Evaluation of the Biomechanical Simulator OpenSim on a Multi-Body System Benchmark

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Robotic assistive devices are increasingly used in rehabilitation to reduce time and cost of the recovery process [1]. The current main challenge is to increase the involvement of the patients developing new systems able to understand patient's intentions and adapt to his/her characteristics and needs in order to pursue a personalized rehabilitation treatment. While the cooperation to produce the final motion can be measured when the subject is wearing the real device often we need the possibility to predict this interaction before the actual device is built. Indeed, knowledge about how to predict human-device interaction would allow to compare different design solutions and evaluate which would, most likely, maximize the impact of the rehabilitation treatment. However, the prediction of this cooperation requires a simulation tool recognized as highly accurate both in the prediction of the behavior of the human body and of the robotics device and able to predict their complex interaction.

We believe that a possible solution could be pursued through the development of a multi-level model simulation using OpenSim [2]. OpenSim is an open source software for biomechanical modeling, simulation, and analysis developed by the Neuromuscular Biomechanics Lab of Stanford University and it has been used in hundreds of biomechanical studies. While OpenSim is definitely recognized as highly reliable in dynamic simulation of human body movements, an in-depth analysis of OpenSim as a mechanical multi-body simulator is still missing. Before tackling the implementation of a multi-level simulation we decided to evaluate its reliability using the Multi-Body System (MBS) Benchmark [3]. We implemented and simulated the five problems included in the benchmark suite. Each problem target a specific challenge in MBS simulation as shown in Tab. 1.

Due to space limitation, we illustrate in the following only the problem A04 - Bricard's mechanism while details about the other problems can be found in our web-page (`http://goo.gl/sjmLcX`). The system is composed of five rods (1m length and 1kg weight) and six revolute joints (Fig. 1). Gravity is acting in the negative y direction. The challenge of the Bricard's mechanism is the simulation of an over-constrained multi-body system. Indeed, despite Grubler's formula resulting in no degrees of freedom, the particular orientation of the revolute pairs produces a system with one degree of freedom.

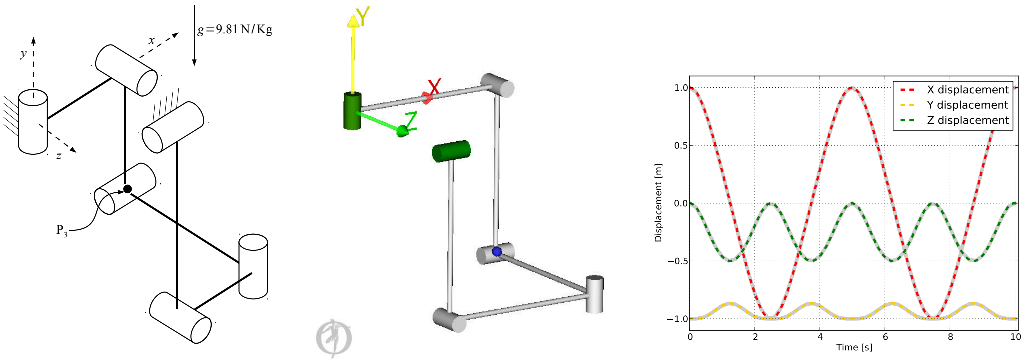
The precision of the simulation was evaluated computing the maximum normalized error in the computation of the 3-dimensional displacement of a referent point with respect to reference solution provided by the benchmark authors as suggested in [4]. At each time sample t_i, the error at j-th coordinate was defined as:

$$e_j(t_i) = \frac{|y_i(t_i) - y_i^{ref}(t_i)|}{max\left\{|y_j^{ref}(t_i)|, y_j^{threshold}\right\}} \tag{1}$$

where y is the simulation output and y^{ref} is the reference. The threshold value was introduced to avoid a singularity when the reference values approach zero and was set to 10^{-3}. The global error (e_{Total}) on

Table 1: Simulation challenge of MBS benchmark problems.

Problem Name	Simulation challenge
A01 Simple pendulum	Example problem (2D)
A02 N four-bar mechanism	Singular positions (2D)
A03 Andrew's mechanism	Very small time scale (2D)
A04 Bricard's mechanism	Redundant constraints (3D)
A05 Flyball governor	Stiff system (3D)



(a) (b) (c)

Figure 1: Bricard's mechanism: (a) sketch, (b) model in OpenSim, and (c) Comparison between simulation results(dashed lines) and MBS benchmark reference (gray lines) for the reference point.

problem composed of m coordinates and with n samples as reference values was defined as:

$$e_{Total} = \sqrt{\frac{1}{m}\sum_{i=1}^{m}\frac{1}{n}\sum_{j=1}^{n}(e_j(t_i))^2} \quad (2)$$

Tab. 2 reports results of the simulation with OpenSim for the whole benchmark suite. All the problem are simulated with quite low errors. The highest error is returned by the A03 problem, that presents the higher complexity in the required motion and the smaller time simulation step. R^2 indexes were also computed with values always quite close to the unit ($R^2 > 0.999$).

Table 2: Global error of OpenSim simulation.

	A01	A02	A03	A04	A05
Total Error [%]	3.6E-3	9.8E-4	4.7E-2	6.4E-4	7.3E-5

Full description of the problems, software implementation through OpenSim APIs (C++), and an extensive evaluation of the simulation results are freely available for download on our web-page (`http://goo.gl/sjmLcX`).
The good results obtained with OpenSim in simulating the problems proposed by the MBS benchmark lead us to conclude that OpenSim can be successfully used to achieve accurate simulation of mechanical and robotic systems.

References

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