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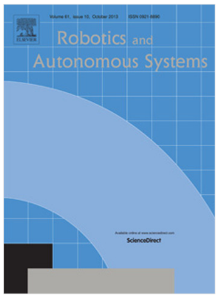

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Online Impedance Regulation Techniques for Compliant Humanoid Balancing

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***Abstract*—This paper presents three distinct techniques, aimed at the online active impedance regulation of compliant humanoid robots, which endeavours to induce a state of balance to the system once it has been perturbed. The presence of passive elastic elements in the drives powering this class of robots leads to under-actuation, thereby rendering the control of compliant robots an intricate task. Consequently, the impedance regulation procedures proposed in this paper directly account for these elastic elements. In order to acquire an indication of the robot's state of balance in an online fashion, an energy (Lyapunov) function is introduced, whose sign then allows one to ascertain whether the robot is converging to or diverging from, a desired equilibrium position. Computing this function's time derivative unequivocally gives the energy-injecting nature of the active stiffness regulation, and reveals that active damping regulation has no bearing on the system's state of stability. Furthermore, the velocity margin notion is interpreted as a velocity value beyond which the system's balance might be jeopardised, or below which the robot will be guaranteed to remain stable. As a result, the unidirectional and bidirectional impedance optimization methods rely upon the use of bounds that have been defined based on the energy function's derivative, in addition to the velocity margin. Contrarily, the third technique's functionality revolves solely around the use of Lyapunov Stability Margins (LSMs). A series of experiments carried out using the COmpliant huMANoid (COMAN), demonstrates the superior balancing results acquired when using the bidirectional scheme, as compared to utilizing the two alternative techniques.**

I. INTRODUCTION

THE topic of bipedal robot balancing has been studied extensively, since it is unquestionably the single most fundamental property whose absence renders a robot incapable of performing any kind of task. A field of research has arisen aiming at systematizing the way through which a humanoid robot's balance is evaluated, with [1] being among the most seminal works, as it introduced the Zero-Moment-Point (ZMP) concept. Strictly speaking, the ZMP describes a point existing under the robot's feet whose position defines the system's overall stability, with a range of possible ankle torque and reaction force combinations yielding a stable robot configuration, which ensures the point's residing within the confines of the convex hull of the support polygon. The literature is replete with works pertaining to humanoid balancing, which are contingent upon the use of this criterion, with quintessential examples of such techniques presented in [2]-[4].

The work described in [2] proposes a method aimed at rendering a humanoid passive, which exploits a combination of translating the ground reaction forces (GRFs) to joint torques, and gravity compensation control, thus obviating the requirement for inverse dynamics calculations. The work described in [3] manifested itself as a breakthrough, as it served the purpose of introducing the Linear Inverted Pendulum Model (LIPM) that significantly facilitated the humanoid control problem, while its simplicity also served as a valuable analysis tool that was exploited in various works thereafter. [4] delves into the use of such simplified models for the purpose of developing an array of decision surfaces, permitting the selection of the most appropriate model and strategy, at a given point in time, that would be capable of reinstating the system's desired state of balance. A closely related balancing criterion referred to as the Centre-of-Pressure (CoP), has also been investigated due to its frequent equivalence with the ZMP, with [5] analysing the discrepancies arising when comparing the actual CoP measurements, to ZMP values computed using two distinct techniques.

In an attempt to produce robots capable of emulating natural, human-like behaviour during interaction with their respective environments, roboticists have striven to engineer appropriate impedance control schemes [6] that would be conducive to this objective. A natural consequence of this effort has been the employment of such control methods on bipedal robots [7]-[14], for the purpose of realizing a desired interaction with the environment, which may potentially lead to successful execution of the specified tasks, provided that the impedance levels are appropriately controlled. As regards humanoid balance maintenance, its achievement necessitates impedance regulation capable of endowing the system with terrain adaptability, in addition to accurate and rapid convergence towards a desired equilibrium point. The use of fixed gain impedance controllers would preclude the coexistence of both features simultaneously, which consequently gives rise to the need for a systematic approach to adjusting a robot's impedance values. However, such an approach ought to incorporate the balancing constraints, as their exclusion would be tantamount to utilising constant gain controllers. Thus, the work described herein has striven to encapsulate real-time analytical impedance selection, and balance monitoring into a single, unified algorithm.

It has been established that admittance control schemes could be utilized for the attenuation of landing forces [7], via

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