# Validation of Computer Simulations of the HyQ Robot

Marco Frigerio, Victor Barasuol, Michele Focchi, Darwin G. Caldwell and Claudio Semini

*Department of Advanced Robotics, Istituto Italiano di Tecnologia*
*Via Morego 30, 16163, Genova, Italy*
*E-mail:* `<first name>.<last name>@iit.it`

This paper illustrates the results of a validation procedure for the computer simulations of our quadruped robot HyQ. We show how simulated and real data recorded during locomotion tests are substantially consistent, providing an argument for the reliability of our simulation software. The main contribution of this work is to illustrate a basic yet effective software system that allows us to simulate – and also control in the real world – a complex articulated robot that can walk and run.

*Keywords*: Robot simulation; Robot software; Rigid-body dynamics; Quadruped robots

## 1. Introduction

Accurate computer simulations of the behavior of articulated robots are a fundamental tool for robotics research. The simulation allows the roboticist to test experimental controllers in a virtual environment, where the cost of a failure is limited to disappointment. Also, simulations are repeatable. On the other hand, tests on the real robot may cause damage to the robot itself and be possibly hazardous for the human operators, in case of powerful actuation. Therefore, it is a straightforward best practice to require a series of successful simulations before experimenting with the real machine.

The gap between the virtual and real environment must not only be addressed by accurate simulation of the physics (e.g. the rigid body dynamics), but also minimizing the variations of the control software being used in simulation and on the real robot.

In this paper, we give an overview of our simulation and robot control software (based on SL[1] – see Sec. 3), and of the validation of the simulations by means of comparisons with real experimental data. We will refer to tests performed with our hydraulic quadruped robot, HyQ (see Section 2).

A popular simulator in the robotics community is Gazebo, a rich tool that simulates both the rigid body dynamics of the robot and the environment as well as a variety of sensors, and offers an appealing graphical interface.[2] Gazebo was not originally intended to seamlessly allow the users to move their control software from the simulator to the real robot; however, Gazebo supports plugins and some users have exploited this option to achieve such an integration.[2] To the best of our knowledge, though, no publication has addressed the point of validating the simulator by comparing it with real data.

In Pepper et al.,[3] the authors also stress the benefits of computer simulations, and propose a standardized set of tests to compare virtual and actual experiments of mobile search and rescue robots. They focus on the problem of identifying inconsistencies in the physical model of the robot/environment. Carpin et al.[4] also address the assessment of a simulator accuracy, but focus on higher level tasks such as vision (using graphical rendering of virtual environments), wireless communication, and human robot interaction.

The costs of experiments with a real robot is a well known issue in the research community. Melo et al.,[5] for example, propose a software framework that allows simulation and control of modular snake robots. The data collection capability of the framework enables the comparison between virtual and real data, but this point is not the focus of the article.

In this work, we show how simulations and experiments with our quadruped robot are consistent, in terms of basic physical quantities such as joint velocity and force, and provide a solid argument for our related work grounded on simulations (e.g. Semini et al.[6]). This paper also illustrates a software package that enables hard real–time control of a complex machine such as the HyQ robot.

This article is an extended version of a technical report that appeared on arXiv.org.[7]

## 2. The HyQ robot

Figure 1 shows a picture of HyQ, a quadruped robot with hydraulically actuated joints.[8] The machine weighs 80 kg, is roughly 1 meter long and has a leg length of 0.78 m with fully-extended legs. All of its 12 degrees of freedom (DOF) are torque-controlled joints: the hip abduction/adduction (HAA) joints are driven by rotary hydraulic actuators with strain-gauge based torque sensors for torque control. All 8 joints in the sagittal plane (hip flexion/extension (HFE) and knee flexion/extension (KFE)) are ac-

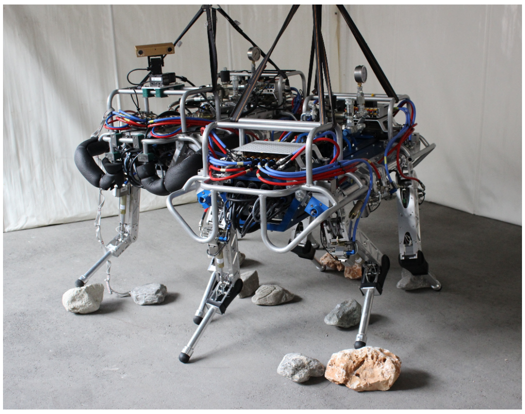


Fig. 1. A picture of IIT's hydraulic quadruped robot, HyQ.

tuated by hydraulic cylinders, that are connected to load cells for force measurement. High-performance servo-valves (MOOG E024) enable joint-level torque control with excellent tracking that led to the implementation of active impedance.[9,10]

Table 1 lists the main specifications and features of the robot.

## 3. Software environment

The *SL simulator and motor controller package*[1] was adopted as the first software control system of HyQ. SL is an implementation of a conceptual architecture which is basic yet very effective, and comprises two main computational activities: motor control – i.e. low level control of the joint motion/force, generating commands for the actuators – and trajectory generation – i.e. set-points generation acting as a demand for the motor control.

A general I/O interface decouples the motor control from the actual component that receives the actuator commands. Therefore, the software can be deployed either on a computer connected with the real hardware (sensors and actuators), as well as on a computer running a physics simulator of the same robot. Limited change of code is required between the two options, guaranteeing that simulations and real experiments are driven by the same software.

To practically allow such interchange between simulation and real robot, SL is entirely written C/C++, is compatible with hard real–time constraints, and can be built and executed on top of a real–time Xenomai–based Linux system (as well as on a regular Linux system, of course). The

| Property/Feature | Value |
|---|---|
| dimensions | 1.0 x 0.5 x 0.98 m (LxWxH) |
| approximative leg length (fully extended) | 0.78 m |
| weight | 80kg |
| active DOF | 12 |
| hydraulic actuation | double–vane rotary actuators and double–acting asymmetric cylinders |
| motion range | 90° (HAA), 120° (HFE, KFE) |
| max joint torque (HAA) | 120Nm (peak torque at 20MPa) |
| max joint torque (HFE, KFE) | 181Nm (peak torque at 20MPa) |
| position sensors | relative encoder, 80000CPR |
| torque sensors | custom torque sensor (HAA), 5kN loadcell (HFE, KFE) |
| perception sensors | IMU, stereo camera, lidar |
| onboard computer | Intel i5 based computer, 8GB of RAM |
| joint control (rate) | position and torque (1kHz) |
| locomotion skills | walking (crawl, trot), running (flying trot), hopping, squat jumping, rearing |

complete SL package includes also a rigid body simulator, which is the one we use in this work; although not sophisticated (e.g. no simulation of vision sensors), it is perfectly suitable to test behaviors such as trotting or jumping. To summarize, the reader shall keep in mind that, whenever we refer to simulation or real experiment, the actual code running in the two cases differs only slightly.

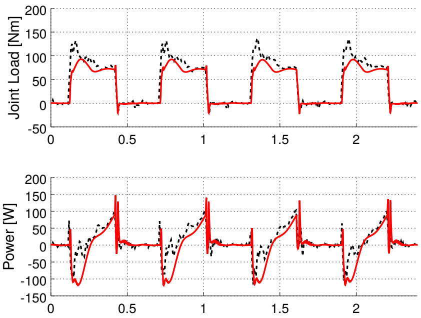
The kinematics and dynamics engines for the HyQ robot (e.g. the forward dynamics routine required by the simulator) have been implemented using RobCoGen, a generator of robot–specific, optimized code for the most common kinematics and dynamics routines used in robotics.[11] RobCoGen was not validated by any formal method, but the generated code was tested by numerical comparisons with other libraries/tools, for a variety of articulated robot models, and also used in real–time control loop of real robots.[11]

## 4. Experimental Validation of the Simulator

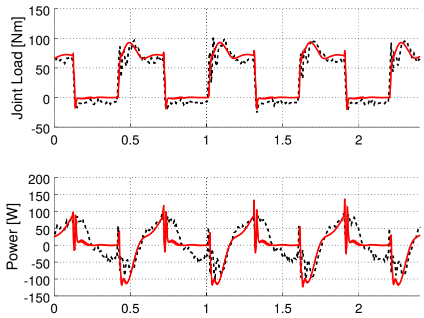
To validate our simulation we performed $1m/s$ walking trot experiments both within the simulator and with the actual robot. To generate a stable trotting motion we used the locomotion controller presented in Barasuol et al.[12]

Figure 2 shows the knee torque profiles of all the legs, in the case of both simulation and real experiments. The plots in the bottom show the power obtained by multiplying the joint torque with the joint velocity. The negative power regions in the gait cycle, e.g. at foot touch down in the beginning of each stance phase, are due to the potential/kinetic energy of the whole robot which is back-driving the joint.

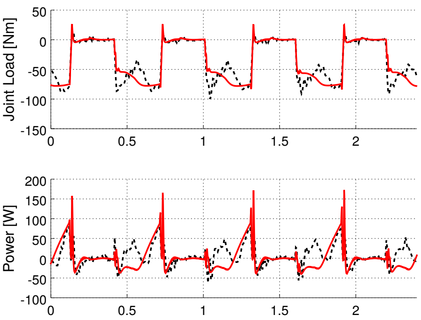
Note that the torque peaks during foot touch down in the left front leg are only present in the experimental data. These peaks are created by an imperfect trotting motion, possibly due to inaccurate state estimation.



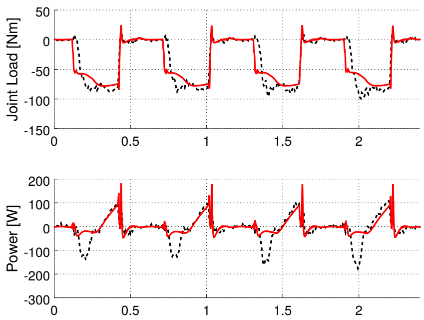

(a) Left Front leg




(b) Right Front leg




(c) Left Hind leg




(d) Right Hind leg

Fig. 2. Comparison between simulation (red solid) and experimental (black dashed) results of a 1.0 m/s walking trot with the HyQ robot. The bottom plots illustrate the mechanical power profile obtained by multiplying the joint torque with the joint velocity. All plots refer to the knee joint. The negative power areas indicate periods in which the joint is back-driven by the weight and inertia of the whole robot.

Figure 3 shows the position and velocity profiles for the same joint during the same motion. All the plots of both figures show a good similarity between simulation and real experiment, showing that the simulation is sufficiently predicting the overall behavior of the robot.

Similarly, Fig. 4 refers to a fast (5 Hz) sinusoidal trajectory tested on a single hydraulic leg of the HyQ robot. The same data for the real experiment was originally presented in Boaventura et al.,[9] to illustrate the performance of the force controller and the accuracy of the dynamics model. Here we compare joint load and velocity with a simulation of the same motion. Again, simulated and real data are similar, although the real experiment exhibits higher peaks in the joint load, probably due to unmodeled dynamics that becomes relevant at such high speed.

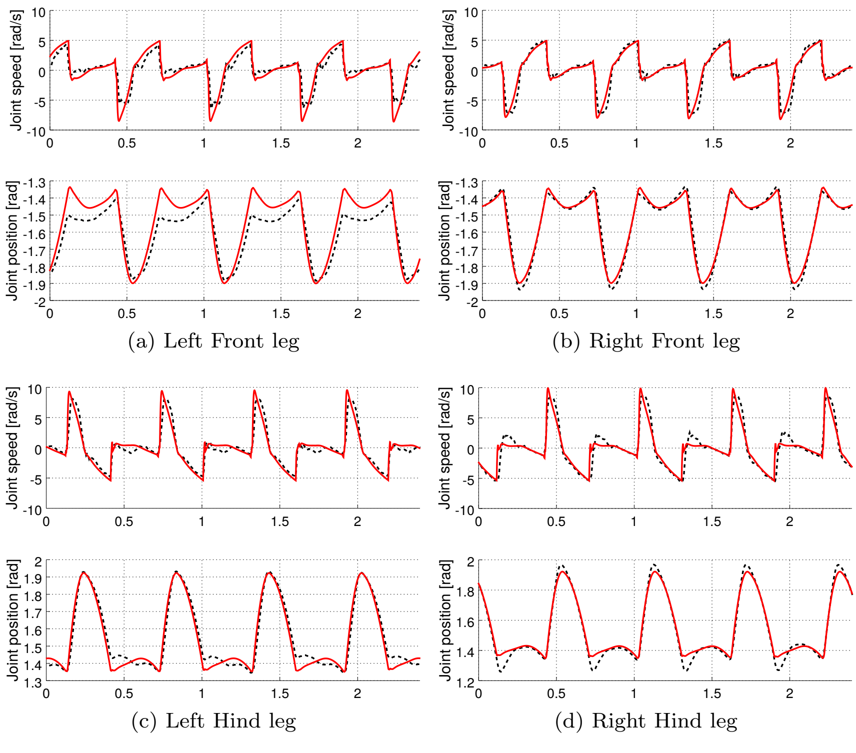
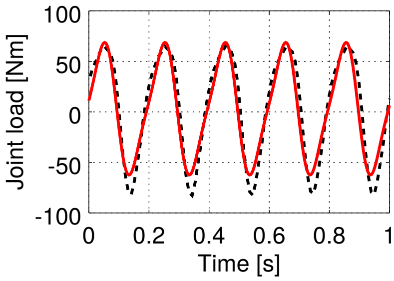
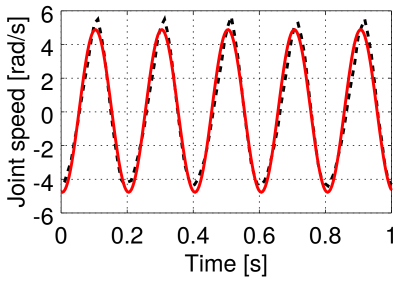



Fig. 3. Comparison between simulation (red solid) and experimental (black dashed) results of a 1.0 m/s walking trot with the HyQ robot; see Figure 2. The bottom plots show the knee joint position, whereas the top ones show the velocity.




(a) Load




(b) Speed

Fig. 4. Comparison between simulation (red solid) and experimental (black dashed) results of a fast (5 Hz) sinusoidal trajectory of a hydraulic leg. The plots refer to the HFE joint.

## 5. Conclusions and discussion

In this paper we have presented some comparisons between simulated and real experiments on our quadruped robot HyQ, in order to validate our simulation environment. Although this is not a formal verification, the results provide a qualitative argument in favor of the accuracy of our simulator and of its effectiveness in predicting the robot behavior. It is our personal experience that after performing several trials in simulation, switching to the real robot usually requires only a limited retuning of the controller parameters (of course other problems are possible and do occur, often because of the unmodeled hydraulic dynamics – see below).

In this paper we have also briefly introduced our robot software, which is based on a simple and sensible architecture that enables to share the same joint level controller and trajectory generation between the real and the simulated robot. Without this feature, even an accurate physics simulator would be of little use.

A current limitation of our simulator, which we want to address in future developments, is the lack of modeling of the actuation dynamics; joints are assumed to have ideal force sources. Although this issue might be mitigated by having a high performance force control on the real robot, simulating the hydraulic dynamics would make our simulations even more accurate and further reduce the chance of unexpected responses of the real robot.

### Acknowledgments

This work was supported by Istituto Italiano di Tecnologia (iit), with additional funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 601116 as part of the ECHORD++ (The European Coordination Hub for Open Robotics Development) project under the experiment called *HyQ-REAL*.

### References

1. S. Schaal, *The SL simulation and real-time control software package*, tech. rep., CLMC lab, University of Southern California (Jan 2009).
2. N. Koenig and A. Howard, Design and use paradigms for gazebo, an open-source multi-robot simulator, in *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Sept 2004.
3. C. Pepper, S. Balakirsky and C. Scrapper, Robot simulation physics validation, in *Workshop on Performance Metrics for Intelligent Systems*, PerMIS '07 (ACM, New York, NY, USA, 2007).
4. S. Carpin, T. Stoyanov, Y. Nevatia, M. Lewis and J. Wang, Quantitative assessments of usarsim accuracy, in *Performance Metrics for Intelligent Systems (PerMIS)*, 2006.
5. K. Melo, J. Leon, J. Monsalve, V. Fernandez and D. Gonzalez, Simulation and control integrated framework for modular snake robots locomotion research, in *IEEE/SICE International Symposium on System Integration (SII)*, 2012.
6. C. Semini, V. Barasuol, J. Goldsmith, M. Frigerio, M. Focchi, Y. Gao and D. G. Caldwell, Design of the hydraulically-actuated, torque-controlled quadruped robot HyQ2Max, *IEEE/ASME Trans. on Mechatronics* 2016.
7. M. Frigerio, V. Barasuol, M. Focchi and C. Semini, Validation of computer simulations of the hyq robot (arXiv.org, 2016).
8. 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 *IMechE Part I: Journal of Systems and Control Engineering* **225**, November 2011.
9. T. Boaventura, C. Semini, J. Buchli, M. Frigerio, M. Focchi and D. G. Caldwell, Dynamic torque control of a hydraulic quadruped robot, in *IEEE International Conference in Robotics and Automation*, May 2012.
10. C. Semini, V. Barasuol, T. Boaventura, M. Frigerio, M. Focchi, D. G. Caldwell and J. Buchli, Towards versatile legged robots through active impedance control *The International Journal of Robotics Research (IJRR)* **34**, 2015.
11. M. Frigerio, J. Buchli, D. G. Caldwell and C. Semini, RobCoGen: a code generator for efficient kinematics and dynamics of articulated robots, based on Domain Specific Languages *Journal of Software Engineering for Robotics (JOSER)* **7**, July 2016.
12. V. Barasuol, J. Buchli, C. Semini, M. Frigerio, E. R. D. Pieri and D. G. Caldwell, A reactive controller framework for quadrupedal locomotion on challenging terrain *IEEE International Conference on Robotics and Automation (ICRA)* May 2013.