The Influence of a Non-Instantaneous Double Support Phase on the Efficiency of a HZD Controlled Bipedal Robot

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Abstract. This work introduces the extended hybrid zero dynamics control for periodic gaits containing alternating single and non-instantaneous double support phases of a planar bipedal robot. The model consists of five rigid body segments which are connected by four actuated revolute joints. During both continuous phases, the controller synchronizes the joints to their reference trajectories, which are numerically optimized to minimize the energy consumption of locomotion. The resulting efficiency is compared against gaits with an instantaneous double support phase.

Introduction

Hybrid zero dynamics (HZD) control is a popular control concept to create stable walking gaits for bipedal robots. One of its advantages is that the controller uses the passive dynamics of the system which is suitable for high energy efficiency. The existing HZD control concept is commonly developed for periodic walking gaits that consist of an under-actuated single support phase (SSP) and an instantaneous double support phase (DSP) [1]: during the SSP, the stance leg contacts the ground without slipping and the swing leg moves forward without scuffing. The DSP is described as a discrete transition event, namely an inelastic impact of the swing leg with the ground, immediate lift-off of the former stance leg and swapping the roles of the former swing and stance leg.

Based on a planar five-segment robot model driven by four electric actuators in its joints, our research extends the HZD control strategy to periodic gaits with non-instantaneous DSP. Since both non-slipping stance feet remain on the ground, the legs form a closed kinematic chain that results in one degree of over-actuation (Fig. 1 left). In order to artificially create an under-actuated DSP, two independent virtual actuators are introduced and mapped to the four physical actuators by a projection matrix $\mathbf{P}_{(4\times2)}$. In both SSP and DSP, the HZD controller synchronizes the independent joints to their reference trajectories which are parameterized by Bézier curves. For vanishing control errors, the states of the un-actuated absolute orientation are the zero dynamics of the controlled system. Its periodic solution can be obtained by a numerical optimization process, which minimizes the energy consumption of locomotion (evaluated by the cost of transport) while optimizing the Bézier parameters and the projection $\mathbf{P}_{(4\times2)}$. The resulting energy efficiency is compared against the original assumption where the DSP is modeled as instantaneous.

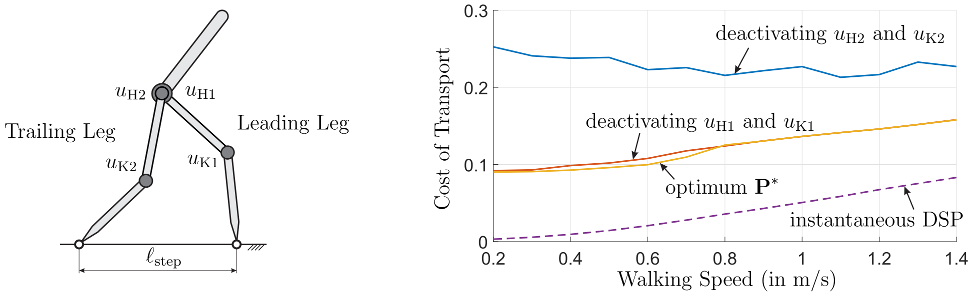

Figure 1: Left: The over-actuated double support phase with the constant step length ℓ_{step}. Right: Optimized cost of transport of different continuous under-actuated DSPs (solid lines) in comparison to the instantaneous DSP (dashed line).

Results and Discussion

As depicted in Fig. 1 (right), the efficiency study is conducted for the speed range $v \in [0.2, \dots, 1.4]\,\mathrm{m/s}$. The optimum actuator mapping $\mathbf{P}_{(4\times2)} = \mathbf{P}^*$ is compared to two other configurations that result in an under-actuated DSP: simply deactivating the actuators of the leading or the trailing leg. According to the optimization results, the actuation in the trailing leg's knee joint should be utilized during DSP to achieve a high efficiency independent of the walking speed. In contrast, the trailing leg's hip actuator is advantageous for high speeds ($v > 0.8\,\mathrm{m/s}$) and the leading leg's hip actuator for lower speeds. Regarding the DSP as an instantaneous impact event, however, results in the highest efficiency, because its optimum gaits need less negative work (braking) to slow down the movement.

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References

[1] E.R. Westervelt, J.W. Grizzle, and D. Koditschek, Hybrid Zero Dynamics of Planar Biped Walkers, *IEEE Transactions on Automatic Control* 48(1), pp. 42–56. (2003).