On Dynamic Quadrupedal Gaits Using Active Compliance Control

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Summary

In this work, we propose a control framework capable of generating dynamic quadrupedal gaits, employing biomimetic bean-shaped trajectories at the toes, and active compliance control at the actuated joints. Simulations with biomimetic robots consisting of three-segment legs have shown stable and robust locomotion for a large range of forward velocities with various dynamic gaits (e.g. flying trot and gallop). Results from a trotting experiment are presented as an example. Interestingly, the simulated robot was able to perform a complete locomotion scenario with acceleration from stance, stable flying trot at constant speeds, and deceleration back to stance, by regulating a single control parameter of the whole system, the virtual stiffness of all the actuated joints, also called the *system virtual stiffness*.

Introduction

Recently, several quadruped robots, including the MIT Cheetah 2, [1], the HyQ, [2], and the Boston Dynamics Spot, [3], were able to perform complex dynamic gaits on uneven terrains while maintaining high forward velocity. Despite the promising results, numerous issues still need to be tackled in design, technology and especially in control, until such robots can cope with real life tasks. It is evident so far that compliant interaction with the ground is a key parameter in dynamic locomotion, and robots that can adjust their legs' stiffness mechanically, [4], or electrically, [2], [5], seem to have an advantage. Along these lines and based on our previous work, [6], we devise a control strategy, as a contribution to a class of controllers that combine indirect force control schemes, such as active compliance control, [7], and equilibrium point control, [8], with trajectory planning techniques at the toe level, [5], [9].

Controller Design

The control scheme proposed herein is based on the three-part framework presented in [6]. Taking inspiration from the cheetah's toe trajectories, [10], we apply the same elliptical trajectories, but this time at the ankles of a robot with four three-segment legs, resulting in bean-shaped trajectories at its toes, see Fig. 1. These trajectories are called *virtual*; it is not the aim of the controller to follow them strictly, since simple PD controllers act at the joints to interact compliantly with the ground. We claim that by properly regulating the proportional gain k_p of all the PD controllers, also called the *system virtual stiffness*, [6], a robot can easily perform dynamic gaits at various locally stable fixed points, and move between them with smooth accelerations. As shown in Fig. 1, for fixed virtual trajectories, i.e. trajectories close to the boundaries of the legs' workspace, and for increasing virtual stiffness, the actual trajectories approach the virtual ones, while the interaction with the ground becomes more intense.

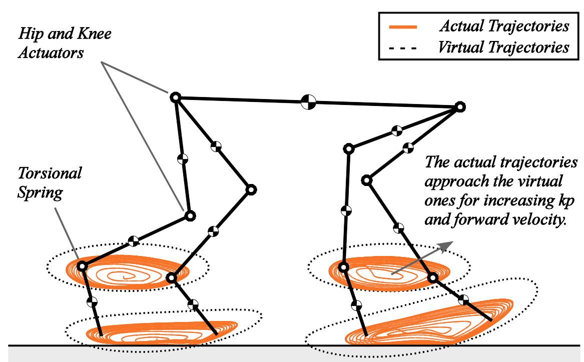

Figure 1. The model used in the simulation in a snapshot from the trotting experiment. The actual and virtual trajectories for ankles and toes are plotted w.r.t. the moving hip-fixed frames.

Results

So far, our simulation results include numerous locally stable fixed points with large regions of attraction for various dynamic gaits like flying trot and gallop. Here, a trotting experiment is presented as an example, in which a $25\,\mathrm{kg}$ robot of structure similar to this of a cheetah, with a body length of $0.6\mathrm{m}$, is commanded to follow fixed elliptical trajectories at the ankle level with a fixed stride frequency of $3.5\,\mathrm{Hz}$, but with varying virtual stiffness at the actuated joints, see Fig. 1. Actuators are placed at the hip and the knee joints, while passive torsional springs of stiffness 100 Nm/rad are placed at the ankle joints. The model starts from stance, and in the time interval 0.5-2s the system virtual stiffness k_p increases linearly with time from 40 to 700 Nm/rad, thus smoothly accelerating the body up to 2 m/s. By keeping k_p constant in the 2.5-4 s interval, the model performs stable flying trot at 2 m/s. In the 4-6 s interval, k_p increases again up to 1200 Nm/rad, making the model reach another stable fixed point at 3 m/s. Finally, in the 8-10s interval, k_p decreases linearly with time to 40 Nm/rad, resulting in a smooth deceleration of the robot back to stance. The virtual damping gain is kept constant at $k_v = 50\text{Nsm/rad}$. In Figures 2(a) and 2(b), the robot's forward velocity and the height of the torso Center of Mass are plotted w.r.t. time, while the virtual and actual trajectories are shown in Fig. 1. The white areas in Fig. 2(a) indicate the phases when none of the legs contacts the ground, justifying the characterization of the gait as a flying trot.

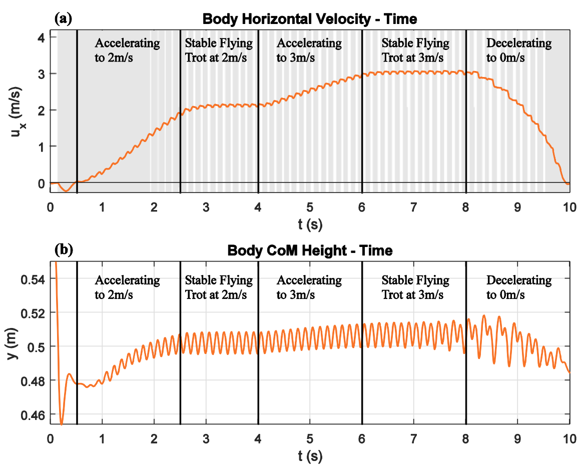

Figure 2. Trotting experiment: (a) The body CoM forward velocity, and (b) the body CoM height w.r.t. time, with gray areas denoting the phases when at least one leg contacts the ground.

Discussion

The results show that complex dynamic locomotion can be achieved by properly adjusting a single control parameter, namely the virtual stiffness k_p, equally applied to all actuated joints. It is evident that there is a mapping between the system virtual stiffness and the robot's forward velocity left to be discovered. We claim that based on this promising result, novel control schemes, simple, yet capable of performing sophisticated and challenging tasks can result. Our work aims at extending this methodology to a generalized control framework capable of generating all known gaits, through the control of a minimum set of parameters. Experiments with a real robot that is being built will reinforce the validity of the ideas presented herein.

Ackgnowledgement

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