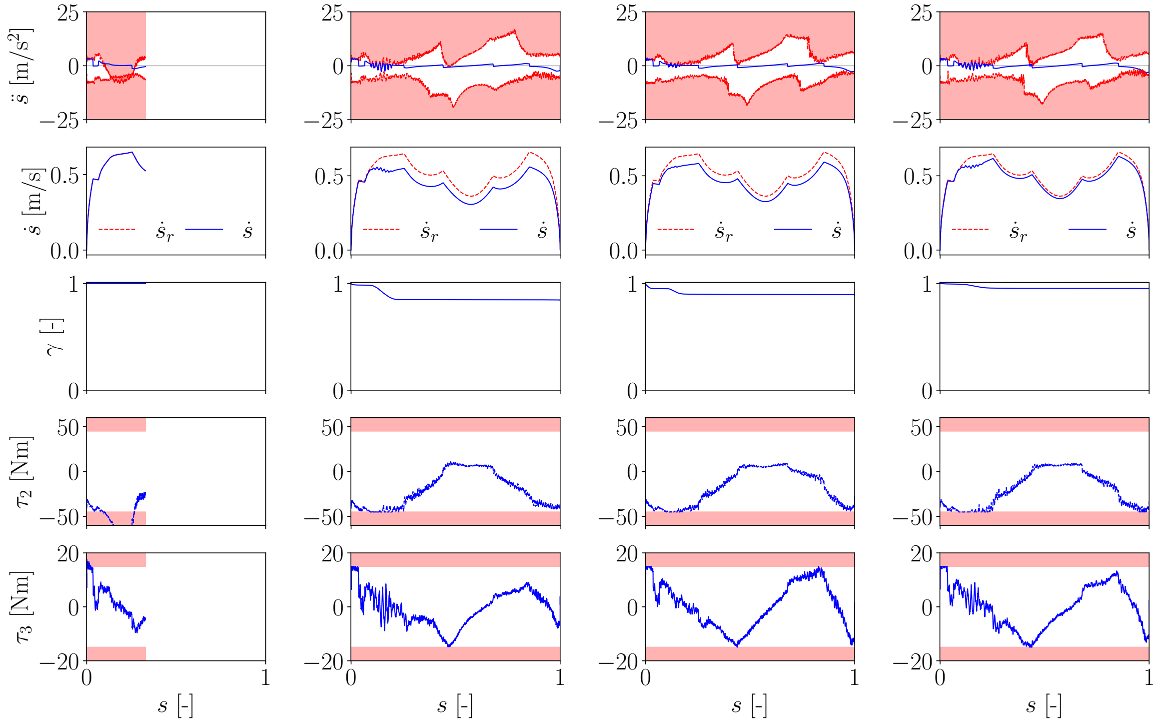


(b) Tool center point position

Figure 1: Panda robot tracking a circular path in Cartesian space. The blue, green, and red solid lines represent the resulting positions for TS-PVC with position-based, damping-based, and trajectory-based nullspace designs, respectively.

This presentation addresses the time-optimal path-tracking problem for torque-limited redundant manipulators based on recent work in [1]. A task-space path-velocity control (TS-PVC) framework is developed by integrating path-velocity control [2] into task-space controllers. The path-parameterized formulation enables online adjustment of the path acceleration to satisfy joint torque constraints, thereby improving the feasibility and accuracy of task-space trajectory tracking (see Fig. 1).

The effect of nullspace control on the performance of TS-PVC is investigated through three representative designs: (1) position-based, (2) damping-based, and (3) trajectory-based. The latter enables



(a) Position-based (b) Position-based +PVC (c) Damping-based +PVC (d) Trajectory-based +PVC

Figure 2: Time-optimal path-tracking in experiments of a circular path under kinematic and dynamic uncertainties. In subplot (a), the experiments are stopped because of joint velocity limit violations. Within each subplot, the signals from top to bottom are path acceleration $\ddot{s}$, path velocity $\dot{s}$, joint torques τ_2 and τ_3. The red areas indicate inadmissible regions for signals.

coordination between task- and nullspace motions by maintaining proximity to an inverse kinematic solution.

Simulation results using a 7-DOF Franka Emika Panda robot model demonstrate that PVC significantly improves the feasibility of time-optimal path tracking, especially when combined with trajectory-based nullspace control. Compared to controllers without PVC, the combined method eliminates torque constraint violations and improves both tracking precision and execution time. Experimental validation confirms these findings, showing that TS-PVC enables feasible execution in scenarios where standard task-space controllers fail because of constraint violations. Among the evaluated nullspace strategies, trajectory-based control consistently gives the best performance in terms of path-tracking accuracy, traversal time, and torque utilization (see Fig. 2).

The study concludes that the integration of path-velocity control into task-space controllers substantially improves performance and robustness under real-world uncertainties. Future work will investigate alternative task-space controllers and extend nullspace strategies to support additional objectives.

References

[1] Z. Jia, Y. Karayiannidis, and B. Olofsson, "A study of task-space path-velocity control for torque-limited redundant manipulators under uncertainties," in *Accepted for 2025 European Control Conference*, IEEE, 2025.

[2] O. Dahl, *Path Constrained Robot Control*. PhD Thesis No. TFRT-1038, Department of Automatic Control, Lund University, 1992.