Dynamic Torque Control of a Hydraulic Quadruped Robot

Thiago Boaventura, Claudio Semini, Jonas Buchli, Marco Frigerio, Michele Focchi, Darwin G. Caldwell

Department of Advanced Robotics, Istituto Italiano di Tecnologia (IIT)
Email: {thiago.boaventura, claudio.semini, jonas.buchli, marco.frigerio, michele.focchi, darwin.caldwell}@iit.it

Abstract— **Legged robots have the potential to serve as versatile and useful autonomous robotic platforms for use in unstructured environments such as disaster sites. They need to be both capable of fast dynamic locomotion and precise movements. However, there is a lack of platforms with suitable mechanical properties and adequate controllers to advance the research in this direction. In this paper we are presenting results on the novel research platform HyQ, a torque controlled hydraulic quadruped robot. We identify the requirements for *versatile* robotic legged locomotion and show that HyQ is fulfilling most of these specifications. We show that HyQ is able to do both static and dynamic movements and is able to cope with the mechanical requirements of dynamic movements and locomotion, such as jumping and trotting. The required control, both on hydraulic level (force/torque control) and whole body level (rigid model based control) is discussed.**

I. INTRODUCTION

Articulated robots such as legged robots have the capacity to evolve into versatile, multipurpose machines that may eventually become useful in many application scenarios such as construction sites, disaster recovery, service robotics and remote inspection. For these tasks a great deal of kinematic flexibility and dexterity is required. Moreover, such scenarios might confront the robot with challenging terrain where wheeled and tracked systems of comparable size cannot go. While this superior all-terrain ability is typically the motivation behind research in legged robots, actual results on robust and versatile locomotion with real robots are not abundant. Moreover, the few existing results do not clarify how to properly build and control such robots to perform both fast dynamic locomotion *and* precise movements.

There are two main causes for this absence of information on robots for versatile locomotion: (a) a lack of suitable, robust platforms due to a prevalence and focus on electrical high-gear-ratio actuation systems both in research and education. The reduction gears of these actuators limit the overall bandwidth and can easily break during the impacts associated with dynamic motions, which in the end reduces the mechanical robustness of the entire system; (b) focus on high gain position control and kinematic planning: while high gain kinematic control is intuitive and works well in structured and well-known environments, many planning and control aspects for situations involving contact with unknown and unstructured environments are best dealt within the force/torque domain.

A versatile robotics platform for research into highly dynamic, autonomous all-terrain locomotion should ideally be (a) able to withstand impacts and crashes, (b) have high actuation bandwidth as well as, (c) high power to weight ratio, (d) offer force sensing and (e) torque controlled joints, (f) have high bandwidth control, (g) be power autonomous, (h) have sufficient sensing for body acceleration and orientation, and terrain perception, (i) be able to exert large forces at the end-effectors, yet, (j) be compliant and (k) have a large leg workspace.

In this paper, we show that our quadruped robot HyQ, Fig. 1, covers most of these requirements using a torque-controlled hydraulic actuation system, which is mechanically simple and robust, as well as accurate and fast.

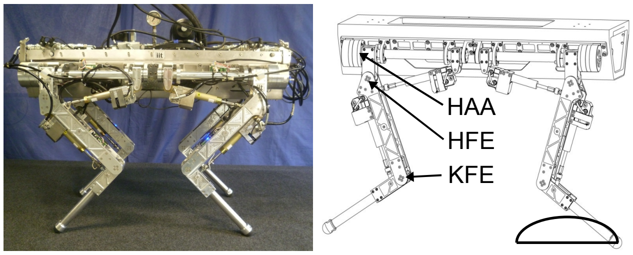


Fig. 1. HyQ: Hydraulic Quadruped robot. **Left:** picture of the robot. **Right:** sketch with labels of the three leg joints, hip abduction/adduction (HAA), hip flexion/extension (HFE) and knee flexion/extension (KFE) and endeffector trajectory of the trot experiment presented in Section V.

We recently presented the design of HyQ and a ZMP walking [1], [2]. In this work we focus on the development of a high-performance hydraulic torque control that satisfies the requirements to perform dynamic locomotion. We demonstrate how our torque controller and actuation system enable the use of model based control, such as inverse dynamics control, resulting in excellent position tracking with low position control gains and impact robustness during dynamic locomotion tasks such as trotting and jumping.

The paper is structured as follows: firstly, in Section II we discuss important contributions and concepts in legged locomotion. Section III gives an overview of the HyQ hardware and control. The torque controller design for the hydraulically actuated joints is described in Section IV; next, Section V describes the experiments carried out on HyQ and presents the results. In Section VI we discuss the results obtained and then in Section VII, draw conclusions and discuss future works.

II. RELATED WORK

The body of research in legged locomotion is vast, and while it is not possible to give exhaustive reference to all the work done, we discuss some of the important contributions and concepts and show how they are related to our work.

An important, and very closely related line of research in dynamic legged locomotion was initiated in the 1980s by Raibert and collaborators [3]. They showed an amazing display of dynamic gaits and maneuvers on one, two and four-legged robots. However, due to a relatively small workspace of the prismatic legs and the absence of terrain sensing, the versatility of these machines was limited.

Raibert's research recently culminated in the presentation of *BigDog* [4]. While *BigDog* is clearly a very impressive machine and raises the bar of what is achievable, a lot of research questions remain unanswered. Details of neither the design of *BigDog*, nor its control aspects are available to the research community at large.

Recently, locomotion through challenging terrain (with obstacles of a size up to the leg length of the robot) was the focus of the *Learning Locomotion* project [2]. The aim of this project was on control and planning aspects. The platform (*LittleDog*), however, was a high-geared robot built mainly for static locomotion and therefore suggestions for control of dynamic locomotion could not easily be validated.

Inspired by Raibert's work of the 1980s, several other quadruped robots were constructed that successfully demonstrated dynamic locomotion with limit cycle stability. For example, *Scout II* [5] and *Rush* [6] performed bounding, *KOLT* [7] and a modified version of *Scout II* [8] showed trotting. *Airhopper* [9] achieved an explosive vertical jump out of a squat posture.

While most machines employ either limit cycle walking/running or support-polygon based control (e.g. ZMP), a versatile machine should be able to cover the whole spectrum from completely static locomotion (such as climbing and walking on ice) to highly dynamic locomotion (such as trotting and bounding). In addition, it should be able to exert explosive jumps to move through terrain with high obstacles, steps or ditches. To the best of our knowledge, no versatile quadruped machine other than *BigDog* has yet demonstrated such a wide range of statically and dynamically stable locomotion.

III. HyQ OVERVIEW

Our research platform *HyQ*, Fig. 1, is a quadruped robot with a primary focus on highly dynamic motions. This section will briefly describe the hardware and the control schemes.

A. Hardware

HyQ has 12 active degrees of freedom (DOF) and it is currently tethered to an external power supply. The torso and legs are constructed from an aerospace-grade aluminum alloy. In this version of the robot, no springs are present anywhere on the robot. The hip abduction/adduction (HAA) joints are driven by brushless DC electric motors and connect the legs to the robot torso, creating the lateral leg motion. The hip and knee flexion/extension (HFE and KFE, respectively) are actuated by hydraulic cylinders, which are driven by high performance servovalves (bandwidth around $250Hz$) [10].

TABLE I

CHARACTERISTICS OF THE HyQ ROBOT

Property	Value
Dimensions	1.0m x 0.5m x 0.98m (LxWxH)
Weight	65kg
Active DOF	12
Joint range of motion	120° (for each joint)
Hydraulic actuation	double-acting asymmetric cylinders
Electric actuation	DC brushless motors + harmonic gear
Max. torque [electric]	140Nm (after gear reduction)
Max. torque [hydraulic]	145Nm (peak torque at 16MPa)
Position sensing	absolute and relative encoders at joints
Force sensing	load cell at the cylinder rod
Body sensing	inertial measurement unit (IMU)

Hydraulic actuation has many properties that make it an ideal choice for highly dynamic articulated robot applications. Firstly, hydraulic drives have a substantially higher power-to-weight ratio than electric drives [11]. They are also much stiffer, resulting in the possibility of having higher closed loop torque control bandwidth, greater accuracy, and better frequency response [12]. Furthermore, hydraulic actuators are mechanically very simple and allow for robust design against impacts and overload. This is very important in dynamic applications, where high peak forces on the robot structure cannot be avoided and are even part of the requirements [13]. As we will show, hydraulic actuation also guarantees sufficiently high bandwidth to achieve high-performance torque control suitable for dynamic locomotion. High-bandwidth torque control allows the straightforward implementation of active compliance. In other words, hydraulics allows both very fast and strong movements and a regulation of impedance in a wide range.

Table I summarizes the most important characteristics of the HyQ robot platform. A more detailed presentation of the robot design and components is found in [1] and [13].

B. Control

In general, to achieve high control performance it is important to measure and to control the inputs applied to the plant with the highest possible accuracy. Since robots are typically modeled as rigid body systems, they have torques as input to their dynamics, and therefore a high-fidelity torque source is of great significance.

Being able to apply precise joint torques to a robot has many advantages. Torque control allows various forms of impedance control, control of contact forces, virtual model control, as well as model-based controls, such as rigid body dynamics based control (inverse dynamics, gravity compensation), and operational space control.

HyQ employs a control scheme composed of two different closed-loop controls: an outer position loop and an inner torque loop, as described in the block diagram in Fig. 2. These controllers are set in cascade, where the output of the position controller τ_{fb}, together with a feed-forward

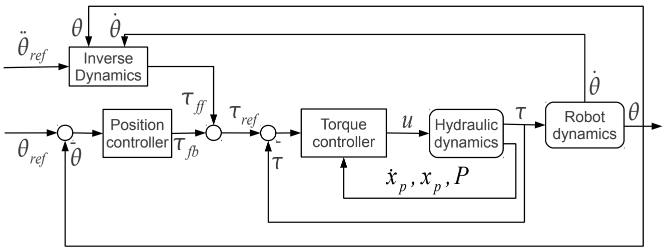


Fig. 2. Block diagram of the control scheme of HyQ's hydraulic joints. Besides the inner torque loop and outer position loop, it includes a feed-forward term for the robot rigid body inverse dynamics (τ_{ff}). The torque controller uses state feedback: cylinder position x_p and velocity $\dot{x}_p$, and system pressures P.

torque τ_{ff} that comes from the inverse dynamics control, manipulates the set-point τ_{ref} of the torque controller.

The inverse dynamics control part uses the rigid body dynamics model of the robot to calculate the joint torques that are required to generate a desired motion. As we demonstrate in Section V, one immediate advantage of inverse dynamics control is that it allows for compliant and more robust locomotion since it allows the reduction of the position gains without sacrificing tracking performance. Having these capabilities is not only desirable but mandatory for locomotion in unstructured and partially unknown environments [14]. To overcome the intrinsic complexity related to floating base robots (i.e., robots that are not fixed to their environment) such as under-actuation, dynamically changing contact states, and contact forces that may not be known, an orthogonal decomposition [15] is used to calculate the floating base inverse dynamics.

The output of the torque controller u is the signal that commands the hydraulic servovalve. The position loop is closed through a high-resolution encoder feedback (80,000 counts per revolution) and the torque loop through a feedback by a load-cell measuring the cylinder force ($\pm 5kN$ range). Both controllers run a PID law at a frequency of $1kHz$.

To control the joint torques is equivalent to controlling the force at the hydraulic cylinder since the cylinder rod is rigidly connected to the joints. Thus, the joint torques can be computed by simply multiplying the cylinder force by the actual lever arm [13]. Note that throughout this paper the terms *force control* and *torque control* are used interchangeably. We discuss the hydraulic force controller in details in Section IV.

IV. HIGH-PERFORMANCE HYDRAULIC FORCE CONTROL

As discussed in the previous section, an accurate torque source is very important for robots that are modeled as rigid body systems. Thus appropriate hardware has to be chosen and a high-performance torque controller has to be designed. The key aspects for achieving high-performance torque control with a hydraulic system are: (a) to use servovalves with high flow control bandwidth to exploit the naturally high hydraulic stiffness; (b) to improve the controller using model-based control. Both aspects together are able to provide a bandwidth of around $40Hz$ for the torque control. We will describe item (b) in this section, which is represented by the block 'Torque controller' in Fig. 2.

Due to the naturally high hydraulic stiffness, the pressure dynamics has a high bandwidth and requires a very fast flow controller. Servovalves with sufficient bandwidth for a torque control application have been a very well established technology for many decades [16]. While at the time of their introduction analog control technology had to be used to exploit their full bandwidth, today even low-cost commodity hardware is powerful enough to be used to develop flexible digital controllers for such a system.

The electro-hydraulic system can be modeled by employing the continuity equation at the valve+actuator subsystem. Bernoulli's equation can be used to describe the flow through the valve orifices. A detailed model for the hydraulic force dynamics can be found in [17]. By applying force and flow balance and neglecting the hydraulic viscous friction, the dynamics of the hydraulic force F for positive valve command $u > 0$ can be written as follows:

$$\dot{F} = f(P, x_p) + g(x_p, \dot{x}_p)u \tag{1}$$

where $f(P, x_p)$ is a function, which depends on the cylinder position x_P and on the system pressures P (i.e., the cylinder chamber pressures P_A and P_B, the supply pressure P_S, and the tank pressure P_T). The function $g(x_p, \dot{x}_p)$ depends also on the cylinder velocity $\dot{x}_p$ and represents a natural velocity feedback that is intrinsic in hydraulic actuators [18] and influences significantly the force dynamics at high cylinder velocities. These functions can be modeled as:

$$g(P, x_p) = K_v A_p \beta \left[\frac{\sqrt{P_S - P_A}}{V_A(x_p)} + \frac{\alpha\sqrt{P_B - P_T}}{V_B(x_p)} \right] \tag{2}$$

$$f(x_p, \dot{x}_p) = -A_p^2 \beta \left[\frac{1}{V_A(x_p)} + \frac{\alpha^2}{V_B(x_p)} \right] \dot{x}_p \tag{3}$$

where $V_A(x_p)$ and $V_B(x_p)$ are the variable volumes of the cylinder chambers, which are a function of the cylinder position x_p, and include the pipe volume; A_p is the piston area; and α is the piston/annulus area ratio; β is the oil's bulk modulus, the physical property of a fluid that governs its stiffness; and K_v is the valve gain. The internal laminar leakage between the two chambers is negligible for the selected cylinder.

A feedback linearization technique can be applied to improve the force (and consequently position) tracking. This technique permits linearization of the force dynamics, compensating for flow and pressure non-linearities. By choosing a valve command u in the form:

$$u = \frac{1}{g(x_p, \dot{x}_p)} \left[v - f(P, x_p) \right] \tag{4}$$

a control law v can be designed to satisfy system requirements for the force dynamics, such as rise time and overshoot. We chose v to be a PID control law.

To demonstrate the high performance obtained with our controller, we show in Fig. 3 an experiment with position and force tracking for a 5 Hz sine position reference for the hip (HFE) joint (first and second plot, respectively). The

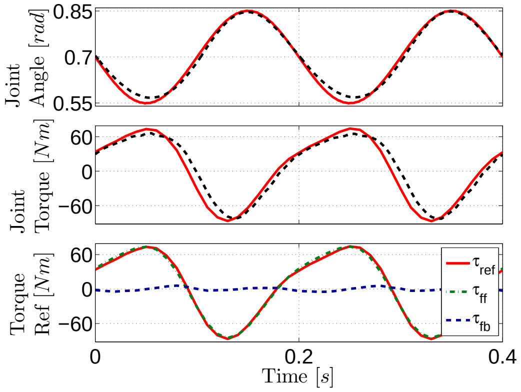


Fig. 3. Precise position and force tracking for a 5 Hz sine position reference for the hip joint (HFE). In the first two plots, the red solid lines indicate the reference command and the black dashed ones the actual value. The last plot shows how the reference torque τ_{ref} is generated as the sum of feed-forward and the position error feedback term: $\tau_{ref} = \tau_{ff} + \tau_{fb}$. The reference torque is almost completely obtained by the feed-forward term, indicating a very accurate rigid body dynamics model of the leg segments.

third plot illustrates the importance of the inverse dynamics for such fast movements. The feed-forward term τ_{ff}, that is calculated with the inverse dynamics model, acts *a priori* on the system according to the system model and position reference and therefore does not need a position error to be created. The feedback term τ_{fb}, on the other hand, is purely based on the position error. The fact that practically all the torque reference τ_{ref} comes from the inverse dynamics means the rigid body model of HyQ's leg is very accurate.

V. EXPERIMENTAL RESULTS

We performed several experiments with HyQ to assess its capability to execute highly dynamic motions, its strength, and its mechanical robustness, verifying the fulfillment of the specifications listed in Section I. In this section we present a trot and a squat jump, describing briefly their implementation and showing the experimental results. Moreover, to underline the HyQ's versatility (i.e. that it is able not only of limit cycle gaits but also static locomotion), we show also a ZMP walk in the accompanying video.

A. Trot

A trot is characterized by synchronously moving diagonal leg pairs. The implementation of our trot is based on desired end-effector position trajectories, which are then mapped into joint position reference trajectories by use of inverse kinematics. The foot follows a half-period sinusoidal trajectory during the flight phase and a flat trajectory during the stance phase, as shown in the very right of Fig. 1.

Results – Fig. 4 shows vertical ground reaction forces at the four feet obtained from a $2.25Hz$ *walking trot* at $1.7m/s$ with a duty factor of 53%. The data is based on the joint torque measurements of the two hydraulic joints that are projected into Cartesian coordinates at the foot via the leg Jacobian matrix [1]. The ground reaction forces at the feet of a running robot give important insights into each leg's contribution to the robot propulsion and the stress the mechanical structure has to deal with.

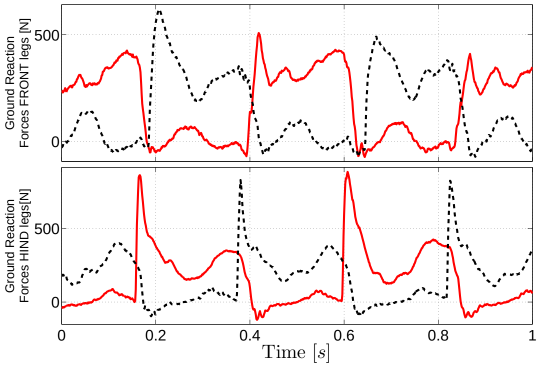


Fig. 4. Vertical ground reaction forces at the robot's feet during one second of a 2.25Hz trot. The forces are obtained through the projection of the measured joint torques into Cartesian coordinates at the foot. Top: Front Left (red solid), Front Right (black dashed). Bottom: Hind Left (red solid) and Hind Right (black dashed) leg.

The peak forward velocity of $1.7m/s$ corresponds to a Froude number of 0.5, using the distance between the ground and the hip axis as characteristic leg length [19]. As the robot is currently moving on a relatively narrow treadmill with respect to its size, faster velocities are dangerous to test. Running experiments without the treadmill are part of ongoing work.

During the experiments, for safety, two *robot wranglers* use laterally fixed ropes to monitor, and if needed, correct the robot's direction of motion to keep it on the treadmill. The onboard IMU is currently only used for robot body state estimation, but not yet for active control of roll, pitch and yaw. We recently presented experimental results of a *running trot* with 36% duty factor [20].

B. Squat jump

The next experiment demonstrates the speed and force of HyQ's legs, as well as the robots ability to cope with impacts during landing. Additionally, it shows the capabilities and benefits of torque controlled joints and rigid body model based control and their importance for highly dynamic robots. Starting from a squat posture, the robot pushes its body $0.36m$ upward vertically to the ground plane until it lifts off the ground after about $0.35s$. Once the robot is in its parabolic flight phase the legs are repositioned to prepare for the landing.

To achieve compliant behavior during the impact of the landing we used low knee position gains of $200Nm/rad$.

Results – To demonstrate the contribution of the feed-forward torque obtained by the inverse dynamics (see Section III-B), we performed the same jump with and without inverse dynamics during the acceleration phase. Fig. 5 shows the resulting position and force tracking performance and the composition of the torque reference with and without inverse dynamics, left and right plot respectively. The plots show how the inverse dynamics' contribution improved position tracking before the jump (0 to 0.2s in the plot) and especially during the vertical acceleration (0.2 to 0.55s), even though the position gains were low.

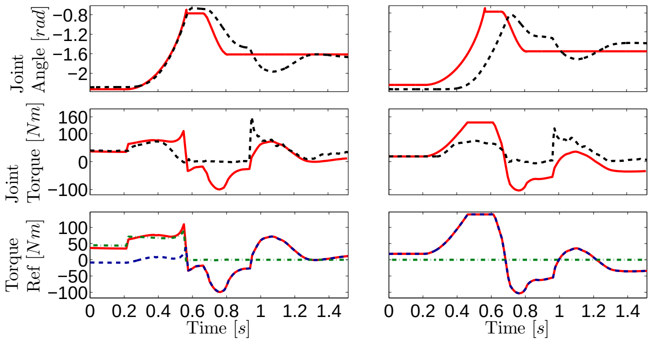


Fig. 5. Position and force tracking of the right hind knee joint during a squat jump. **Left:** inverse dynamics switched on during the acceleration phase. **Right:** inverse dynamics switched off. The first plot shows the acceleration phase (from $t = 0.2s$ to $0.55s$) with consecutive landing preparation. The parabolic flight phase lasts from $0.55s$ to $0.95s$. In the first two plots, the red solid lines indicate the reference command and the black dashed ones the actual value. The last plot shows how the reference torque τ_{ref} is generated (as in the last plot of Fig. 3).

The resulting jump lifts the robot's center of mass about $0.2m$ from its position when the robot loses contact with the ground. Peak knee joint velocity reaches $11rad/s$ at the end of the acceleration phase. The low position gains act as virtual rotational springs that create a compliant landing. The impact torque peaks are kept at safe levels ($< 160Nm$) and thus protect the mechanical structure of the robot. Note that no mechanical springs are present anywhere on the legs, but a layer of 5mm visco-elastic rubber at the feet to increase traction. Active control in combination with the mechanical robustness of the actuators make this performance possible.

VI. DISCUSSION

A versatile robot should ideally be able to accomplish tasks ranging from quasi-static motions, with careful and accurate movements, to highly dynamic motions, such as jumping and running. Moreover, the robot is supposed to perform these tasks without breaking, and resisting the impacts and forces associated to them. We listed in Section I several specifications (from *(a)* to *(k)*) for such machines to achieve the appropriate versatility required for all-terrain locomotion. In the remainder of this section we will go through this list and show that HyQ's characteristics satisfy most of these requirements.

Hydraulic systems are usually supplied with high pressure (typically around 16-21MPa), which permits relatively small actuators to simultaneously exert high forces and have high velocities without reduction gears. Thus, the hydraulic system by itself already satisfies requirements (a),(b),(c), and (i). Moreover, the high-performance hydraulic servovalves meet the requirements necessary to implement a high-performance control in both position and torque space (see Fig. 3).

In the early days of robotics research there were many challenges to apply the theoretically very appealing concept of torque control and build platforms suitable for dynamic locomotion: lack of suitable actuation and sensing technology; lack of fast enough multi-purpose computers, which are required to calculate complex models to exploit the model based controllers such as inverse dynamics; limited data acquisition hardware; etc. Therefore, torque control has been avoided and, for many applications, simple high gain position control schemes have been used. Especially scarce are torque controlled legged robots, even though they would be one of the main applications to benefit greatly from the advantage of torque control [14]. As HyQ offers force sensing at joint space using miniaturized load cells and a fast CPU and data acquisition hardware, a torque control loop could be closed, fulfilling also requirements (d) and (e).

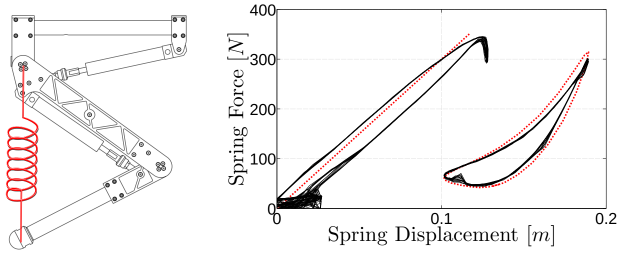
HyQ also has a large range of motion for all the joints [1] (requirement (k)) and the IMU gives preliminary sensing for orientation, satisfying partially requirement (h). In the current version of HyQ, neither direct sensing of end-effector forces nor terrain perception are available, and the hydraulic power is supplied externally. So, points (g) and (h) are not fully satisfied yet, limiting HyQ's autonomy. However, the addition of an on-board pump unit and sensing for environment mapping are on-going work and a power-autonomous version will be available in the near future.

By the use of inverse dynamics and other model-based techniques for the low-level hydraulic control, high performance was achieved for the force and position control (see Fig. 3), fulfilling requirement (f). This high bandwidth permits the implementation of virtual components [21], such as springs and dampers, making the robot actively compliant. Besides satisfying requirement (j), virtual components allow to change stiffness and damping at runtime, which is clearly an advantage over passive elements. Furthermore, it is easier to investigate hypotheses from other fields, such as biological motor control and biomechanics, and to emulate different muscle-based actuation models [22]. At this current stage of the project, we tolerate the lower energy efficiency of virtual elements, when compared to passive elements, due to the gain in system versatility. In Fig. 6, we demonstrate that HyQ is able to create different impedance profiles by showing two different virtual systems: a linear spring without damping and an exponential spring with constant damping coefficient. The placement for both virtual components is the same (Fig. 6(a)). Even though the stiffness tracking (Fig. 6(b)) is bounded by nonlinear phenomena such as hysteresis and static friction, the experimental results prove that it is satisfactory for most locomotion purposes. The experimental implementation of virtual springs and dampers is shown in the video.

VII. CONCLUSION AND FUTURE WORK

HyQ's suitability for dynamic locomotion is achieved by an adequate hardware design and a high-performance torque controller. Together, they allow our robot to be actively compliant by using virtual components and, therefore, resist big impacts even without passive elements such as springs or dampers.

In this work we listed several essential requirements for a versatile locomotion platform. We also showed that HyQ fulfills most of them. The key aspects behind these



(a) (b)

Fig. 6. Virtual components: **(a)** placement of a linear spring on the HyQ leg and **(b)** impedance tracking for two different virtual components: a linear spring and an exponential spring-damper. The plot shows the reference profile created by the virtual component (dashed red) and the real profile obtained (solid black).

capabilities are the fast and strong hydraulic actuation used in HyQ's legs and appropriate controllers.

A relatively simple low-level force control was developed using feedback linearization techniques. This controller permits to straightforwardly exploit the benefits of model-based control approaches such as inverse dynamics. The high performance reached with the force controller allowed us to obtain an almost perfect position and force tracking at $5Hz$ as well as to exploit active compliance. It gives this robot the flexibility to have a variable impedance behavior as well as dexterity and robustness to handle mechanical impacts.

The high-performance controller also allowed our platform to successfully demonstrate highly dynamic tasks, such as trotting, and squat jump motions that catapulted the robot $0.2m$ in the air. These results show HyQ's versatility in terms of being able to cover the whole range from precise motions and completely static gaits to dynamic limit cycle locomotion and jumping.

While we have shown that HyQ covers many of the points we listed as desired specifications for dynamic locomotion, there are some remaining issues. Further work focuses on making the robot power-autonomous for several hours, and on the addition of sensors for navigation (cameras and laser range finders). Currently we are working on generalizing our promising results towards truly versatile locomotion and we aim at providing a useful research platform for a wide range of studies, e.g. into biomechanics, locomotion and control.

VIII. APPENDIX – VIDEO CONTENTS

The video shows experiments with a single leg (LEG) and with the full robot (HyQ): (1) ZMP walking (HyQ); (2) Force control with $F_{ref} = 0$. Mimics passive system (LEG); (3) Model based gravity compensation (LEG); (4) Fast 'running' movements, using rigid body inverse dynamics (LEG); (5) Virtual spring damper. Interaction with human, drop experiments, hopping (LEG); (6) Fast walking trot on treadmill (HyQ); (7) Squat jump with and without inverse dynamics (HyQ).

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