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Comparison of control and optimization approaches for trajectory tracking in the forward dynamic simulation of biomechanical multibody systems

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Abstract

In the study of biomechanical systems and, more specifically, in the study of human gait, it is common to have the motion capture, obtained with certain precision, from which the histories of the drive torques can be obtained by inverse dynamic analysis.

However, when these torques are introduced in the forward dynamic simulation of human walking, the results usually show an unstable gait, very different from the experimental measurements.

Reasons for this can range from the high sensitivity of the multibody system to small variations of the drive torques (related to inaccuracies in the modeling of the ground contacts) to numerical errors inherent to the process of numerical integration that are amplified during the simulation.

Forward dynamic analysis has several advantages over inverse dynamic analysis. For instance, muscle-tendon models can be introduced in the system so as to take into account the physiological nature of the movement.

Different approaches have been proposed in the literature to carry out the forward dynamic analysis of a given motion [1] and, in this paper, several methods are compared. On the one hand, the forward dynamic simulation is run with control in the drive torques [2]. On the other hand, an optimization problem is stated to obtain the desired movement by modification of the histories of the drive torques, using either an artificial neural network (ANN), a cubic spline or a parametric function [3].

A simple multibody model of one degree of freedom that simulates a human forearm lifting a weight in the hand is used. The degree of freedom is the rotation of the elbow and the desired movement is defined by means of the history of this rotation. The model is shown in Figure 1.

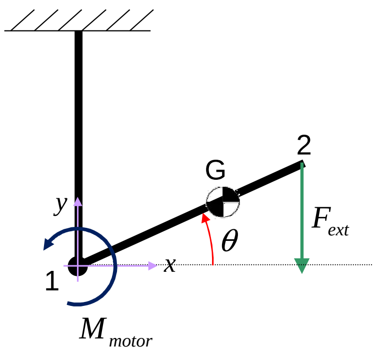

Figure 1: Model to compare the different approaches

In order to have a reference to compare, first, inverse dynamic analysis is made for the desired movement and the history of the drive torque at the elbow joint is obtained.

Then, the forward dynamic simulation, in which a PD control with computed feedforward is introduced to define the drive torque, is carried out. The rotation and torque histories are shown in Figure 2.

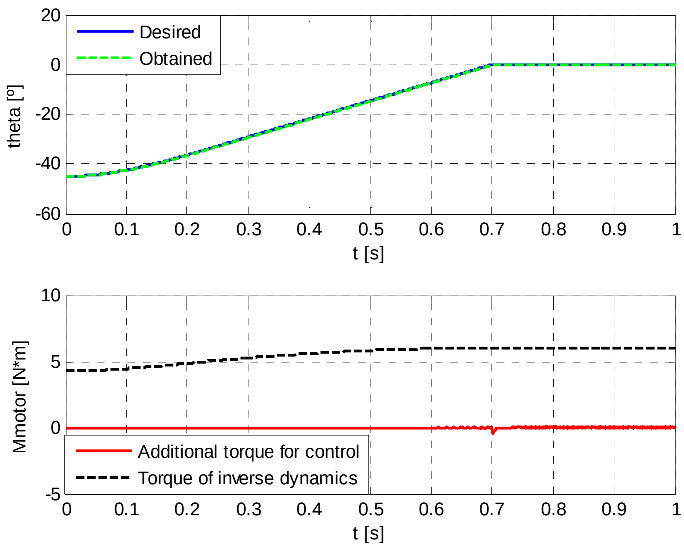

Figure 2: Rotation and torque histories from forward dynamic analysis through PD control with computed feedforward

Finally, an optimization problem is stated where the error on the time evolution of the elbow rotation must be minimized. The variables of this problem parameterize the drive torque that is applied to the elbow. The torque history is modeled with an ANN, a cubic spline or a parametric function, with and without computed feedforward. These three approaches differ in flexibility and in the number of parameters needed to define the torque history. Given the shape complexity of the objective function, the number of variables and the existence of an initial approximation to the solution (the solution of the inverse dynamic analysis), several optimization methods have been tested (an evolutionary method CMA-ES algorithm, a quasi-newton method and a Simplex search method).
The root of mean square error of the solution obtained by the methods with respect to the one obtained from the inverse dynamic analysis is measured along with the time required by each method.
The results offer three conclusions. First, that despite the simplicity of the proposed multibody model, it can generate the same problems as more complex models when running forward dynamics. These problems seem to come from the difficulty of the integrator to solve situations where there are discontinuities in the solution or its derivatives. Second, the simulation based on PD control with computed feedforward is notably faster and generates a solution with good accuracy. When the solution is smooth, the PD control does not act and the integrator is able to work efficiently. At discontinuities, the integrator tends to diverge and, then, the PD control acts stabilizing the solution and allowing the integrator to continue the process without a significant reduction in the integration step. Third, the optimization approaches are slow due to the computational cost required to evaluate the objective function at each iteration, which implies a full simulation, and the high number of iterations needed to reach an acceptable level of accuracy.

References

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