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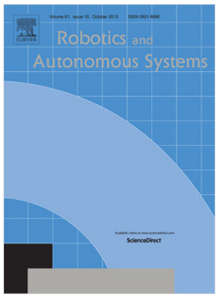

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Hybrid-State driven autonomous control for planar bipedal locomotion over randomly sloped non-uniform stairs

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Abstract

This paper extends the hybrid-state driven autonomous control (HyDAC) algorithm developed for planar bipedal locomotion to dynamic walking situation over randomly sloped ascending and descending stairs with non-uniform tread depth and riser height. Dynamic walking over non-uniform stairs requires to control the swing foot placement at predetermined feasible foothold on each toe-impact event in addition to forward velocity regulation. HyDAC law is modified in both task level and supervisory level to meet these demands. A novel scheme for forward velocity control by direct regulation of the ground centre of pressure (GCoP) is developed as a part of HyDAC. Nonholonomic constraints corresponding to friction cone and actuator torque limit are also introduced in HyDAC formulation. The agility of the control algorithm is demonstrated for a forward velocity range upto 0.5 m/s over ascending and descending stairs with tread depth of $1.5L_f$ to $2.5L_f$, riser height up to $2L_f$ and tread slope within $\pm 15^o$, for a planar biped with foot-sole span of $L_f = 0.2m$, nominal hip height of $h_{hip} = 0.98m$, and nominal centre of mass height of, $h_{com} = 1.13m$. The robustness of the algorithm is demonstrated through dynamic model simulation of a 12-link planar biped having similar size and mass properties of an adult sized human being restricted to sagittal plane. Cases with wide range of link parameter perturbation, external force disturbance and with random perturbation of stair-parameters have been considered for simulation.

Keywords: Planar biped, Autonomous control, Non-uniform stairs, Ground envelope segments, Motion control primitive, Aperiodic orbital stability

1. Introduction

Bipedal locomotion control over non-uniform terrain with step and slope discontinuities is a potential area of research in the field of generic uneven terrain locomotion. Maintaining stable dynamic walk over ascending and descending stairs with random step parameters like tread depth, riser height and tread slope is a challenging control problem within this category [1]. Due to the hybrid nature of dynamic human walk, a single phase analytical solution is not practically feasible for locomotion control. Many of the control solutions reported in the literature for bipedal locomotion use a two phase approach [2, 3, 1]. The first phase is used for the synthesis of feasible gait trajectory or orbit followed by a second phase for enforcing the same on biped joint level control. For example, ZMP based control pre-plans the ZMP trajectory for the biped followed by appropriate joint level control to track the same with necessary on-line correction [4, 5, 1, 3, 6]. The gait stability is based on the heuristic ZMP stability concept which has been proven to be neither necessary nor sufficient [7] and leads to unnatural gaits with bent knee resulting in significant loss of energetic efficiency. Similarly, analytically motivated HZD based control generates a provably stable trajectory for bipedal gait followed by closed loop implementation of the same through trajectory tracking [7]. The gait is defined by a viable set of virtual constraints to be designed prior to each walking step using non-linear optimizers. Periodic stability is guaranteed off-line during the gait synthesis phase by constraining the eigenvalues of linearized Poincaré map on each heel impact within the unit circle of complex plane. There are two practical difficulties when the same is to be applied to locomotion over non-uniform stairs. The primary issue is related to the convergence of the optimal solver to a feasible gait for stair-walking and the second is related to the robustness of control algorithm w.r.t. the unaccounted stairway dispersions. These issues are addressed by the team of A.D.Ames [8, 9, 10, 11]. Their approach is based on the argument that the human locomotion behaviours can be expressed in terms of three basic kinematic functions called, extended canonical human functions (ECHF) corresponding to walking on flat ground, upstairs and down stairs and in terms of four transition modes corresponding to the transition between the above motion patterns [8, 9].

To the best of authors' knowledge, successful bipedal locomotion control over updown stairs employing actuated ankle has been reported in the literature only by using ZMP control approach [1]. However many such control algorithms have realized only slow walking. In [1], the authors have demonstrated ZMP based dynamic stair-walking on HUBO humanoid which takes 2 s per step. They use a controller structure which em-

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