Gaits and Energetics in Robotic Locomotion

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Motivation & State of the Art

Nature shows us that enabling natural dynamics (i.e., motion induced by the interaction of gravity, inertia, and elastic oscillations) can greatly improve the efficiency and locomotion velocity of legged systems. The mechanical structure of animals and humans is built in such a way that a substantial part of their movement emerge passively from their mechanical dynamics. In the process, energy is stored elastically in muscles and tendons, and motions are shaped by the pendulum dynamics of the leg segments. By exploiting these effects, the necessary active contribution to the motion can be reduced greatly.

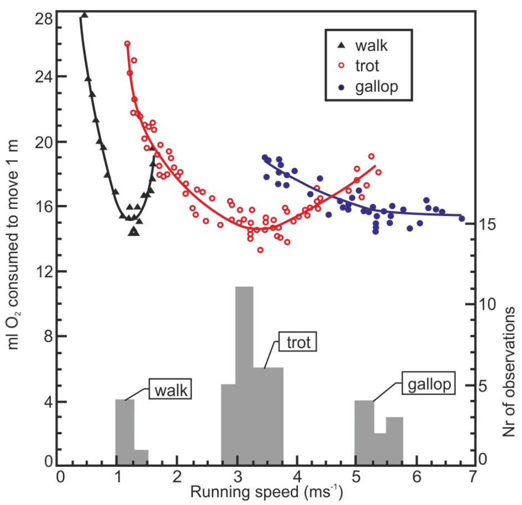

Figure 1: The metabolic COT as a function of speed and gait selection for horses moving on a treadmill. For each gait, an optimal velocity can be identified which minimizes the COT and is chosen when the animals are allowed to self-select their locomotion speed (from [1]).

It seems oobvious, that such dynamics can contribute optimally only for certain modes and at certain (eigen-) frequencies of the mechanical dynamics. This fact might be a cause for the selection of gaits and locomotion velocities in nature. Figure 1 shows the metabolic cost of transport (COT) of horses that are walking, trotting, and galloping at different velocities. The locomotion speed was prescribed by a treadmill and the metabolic rates were determined by the oxygen consumption VO_2. We can observe that each of the different modes of locomotion has a certain velocity for which the COT is minimized while higher or lower speeds degrade efficiency. One possible interpretation of this observation is that each of these gaits corresponds to a certain set of natural dynamic *modes* which '*resonate*' best at these distinct velocities.

In our work, we analyze the implications and the meaning of different gaits in the context of robotic systems. To this end, we consider locomotion as a complex nonlinear oscillation which is to a large degree passive and only excited and maintained through periodic actuator inputs. We employ numerical optimization (c.f., [2, 3]) in a limit-cycle based framework as a tool to identify actuator inputs for conceptual robots with series elastic actuation (similar to the systems presented in [4, 5, 6, 7]). This idea of using optimization to create motor inputs for legged systems (both in biology and robotics) goes back to the work by Chow and Jacobson [8] and has since then found wide-spread application (see [9] citations 17-27 for further references). In the context of exploring different gaits, our work extends on a study of Srinivasan and Ruina [10] which discovered walking and running by optimization of conceptual models.

Our Approach

Methods

We studied planar models of conceptual robots with prismatic legs (Fig. 2). All segments have distributed mass and inertia, and all model parameters were normalized to allow applying the results to a large class of robotic systems. In the joints, the motion of two adjoining segments is coupled by linear springs which are rigidly attached to the distal segment and, on the other side, connected to an electrical servo-controlled motor. Having damping in the springs and a mass associated with the foot, means that the system is energetically not conservative and positive net work must be performed by the actuators over the course of a stride.

For analysis, the equations of motion (EoM) were stated in a floating base description, assuming that during ground contact the foot is restricted to a pure rolling motion. Actuators are modeled as geared DC-motors [11] for which we neglect the electrical dynamics in the inductance of the rotor, but model the influence of the actuator inertia and limitations on available power and speed. The motion of the actuators $\mathbf{u} = \mathbf{u}(\mathbf{s})$ is defined by a parametric representation (Fourier series or piecewise linear/cubic). Gait synthesis is considered as the search for initial model states $\mathbf{q}(t_o)$, $\dot{\mathbf{q}}(t_o)$ and excitation parameters $\mathbf{s}$ that generate a periodic motion. Only x is allowed to be aperiodic, thus reflecting the desired forward motion. With these two requirements fulfilled, the model is able to perform a continuous movement, or in other words, it exhibits a steady gait. With the additional requirement of minimizing a cost function c (for example a COT), we transform the search for periodic locomotion into a con-

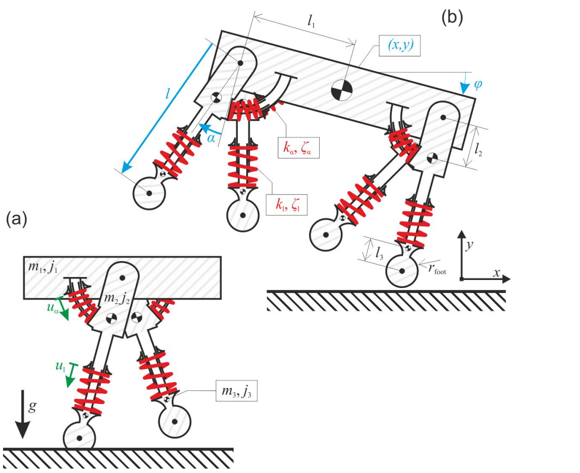

Figure 2: Planar models of conceptual bipedal and quadrupedal robots driven by series elastic actuators.

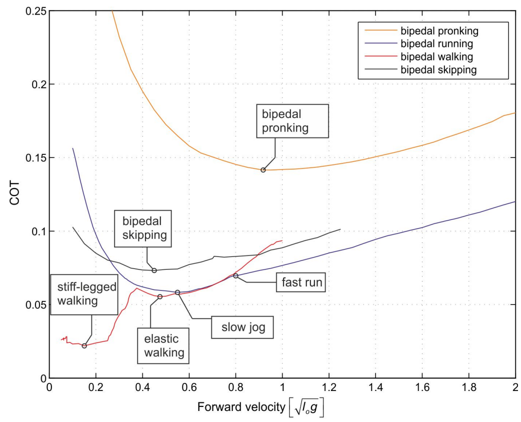

Figure 3: The mechanical COT is shown as a function of forward velocity for four different foot-fall sequences of the bipedal model. A number of local minima can be identified, each corresponding to an individual gait.

strained optimization problem:

$$\begin{aligned} &\min\left\{c\left(\mathbf{s},\ \mathbf{q}\left(t_o\right),\ \dot{\mathbf{q}}\left(t_o\right)\right)\right\} \\ &s.t. \quad \mathbf{q}\left(T\right)=\mathbf{q}\left(t_o\right) \\ &\qquad\ \ \dot{\mathbf{q}}\left(T\right)=\dot{\mathbf{q}}\left(t_o\right) \end{aligned}$$

.

Results

Within this framework, we initially restricted our search to bipedal systems while minimizing the mechanical cost of transport. Figure 3 shows the resulting energetics of the bipedal model as a function of locomotion velocity for four different foot-fall sequences. They correspond to pronking, walking, running, and skipping gaits. Depending on the locomotion speed, multiple gaits were identified for some of these foot-fall patterns. They can be distinguished visually, but also by their contact pattern or by the ground reaction forces they create (particularly for walking, the characteristic double-hump vs. single hump in vertical ground reaction forces could be distinguished clearly). Additionally, when looking at the cost of transport as a function of velocity, the different gaits can be clearly identified as local minima in the COT.

It becomes evident that once natural dynamic effects are enabled in the mechanical structure and actuation of a system, the use of different gaits can greatly increase efficiency. Picking or changing a locomotion velocity is then no longer the continuous adjustment of a basic motion pattern, but starts with the identification of the appropriate gait. Moreover, the existence of different gaits influences the choice of the locomotion velocity. Similar to animals in nature, robots built this way will thus have a set of particular velocities at which the natural dynamics are exploited best and at which they can move most efficiently.

Ongoing Research

We are currently expanding this research into three directions, that we would like to discuss at DW2012:

First, we are evaluating the influence of cost functions that take into account the motor model and thus create more realistic values for the computed COT. This includes thermal losses in the motor and work that is required to overcome the inertia of the actuator. So far we could show that purely force-based cost functions prove to be ill-suited for non-conservative systems and that thermal electrical losses, in contrast to common belief, do not dominate energy expenditure. However, with respect to the overall energetics (and thus the choice of gait), the influence of using different cost functions was rather small.

Secondly, we are extending our study to quadrupedal locomotion, which allows for a much richer variety of motion patterns (walk, trot, pace, canter, bound, gallop, etc.). This variety, which is largely unstudied in terms of robotic locomotion, is particularly interesting for us, since our research on robotic hardware is focused on quadrupeds, as well [12].

Thirdly, we are looking at parameteric and structural adaptations to improve the overall locomotion performance. By tuning the spring-stiffness or mass distribution, or by adding additional degrees of freedom (such as a spine) we seek to shape the energetics of the system. The goals are to find suitable morphologies for fast and efficient motions and user-selected velocities, to evaluate the advantage of additional degrees of freedoms in a robot, and to look at the benefit of additional passive elements.

Discussion Outline

We strongly believe, that this topic will spark a debate that is interesting both for biologists and roboticists. It might range from a discussion to what degree the Hoyt and Taylor figure (and its equivalent for human gaits) is actually true, over the question what is its cause in biology, to a debate about suitable morpholgies, adaptive compliances, and the role of gait in robotic systems.

Keywords

Natural Dynamics - Optimization - Gait Selection

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