Virtual model control for quadrupedal trunk stabilization

Ioannis Havoutis Claudio Semini Darwin G. Caldwell
Department of Advanced Robotics, Istituto Italiano di Tecnologia, via Morego, 30, 16163 Genova, Italy.
{ioannis.havoutis, claudio.semini, darwin.caldwell}@iit.it

I. Motivation

Legged robots have the advantage of being able to access a large variety of terrain types. In unstructured environments, where only a number of discrete footholds are possible (disaster sites, construction sites, forests, etc.), legged quadrupedal systems can utilize static stability crawl gaits or dynamic stability –often ZMP-based– gaits. In environments where smooth, continuous support is available (flats, fields, roads, etc.), where exact foot placement is not crucial for the success of the behaviour, legged systems can utilize a variety of more dynamic gaits, e.g. trotting, galloping.

In this work we focus on a trotting controller for the hydraulically actuated quadruped HyQ [1]. The trot is a symmetrical gait in which diagonally opposite legs swing in unison. This allows a desirable division of the total force that the leg actuators should be able to provide when supporting the weight of the robot, when thrusting and when receiving impact forces at touchdown. In addition, the center of gravity of the system is on average kept above or very close to the *line of support* that the stance legs define. This leads to a more stable gait with respect to the robot's attitude, in contrast to bounding and pacing.

In practice implementing trotting controllers in real world quadrupeds has proven a challenging task, especially for large robots such as the HyQ ($\sim 75kg$). This is due to a number of factors, the most significant two being the need for compliance when legs are touching down, both for impact absorption and surface uncertainty handling, and the need for accurate control, both for foot placement during swing and attitude stabilization during the stance phase of each leg pair.

In this extended abstract we present our efforts towards a trotting controller with an explicit trunk stabilization goal. Trunk stabilization serves to reduce oscillations of the body in the vertical direction, that often lead to increased load for the leg actuators, while also allows for more accurate foot placement of the swing legs. In addition, trunk stability is crucial for the successful operation of higher order on-board sensory modalities, such as lidars or stereo cameras, that are essential for perceptual processes as mapping and localization.

II. State of the art

A large body of literature in robotics is devoted to quadrupedal locomotion. Early examples include the work of Raibert [2], where a small quadruped with hydraulically actuated and pneumatic spring loaded telescopic legs was used with a simple state machine based control architecture, relying on velocity feedback and experimental tuning. Recent examples include Hawker and Buehler [3], and Remy et al. [4], for systems that are designed with passive compliant elements and light-weight leg structures. Very close to our research stands Boston Dynamics' BigDog though little is still known about its control structure or experimental evaluation. In previous work we have experimented with a feedback/feedforward control structure similar to the one presented here, coupled with a CPG-based trajectory generation procedure [5]. We have also experimented with an active compliance control structure for each leg that emulates the passive telescopic leg behaviour [6].

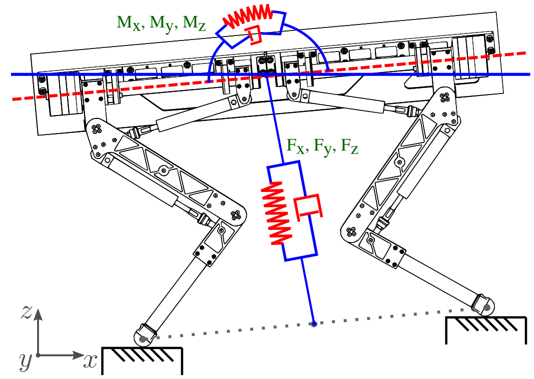

Fig. 1. The virtual elements used to calculate forces and moments that stabilize the quadruped's trunk. The virtual forces and moments are transformed to feedforward torques for the pair of legs in stance phase.

III. Own approach

Our approach divides the control procedure into two distinct subsystems. One generates the trajectories that the two leg pairs execute given external user input, while the other calculates a feed-forward trunk stabilizing input according to the current state of the system.

A. Trajectory generation

While trotting, the legs are naturally divided into two pairs. The legs of each pair follow an identical foot trajectory, transformed according to each leg in consideration. This trajectory is generated according to user input and depends on the commanded forward velocity, turning rate, step and swing height and the gait cycle period. The step height dictates the body height in the body reference frame during the support phase, and the swing height defines the leg swing apex. The gait cycle period is used to calculate the timing of

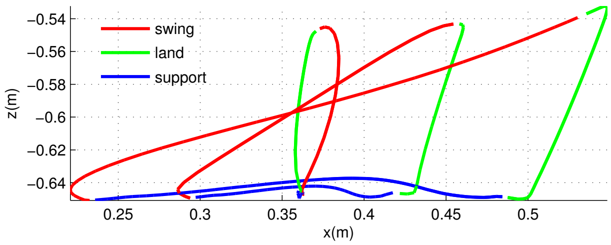

Fig. 2. Trotting trajectories that correspond to the foot of the left front leg in the robot's body reference frame. The different colors denote the three gait cycle phases while the three trajectories correspond to trotting in place, trotting forward with a velocity of 0.5m/s and 1.0m/s.

the leg trajectories as this is intuitively further subdivided in three distinct phases; swing, land and support (Fig. 2). We set the step height to -0.65m and the swing height to -0.55m. In our experiments we use a gait cycle period of 0.5s (2*Hz*), that is suitable for velocities up to 1m/s.

B. *Trunk stabilization*

To stabilize the trunk of the robot we follow a virtual model control approach [7]. We calculate virtual forces (F_x, F_y, F_z) and moments (M_x, M_y, M_z) according to a reference state and the current state of the system (Fig. 1). Note that the reference state changes according to external parameters, e.g. pitching up while trotting uphill and pitching down when trotting downhill. The virtual forces and moments are then transformed to feedforward torques for the joint actuators of the legs that provide support, i.e. the pair in stance phase. This is done by computing the constraint Jacobian of the system's current state,, to subsequently map trunk forces and moments to joint torques.

IV. Current Result

We experimented with trotting up to 1.0m/s with the current controller parametrization in simulation (Fig 4). Note that we can achieve higher speeds with the same stable

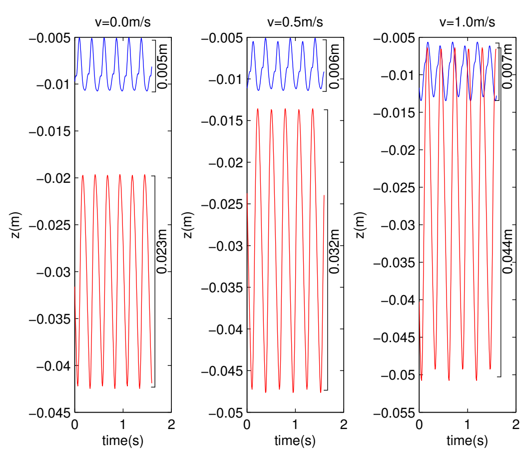

Fig. 3. Vertical oscillation of the trunk of the robot while trotting in place and trotting forward with a velocity of 0.5m/s and 1.0m/s. The blue line corresponds to trials where the trunk stabilization is active, while the red lines denote trials without trunk stabilization.

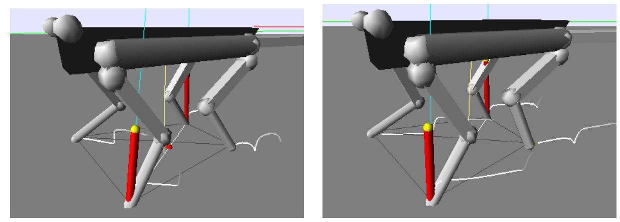

Fig. 4. HyQ trotting in simulation. The images show the robot in mid-stance phase, trotting at 0.5m/s (*left*) and 1.0m/s (*right*). The red cylinders represent the ground reaction force vectors.

response though the gait cycle period needs to be reduced accordingly. Trotting without the trunk stabilization feedforward term results in unwanted trunk oscillation in the vertical direction and in attitude, that increases in amplitude as the forward velocity increases. When trunk stabilization is used the undesired oscillations are kept minimal. A comparison is presented in Fig. 3 where the oscillation along the vertical axis for the stabilized case maintains an amplitude of ∼0.006m throughout all trials, while in the non-stabilized trials we see the amplitude increase proportionally to the forward velocity (0.04m at 1.0m/s). Also the oscillations in attitude are kept similarly small, 0.01rad in pitch and 0.012rad in roll. These results are produced with a walking trot, i.e. there is no flight phase.

V. Best possible outcome

Our current objective is to thoroughly evaluate this controller's behaviour on the real quadruped robot in various conditions. We aim to demonstrate that this controller can successfully navigate on natural terrain, e.g. soil, gravel, of varying inclination, while maintaining a consistently stable behaviour. In turn, this will provide a solid foundation for higher level perceptual processes that we aim to integrate.

Acknowledgement

This research is funded by the Fondazione Istituto Italiano di Tecnologia.

References

[1] C. Semini, N. G. Tsagarakis, E. Guglielmino, M. Focchi, F. Cannella, and D. G. Caldwell, "Design of HyQ – a hydraulically and electrically actuated quadruped robot," *Journal of Systems and Control Engineering*, 2011.

[2] M. H. Raibert, *Legged robots that balance*. Cambridge, MA, USA: The MIT Press, 1986.

[3] G. Hawker and M. Buehler, "Quadruped trotting with passive knees: design, control, and experiments," in *2000 IEEE International Conference on Robotics and Automation (ICRA'00)*, vol. 3, 2000.

[4] C. Remy, M. Hutter, and R. Siegwart, "Passive dynamic walking with quadrupeds - extensions towards 3d," in *Robotics and Automation (ICRA), 2010 IEEE International Conference on*, 2010.

[5] V. Barasuol, J. Buchli, C. Semini, M. Frigerio, E. R. De Pieri, and D. G. Caldwell, "A reactive controller framework for quadrupedal locomotion on challenging terrain," in *IEEE International Conference on Robotics and Automation (ICRA)*, 2013.

[6] I. Havoutis, C. Semini, J. Buchli, and D. G. Caldwell, "Quadrupedal trotting with active compliance," *IEEE International Conference on Mechatronics (ICM)*, 2013.

[7] J. Pratt, C.-M. Chew, A. Torres, P. Dilworth, and G. Pratt, "Virtual model control: An intuitive approach for bipedal locomotion," *The International Journal of Robotics Research*, 2001.