Robot Trotting with Segmented Legs in Simulation and Hardware

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1 Motivation

This research is focusing on the implementation, testing, and analysis of quadrupedal, bio-inspired robot locomotion. Our tool of research is a light-weight, quadruped robot of the size of a house cat, both in simulation and hardware. We are currently following the idea of testing bio-inspired blue-prints such as leg-segmentation, directional leg compliance (bio-mechanical), and central pattern generators (bio-inspired neuro-control) for their feasibility, and advantages against more traditional, engineered solutions. Clearly, our first goal would be to reach a same level of performance as animals, e.g. in terms of speed, cost of transport, or versatility. Much research has been done on bio-mechanical and neuro-physiological research on legged vertebrates. Hence, data is available for animal locomotion such as gait patterns, speed, cost of transport, duty factor, joint angles, torque patterns, body angles, and ground reaction force (GRF) data. While this data allows one to study a subset of locomotion characteristics, it often lacks an intuitive way to compare animals of different species, or as for us, quadruped robots. We started applying the collision angle analysis (Lee, Bertram, et al. 2011) for trot gait, based on qualitative and quantitative results from goats and dogs (taken from (ibid.)), and experimental recordings of our robot's center of mass (COM) and GRF.

2 State of the art

Recently strategies have been developed which combine several of the above characteristics, namely the vector of speed of the center of mass (COM) of an animal (or robot) and the vector of ground reaction forces into the *instantaneous collision angle* (ibid.). (ibid.) showed that the collision angle of an animal has unique characteristics, which are also gait dependent.

Another aspect of quadrupedal locomotion research can be found in the difference of intrinsic, mechanically based self-stabilization of locomotion patterns, versus the need for feed-back control loops, monitoring the state of the robot (or the animal). Lee and Meek 2005 showed that by using two-segmented legs at a simulated, trotting quadruped robot, self-stabilization improves depending on the orientation of the knee joints. This leg orientation can be found in many two-segmented quadruped robots, the most prominent example being BigDog (version until 2011, (Raibert et al. 2008)).

Herr et al. 2000 on the other hand reported on the importance of control patterns for a trotting horse model for stable locomotion, e.g. the speed of the foot trajectory during stance phase. Once this parameter was adjusted, robot model pitching stability emerged.

One often used abstraction of legged locomotion is the SLIP model (Blickhan 1989). The (initial) SLIP model is energy conservative, uses no leg inertia, and no swing leg dynamics. One of the model's main outcomes concerns the importance of leg-knee compliance during dynamic locomotion, for self-stable running.

A bio-inspired locomotion control has been identified with central pattern generators, and used for multiple robots (Fukuoka et al. 2003; Ijspeert 2008). CPG can provide an abstraction for the creation of rhythmic locomotion patterns ideally suited for robotics (Ijspeert 2008).

3 Approach and results

As a research tool, we designed and implemented a light-weight, compliant, quadruped robot. It is equipped with passive compliant four-segmented legs, three leg segments and one foot segment, similar to (Rutishauser et al. 2008). We dimensioned weight of the robot ($m = 1.1\,\mathrm{kg}$), COM placement, and gear transmission system such that we can replay typical trot gait locomotion patterns up to a hip frequency of $f = 3.5\,\mathrm{s}^{-1}$. This is only little less than typical locomotion patterns of animals of this size. We produced feed-forward gait patterns, based on a CPG network, generating gait patterns for hip and knee joints of the robot.

We further implemented a copy of our hardware robot in a physics-based 3D simulation (Michel 2008). With the simulated robot model we extensively searched the control parameter space, and collected data of cost of transport, ground reaction forces, and speed of the simulated robot.

With the hardware setup, we were able to speed the robot up to Froude numbers of $\mathrm{FR} = 1.34$, i.e. a speed of $v = 1.42\,\mathrm{m\,s}^{-1}$ ($1.50\,\mathrm{m\,s}^{-1}$ for the simulated robot model), or 6.9 body lengths per second. Only feed-forward locomotion patterns were applied. To the best of our knowledge this is the currently fastest mobile, legged, quadruped robot running non-constrained in trot gait. The robot reached dy-

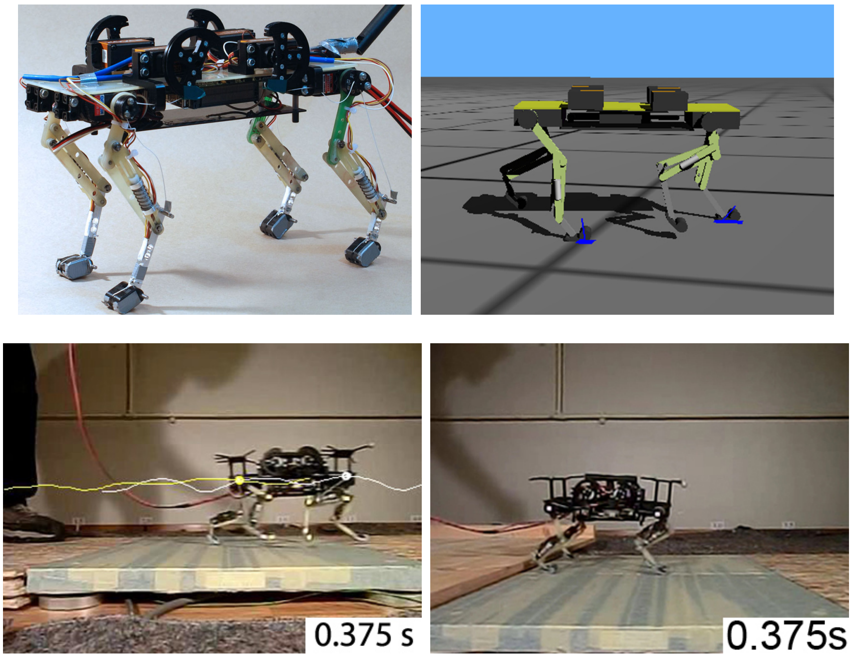

Figure 1: Robot in hardware, and simulation. Running on flat ground, and with a step-down perturbation.

namic gaits with short flight phases, with a duty factor of $d = 0.4$.

As for the comparison to other robot platforms and animals, we recorded individual limb GRF data, and the COM speed vector. This allowed us to calculate collision angle, and collision fraction numbers for our robotic setup, and compare them to animal data from e.g. goats and dogs (Lee and Meek 2005).

Preliminary experimental results with the hardware quadruped showed similar v-like shapes of the instantaneous angle of collision profile, compared to goat and dog trot gait. This indicates that our robot applied characteristics of animal-like trot gait. However, mean collision angle ($\approx 0.4\,\mathrm{rad}$) and collision fraction numbers (≈ 0.75, measured at robot speed of $1.24\,\mathrm{m\,s^{-1}}$) are higher as for goats and dogs. Hence, albeit bio-inspired leg compliance, the robot's locomotion motions are still too abrupt and stiff.

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