HyQ - A Dynamic Locomotion Research Platform

Claudio Semini, Jonas Buchli, Marco Frigerio, Thiago Boaventura, Michele Focchi,
Emanuele Guglielmino, Ferdinando Cannella, Nikos G. Tsagarakis and Darwin G. Caldwell

Dept. of Advanced Robotics, Italian Institute of Technology (IIT), Genoa
URL: http://www.iit.it/en/advanced-robotics/hyq.html

I. Motivation

Articulated robots such as legged robots hold the promise to lead to versatile, multi purpose machines that 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. As the inspiring examples in biology show, arms and legs are useful both for manipulation and locomotion. Legs become very advantageous for highly dynamic locomotion in severely challenging terrain, i.e. terrain where wheeled and legged system of comparable size cannot go. This fact is easily appreciated by observing cats going about their daily lives, or mountain goats effortlessly bounding up steep rock faces. While this superior all-terrain agility is typically the motivation behind research in legged robots, actual results on robust and versatile all-terrain locomotion are not abundant.

To achieve such locomotion, dynamic legged machines with torque controlled joints are required, but they are not available. Active compliance via torque control would allow the implementation of a big range of all-terrain locomotion controllers.

Furthermore, such machines would enable the experimental verification of bio-mechanical hypotheses including animal locomotion models, such as the influence of muscle models or spring-mass models. The latter is often used to describe bouncing gaits (running, hopping, trotting, galloping) in animal and human locomotion and robotics [1], [2]. Experimentally obtained data allow the comparison of various gaits and speeds, and have the potential to provide a deeper understanding of animal locomotion, which animal studies using force plates and motion capture systems cannot provide.

II. Problem Statement

Contributing factors to the rather small amount of results on robotic all-terrain locomotion are: (a) a lack of suited platforms (i.e. a prevalence and focus on electrical high-gear-ratio actuation systems both in research and education, as well as availability of affordable, yet sophisticated off-the-shelve elements) and (b) focus on high gain position control and kinematic planning.

For legged systems this means that most robots are built for static or quasi-static gaits, because their reduction gears break during fast motions and their associated impacts. Additionally, actuation bandwidth is usually low due to the gears, which makes fast controlled movements impossible.

However, while high gain kinematic control is intuitive and works well in structured and well-known environments, for problems with contact with unknown and unstructured environments many planning and control aspects are best discussed in the force/torque domain, e.g. impedance controllers [3], inverse dynamics controllers [4].

Therefore a research 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 torque controlled joints and force sensing, (e) have high bandwidth control, (f) be power autonomous, (g) have sufficient sensing for orientation and terrain perception, (f) be able to exert large forces at the end-effectors, yet (h) be able to be compliant (i) and have large leg workspace.

III. Related work

An important, and very closely related line of research in dynamic legged locomotion was initiated in the 80s by Raibert and collaborators [5].

Raibert *et al.* showed an amazing display of dynamic gaits and maneuvers on one, two and four-legged robots, such as summersaults and hopping over boxes and stairs. However, the versatility of these machines and their controllers were limited. This research recently culminated in the presentation of the quadruped robot *BigDog* [6], [7] and biped *Petman* [8]. The former demonstrated highly dynamic locomotion and reflex maneuvers in outdoor settings and challenging situations such as slipping on ice.

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 was the focus of the *Learning Locomotion* project [9], [10]. The focus of this project was on control and planning aspects, however, the platform was a high geared robot built mainly for static locomotion and therefore suggestions for control of dynamic locomotion could not easily be validated.

Most bipedal robots use the ZMP criterion [11], which is a sufficient but not necessary stability criterion for legged locomotion. It leads to overly conservative and quasi-static locomotion. Using the ZMP criterion leads to kinematic plans that are then typically tracked with high gain position control and therefore require detailed terrain knowledge. ZMP walking is mostly demonstrated on flat or quasi flat ground and does not easily generalize to non-flat conditions [12].

In order to to tackle the aforementioned problems of gears not being able to withstand impacts, researchers have put springs (with a relatively low, constant stiffness) in series with the actuators [13], [14]. However, control theory shows that this fundamentally limits the control bandwidth of the system and it is presently not quite clear where these elements should be placed and how they should be dimensioned.

IV. Results

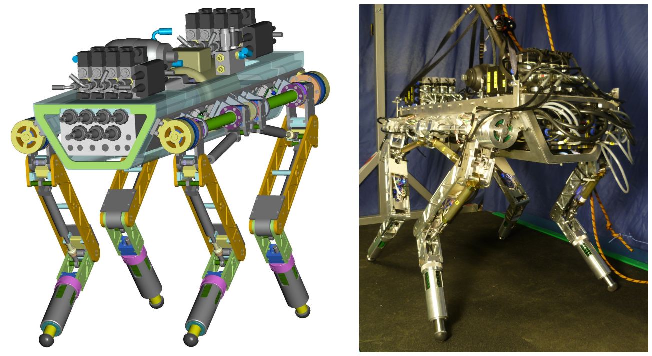
In this abstract we present our work towards building a research platform that allows the study of highly dynamic, all-terrain locomotion. To demonstrate the robot's dynamic motion capability, we present the experimental results of a running trot.

Our 16-DOF research platform (named HyQ) stands 1m tall, weighs around 70kg and is currently tethered to an external power supply. Each of the 12 actuated revolute joints features a range of motion of 120°. While the hip abduction/adduction joints are actuated by DC brushless electric motors, the hip and knee flexion/extension joints are driven by fast and strong hydraulic cylinders. With a piston diameter of only 16mm, they achieve a maximum output velocity above 1m/s and a peak force of around 3200N. Hydraulic actuation meets the required properties of dynamic legged robots due to its high power-to-weight ratio, high speed and force capabilities, and its intrinsic resistance to impact peaks. The electric and hydraulic joints have a maximum output torque of 140Nm and 145Nm, respectively. All joints feature high resolution position and torque sensing.

Most parts of the robot legs are built in aerospace-grade aluminium alloy with a very high strength-to-weight ratio. Stainless steel has been used for the heavily stressed parts. A combination of parallel plates and tubes resulted in a robust yet light-weight design. The robot feet are coated by a visco-elastic rubber that helps to increase traction. The feet are connected to the lower leg segment via a passive linear joint with a stiff spring of 50kN/m stiffness.

The robot torso is constructed with a folded 3mm thick sheet of the same aluminium alloy. Internal walls increase its torsional robustness. Fig. 1 shows a picture and the CAD model of HyQ. A detailed discussion of the robot design and its specifications can be found in [15] and [16].

To show the ability of the research platform to perform dynamic motions, we implemented and experimentally tested a running trot. The load cell measurements confirmed that the joint torques stays inside the actuator limits during most of the stride period. The torque peaks that exceeded the limits, however, are well absorbed by the hydraulic system and damage neither the actuators nor the mechanical structure of the robot.



(a) (b)

Fig. 1. The hydraulically and electrically actuated quadruped robot HyQ: **(a)** CAD model and **(b)** picture with robot standing on treadmill [16].

V. Experiments

We present the results of HyQ performing a running trot with a frequency of 2Hz on our laboratory treadmill. A running trot gait is characterized by a flight phase between single steps and diagonally coupled leg pairs that move synchronously.

The joint position trajectories were created with the robot controller and simulator software SL [17] and the locomotion controller implemented by Kalakrishnan *et al.* [10]. We ran the periodic trotting motion at 2Hz, since it matches the resonant frequency of the system. This resonance depends on the joint position controller gains, the elasticity in the hydraulic hoses, the spring stiffness of the foot and the ground, and on the robot weight.

The scope of the experiment was to test the ability of the robot to perform a running motion with a large vertical travel and therefore a relatively long flight phase between the steps but small stride length. We did not try fast running speeds (with the associated required long strides) with the current laboratory setup due to safety reasons.

VI. Main Experimental Insights

The ground reaction forces at the feet of a running robot give important insight into each leg's contribution to the robot propulsion and the stress the mechanical structure has to deal with. Fig. 2 shows the vertical ground reaction forces of the four feet during 2 cycles of the periodic running trot. The values are 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 [16].

The plot shows four distinct force peaks indicating the periods in which the two diagonal leg pairs FL/HR and FR/HL are in contact with the ground. Between these peaks all four legs are in the air for approximately 70ms. The presence of this *flight phase* shows that the robot is running.

Let us now compare the timing of the legs and the ground contact forces with studies of running quadruped animals. Heglund and Taylor [18] compared the speed and frequency of running quadruped animals of various sizes. They concluded that these animals have preferred trotting and galloping speeds and frequencies that are directly related to the animal's body

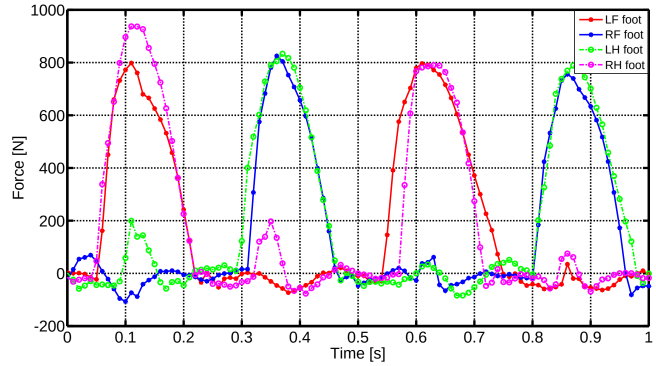


Fig. 2. Vertical ground reaction forces at the robot's feet during 2 cycles of a 2Hz running trot. The forces are obtained through the projection of the measured joint torques into Cartesian coordinates at the foot. Front Left (FL), Front Right (FR), Hind Left (HL) and Hind Right (HR) leg.

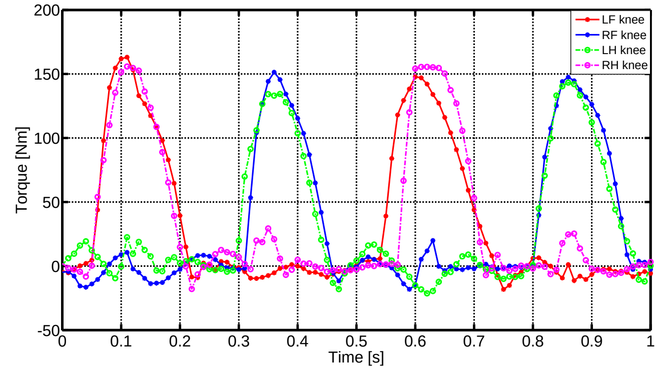


Fig. 3. Torques of the knee joints of the four legs, corresponding to the plot in Fig. 2

weight. The preferred trot frequency of a 70kg animal is 1.9Hz and its trot-gallop transition usually happens at 2.2Hz. These frequencies match with the 2Hz resonant frequency of our experiments.

Another important characteristic number to analyse and describe legged locomotion is the *Duty-Factor* (DF), which is defined as the fraction of the stride period that a limb is in contact with the ground [19]. Values below 50% lead to running. In our experiment the 180ms stance phase leads to a DF of 36%. Biewener concluded that at the trot-gallop transition it is around 40% for a wide range of quadruped animals [19]. Therefore in nature, a running trot is often seen with a DF between 40% and 50%. This shows that in the experiments with HyQ we achieved a flight phase duration that is longer than that of common trotting, which is a requirement for fast running.

A comparison of the ground reaction forces of HyQ with the measurements of trotting dogs [20] shows that similar peak forces up to 1.2 times body weight are exerted on each limb. HyQ's mass is around 686N. Lee *et al.* found that the forces of the front legs are higher than the ones of the hind legs. Fig. 2 on the other hand shows that the legs of HyQ experience equally sized force peaks. This difference is explained by the location of the dog's centre of mass that is shifted more towards the front legs if compared to HyQ.

Fig. 3 illustrates the measured torques that act in the knee joints of the four legs corresponding to the data shown in Fig. 2. The torque peaks temporarily exceeded the actuator limits of 145Nm, but the overload capabilities of the hydraulic actuators protected the mechanical structure from damage.

REFERENCES

[1] R. Blickhan, "The spring-mass model for running and hopping," *Journal of Biomechanics*, vol. 22, pp. 1217–1227, 1989.

[2] J. Rummel and A. Seyfarth, "Stable running with segmented legs," *International Journal of Robotics Research*, vol. 27, pp. 919–934, 2008.

[3] N. Hogan, "Impedance control: An approach to manipulation: Part II – Implementation," *ASME, Transactions, Journal of Dynamic Systems, Measurement, and Control*, vol. 107, pp. 8–16, 1985.

[4] J. Buchli, M. Kalakrishnan, M. Mistry, P. Pastor, and S. Schaal, "Compliant quadruped locomotion over rough terrain," in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2009.

[5] M. H. Raibert, *Legged Robots That Balance*. The MIT Press, 1986.

[6] M. Raibert, K. Blankespoor, G. Nelson, R. Playter, and the Big-Dog Team, "Bigdog, the rough-terrain quadruped robot," in *Proceedings of the 17th World Congress The International Federation of Automatic Control (IFAC)*, 2008.

[7] R. Playter, M. Buehler, and R. M., "Bigdog," *Proceedings of SPIE*, vol. 6320, 2006.

[8] Boston Dynamics Corp. (2011) Website. Accessed February 2011 at *http://www.bostondynamics.com*.

[9] J. Pippine, D. Hackett, and A. Watson, "An overview of the Defense Advanced Research Projects Agency's Learning Locomotion program," *Int. J. of Robotics Research*, vol. 30, pp. 141–144, 2011.

[10] M. Kalakrishnan, J. Buchli, P. Pastor, M. Mistry, and S. Schaal, "Learning, Planning, and Control for Quadruped Locomotion over Challenging Terrain," *Int. J. of Robotics Research*, vol. 30, pp. 236–258, 2011.

[11] M. Vukobratovic and B. Borovac, "Zero-moment point - thirty five years of its life," *International Journal of Humanoid Robotics*, vol. 1, no. 1, pp. 157–173, 2004.

[12] L. Sentis, J. Park, and O. Khatib, "Compliant control of multi-contact and center of mass behaviors in humanoid robots," *IEEE Transactions on Robotics*, vol. 26(3), pp. 483–501, 2010.

[13] G. Pratt and M. Williamson, "Series elastic actuators," in *IEEE International Conference on Intelligent Robots and Systems (IROS)*, 1995.

[14] J. Pratt, B. Krupp, and C. Morse, "Series elastic actuators for high fidelity force control," *Industrial Robot: An International Journal*, no. 8, pp. 234–241, 2002.

[15] C. Semini, "HyQ - design and development of a hydraulically actuated quadruped robot," Ph.D. dissertation, Italian Institute of Technology and University of Genoa, 2010.

[16] C. Semini, N. G. Tsagarakis, E. Guglielmino, M. Focchi, F. Cannella, and D. G. Caldwell, "Design of hyq - a hydraulically and electrically actuated quadruped robot," *Journal of Systems and Control Engineering*, 2011, (in print).

[17] S. Schaal. (2006) The SL simulation and real-time control software package. Technical Report, (Online) Accessed February 2011 at *http://www-clmc.usc.edu/publications/S/schaal-TRSL.pdf*.

[18] N. Heglund and C. Taylor, "Speed, stride frequency and energy cost per stride: how do they change with body size and gait?" *J. of Experimental Biology*, vol. 138, no. 1, pp. 301–318, 1988.

[19] A. A. Biewener, "Allometry of quadrupedal locomotion: The scaling of duty factor, bone curvature and limb orientation to body size," *J. of Experimental Biology*, vol. 105, pp. 147–171, 1983.

[20] D. V. Lee, J. E. A. Bertram, and R. J. Todhunter, "Acceleration and balance in trotting dogs," *J. of Experimental Biology*, vol. 202, pp. 3565–3573, 1999.