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Trajectory Design Trade-offs in a 1-DoF Transformable Wheel for Obstacle Climbing*

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As mobile service robots expand into human living environments, their ability to negotiate structured obstacles—such as thresholds, curbs, and stairs—has become increasingly important. Transformable wheels offer a compelling alternative to high-DoF locomotion by preserving the efficiency and maneuverability of conventional wheels on flat ground while selectively reconfiguring their geometry only when obstacle negotiation is required. Among such systems, the 1-DoF RPRP transformable wheel achieves step climbing with minimal actuation by mechanically coupling radial transformation and spoke tilting through an internal linkage. This reduced-actuation architecture, however, also creates a distinctive design challenge: because the mechanism lacks kinematic redundancy, a very small number of trajectory parameters exert a disproportionately large influence on climbing behavior. As a result, performance is governed less by control flexibility and more by how transformation timing and posture are coordinated throughout the climbing cycle. Despite this, prior studies on transformable wheels have largely focused on mechanism design and kinematic feasibility, leaving insufficient understanding of how trajectory design shapes the trade-offs among motion smoothness, actuator load, and power demand [1]–[3].

To address this gap, this study presents a trajectory-level design-space exploration framework for a 1-DoF transformable wheel, in which the obstacle-climbing motion is parameterized using three intuitive variables: transformation start angle (TS), transformation end angle (TE), and pivoting angle (α). A closed-form kinematic mapping is used to relate wheel posture—defined by the effective radius r, tilting angle θ, and pivoting posture α—to obstacle geometry characterized by step depth S and height H. On this basis, smooth cubic Hermite spline profiles generate continuous transformation trajectories over the climbing cycle. A quasi-static model then evaluates the actuator torques required along each trajectory, from which six performance indices are derived to quantify three practically important aspects of climbing performance: average and maximum center-of-rotation (CoR) acceleration for motion smoothness (PI1, PI2), average and maximum motor torque for actuator loading (PI3, PI4), and average and maximum mechanical power for power demand (PI5, PI6). **Fig. 1** summarizes the overall framework, including the kinematic modeling, quasi-static analysis, design-space exploration, and experimental validation.

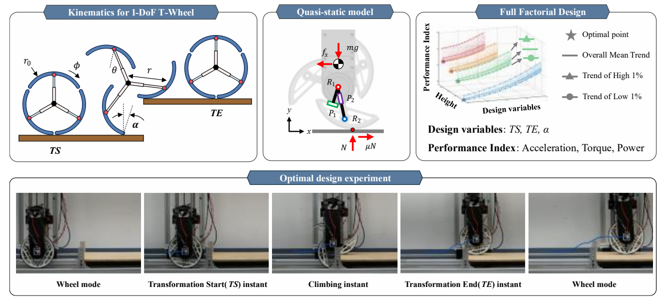

Fig. 1. Overview of the proposed framework for a 1-DoF transformable wheel, illustrating the kinematic and quasi-static modeling, full factorial design for design-space exploration, and hardware validation.

A full factorial design evaluates 125,000 TS–TE–α combinations, of which 71,450 satisfy the no-slip and collision-free constraints for a representative step height of H = 100 mm. The resulting four-dimensional performance maps reveal that motion smoothness, actuator load, and power demand cannot be simultaneously optimized, and instead occupy distinct regions of the feasible design space. Acceleration-oriented designs favor small α values and long transformation intervals, yielding smoother CoR trajectories at the cost of higher actuator torque. Torque-oriented designs place TE near a kinematic singular configuration where the required transformation torque becomes very small, but this benefit is accompanied by larger acceleration peaks. Power-oriented designs adopt a different strategy by temporally separating torque peaks from high angular-velocity intervals, thereby suppressing peak power without fully coinciding with torque-optimal solutions. These trade-off structures persist across multiple obstacle heights, indicating that the identified trajectory-design tendencies reflect broader characteristics of the mechanism.

Experimental validation was conducted on a 1-DoF RPRP prototype using a planar testbed with ArUco-based tracking of the CoR trajectory. Six single-objective optimal trajectories were tested at three step heights. The experimental results show that the simulation-derived optimal trajectories remained within the best-performing group on hardware, and that the overall trade-off structure among the tested solutions

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was largely preserved, even though the exact minimizer shifted to a neighboring design in some indices due to stick-slip friction, drivetrain resistance, and structural compliance. Simulation-experiment correlations of $R^2 = 0.64–0.90$ across all tested indices and step heights support the predictive usefulness of the proposed framework for trajectory selection and actuator sizing in low-DoF transformable-wheel systems.

Keyword - Mobile service robot, Transformable Wheel, Design space exploration, Trajectory parameterization, Performance mapping

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