Progress in quadrupedal trotting with active compliance

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I. Introduction

Legged robots can provide superior locomotion characteristics in terms of agility and efficiency. Legged platforms can perform both in unstructured environments, where only a number of discrete footholds are possible (disaster sites, construction sites, forests, etc.), and in situations of smooth, continuous support (flats, fields, roads, etc.).

Legged animals employ a multitude of gaits to successfully locomote through varying terrains, ranging from slow walking to fast running gaits. In addition, as gaits become more dynamic a set of characteristics that allow for increased energy efficiency and stability/controllability come into play.

We are interested in the study of such dynamic gaits for legged systems, focusing on quadrupedal locomotion, with the aim of realizing a range of possible gaits on a physical robot.

II. Motivation

We are developing a number of quadrupedal gaits for the hydraulically actuated quadruped HyQ [1]. As observed in nature [2], different gaits are more suitable for different locomotion speeds, while gait transitions also depend on the physical characteristics of the systems in question [3], [4]. Gait preference is affected by given locomotion requirements (short sprint, long run, walk) and the dynamical properties of the system (mass, springs/tendons, muscle/motor capabilities), leading to locally optimal solutions with respect to stability, speed, energy expenditure, etc [5], [4].

In this abstract we describe our efforts to develop and optimize a trotting gait on a quadrupedal robotic platform. Trotting is a symmetrical gait in which diagonally opposite legs swing in unison. This provides significant stability advantages while the legs work together to propel the animal/robot and to cushion impact forces. Most mammals use the trot when running while a considerable subset of quadrupeds have no other running symmetrical gait [2].

An abundance of models and comparative studies of mammalian quadrupedal locomotion exist in the literature. Nonetheless a wide range of factors, such as controllers, actuator capabilities, foot-terrain dynamics etc., greatly influence the resulting dynamic interaction of the robot with its environment [6]. Our goal is to test such biological hypotheses and experimentally validate predictions of biological models that concern the mechanical characteristics of quadrupedal systems.

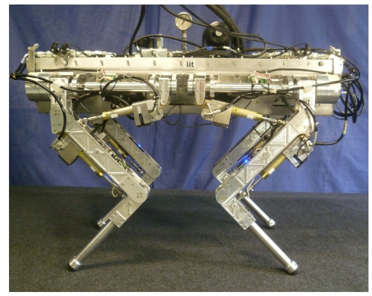

Fig. 1. The hydraulically actuated quadruped robot - HyQ. It has 12 degrees of freedom and its size is comparable to a goat. HyQ is designed for highly dynamic behaviour, e.g. trotting and jumping (http://youtu.be/wPxXwYGZmd8).

A. State of the art

A sizeable body of literature has been devoted to modelling the various aspects of quadrupedal locomotion in nature, typically based on the *Spring Loaded Inverted Pendulum* (SLIP) model. Heglund and Taylor [4] presented a study of quadrupedal locomotion ranging from mice to horses, analysing the relationship between speed, stride frequency and the relationship to different body sizes and gaits. Farley et al. [7] in another large scale biological study estimated from observed data the relationship between speed and animal size with the spring stiffness that the SLIP model predicts and how this is reflected to individual legs of the animals. Lee and Biewener [6] have presented a study on the cost of transport, the leg compliance and the leg geometry to inform the design of a large-dog sized quadrupedal robot, Boston Dynamics' *BigDog*. The stability and robustness of *BigDog* has been demonstrated through various media outlets, alas, apart from the aforementioned theoretical predictions, no experimental data concerning the mechanical design or control of the robot has been published to date.

III. Approach

We attempt to assess how well biological model predictions transfer to a real robotic quadruped. Our platform, HyQ (Figure 1), is a hydraulically actuated quadruped robot comparable in size to a goat ($\sim$70kg), e.g. an *Alpine ibex*. HyQ is capable of highly dynamic locomotion as hydraulic actuation allows the handling of large impact forces, high bandwidth control, high power-to-weight ratio and superior robustness.

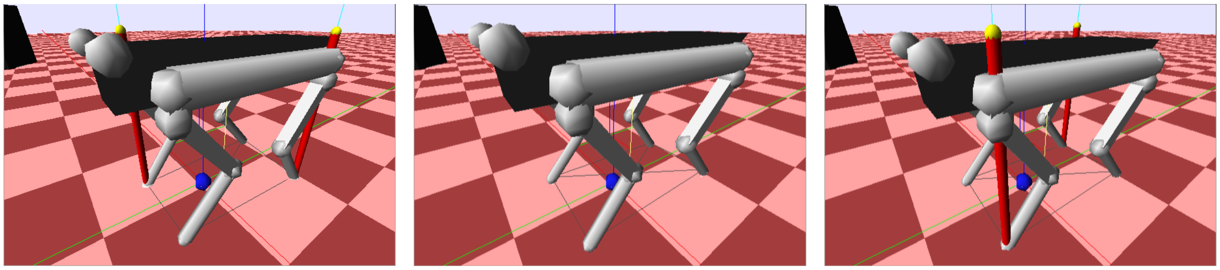

Fig. 2. HyQ trotting in place in simulation. The left and right images show the robot in two consecutive mid-stance phases. The middle image shows the robot in flight phase. The red cylinders represent ground reaction forces.

We employ a virtual model control approach to emulate the dynamic characteristics of linear springs for each leg, acting pairwise-symmetrically as part of a trotting controller [8]. This active compliance scheme allows us to greatly vary the dynamical behaviour of the system on-the-fly, without altering the physical characteristics of the plant [9]. This way we are able to evaluate a wide range of trotting gaits with varying parametrisations.

The implementation of a trotting controller requires the definition of a number of parameters. Related work in biological studies, as mentioned earlier, has helped inform such parameter choices, e.g., the preferred trotting speed ($\sim$2.79*m/s*), the frequency of the stride ($\sim$1.93sec^{-1}), the length ($\sim$0.6m), displacement ($\sim$0.1m) and stiffness ($\sim$5kN/m) of the virtual-leg springs.

A. Experiments

We evaluate a number of trotting controllers with different parametrizations within a reasonable value range. We distinguish two scenarios, one where the robot is trotting in place and one when the robot is trotting at varying target speeds. The parameter sets that result in stable trotting gaits are further evaluated. Their performance is assessed based on the dynamical behaviour of the system. This is done by measuring the body attitude and the angular accelerations of the robot with an on-board sensor. We begin with experiments in simulation and we then evaluate the most promising controllers on the real robot. Evaluations are reported both in simulation and on the real robot.

B. Preliminary results

We started by testing a number of controller parametrisations performing trotting-in-place in simulation (Figure 2). We have experimented with different leg stiffness values that reflect the predictions of the biological observations, that is around 5kN/m for each virtual-spring-leg, acting in unison in symmetric pairs. Stiffness values below 3.5kN/m result in controllers that barely trot as the legs behave very compliantly. In contrast stiffness values above 6.5kN/m result in the legs behaving very aggressively, having torque outputs that reach the actuator limits of the real robot.

These preliminary experiments in simulation suggest that the predictions of the biological models result to reasonably successful trotting controllers though further evaluations, in simulation and on the real robot, are required to make conclusive observations.

IV. Discussion

In this talk we will discuss the key difficulties in developing a robust trotting controller for a real quadruped robot. One of the key challenges is the identification of the parameter sets that optimize the systems' stability and performance, and how successfully these transfer to the real quadruped robot.

- Format: talk
- Keywords: quadrupedal locomotion, active compliance, trotting robot.

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