Performance evaluation of different control strategies for the forward dynamic simulation of human gait

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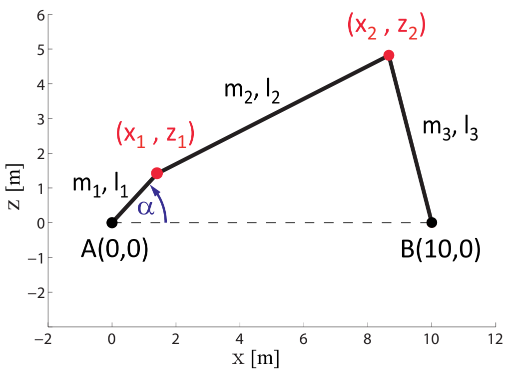
Abstract

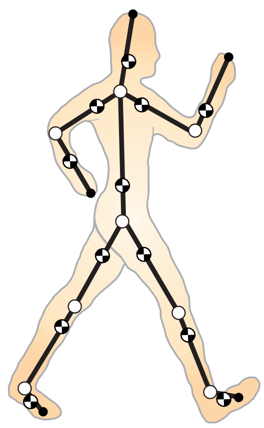
During the last years, a growing interest in motion prediction has appeared in the biomechanics community, since it contributes to the anticipation of surgery results, to an enhanced design of prosthetic and orthotic devices, or to the study of the dynamics of different human movements. The authors are working in a project aimed at developing an active knee-ankle-foot orthosis to assist the gait of incomplete spinal cord-injured subjects [1]. One of the objectives of this project is to develop a predictive computer application that enables to virtually test different designs of lower limb active orthoses on the computational model of a disabled subject.

With the previous perspective, the aim of this work is to address the analysis of a certain known motion through forward dynamic analysis (FDA), which can be considered an intermediate step towards the prediction problem. Due to the unstable character of human gait in FDA and numerical errors during the integration process, control modules are of particular importance to ensure stability and robustness in the performed simulation.

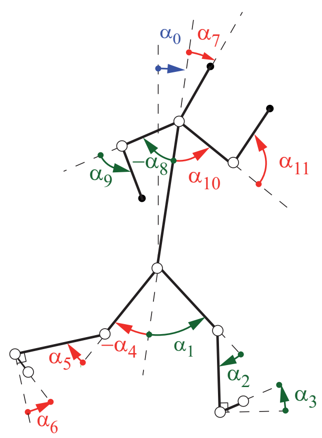
In this work, two different control strategies are applied to the FDA of multibody systems in order to track a given reference motion. For this purpose, two different computational models are used: a four-bar linkage model with one degree of freedom (DOF), Figure 1a; and a two-dimensional human body model that consists of 12 segments (trunk, head, two arms, two forearms, two shanks, two thighs and two feet) with 14 degrees of freedom, Figures 1b and 1c.



(a) Four-bar linkage model.



(b) Human body segments.



(c) Relative (green and red) and absolute (blue) angles.

Figure 1: Multibody models.

The simple four-bar linkage model is introduced to easily test suitable control strategies to a one DOF system, reducing the complexity of the problem and decreasing computational time. While the reference motion of the four-bar linkage is defined analytically using a trigonometric function, the reference human gait motion was captured for a healthy subject in the biomechanics laboratory [4].

The input data for the FDA are the driving forces and torques (associated to each DOF) and the dynamic parameters of the model. So, previous to the FDA, inverse dynamic analyses have been conducted for each model to calculate the forces and torques related to the reference motion. Then, the forward dynamic simulation of both models is carried out by means of multibody dynamics techniques, using the R-matrix formulation to solve motion equations [2] and the variable-step solver “ode23” from Matlab.

In order to stabilize the simulation and to enable the accurate tracking of the reference motion, two different control approaches are introduced: a proportional-derivative (PD) control and a computed torque control (CTC) using feedback linearization [3, 5]. Both control algorithms have been developed and applied to each system DOF in the forward dynamic simulation of the mentioned models. The system performance is evaluated by comparing the computed motion with the reference one.

The application of the two control methods to the FDA of the four-bar linkage model yields simulated motions that overlap the prescribed ones (position errors are below 10^{-7} rad). In order to compare the performance of both controllers, two different fault cases are introduced to the model. In the first one, the masses of two segments are increased by 20% and the mass of the third segment is decreased by 20%. The second fault case analyses the influence of the driving torque, which is reduced by 50%. In all cases, CTC and PD approaches are capable of controlling the system properly. The comparison of results shows that the CTC control performs without overshoot, faster and more accurately (with a factor of 10 in position) than the PD control.

Even though the PD control performs still very well in the case of the four-bar linkage, it has its limitations in the case of the human body model due to the presence of non-linearities and couplings among DOF. The CTC control instead is able to guide the human motion during the whole gait simulation following the reference data with a very high accuracy and fast response. The robustness of the CTC method is tested introducing several fault cases to both models by randomly changing masses, lengths and torques. It can be pointed out that the CTC control performance is very robust for the four-bar-linkage model but the robustness for the human body model features more difficulties. Changes by 1% in the masses of the human body segments already show considerable differences between the simulated and the captured motions. Moreover, by changing the masses more than 2,5% the simulation drifts away. The system is even more sensitive concerning uncertainties in the segment lengths. Disturbing the input forces and torques leads to similar results, the simulation of the gait cycle can only be completed with disturbances lower than 0,01% of the joint torques.

In summary, two model-based control methods have been implemented in two different multibody systems and the computed motion has been compared with the reference one. From the results obtained, it can be concluded that the CTC control with feedback linearization is a powerful tool for forward dynamic simulations of nonlinear multibody systems and has a high potential for human motion control. Future studies will focus on improving the robustness of this method in the presence of uncertainties.

References

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