Optimization of the dynamics of multibody systems and applications

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Abstract

Multibody dynamics emerged as a separate discipline of mechanics and theory of machines in the late 77s and 80s, with the first conferences [1, 2] on multibody systems. Aspects like the systematic motion parameterization, the form of the dynamic terms for the coordinates chosen, the way of considering kinematic constraints between bodies and the computational methods needed to solve the equations, were in the core of the incipient multibody theory. The first books on rigid multibody dynamics emerged soon [5, 4, 5, 6], establishing the basic concepts and methods on which the modern multibody theory was developed. Nowadays, multibody dynamics is a mature discipline, with a bunch of very different but well-established general methods and commercial software implementing them. Optimization and sensitivity analysis are nowadays among the most active research topics.

Given the generality and complexity of the mechanical systems present in industry, there is not a unique approach, universally accepted as superior, for writing and solving the equations of motion of any multibody system. As a consequence, the first decades of research were largely devoted to exploring different sets of coordinates, equations of motion and techniques for efficiently writing and solving those equations. Another aspect which drew attention from the beginning was the consideration of complex phenomena in the multibody equations: contact and flexibility appear in many industrial mechanical systems of practical interest, and they have been ubiquitous in multibody conferences and specialized journals, being the main results collected in paramount books [7, 8, 9, 10].

Optimization is a powerful tool with applications in design, control and parameter identification, thus, the interest and first publications on optimization of mechanical systems are previous to multibody systems themselves. Nevertheless, several early works set the basis of gradient based dynamic optimization and sensitivity analysis of multibody systems [11, 12].

There are two main types of dynamic optimization, global and local: global optimization can make use of the multibody code as a black box for evaluating the objective function, which depends on the dynamics of the system; local optimization requires gradients (and sometimes Hessians) of the objective function which means that either the optimization algorithm needs to calculate them using numerical perturbations of the dynamic solution, or the multibody code needs to be able to provide them for the optimization process, by means of sensitivity analyses of the equations of motion. Global methods are very easy to combine with multibody simulations, and they are suited to optimal design of simple systems with few parameters, especially when multiple local minima can be found, but for certain types of problems like optimal control or complex systems with many parameters, the computational times render unfeasible. Gradient based local methods, on the other hand, are very efficient but challenging, since they require additional calculations on the multibody equations than just evaluations of the objective function.

Calculating the sensitivities of the equations of motion is not a trivial task, therefore they are often calculated by means of finite differences, in order to avoid the complexity of dealing with the sensitivity equations which are additional ODE or DAE systems that imply systematically taking exact derivatives of each kinematic and dynamic term with respect to states and parameters of the system. Depending on the number of parameters involved, the numerical procedures can be very demanding in terms of computational time and the accuracy obtained can be very poor in many cases. In this work, different techniques for obtaining the sensitivity equations of rigid and flexible multibody systems are covered with special attention to analytical expressions (the most challenging but the most efficient and accurate) for the core of the multibody formulation, automatic differentiation for user defined expressions and numerical perturbations or symbolic expressions for validation purposes.

Two different sets of sensitivity equations are possible for a particular formulation of the equations of motion: direct and adjoint sensitivity equations. The two sets are very different in their final form but they make use of the same intermediate derivatives. These two very different options are going to be

explained for getting insight, remarking on the advantages and drawbacks of each one and their usual applications.
In order to illustrate the applications of the optimization and sensitivity analysis theory to multibody systems, solutions for optimal design, optimal control and identification of parameters of multibody systems are presented. The multibody systems involved are 3D and include flexible bodies, contact-impact forces, friction and tire force models. The general-purpose multibody library MBSLIM [13] has been used for the sensitivity analysis and optimization, proving one of the key ideas of this work: sensitivity analysis formulations based on analytical expressions can be generalized and implemented in general purpose codes, the same as dynamics was generalized and implemented many decades ago.

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