Planning for Crossed-Leg Disturbance Rejection

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I. Introduction

Disturbance rejection is an essential capability of bipedal legged robots and has been widely studied in the locomotion literature. However, adversarial lateral disturbances and aggressive turning can induce leg cross scenarios (negative step width) and self-collision risk, which have not been explicitly addressed by previous works, such as Capture Point based planning framework [1]. Crossed-leg foot placement planning, a common behavior in human locomotion, combines the merit of disturbance rejection and collision avoidance. Inspired by human walking, we aim to improve bipedal walking robustness by designing safe crossed-leg motions for disturbance rejection. This work extends the robust phase-space planning approach [2] by designing full-body crossed-leg motions via trajectory optimization (TO), which incorporates both foot placement and Center-of-Mass (CoM) planning. Furthermore, the generated motion provides a dynamic balancing guarantee while respecting the leg kinematic limits and self-collision constraints. Finally, we simulate the collision-free crossed-leg recovery behavior and verify its ability to resist lateral treadmill pushes on the bipedal robot Cassie.

II. Approach

A. Robust Keyframe Transition Decision-Maker

We design a Robust Keyframe Transition Decision-maker (RKTD) to address terrain perturbations and compute robust step-to-step keyframe transitions to prevent the robot from falling. As shown in Fig.1, the system starts from a perturbed unstable CoM phase-space state. We partition the local phase-space keyframe state region into $N \times M$ cells using analytical Riemannian locomotion tangent and cotangent manifolds derived from a reduced-order model [2]. This Riemannian-space partition is consistent with the locomotion dynamics and is further used to design robust transitions to the target keyframe cell of the next walking step. The feasibility of keyframe transitions is determined by the low-level TO incorporating self-collision and kinematic constraints (introduced in the next section). The RKTD represents a discrete-level robust keyframe transition strategy given the phase-space robustness margin design.

B. Self-Collision-Free Whole-Body Trajectory Generation

We bridge the connection between high-level RKTD and low-level full-body TO for online recovery motion design. The RKTD outputs desired keyframe states to the low-level TO as initial and final configuration parameters. The TO problem is formulated as a Nonlinear Program (NLP) [3], which solves full-body trajectories connecting locomotion keyframe pairs. The NLP comprises full-body dynamics and self-collision constraints to generate optimal motions. Cassie has a unique four-bar-linkage, which we solve by introducing a virtual joint to break the closed-loop kinematic chain and constructing a Swept Sphere Volume model for fast self-collision proximity evaluation. The NLP designs a set of dynamic whole-body trajectories, each encoding a feasible transition between Riemannian-space keyframe cells.

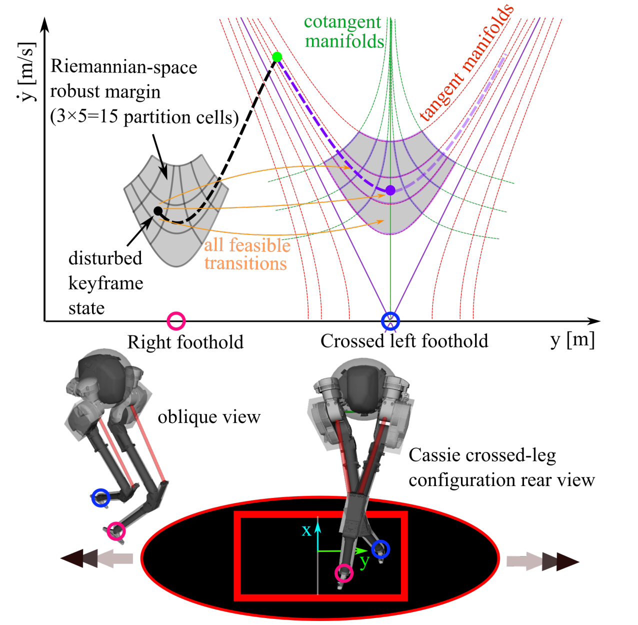

Fig. 1. The robot is perturbed laterally during a periodic walking cycle, resulting in a leg cross scenario. The orange lines in the top figure illustrate a set of feasible RKTD transitions from the perturbed state in a Riemannian-space cell to a stabilized keyframe for the crossed leg motion.

III. Proposed Experiments

We formally guarantee the feasibility of the crossed-leg recovery motion given by the RKTD and its ability to drive the system back to nominal states within two steps at varying nominal speeds. We are verifying the recovery behavior with perturbations from various directions and analyze the robustness against large perturbations with more recovery steps. Future experiments will also explore more crossed-leg scenarios such as aggressive turning.

References

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[3] A. Hereid and A. D. Ames. “FROST: Fast robot optimization and simulation toolkit”. In: *IEEE International Conference on Intelligent Robots and Systems* (2017).