A Compliant Control Architecture for the Hydraulic Quadruped - HyQ

Ioannis Havoutis† Alexander Winkler†,⋆ Claudio Semini†
ioannis.havoutis@iit.it, alexander.winkler2@kit.edu, claudio.semini@iit.it
†Department of Advanced Robotics, Istituto Italiano di Tecnologia (IIT), via Morego, 30, 16163 Genova, Italy.
⋆Karlsruhe Institute of Technology (KIT), 76131 Karlsruhe, Germany.

I. Introduction

Locomotion is an important skill for autonomous systems, both for robotic and biological ones. Legged locomotion is well suited for crossing highly unstructured and challenging terrain (Fig. 1). This follows naturally as with legged locomotion one can decouple the path that the body follows (e.g. the center of mass (CoM) trajectory) and the footholds that provide the necessary support.

Legged locomotion requires actuators with high power density and robustness, as the legs need to support the entire system, and its safety critically depends on the nominal functioning of the actuation system, even in adverse conditions.

Hydraulic actuation has proven an enabling technology in the context of legged locomotion. It allows a large range of possible torque capabilities, high bandwidth control, it is inherently rugged and robust, and can withstand large impacts, both planned and unexpected. In addition, we have shown that hydraulic actuators can be efficiently torque controlled [2], a fundamental feature that increases the system's flexibility and gives access to a set of benefits.

Most importantly torque control allows the use of a variety of control approaches, many of which regulate the system's (active) compliance and/or the forces at its end-effectors, traditionally the feet in the legged locomotion case. This is required for smooth interaction with the environment without trading away a significant amount of accuracy. In this abstract we present our approach, utilizing a virtual model based controller that guarantees the overall compliant behaviour of the system, while also maintaining a high level of accuracy in whole body trajectory execution.

II. Related work

Much work in quadrupedal locomotion makes explicit use of compliant elements within the structure or actuation system, e.g. *BigDog* [3] and *StarlETH* [4]. Traditionally dynamic gaits, like trotting or bounding, require compliance to handle impacts. In such approaches often the accuracy of foot placement plays a secondary role as continuous, yet non-smooth, support is assumed.

Fig. 1. Two cases where smooth interaction with the environment is crucial for the success of the behaviour. The two pictures show our $80kg$ hydraulic quadruped robot, HyQ [1].

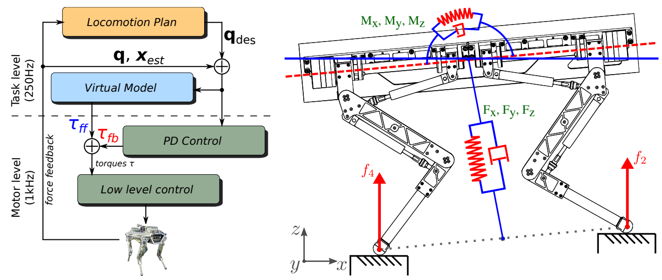

Fig. 2. *Left:* Our control architecture that uses the virtual model in tandem with a low-gain joint level PD loop. *Right:* The virtual elements used to calculate forces and moments around the trunk of the robot.

In cases of challenging and *unstructured* environments (e.g. stairs, stepping stones, ledges, etc), where foot placement is crucial for the success of the behaviour (Fig. 1), control has been traditionally somewhat stiff [5], [6]. A step towards compliance in this framework, without the use of passively compliant elements was taken by Kalakrishnan et al. in [7] where the inverse dynamics approach in [8] was used in tandem with a low-gain joint PD controller. Hutter et al. [4] experimented with a similar control architecture also allowing the optimization of the contact forces according to the situation at hand. We have previously experimented with active compliance approaches, for example [9] uses inverse dynamics, [10] with the use of an admittance controller, [11] with the use of in-series virtual elements. Our most recent approach uses a virtual model that is grounded between the system and its environment, as sketched in Fig. 2.

III. Our Approach

Our approach couples a low-gain joint-level PD controller and a virtual model controller. The virtual model in tandem with the PD controller provide the (feed-forward and feedback) torques that realize the planned whole body motions.

A. Virtual Model

As outlined before we aim for a highly compliant behaviour in order to naturally interact with the environment and estimation inaccuracies during locomotion. Nonetheless we require precise foothold landing, something crucial for the overall success of the behaviour. We follow a virtual model control approach similar to [12]. We calculate virtual forces (F_x, F_y, F_z) and moments (M_x, M_y, M_z) according to a desired state and the current state of the system (Fig. 2). Note that the reference state is generated by a higher-level procedure, here generally termed as *locomotion planner*. The virtual forces and moments are then transformed to forces that the feet in contact need to apply. The forces are subsequently mapped to feed-forward torques, $\boldsymbol{\tau}$, for the joint actuators of the legs that are in stance, using the Jacobian of the system's current state. This is done by $\boldsymbol{\tau} = J^T \mathbf{f}$, where $\mathbf{f}$ is the vector of (linear) forces that each foot in stance needs to apply to emulate the virtual model behaviour, and J is the Jacobian of the legs that are in contact. The force, f_i, for each foot can be optimized with a number of methods. In our case we use a least squares optimization that provides the least norm solution, i.e. the minimum force solution. Fig. 3 gives an example of the torques in joint level produced by the virtual model during locomotion. Note that without the virtual model controller, successful execution of the planned motions is impossible.

B. PD Controller

We use a joint-level 1kHz PD controller with low feedback gains (*proportional*: $300 Nm/rad$ and *derivative:* $6 Nms/rad$) for all joints of the robot as we are aiming at a very compliant behaviour, something important for smooth interaction with the environment. Note that the leg(s) in swing phase is(are) controlled only through this loop as the virtual model produces torque inputs only for the legs in stance. The control input that the PD control loop provides is generally very small in comparison to the feed-forward control input that comes from the virtual model. Fig. 3 is an illustrative example of this hybrid control setup, where the virtual model accounts for most of the control input throughout a full gait cycle in a typical crawl gait locomotion pattern.

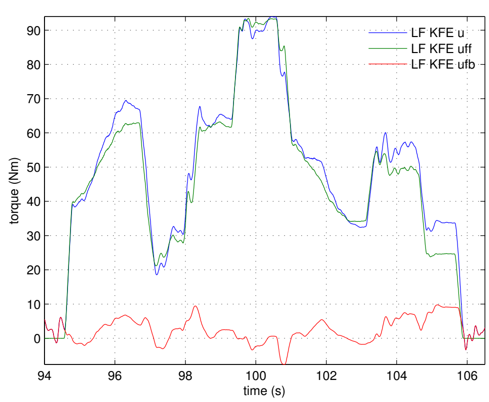

Fig. 3. Torque profiles of the knee joint of the front left leg during a complete gait cycle, i.e. foot swing to landing in a crawl gait example. In red the torque input that the PD controller produces [*ufb*], note that on average this remains very low. In green the torque input that the virtual model controller produces [*uff*]. This accounts for most of the torque that the joint produces throughout locomotion. The blue signal [*u*] is the torque signal that the low-level torque controller is asked to track and is the sum of the two aforementioned terms.

IV. Results and Future Work

We have tested our approach both with a static crawl gait controller and a dynamic trotting controller. In both cases the virtual model subsystem produces the 'bulk' of the torque input that the low-level torque controlled loop is called to track. This way that the feedback torque input is constantly low while the control of the system is largely performed by the feed-forward torques of the virtual model.

In the future we aim to incorporate also information about the support surface geometry and its physical properties to the feet-force optimization step. We believe that optimizing the contact forces in accordance to the environmental conditions will have a crucial role in planning more dynamic motions, such as jumping, rearing, etc.

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