Actively-compliant Leg for Dynamic Locomotion

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Abstract: Dynamic legged locomotion of animals and humans is often described and studied by models, such as spring-mass or muscle models. To experimentally verify a wide range of such models, machines with torque-controlled joints are required. To this end, we present a torque-controlled robotic leg with high control performance that allows for example to implement virtual components such as exponential springs and dampers. A series of hopping experiments with different spring stiffness profiles demonstrates the versatility and advantages of this approach.

Keywords: Variable compliance, Spring mass model, Virtual components, Torque control.

1. INTRODUCTION

The use of legs for mobile robots is mainly motivated by the legs' superior ability to locomote in challenging terrains. The versatility needed to move in uneven environments usually limits the applicability of wheeled robots in scenarios such as construction sites, disaster recovery areas, and the field of service robotics.

To achieve the locomotion performance that is required for this kind of applications, a robot with torque controlled joints is needed. Torque control permits, for example, the control of the end-effector contact forces and impedance [1]. Moreover, Jacobian transpose force control (e.g. virtual model control [2]) and model based control techniques, such as inverse dynamics control, gravity compensation, and operational space control can be implemented straightforwardly. Having these control capabilities is not only desirable but mandatory for robust performance of robots in unstructured and partially unknown environments [3].

Furthermore, torque-controlled articulated robots can be exploited also for investigating hypotheses from other fields, such as biological motor control [4] and biomechanics. In these areas, systems-theoretical hypotheses on the control systems and the role of the mechanical structure of animals and humans are frequently formulated (e.g. [5]), but notoriously hard to validate. Moreover, theories about leg stiffness variations for different surfaces [6] and reasons for gait transitions and selection in running quadrupeds [7, 8] for instance can be experimentally validated.

In this contribution we will show that hydraulic actuation provides both robustness for handling large impact forces, and also high bandwidth for actively emulating passive elements. In dynamic locomotion, having virtual components instead of real ones represents a great advantage since it is possible to emulate elements that are hard to physically realize (e.g. nonlinear springs or muscle models). Furthermore, they permit to set parameters such as stiffness and damping for adapting to a specific task or terrain on the fly. This allows for instance to imitate the adaptation that constantly happens in Nature during dynamic locomotion. Legged animals, for example, adjust their leg stiffness according to the performed motion. With the actuation technology and control approach we present here, this natural behavior can be mimicked.

2. HYQ: A LOCOMOTION PLATFORM

The results we present here are part of the HyQ project [9]. HyQ is a quadruped robot that allows the study of highly dynamic, all-terrain locomotion, Fig. 1. It has 12 active degrees of freedom. The hip and knee flexion/extension joints are driven by hydraulic cylinders. The naturally very stiff hydraulic actuation has very peculiar characteristics that make it a good choice for highly dynamic articulated robots, such as its high power-to-weight ratio, fast response, robustness, and high force capabilities.

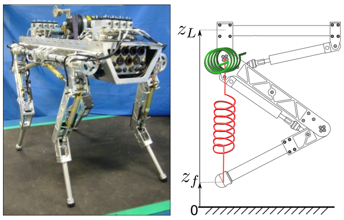

Fig. 1 HyQ robot (left) and leg virtual elements (right).

We implemented a high performance force-based impedance control for the HyQ leg. In a gait cycle, this controller is able to offer both fast movements during the flight phase and accurate force tracking during the stance phase.

3. EXPERIMENTS AND RESULTS

Spring mass models are generally known as good abstractions to describe the spring-like leg behavior found in human and animal walking and running [10]. To mimic this behavior, a Jacobian transpose based force control was used to emulate virtual systems on the articulated HyQ leg. The hip joint uses a rotational spring-damper. The knee instead employs a linear spring-damper, which is placed between the foot and the hip joint, Fig. 1. These virtual components are used to parametrize the desired compliance, e.g as needed for walking. We experimentally tested different stiffness profiles among them linear and exponential springs.

To implement hopping in place, we fixed the leg to a vertical slider that constrains it to perform only vertical movements. The length of the virtual linear spring ($l = 0.55\ m$) is then varied sinusoidally ($\delta l = 0.04\ m$) at a constant frequency of $1.6\ Hz$. Moreover, its stiffness is linearly changed from $800\ N/m$ to $3000\ N/m$.

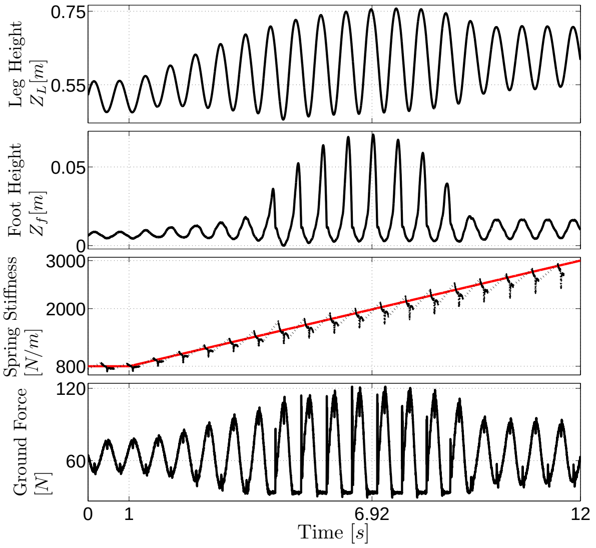

Fig. 2 Variably compliant system: keeping a sinusoidal excitation for the virtual spring length, the stiffness is linearly increased at a rate of 200 N/ms. This changing in stiffness alters the resonance frequency of the leg (spring-mass system) and for a certain range of stiffness it resonates and starts to hop.

As we can see in Fig. 2, during the first second the leg height Z_L is oscillating with a constant amplitude due to the sinusoidal variation in the length of the virtual linear spring. After $1\ s$, the spring stiffness starts to increase and, consequently, the amplitude of the leg height oscillation grows due to resonant effects. When the stiffness and thus the natural frequency of the spring mass system resonates with the sinusoidal spring length excitation, the leg starts to hop, as can be seen in the foot height (Z_f) plot. The resonance peak occurs at $6.92\ s$, when the stiffness is about $2000\ N/m$. The ground contact forces were measured by a force plate and, during the hopping, they reach a peak value of $120\ N$. The stiffness created by the virtual linear spring was plotted only for the stance phase and interpolated during the flight phase (dashed black line).

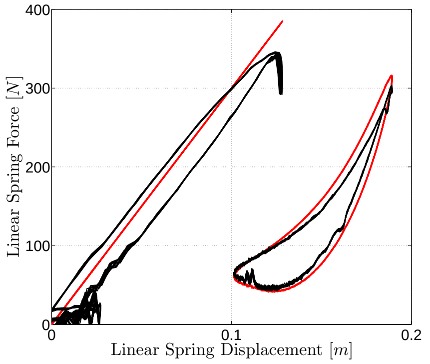

Fig. 3 Implementation of two different compliance profiles: a linear spring and an exponential spring-damper. The plot shows the reference profile created by the virtual component (red) and the real profile obtained (black).

The versatility of employing virtual components goes beyond the capability of dynamically changing parameters such as stiffness. They permit also to emulate muscle based actuation models of different complexities, ranging from simple springs to more complex models as shown in [11]. To demonstrate this ability, we present two different virtual components: a linear spring, and an exponential spring with constant damping coefficient. As it can be seen in Fig. 3, the stiffness tracking for both systems is limited by nonlinear phenomenas such as hysteresis and static friction. However, we consider the stiffness tracking satisfactory for most locomotion tasks.

4. CONCLUSIONS

Virtual components can, by using a high-performance force control, actively create a variable compliance actuation system without the insertion of any additional mechanical component. In our case, this compliance is entirely virtual (actively controlled), since hydraulic actuation is intrinsically very stiff. To demonstrate the versatility and dynamic motion capability of the HyQ leg, we implemented a virtual spring-damper system between the foot and the hip. Using this virtual system, as en example, we successfully implemented a hopping task by changing the leg stiffness on the fly.

The high-performance system we present opens new possibilities for investigating multidisciplinary aspects. Consequently, it represents a potential way to expand the current boundaries for dynamic locomotion in robotics.

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