Integration of Dynamic Walking with Arm Impedance Control for Safe Physical Human-Biped Collaboration

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1. Motivation

Bipedal robots must be capable of dependable locomotion in human-centric environments while simultaneously engaging in tasks that involve physical interaction with humans or other robots by means of their manipulators. In a number of such tasks – cooperative object transportation between a robot and a leading co-worker is one example – the robot's walking pattern should be adapted according to external commands, implying that the locomotion and manipulator systems *cannot* be treated in isolation. Aiming at safe cooperative manipulation and transportation, we focus on combining dynamic walking with manipulator impedance control in a way that enables a biped robot model to be responsive to its collaborator's intentions.

2. State of the art

Integrating manipulation tasks within bipedal locomotion has been studied extensively in the context of humanoid robots that walk based on the zero moment point (ZMP) criterion for stability. The book [1] contains several examples of humanoids that engage in activities that involve their manipulators, such as pushing objects, moving obstacles out of their way, or carrying objects over a distance. However, *dynamically* walking bipeds, have not enjoyed the popularity of their quasi-static counterparts in such activities. To the best of the authors' knowledge, only [2] investigates how manipulation tasks can be integrated with dynamic walking gaits. In this case, however, the control law is designed so that manipulation does *not* interfere with locomotion. Our recent work [3–5] integrates dynamic walking gaits generated using the notion of hybrid zero dynamics (HZD) [6] with manipulation while permitting gait adaptation to facilitate cooperative tasks.

3. Our Approach

The underactuated bipedal dynamic walking model in Fig. 1 is the subject of our study. The model is composed by a torso and two identical legs connected to the torso via the corresponding hip joints. A two-link manipulator is attached to the torso through the shoulder joint, allowing the model to interact with its environment via external forces applied at its end effector.

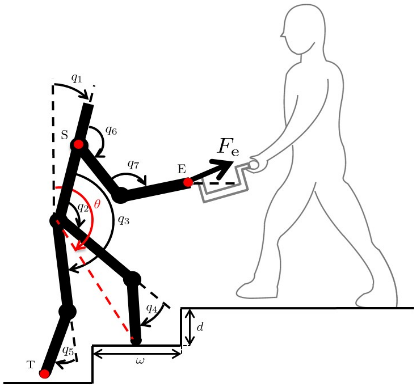

Figure 1: Bipedal robot (left) carrying an object with a human (right) collaborator exerting an external force.

3.1. Dynamic (limit-cycle) Locomotion

Unforced ($F_e = 0$) walking motions are computed with the method of Poincaré. The switching surface $\mathscr{S}$ is chosen as the set of states x for which the robot has a valid impact with the ground. The controller is designed in accordance to HZD [6] and it induces parameters represented by $\alpha \in \mathscr{A}$. The Poincaré map $\mathscr{P} : \mathscr{S} \times \mathscr{A} \to \mathscr{S}$ can then be defined as

$$x[k+1] = \mathscr{P}(x[k], \alpha) \ . \tag{1}$$

Periodic walking motions are computed by searching fixed points $x^* \in \mathscr{S}$ and parameters $\alpha^* \in \mathscr{A}$ that satisfy

$$x^* = \mathscr{P}(x^*, \alpha^*) \ .$$

Three types of unforced periodic gaits are computed, corresponding to flat ground $(x^*_\mathrm{f}, \alpha^*_\mathrm{f})$, upstairs $(x^*_\mathrm{u}, \alpha^*_\mathrm{u})$ and downstairs $(x^*_\mathrm{d}, \alpha^*_\mathrm{d})$ walking.

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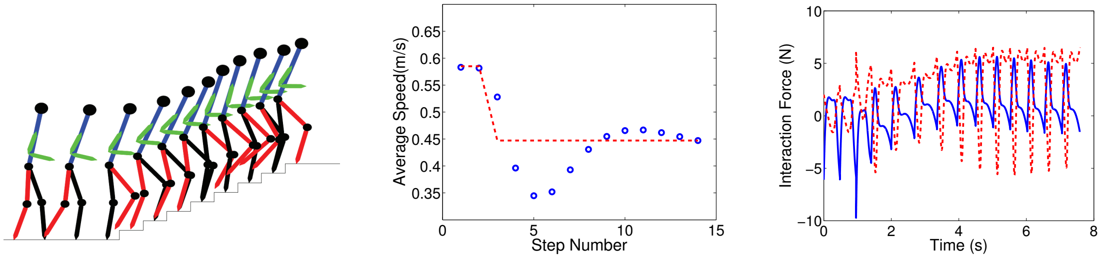

(a) (b) (c)

Figure 2: Biped transitions from flat ground to upstairs and the leader reduces its speed. (a) Snapshots of walking. Black and red links correspond to the stance and swing foot respectively. (b) Average walking speed of the biped (blue markers) and desired speed of leader (red line). (c) Interaction force. Solid blue is the horizontal component and dashed red is the vertical.

3.2. Forced Locomotion

Unforced dynamic gaits generated in Section 3.1 respond to exogenous forces by favorably adapting their walking motions [3]. Safe interaction with the leader can be ensured by employing an impedance controller in the arms. The controller design approach proposed in [4] integrates these two components, i.e. dynamic gaits with manipulator impedance, such that gait adaptation and safe interaction is achieved simultaneously.

To investigate how the biped adapts to changes in the speed of the leader – communicated to the biped through the interaction force, F_{e} – consider the case when the leader reduces its speed. The biped responds to this interaction by taking slower steps, eventually matching its speed to that of the leader as shown in Fig. 2(b). Fig. 2(c) indicates that the leader does not need to make excessive effort to guide the motion of the biped. It is worthwhile to note that with mere knowledge of the interaction force – that is, *without* knowing the intended trajectory of the leading collaborator – the biped is capable of altering its speed as it walks on flat ground as well as up and down the stairs of a known geometry by changing its stride frequency while keeping its stride length constant; see [3] for a detailed explanation of the speed change mechanism.

3.3. Input-to-state Stability (ISS)

Collaboration of a dynamically (limit-cycle) walking bipedal robot with an external agent whose intentions are not explicitly known to the robot calls for gait adaptation based on the interaction force, while simultaneously ensuring that the biped does not fall. To study such motions, the notion of ISS is used, treating the force as an input. Intuitively, an ISS system exhibits bounded state trajectories in response to bounded inputs and the trajectories converge to the nominal motion as the inputs tend to zero. We prove this property for piecewise-constant forces and fast enough output convergence rates by exploiting the time-scale separation between the output dynamics (fast) and the dynamics of the uncontrolled degree of freedom (slow) with a singular-perturbation argument; see [5] for details.

4. Discussion Outline

This work presents a method for integrating locomotion and manipulation tasks in a way that *dynamic* walking motions of an underactuated biped can be modified in response to the interaction forces developed at the manipulator's end effector. Stability of the system when driven by the interaction force is proved using the notion of ISS. The approach can be used towards accomplishing safe physical human-biped cooperation.

References

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