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Exploiting Hybrid Parallelism in the Kinematic Analysis of Multibody Systems Based on Group Equations

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Abstract

Computational kinematics is a fundamental tool for the design, simulation, control, optimization and dynamic analysis of multibody systems. The analysis of complex multibody systems and the need for real time solutions requires the development of kinematic and dynamic formulations that reduces computational cost, the selection and efficient use of the most appropriated solvers and the exploiting of all the computer resources using parallel computing techniques. The topological approach based on group equations and natural coordinates reduces the computation time in comparison with well-known global formulations and enables the use of parallelism techniques which can be applied at different levels: simultaneous solution of equations, use of multithreading routines, or a combination of both. This paper studies and compares these topological formulation and parallel techniques to ascertain which combination performs better in two applications. The first application uses dedicated systems for the real time control of small multibody systems, defined by a few number of equations and small linear systems, so shared-memory parallelism in combination with linear algebra routines is analyzed in a small multicore and in Raspberry Pi. The control of a Stewart platform is used as a case study. The second application studies large multibody systems in which the kinematic analysis must be performed several times during the design of multibody systems. A simulator which allows us to control the formulation, the solver, the parallel techniques and size of the problem has been developed and tested in more powerful computational systems with larger multicores and GPU.

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1 Introduction

Multibody systems (MBS) are mechanical systems formed by rigid and flexible bodies which are connected by means of mechanical joints in such a way that there is relative movement

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between their bodies. The study of these relationships is known as kinematic modeling and analysis of the multibody system. Large and complex multibody systems require the use of computational methods to solve their kinematics, which is the basis for the design, simulation, control, optimization and dynamic analysis of the multibody system. All these tasks must either be performed for real time applications, like the simulation, control and dynamic analysis, or repeated a large number of times, for design and optimization processes. In both cases, efficient kinematic formulations are needed together with the selection of the most appropriate solvers and the best exploitation of the computer resources.

With regard to the kinematic modeling and analysis of a MBS, the analyst must select a vector $\boldsymbol{q}$ of coordinates that defines the position and orientation of each body of the MBS in the space. Then, these coordinates are related by means of a nonlinear system of constraint equations $\boldsymbol{\Phi}(\boldsymbol{q}) = 0$. Different formulations use different sets of coordinates, types of constraint equations and methods to solve the kinematic problem. Global formulations, on the one hand, select as many coordinates as needed to define the position of each body independently of the other bodies, and then all these coordinates are related by using the constraint equations associated to each type of mechanical joint in the MBS. These formulations use a large number of coordinates and constraint equations, and their size increases with the complexity of the MBS. On the other hand, topological formulations exploit the topology of the MBS to reduce the dimension of the problem by relating the position of each body with respect to its preceding one, which reduces the size of $\boldsymbol{q}$, or by dividing the MBS into an ordered set of simpler subsystems (known as the kinematic structure of the MBS), whose kinematics can be solved in the specific sequence in which they have been ordered [11].

The topological approach based on Group Equations has proved to be more efficient than global formulations, with reductions in the execution times of up to 50% in the kinematic analysis of 2D and 3D MBS [12]. One drawback of that work is that the results have been obtained for small subsystems, and one advantage is that, depending on the kinematic structure of the MBS, the kinematic analysis of some of the subsystems can be performed independently, which allows us a better exploitation of the computer resources by applying parallelism to reduce the execution time in real-time applications or for highly demanding computations.

The two aforementioned considerations (limitation in the number of subsystems and possibility of exploitation of parallelism) motivate the present work, which aims to develop a simulator for the computational kinematic analysis of multi-body systems to allow us to analyze the efficiency of the group equations approach and to identify the most efficient parallelization strategy, depending on the topology of the system to be analyzed.

The remainder of the paper is organized as follows. Section 2, briefly shows the main ideas of the kinematic analysis based on Group Equations. The case study (Stewart platform) used is introduced in Section 3. The parallel implementations of the simulator based on Group Equations are discussed in Section 4. The experimental results obtained with the application of these parallel implementations are summarized in Section 5. Experiments are conducted in different computational systems (multicore, Raspberry Pi and GPU) to analyze the preferred system depending on our goal: reduction of time or energy consumption, or use for control in real-time or for simulation. The use of various linear algebra libraries is also analyzed. Finally, Section 6 concludes the paper and outlines some possible research directions.

2 Computational Kinematics Based on Group Equations

The topological approach based on Group equations has been shown to be more efficient than a global formulation, using the same type and size of the vector of coordinates $\boldsymbol{q}$. This result