HyQ – Hydraulically Actuated Quadruped Robot: Hopping Leg Prototype

Claudio Semini, Nikos G. Tsagarakis, Bram Vanderborght, Yousheng Yang and Darwin G. Caldwell

Abstract— **This paper describes the concept, specifications and design of the biologically inspired quadruped robot HyQ, with special focus on the leg design. The main scope of this new robotic platform is to study highly dynamic tasks such as running and jumping. To meet the specifications in terms of performance and dimensions, hydraulic actuation has been chosen due to its high power to weight ratio and fast response. Guidelines on how to choose the design parameters of the hydraulic cylinders including lever length are reported. A two DOF leg prototype has been designed and constructed. The experimental test setup for the leg prototype is explained and the results of first hopping experiments are reported.**

Key Words— **Quadruped Robot, Hydraulic Actuation, Bio-inspired Design, Compliance**

I. INTRODUCTION

AN important motivation for the research and development of legged robots is their potential for higher mobility. Since these machines only need a discrete number of isolated footholds, their mobility in unstructured environments can be much higher than their wheeled counterparts, which require a more or less continuous path of support [1]. Legged robots are often grouped depending on their number of legs. Bipedal locomotion is mainly studied for use in humanoid robots, developed to be our future assistant robots in human environments such as houses and offices. The control of bipeds is considered to be difficult due to their small support base. On the other hand, quadrupeds and hexapods have less stability problems and can therefore be beneficial for outdoor mobility to perform exploration and inspection tasks or carry payloads. The first manually controlled walking truck was the GE Quadruped, General Electric Walking Truck by Mosher [2]. Well known are also the different versions of the TITAN quadrupeds capable of statically walking [3].

Sony commercialized the robot dog AIBO [4]. Besides entertainment purposes this robot is also extensively used in the research community, because it is a stable hardware platform and was used in the RoboCup Four-Legged Robot Soccer League. The joints are driven by servomotors, which are sufficient for known environments as flat terrain and known obstacles. However, the potential of such robots is strongly limited by the mechanical design and especially their actuation system. Position controllers cannot adapt to external forces and irregular terrain. Force is the key for walking and running because it produces acceleration and consequently motion. Therefore force controlled joints are preferable over position controlled robots.

If the joints are only force-controlled by software and have no compliant elements, the disadvantage is that there is no possibility to store and release motion energy. At touch down all the motion energy is lost and has to be injected from the power source in the system. Passive compliant elements can absorb impact shocks, which cannot be accomplished by active compliance schemes due to the delay in the control system. Especially for running this is important for energy efficient locomotion and there is biological evidence that all kinds of running animals and humans have a spring-like behavior [5]. Because the movements of the center of mass during running are similar to a bouncing ball, running is often referred to as a "bouncing gait". The compliance in the tendon muscle system makes it possible for the whole body to operate at an efficiency of 40-50% during running [6]. The Spring Loaded Inverted Pendulum (SLIP) model is often used to describe the motion of the center of mass [7].

Pioneering work in this area was performed by Marc Raibert, who has studied different running robots, including also quadruped systems [8], [9]. These famous hopping robots were powered by pneumatic and hydraulic actuators and performed various actions including somersaults [10]. The key feature in these machines was the spring mechanism, which stored the kinetic energy during running cycles. Whereas the quadruped ScoutI had stiff legs, its successor ScoutII was powered by compliant prismatic joints [11]. The biologically inspired hopping robot Kenken has an articulated leg composed of three links, and uses two hydraulic actuators as muscles and linear springs as tendons [12]. The robot has succeeded in running several steps in a plane. KenkenII has two legs to realize not only hopping, but also biped walking and running [13]. Another biologically inspired quadruped robot is the KOLT vehicle, featuring mechanical springs with nonlinear characteristics in its legs [14]. The most advanced quadruped BigDog [15], [16], developed by Boston Dynamics, is driven by hydraulic

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actuation and uses force controlled architecture in combination with passive linear pneumatic compliance in the lower leg to be able to cope with unstructured terrain.

The compliance of these actuators is fixed and is determined in the design and cannot be changed during operation. Adaptable compliant actuators, comparable to a spring with a variable spring constant, are developed at the cost of an extra actuator per joint. This allows tuning the natural frequency of the system according to the desired running motion. So the stiffness of the actuator can be controlled as a function of speed, step length and ground surface properties. Also this is found in biomechanical studies. Leg stiffness is adjusted to achieve different stride frequencies at the same speed [17] and to accommodate surfaces with different properties [18]. The BiMASC is a hopping prototype leg with three degrees of freedom (DOF): the leg length, leg angle, and leg stiffness and is designed to closely resemble the SLIP model [19]. The so called Puppy robot is a bio-inspired quadruped robot actuated by pneumatic muscles, developed at Case Western Reserve University [20]. Due to their antagonistic configuration, the joint stiffness is adjustable to some extent.

To sum up, the above review follows a logical line of thinking: from position control over force control with software compliance to a force control with passive compliance. Finally adaptable compliance strategies will be studied, here two options are possible: using a fixed compliant element and changing the stiffness by software control (using the length of the spring as force measurement) or using adaptable compliant actuators. This is the research line we want to follow with the hydraulic quadruped **HyQ** (pronounced [haI-kju:]). In this work, the design of the first leg prototype and preliminary results of hopping experiments are presented. The leg has two DOF without a foot and is attached to an experimental test setup with vertical slider that allows the leg to freely move up and down.

The paper is organized as follows: Section II presents the specifications of the HyQ robotic platform. Section III introduces the bio-inspired kinematic design of the first leg prototype accompanied by simulation studies. Section IV presents details on the experimental prototype system setup and section V depicts results from preliminary trials conducted with the prototype system. Finally, section VI addresses the conclusions and comments on future work.

II. SPECIFICATIONS OF THE HyQ ROBOTIC PLATFORM

As explained in the previous section, the main motivations for the development of the quadruped robot presented in this paper are the following:

- Creation of a robotic platform able to perform highly dynamic tasks such as running and jumping, and able to move autonomously (in terms of energy and control) in difficult terrain, where wheeled robots cannot go.

- Study of biologically inspired locomotion focusing on the importance of adjustable joint stiffness, reduction of energy consumption and stability on uneven ground.

Secondary goals of the project are the study of different foot trajectories, neural-network based controllers, gait patterns and transitions, new actuation systems and the development of compact and light-weight components for robotic applications.

A. Performance

As stated above, the quadruped robot has to be able to perform highly dynamic tasks, which include jumping and running gaits such as gallop.

Furthermore, the robotic platform should be able to carry a payload of 10 kg, walk on uneven terrain such as rubble and stones, overcome obstacles like steps (up/down) of 0.2 m, keep balance on slippery ground and stabilize its posture even after strong disturbances on its main body.

B. Dimensions and Weight

The most extensively studied quadruped animals, besides mice and rats for pharmaceutical experiments, are probably cats and dogs. Researchers from various fields such as biology, medicine and robotics are interested in understanding their anatomy, kinematics and locomotion. According to the above mentioned specifications dogs and cats are very well suited to serve as an inspiration for the design of the current robot.

To achieve the performance outlined above, the overall dimensions of the quadruped robot should be comparable to the size of a large dog, such as the Irish Wolfhound or Great Dane for example. The highest point of the robot with maximally stretched legs should not exceed one meter. The same applies to the length. The width of the robot should be less than 0.4 m.

The total mass of the energy autonomous version of the robotic platform should stay within the limit of 60 kg, excluding payload.

C. Actuation System

In order to accomplish the above stated requirements in terms of dimension, weight and performance, the actuation system needs to have a high power to weight ratio, allow high bandwidth control with fast response and provide energy autonomy for several hours. Furthermore, the energy source, whether battery or fuel, should be easily and rapidly recharged or refueled.

As mentioned in [21] hydraulic actuation with cylinders can meet such specifications, as they have high power to weight ratio, and thus are the smallest actuation option available. Also, hydraulic fluid is generally incompressible, leading to a relatively high control bandwidth.

The next section will focus on the design of a biologically inspired leg prototype including the results of different simulations for the selection of the desired actuator characteristics.

III. BIO-INSPIRED LEG DESIGN AND SIMULATION

To simplify the control and design of the first prototype, both front and hind limbs will have the same design. Each leg will feature three actuated DOF: Two in the hip (sagittal and frontal plane) and one in the knee (sagittal plane).

The study of mammal skeletons show clearly that the configuration of the front and hind legs form an x-shape in the sagittal plane; in other words, the elbow opens to the front just as in a human, and the knee opens to the back. The same configuration has been used in a few previous quadruped robot designs, such as AIBO from Sony Corp. [4], the 2006-version of BigDog from Boston Dynamics [15], one of the possible configurations of KOLT [14] and the Puppy [20].

A. General Kinematic Design

Among the most important questions to be addressed when considering the hardware design of a quadruped robot is the fundamental layout of the leg, to enable natural, stable, robust actions found in quadruped animals. The fundamental layout of the leg of HyQ includes the definition of the number of DOF required and their actual location as well as the actual size of the leg segments.

The main functions of legs are to move and support the body. To allow the robot to perform dynamic motions, the leg inertia has to be small. This is mainly achieved by reducing the weight of the leg segments and by moving most parts of the actuation system into the robot body. Furthermore, the leg should be designed strong enough to withstand impacts after jumping and to carry the actuators.

Thus the following general design rules have to be taken into account: low leg inertia, robust but light structure and passive compliance.

The range of motion of the two DOF in the sagittal plane is determined according to a study of Labrador Retrievers [22]. As shown in the center column of Table I, the two joints of both front and hind legs feature a similar range of motion and therefore, both hip/shoulder and knee/elbow joints of the HyQ Leg prototype are able to rotate 120°.

TABLE I
JOINT RANGE OF MOTION

Joint	Labrador Retriever	HyQ Leg Prototype
shoulder	108°	120°
elbow	129°	120°
hip	112°	120°
knee	121°	120°

The range of motion of the third DOF, which is the motion of the hip joint in the frontal plane, is set to 90°. This allows the robot to stabilize its body and retain its balance in case of disturbances from the side.

Day *et al.* [23] analyzed the leg anatomy of different felids (members of the biological family of cats (felidae)). The study shows that the lengths of individual limb segments (in the hind leg: *femur*, between hip and knee; *tibia*, between knee and ankle; *metatarsal+phalange*, between ankle and end of toes) are equal on average and each segment contributes about one third to the total limb length. The first version of the HyQ Leg prototype consists of two limb segments: the femur and tibia. Each of them has a length of 0.3 m which corresponds to the average limb segment length of felids with similar size to the robot specifications [23].

B. Leg Actuation Arrangements and Optimization

In order to select the characteristics and design parameters of the actuators, dynamic simulations were carried out. To match the performance demanded from the specifications, usually maximum joint torque and rotational velocity are sufficient if selecting rotational actuators such as electric motors. This is not the case for the actuation system used in the HyQ robot. HyQ uses double-acting linear hydraulic actuators because of their compactness, low weight, and high-force capabilities. The double acting cylinders are arranged in a triangular configuration between the two leg segments, forming the joints as shown in Fig. 1 for the knee joint.
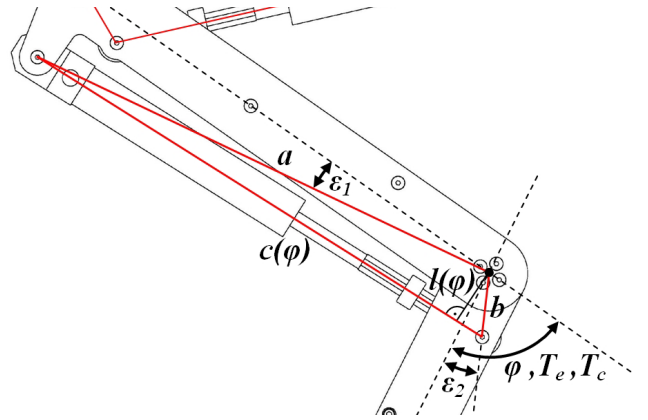

Fig. 1.   Detailed view of HyQ Leg prototype design with definition of parameters for knee joint actuation used in (1) to (4).

According to this configuration the maximum static torque output of the joint as a function of actuator parameters is given by (1) to (4)

$$T_e = P \cdot \frac{\pi \cdot D_b^2}{4} \cdot l(\varphi) \tag{1}$$

$$T_c = P \cdot \frac{\pi \cdot (D_b^2 - D_r^2)}{4} \cdot l(\varphi) \tag{2}$$

$$l(\varphi) = a \cdot \sin(\cos^{-1}(\frac{a^2 + c(\varphi)^2 - b^2}{2ac(\varphi)})) \tag{3}$$

$$c(\varphi) = \sqrt{a^2 + b^2 - 2ab\cos(\pi - \varphi - \varepsilon_1 + \varepsilon_2)} \tag{4}$$

where a, ε_1 and ε_2 are construction parameters depending on the cylinder length, maximum stroke and joint range , b the lever length, $c(\varphi)$ the variable length of the cylinder, φ the joint angle, T_e the torque generated at the joint due to the extension of the piston, T_c the torque generated at the joint

due to the contraction of the piston, P the supply pressure, D_b and D_r the bore and rod diameters and $l(\varphi)$ the lever arm as a function of the joint angle. The above mentioned variables are illustrated in Fig. 1.

The problem of such an actuation design is to find a combination of actuator endpoints and lever length that can provide the necessary torque at the joint. The plot in Fig. 2 shows an example of simulation results obtained during the design optimisation of the actuator endpoints and lever length parameters.
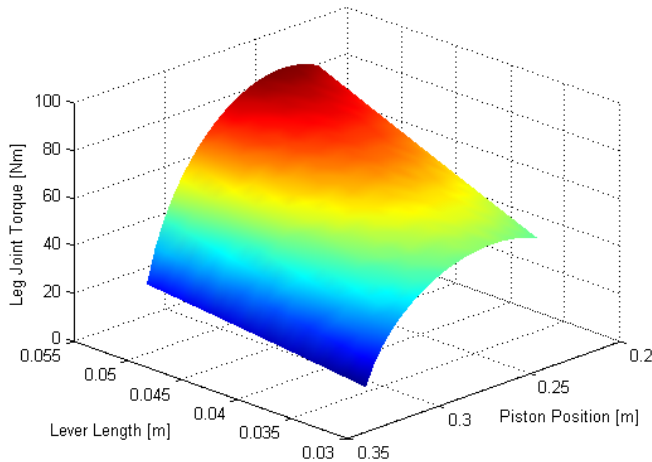
Fig. 2. Simulation results of leg joint output torque as a function of lever length b and piston position, for extracting piston motion at 100 bar.

Due to the nonlinear relationship between joint angle and output torque, it is necessary to make dynamic simulations to obtain the desired torque profiles in relation to joint angle for different task motions.

The dynamic simulation package MSC Adams has been used to run simulations of a simplified robot model where, due to its symmetry, the robot is cut into two parts along the sagittal plane through the center of the robot as shown in Fig. 3. The weight of the upper leg segments (green) has been set to 2 kg each, the lower leg segments (blue) to 1kg each and the box-shaped body (red) to 30 kg, which together with the weight of the legs corresponds to about half of the targeted total weight of the robot including payload.
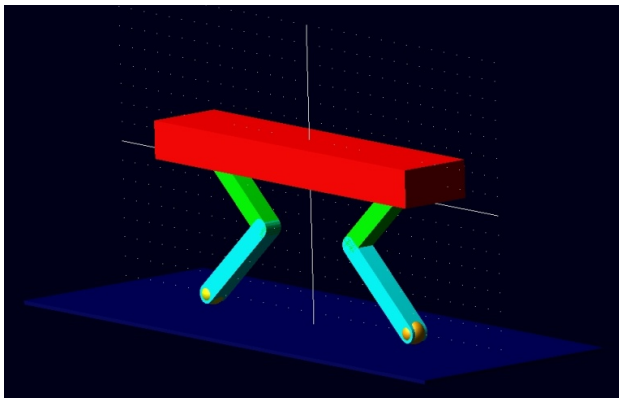

Fig. 3. Simplified model of the robot implemented in MSC Adams for simulations to obtain the desired torque profiles in relation to joint angle.

Fig. 4 shows the torques in the knee joint for different postures expressed in the knee angle φ as defined in Fig. 1. The red line (solid) shows the quasi-static case and the blue line (dashed) the dynamic case, where the main body is kept horizontal and its center of gravity is lifted from its lowest position (where φ=140°) to its highest position (where φ=20°) in 1 second (20 seconds for the quasi-static case). In this simulation, both feet of the model have been fixed to the ground with a rotational joint, separated from each other by the same distance as between the hip and the shoulder joint. Joint friction is neglected. The peak in the blue curve at around 140° is due to the acceleration phase in the beginning of the motion. The superimposed black curve (dash dot) shows the torque output produced at the joint by the selected actuator with its endpoint attachment and lever arm length being optimized with the process described above.
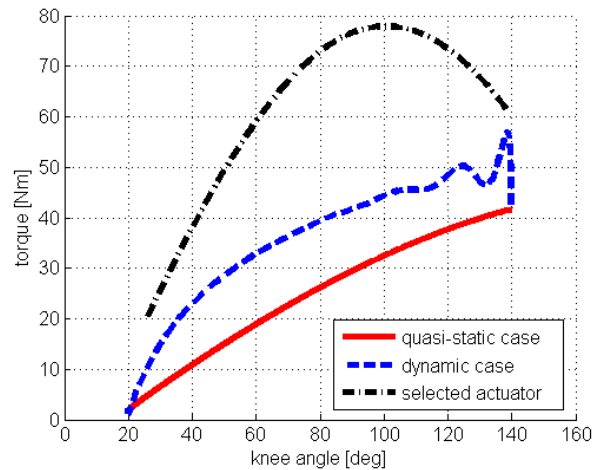

Fig. 4. Torque versus angle plot for the knee joint. The plot shows the simulation results for both the quasi-static (red, -) and the dynamic case (blue, --). The top curve (black, -.) shows the torque output for the selected actuator and lever, calculated based on extracting piston motion at 100 bar.

C. Actuator Selection

Considering the results of the dynamic simulations, the specifications for joint range and availability of commercial components, the characteristics of the hydraulic cylinders and design parameters for the knee joint have been selected as shown in Table II.

TABLE II
ACTUATOR SPECIFICATIONS FOR KNEE JOINT

Design Parameter	Value
Cylinder stroke	70 mm
Minimum cylinder length (from bearing to bearing)	227 mm
Piston area (extending)	2,01 cm^2
Piston ring area (contracting)	1,23 cm^2
Permitted piston speed	up to 4 m/s
Maximum oil pressure	160 bar
Theoretically maximum force at 160 bar (extending)	3216 N
Theoretically maximum force at 160 bar (contracting)	1968 N
Cylinder weight (empty)	0.62 kg
Lever length	39 mm

The cylinder of the hip joint has the same characteristics but features a lever length of 38 mm due to a slightly different end point attachment.

D. Compliant Element

A passive compliant element based on a mechanical spring has been inserted into the tube of the lower leg segment and attached to a half-sphere shaped foot with a 4 mm thick external layer of rubber. The compliant element has been designed so that it allows an easy exchange of the spring to test several sizes with different values of stiffness.

E. Final Prototype Leg Design

The final design of the first leg prototype without compliant element and foot is shown in Fig. 5. A light aluminum alloy has been used for most parts and stainless steel for the shafts, which attach the hydraulic cylinders to the leg segments. The weight of the leg including the hydraulic cylinders is 4.5 kg.

Fig. 5. Picture of HyQ Leg prototype with hydraulic cylinders, without compliant element and foot.

Tension/compression load cells with a range of +/- 4400N will be mounted on each cylinder to measure the cylinder output force. Absolute position encoders are measuring the orientation of both hip and knee joint. A switch attached to the foot element senses whether the foot is touching the ground or not.

IV. EXPERIMENTAL SETUP FOR LEG PROTOTYPE

The main components of a hydraulic system are a hydraulic power pack, servo control valves and hydraulic cylinders. The power pack includes the pump and electric motor, pressure gages, filters, tank and a combination of valves to connect/disconnect the pressure outlet of the pump to the proportional servo valves and to adjust the maximum working pressure. The power pack features a volumetric pump with a 2.2 kW electric motor, adjustable working pressure from 10 to 210 bar, flow rate of 6 l/min and a tank with a capacity of 50 l.

The valves that are used to control the hydraulic cylinders are NG3-type 4/3-way proportional directional spool valves from Wandfluh. A PWM control signal with a frequency of 5 kHz sets the position of the spool.

The valves are connected to the cylinders by 0.8 m long flexible tubes with a diameter of 3/16 in. In order to keep the response time low and thus the dynamics of the actuation system high, these tubes were kept as short as possible.

The cylinder characteristics are reported in section III.C above.

The current version of joint control is a PID based position control for the two joint angles, taking the encoder readings as feedback references with a 1 kHz control rate.
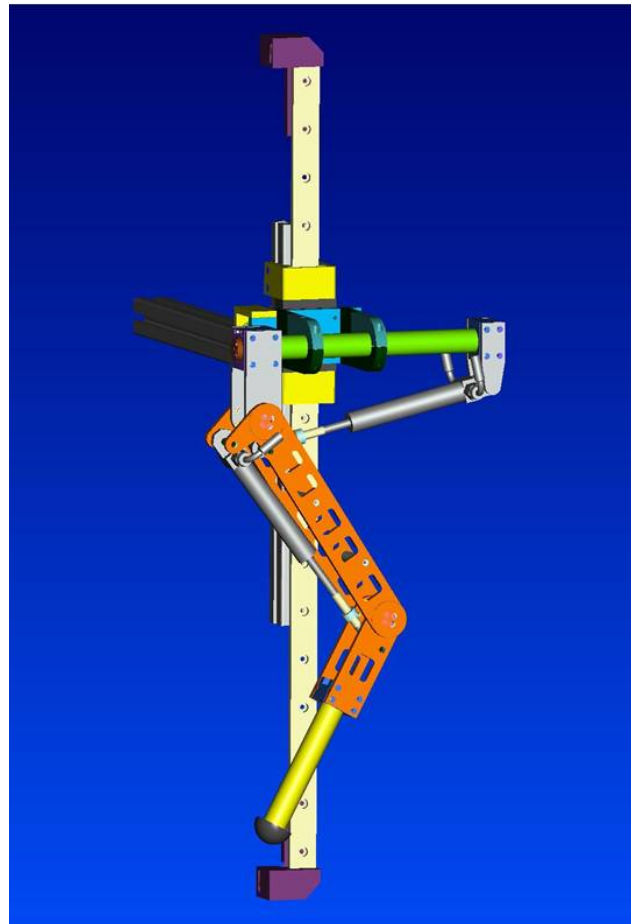

Fig. 6. CAD design of the test bench for the HyQ Leg prototype.

In order to test the performance of the HyQ Leg prototype a test bench as shown in Fig. 6 was developed, which allows the leg to move vertically up and down, guided by a linear slider. To test the leg without touching the ground, two clamps can be attached to the guide to fix the slider at a certain height.

V. EXPERIMENTAL RESULTS

A first series of experiments have been made with the HyQ Leg prototype using the experimental setup as explained in the previous section. All tests have been run with a working pressure of 100 bar and an oil temperature of 60-70 °C. The type of oil was Columbia Special 46 (ISO VG 46) with a viscosity of 46 mm²/s at 40 °C. The spring stiffness in the foot was 12 kN/m.

In order to tune the control parameters and test the general performance of the system, the first experiment has been made with the leg fixed to the slider, so that the leg can freely move in the air without touching the ground. A sine wave reference for both joint angles has been used to study the tracking ability of the control system. The phase between hip and knee joint angle reference is $\pi/2$. The results are shown in Fig. 7 and Fig. 8, which show the plots of the reference and actual angles for both joints as a function of time. The frequencies of the sine wave reference were 0.25 Hz and 1 Hz, respectively.

The tracking delay between reference and actual angle reaches up to 0.2 s and 0.1 s, respectively.

In the second experiment, the leg was free to slide vertically on the slider in order to perform a vertical jumping motion. The reference angles for the joints were calculated through inverse kinematics, in order to make the center of the foot follow a vertical trajectory with a cycle time of 0.7 s. Fig. 9 shows a plot of the reference and actual angles for both joints as a function of time. A picture sequence of the experiment is illustrated in Fig. 10.
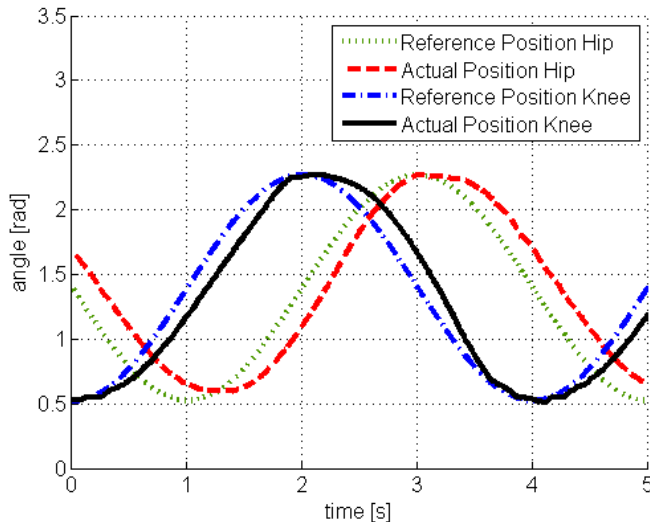

Fig. 7. Plot of reference and actual angles of hip and knee joint versus time for a sine wave trajectory with 0.25 Hz.
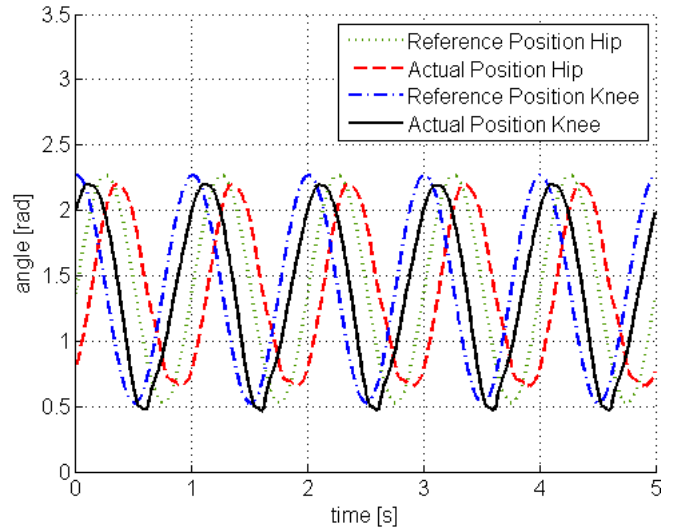

Fig. 8. Plot of reference and actual angles of hip and knee joint versus time for a sine wave trajectory with 1 Hz.
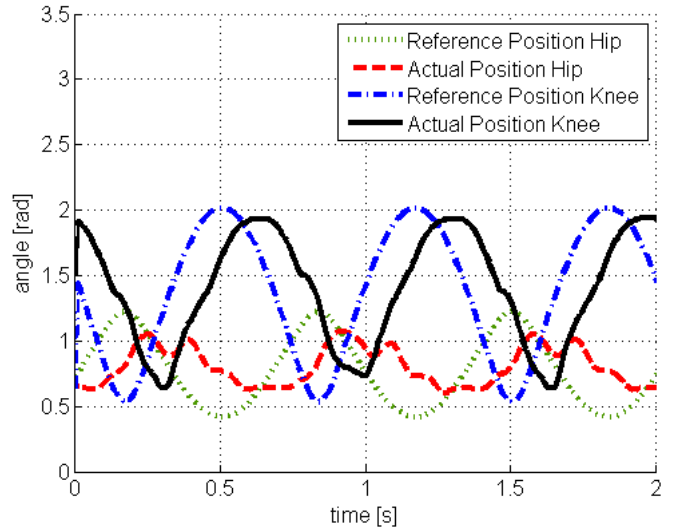

Fig. 9. Plot of reference and actual angles of hip and knee joint versus time for a vertical jumping motion.

The tracking performance of both joints is not yet optimal. Possible reasons and ways to improve it are discussed in the next section.

VI. DISCUSSION AND FUTURE WORK

Some of the issues regarding the hydraulic actuation system and the design of both the leg and the test bench are reported next.

In the vicinity of the posture in which the cylinders are almost fully extended (big angle for hip and small angle for knee), small changes in cylinder length result in a relatively large angular displacement (Jacobian matrix approaches a singularity). This makes an accurate control around this posture difficult, as can be seen in Fig. 7 for small angles of the knee joint, and should therefore be corrected in a future version of the leg.

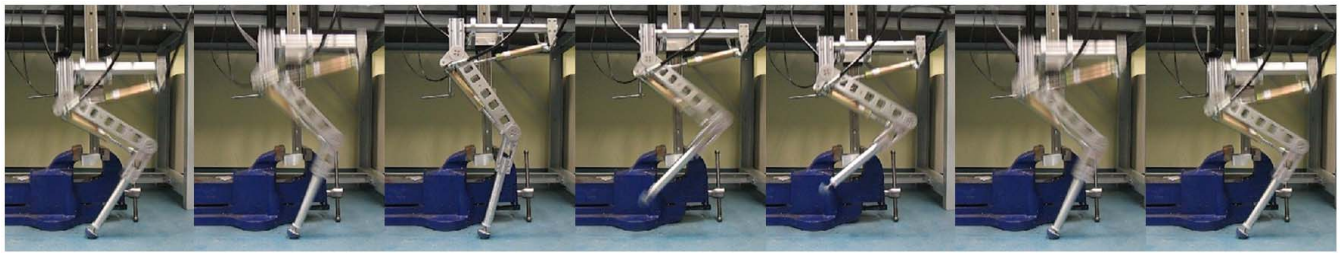The relatively high oil temperature of 60-70 °C at the time

Fig. 10. Picture sequence of the HyQ Leg prototype clamped to the vertical slider test bench, performing a vertical jump motion. Time between two frames: 0.16 seconds.

of the experiments, could lead to a phenomena called cavitation, which is a possible source of delays in the control of the system [21]. The influence of temperature changes on the system performance has to be studied in the future.The quality of the encoder output has to be checked. The derivation of the position signal is important for a good PID controller performance, but very sensitive to noise.

The valves have quite a large dead band around the 0 position, which has to be compensated for with an offset for both negative and positive values of the PWM duty cycle.

Static friction in the cylinders and valve spools could be another source of reduced system performance. The latter could be solved by superimposing a dither signal to the PWM signal, so that the spool is constantly in motion.

The linear slider based on nylon bushings used in the test bench has a big friction due to the moments caused by the leg inertia and the contact forces if in contact with the ground. It should be replaced by one or better two sliders with bearings. Alternatively, the leg could be attached to a boom, which would also allow it to move in a plane.

Future steps of the project include more experiments with the leg with different oil pressures, oil temperatures and spring stiffness values on the actual and a redesigned test setup. Furthermore, a force controller using the load cells for force/torque feedback will be implemented and the main body including the cylinder for the third DOF for the hip motion in the frontal plane will be designed.

Contemporarily, simulation for different quadruped gaits and gait transitions will be carried out. Mechanisms with controllable stiffness will be developed and tested.

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