Impedance control of an agile-locomotion robotic leg

J.C. Arevalo, J. Pestana*, F. Sanchez, J.F. Sarria and E. Garcia

Centre for Automation and Robotics, CSIC-UPM
La Poveda, 28500 Madrid, Spain
**E-mail: jesus.pestana@iai.csic.es*
www.iai.csic.es/dca

The success of an interaction control scheme is tightly related to the capacity of the actuators to follow the force references as much accurately as possible. The use of conventional actuators, usually modest at force control, lead to a inadequate performance of the interaction control system. This paper presents a leg prototype designed and developed for achieving agile locomotion. In the design, the selection of the proper actuation system has been a key issue for the development of the interaction control scheme. The HADE leg is actuated by means of three Series Elastic Actuators, and experimental results show the good performance of the impedance control performed with these actuators.

Keywords: Agile locomotion, Series elastic actuators, impedance control

1. Introduction

The new trends in legged locomotion research are conducted towards the development of lower limb exoskeletons[1,2] and agile quadrupeds.[3] There are major common challenges in the efficient performance of these robots. Besides the need for large power-to-weight actuators and high energy-density power supplies, these types of legged robots interact with the environment and usually with humans. Thus, robot-environment interaction schemes and safety play a key role in the emerging robotics research. Actuators for the new legged robots should have low mechanical impedance to allow the robot's adaptation to the environment and to the human. The adequate interaction scheme should be based on any kind of impedance control scheme, but this impedance control scheme should preferably rely on an internal force loop instead of a conventional stiff position loop to provide fast response. The key for the success of this approach is the use of a family of actuators specially designed for precise force control. Conventional actuators (e.g. electromechanical, hydraulic) are not good at force control because

Link	Length (mm)	Mass (kg)
Thigh	500	3.0
Shank	460	2.6
Foot	190	1.6

of undesired noise and nonlinearities, thus requiring an inner stiff-position control loop acting as a low-pass filter for such noise.[4]

This paper describes our efforts conducted towards the development of a leg prototype for agile locomotion. The leg called HADE is intended to walk dynamically while exhibiting a compliant interaction with the environment. The design of the HADE leg is based on the use of Series Elastic Actuators, a family of actuators specially designed for precise force control of the joints. The robot-environment interaction scheme proposed in this work is based on an impedance control scheme which relies on an internal force loop. The work described in this paper shows preliminar results of the impedance control of independent joints. Section 2 describes the design of the HADE leg and the actuation system used. Sections 3 and 4 present the joint impedance control scheme and its experimental validation respectively. Finally, Section 5 presents some conclusions.

2. The HADE leg

This section describes the robotic leg which has been developed within the HADE (Hybrid Actuator DEvelopment) project. The HADE leg is a prototype for dual use. Two different removable feet are designed so the leg can operate as a quadruped's leg for agile locomotion or as a lower limb exoskeleton. The robotic leg is intended to walk at a speed of 1.5 m/s and carry the load of about twice its own weight. In previous work[5] the actuation requirements in terms of specific power were analysed by means of dynamic simulation. Here we focus on the design aspects and we present the actuation system selected.

2.1. *Leg Design*

The HADE leg is shown in Figure 1. The leg is a planar 3-DOF leg, composed of three links: thigh, shank and foot, connected through the joints hip, knee and ankle. The mechanical structure of each link has been designed in order to achieve large payload-to-weight ratio and provide impact tolerance. Table 1 shows link dimensions and masses of the first prototype.

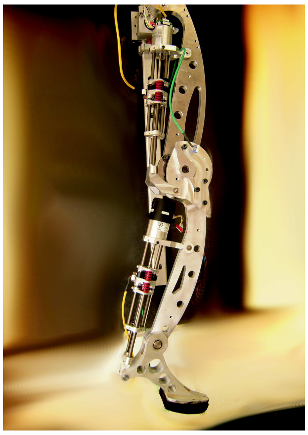


Fig. 1. The HADE Leg

2.2. *Actuation System*

The power requirements of the hip and knee joints obtained from dynamic simulation of the system walking at 1.5 m/s are too demanding[6] requiring an instantaneous power requirement of 400 Watts during the stance phase. To comply with these requirements, added to the restriction of an actuator weight of about 1 kg, the Yobotics Series Elastic Actuator SEA23-23 has been selected. Series Elastic Actuators (SEAs) are a family of actuators specifically designed for force control of robotic systems. The power to weight ratio of this actuator is near 600 W/kg.

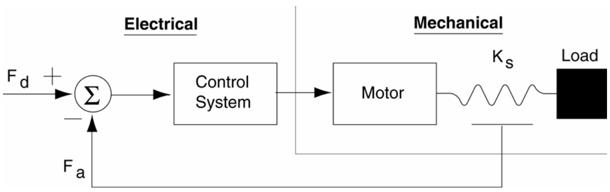


Fig. 2. Schematic diagram of a Series Elastic Acutator[7]

Figure 2 shows a simple diagram of a general SEA. In SEAs, stiff load cells are replaced with a spring placed in series between the motor and the load, allowing to indirectly measure the joint forces by measuring the deflection of the spring.[4] In addition, the elastic element gives the actuator low output mechanical impedance, in contrast with traditional actuators which usually have high output impedance. In SEAs the force control response is improved. The spring outfilters noise and allows to increase the force-controller gain within stable operation.

3. Human-Robot-Environment Interaction Control

The control scheme used in this work implements an inner force loop with an outer position loop. This is unsual to traditional impedance control schemes, which employ an inner position loop and outer force loop to control the mechanical impedance.[8] The key for the successful implementation of the inner force loop impedance control scheme is the use of an actuation system adequate for precise force control. A compliance control scheme was implemented which emulates the behavior of a spring-damper system, which approximates the mammalian muscle behavior.[9] The block diagram of the control scheme is shown in figure 3.

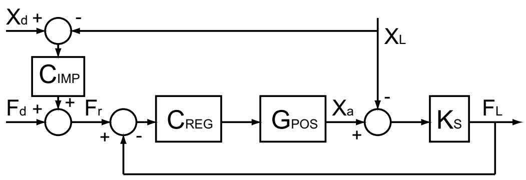


Fig. 3. Compliance control scheme block diagram

Where C_{IMP} is the mechanical impedance controller; C_{REG} is the force loop controller; G_{POS} is the actuator's transfer function; K_S is the die compression spring constant; F_d,F_L and F_r are the desired, exerted, and reference forces; and X_d, X_L and X_a are the desired, load and actuator positions respectively. From the diagram shown in Fig. 3 the mechanical impedance of the actuator can be derived as follows:

$$Z = \frac{F_L}{X_L} = -\left(\frac{AB}{1+AB}\right) \cdot \left(\frac{1}{A} + C\right) \tag{1}$$

Since $AB >> 1$ in the controlled bandwidth of the system:

$$Z = -\left(\frac{1}{A} + C\right) \tag{2}$$

The term $A = C_{REG} \cdot G_{POS}$ has usually high gain in the controlled bandwidth, since C_{REG} implements an integral action. As a consecuence $Z \approx C$.

This statement is correct except near to the cutoff frequency, ω_c, which is defined as $|A(j\omega_c)| = 1$ and is aproximately related to the response time, $\pi = \omega_c \cdot t_{response}$.

In order to obtain a spring-damper behaviour of the mechanical impedance we hace chosen $C = K(1 + bs)$. Fig. 4 shows a Bode diagram of the system behavior (blue line) overlapped with an ideal spring damper (red line) system, both simulated using MATLAB R2007a. Note that at high frequencies the controlled actuator behaves like a spring, just as predicted by.[4]

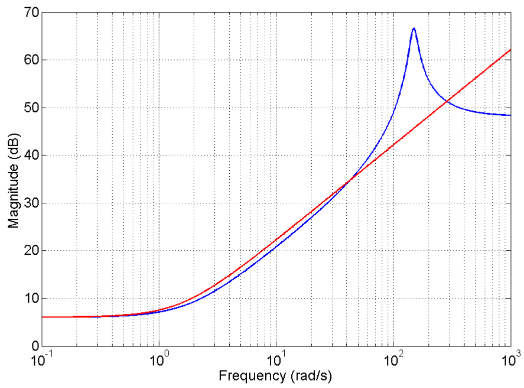


Fig. 4. Bode diagram of the theoretical actuator impedance (blue line) overlapped with the ideal spring-damper system (red line)

4. Experimental Validation of the Interaction Control Scheme

In order to experimentally test if the system is really behaving like a spring-damper system, we externally modified the position of the actuator and then measured the contact force and compared the behavior of the mechanical impedance with the theoretical one. An hydraulic Series Elastic Actuator (HEA) is used as antagonic-load actuator to exert variable loads to the test actuator. Once implemented the controls scheme, in order to obtain the bode diagram of the system's mechanical impedance, the force and position reference signal are set to zero. Then the antagonic HEA changed the load position X_l sinusoidally at different frequencies. Afterwards, the load position and the exerted force in the load are measured and their amplitudes divided in order to get the mechanical impedance of the system. The results are shown in figure 5 for $K = 2$ and $b = 0.5$, where the blue and the red lines show theoretical estimation and the experimental data respectively. The frequency range where the actuator behaves as a spring-damper is limited by the force loop bandwidth.

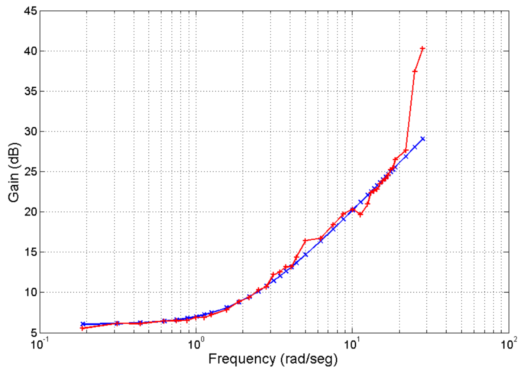
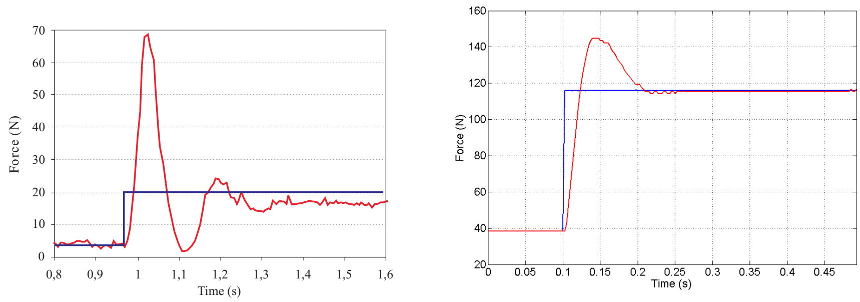


Fig. 5. Bode diagram for the actuator impedance control with k=2 and b=0.5. Experimental results are showed in red, while theoretical values are shown in blue

A second test carried out compared the step response of this control scheme with a compliance impedance control scheme using inner position loop. In order to do so, the results of a prior impedance control realized on the SILO4 robot were used.[10] Figure 6(a) shows the step response of the controller in,[10] while Figure 6(b) shows the step response of the controller implemented in this work using the SEAs.

The advantage for the inner force loop is that it is usually faster, and in interaction control it is more important to have a fast force control rather than a fast position control. As Figures 6(a) and 6(b) show the inner force loop also allows to reduce the steady state error. Also notice that the settling time is lower for the inner force loop.

A last experiment was conducted in order to test the functionality of the proposed control scheme when the actuator is intended to follow Electromiographical (EMG) reference signals, often used in the interface with exoskeletons. Two EMG sensors detect the electric activity in the muscle fibers of the user when the muscle is being contracted. The sensors were connected antagonistically in the leg of a person, one in the Tibialis anterior muscle and other in the Gastrocnemius muscle. The actuator was commanded by



(a) (b)

Fig. 6. Step response of an impedance control (a) using inner position loop; (b) using inner force loop. Reference command in blue and actuator response in red

the force acquired from the EMG sensors. Figure 7 shows the actuator's response overlapped with the EMG command. It is clear from the figure the accuracy of the actuator controller following the reference signal. A video of the experiment is shown at www.iai.csic.es/users/egarcia/hade.html.

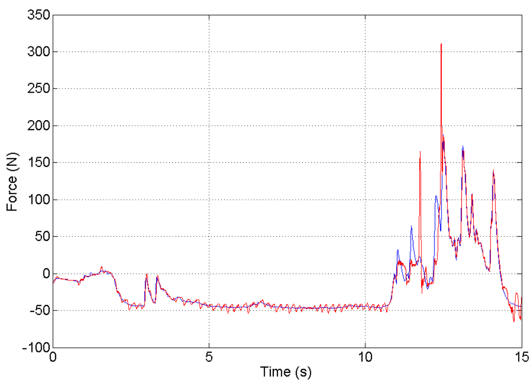


Fig. 7. Actuators response (red line) to the EMG reference (blue line)

5. Conclusions

The new generation of legged robots demand efficient interaction schemes for achieving a natural and safe motion. Usually, work on robot-environment interaction control relies on impedance control schemes that use inner position loops. This is usual in order to filter force noise that are particularly relevant in electromechanical and hydraulic actuators. These actuators feature high mechanical impedance which makes them less efficient at compliant interaction control. Impedance control schemes with a inner force loop improves the interaction control since they are faster to follow force references, and its behavior gets pretty close to the ideal systems, however, using conventional actuators it is not possible to achieve. In this paper we have shown that using SEAs the compliance with the environment is enabled and they facilitate the implementation of inner force control loops.

6. Acknowledgments

This work has been partially funded by AECID through grant PCI-Iberoamrica D/026706/09.

References

1. A. Chu, H. Kazerooni and A. Zoss, On the biomimetic design of the berkeley lower extremity exoskeleton (BLEEX), in *IEEE International Conference on Robotics and Automation*, (Barcelona, Spain, 2005).
2. H. Kawamoto and Y. Sankai, Power assist method based on phase sequence and muscle force condition for HAL, *Advanced Robotics* **19**, 717 (2005).
3. M. Raibert, K. Blankespoor, G. Nelson and R. Playter, BigDog, the rough-terrain quadruped robot, in *Proceedings of the 17th World Congress IFAC*, (Seoull, Korea, 2008).
4. D. W. Robinson, Design and analysis of series elasticity in closed-loop actuator force control, PhD thesis, Massachussets Institute of Technology, 2000.
5. E. Garcia, H. Montes and P. Gonzalez de Santos, Emerging actuators for agile locomotion, in *Proc. Int. Conf. Climbing and Walking Robots*, (Istambul, Turkey, 2009).
6. E. Garcia and P. Gonzalez de Santos, Biomimetic design and control of a robotic leg for agile locomotion, in *Proc. Int. Conf. Climbing and Walking Robots*, (Istambul, Turkey, 2009).
7. J. Pratt, B. Krupp and C. Morse, Series elastic actuators for high fidelity force control, *Industrial Robot: An International Journal* **29**, 234 (2002).
8. B. Siciliano and L. Villani, *Robot Force Control* (Kluwer Academic Publishers, 1999).
9. T. McMahon, *Muscles, reflexes and locomotion* (Princeton University Press, 1984).
10. J. Galvez, Perception, control and force distribution in legged robots, PhD thesis, Polytechnic University of Madrid, 2003.