Using optimal control to generate squat motions for the humanoid robot iCub with SEA

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1 Introduction

Many humanoid robots exist today, however they are all still at a research level and cannot be really used in everyday tasks yet. Most of these robots are meant to serve humans, and so to work safely in close contact with humans. This motivated many researchers to focus their work on safe human-robot interactions, including development of compliant actuators. Different from rigid actuators, they have elastic elements which can absorb shocks and be possibly advantageous from the energy consumption point of view.

One well known compliant actuator is the Series Elastic Actuator (SEA) [1], which introduces a spring in the actuator. In the iCub robot [2] built by the Istituto Italiano di Tecnologia (IIT) a customized version of these actuators was introduced in the knee and ankle joints in a new version of the legs[3], replacing the previous rigid actuators. The new design is derived from the legs design of the humanoid robot COMAN [4] with the aim of making the iCub perform walking tasks. The springs of the SEA of iCub are removable, giving the possibility to test and compare same motions with and without compliance.

However, despite the advantages that passive compliance might bring, it also contributes many factors that increase the complexity in the design of controllers for the robots. The introduction of the elasticity doubles the number of generalized coordinates necessary to describe the system. In the SEA, the actuation is changing the rest length of the spring, however this modulation follows its own dynamic equations. This means that the mechanical system is underactuated and the number of control inputs is much lower than the number of degrees of freedom. Furthermore systems with elastic elements are characterized by non-minimum phase zeros, which require planning of the control.

In the framework of the European Project KoroiBot [5], a reduced version of the iCub with 15 DOF including the torso and the new legs (Fig. 1) was built and delivered to the University of Heidelberg as platform to carry out experiments on walking with compliant actuators. The goal is to achive walking on a compliant platform by means of model-based optimal control, resulting in an optimal exploitation of compliance. However, before addressing walking tasks, we have started to investigate the simpler but still challenging task of squatting, by taking into account the elasticity of knee and ankle joints. In the following we describe briefly the model we are using and the optimal control problem formulation.

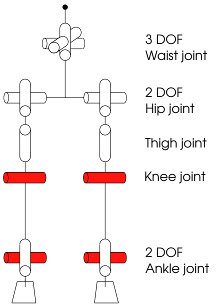

Figure 1: Degrees of freedom of the iCub robot, in red the joints with SEA.

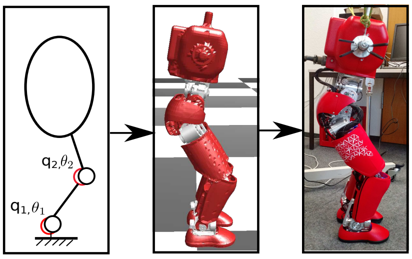

Figure 2: We use a simplified 2DOF model with springs to generate reference motions, then test on the simulator and in the end implement on the real robot.

2 Model description

Bipedal squatting is essentially a planar problem with both half of the problem acting simultaneously. We simplify the system as a 2 DOF robot moving on the sagittal plane and with base fixed on the ground (Fig. 2). This means that the vector of joint angles is $q = [q_1, q_2]^T \in \Re^2$. The dynamic model including elasticity can be formulated as per [6]:

$$H(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) + K(q-\theta) = 0 \qquad (1)$$

$$B\ddot{\theta} + K(\theta - q) = \tau \tag{2}$$

Where $\theta = [\theta_1, \theta_2]^T$ are the motor positions, K is the stiffness matrix and B is a diagonal matrix with the rotor inertia.

In optimal control we are interested in computing $\ddot{q}$ and $\ddot{\theta}$. In this case, $\ddot{q}$ is obtained with forward dynamics formulation by using as input torques:

$$\tau_L = K(\theta - q) \tag{3}$$

While $\ddot{\theta}$ as:

$$\ddot{\theta} = B^{-1}[\tau - K(\theta - q)] \tag{4}$$

Matrix B is easily invertible being diagonal.

3 Optimal control

Our method is to use optimal control to find the optimal joint trajectories and control torques for the robot. Optimal control allows us to minimize an objective function with respect to the states $x(t)$, the controls $u(t)$ and the model parameters p:

$$\min_{x,u,T} \quad \int_0^T \Phi_L(t,x(t),u(t),p)dt + \Phi_M(t_f) \tag{5}$$

subject to:

$$\begin{array}{rcl} \dot{x}(t) & = & f(t,x(t),u(t),p), \\ & & t \in [0,T] \\ g(t,x(t),u(t),p) & \geq & 0 \\ r^{eq}(x(0),\ldots,x(T),p) & = & 0 \\ r^{ineq}(x(0),\ldots,x(T),p) & \geq & 0 \end{array} \tag{6}$$

Whereas g describes the boundaries for states and controls as well as other path constraints, and r^{eq} and r^{ineq} are the pointwise coupled and decoupled equality and inequality constraints of the problem. In this case, the state vector $x(t)$ is represented by $x(t) = [q(t), \theta(t), \dot{q}(t), \dot{\theta}(t)]^T$ and the control inputs $u(t) = \tau(t)$. The right hand side of $\dot{x}(t)$ is computed as illustrated in the previous section.

Several objective functions are considered:

- Joint torque minimization
- Minimization of (positive) mechanical work
- Minimization of electrical energy
- Time minimization, by leaving final time T free (in other cases, squatting time / speed will be imposed)
- Tracking error to predefined trajectories of the center of mass

These objective functions are considered independently or as a combination with different scaling factors.

4 Discussion

Results obtained following the illustrated methodology will be shown at the conference, possibly with different squatting velocities. Several interesting issues can be addressed and serve as a basis for the discussion with Dynamic Walking participants, some of which as future possible improvements of this work:

- Influence of the weights in the combination of objective functions.
- Comparisons between the same motion with and without springs.
- Effects of different spring constants. The springs of the robot have fixed stiffness, however it can be changed both in simulation and on the actual robot [3], new springs with stiffness obtained from optimization can be produced and used.
- Add model details such as friction effects, as in optimal control modeling precision is highly important.
- For larger motion ranges we will need to include also a third joint in the sagittal plane, whether the torso pitch or the hip pitch, more likely the hip pitch is the optimal choice and the torso will be kept stiff.

5 Acknowledgment

Financial support by the European Commission within the FP7 project KoroiBot (GA 611909) is gratefully acknowledged.

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