Hybrid-state Driven Autonomous Control for Planar Bipedal Locomotion

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by

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Abstract

The bipedal locomotion control is identified as a challenging problem by the control community due to its multiphase, hybrid nature and the unilateral characteristics of ground contact forces. The underactuation during heel and toe centred rolling motions and the intermittent ground impacts introduce additional complexity. The focus of this doctoral research is on the development of an autonomous control framework for a planar bipedal robot to realize human-like walking projected onto sagittal plane. In addition, a unified modelling scheme is proposed for the biped dynamics incorporating the effects of various locomotion constraints due to recurrent feet-ground contact states, unilateral ground contact force, contact friction cone, joint torque limit and due to the passive dynamics associated with floating base. The autonomous control synthesis is formulated as a two-level hierarchical control algorithm with a hybrid-state based supervisory control in outer level and an integrated set of constrained motion control primitives, called task level control, in inner level. The supervisory level control is designed based on a human inspired heuristic approach whereas the task level control is formulated as a quadratic optimization problem with linear constraints. The explicit analytic solution obtained in terms of joint acceleration and ground contact force is used in turn to generate the joint torque command based on inverse dynamics model of the biped. The proposed controller framework is named as *Hybrid-state Driven Autonomous Control (HyDAC)*. Unlike many other bipedal control schemes, HyDAC does not require any preplanned trajectory or orbit in terms of joint variables for locomotion control. Moreover, it is built upon a set of basic motion control primitives similar to those in human walk which provides a transparent and easily adaptable structure for the controller.

A control oriented stability theorem, called *Contraction stability theorem*, based on Lyapunov, Poincaré and contraction mapping theorems, is proposed to analyse the stability of bipedal walk in realistic situations. This provides two stability measures, namely, the *contraction factor* and the *radius of convergence* to quantitatively represent the stability margins applicable for both periodic gait over uniform terrain as well as for non-periodic gait over uneven terrain. The multi-phase goal seeking concept of HyDAC is justified on the basis of contraction stability theorem.

HyDAC is further extended to dynamic walking situation over ascending and descending stairs with non-uniform tread depth and riser height and having arbitrary, but bounded

distribution of tread slope. 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 centre of pressure due to ground contact forces is also developed as a part of HyDAC.

The stability and agility of HyDAC for uniform terrain locomotion are demonstrated through dynamic model simulation of a 12-link planar biped having similar size and mass properties of an adult sized human projected onto sagittal plane. Simulation results show that the planar biped is able to walk for a speed range of 0.1 m/s to 2 m/s on level terrain and for a ground slope range of +/- 20 deg for 1 m/s speed. Similarly, the performance of the control algorithm for stair-walk is demonstrated for a forward velocity range of 0.1 m/s to 0.75 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 ± 15 deg, for a planar biped with foot-sole span of $L_f = 0.2\,m$, nominal hip height of $h_{hip} = 0.98\,m$, and nominal centre of mass height of, $h_{com} = 1.13\,m$. Cases with wide range of torso mass perturbation, external force disturbance and with random perturbation of terrain height, slope and stair-parameters have been considered for both the cases of simulation. The simulation results demonstrate the performance robustness and postural reflex behaviour of HyDAC which are essential for unplanned realistic walking situations with unexpected environmental disturbances. The stability margins for uniform terrain walk as well as for stair-walk are analysed based on the proposed contraction stability theorem.

Thus the thesis brings out solutions for many open problems in bipedal walking with respect to modelling, online control design and postural stability analysis, all applicable in realistic walking situations. The superiority of HyDAC over current design methodologies such as Zero Moment Point (ZMP), Hybrid Zero Dynamics (HZD) etc. are also brought out in the thesis. The recommended directions for future research to extend HyDAC towards realization of human like 3D bipedal locomotion are discussed at the end.