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Parallel Algorithms Design for the Motion Simulation of Tethered Satellite Systems Using Graph Models

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Abstract

Tethered satellite systems (TSS) are characterized by uneven distribution of mass and environment parameters in space. As a result the use of mathematical models with distributed parameters is required. This kind of systems is described by the differential equations with complex boundary conditions. The complexity of the boundary conditions is caused by the presence of the end-bodies that perform spatial fluctuations, and by the variable length of the tether. Computer simulation of TSS motion takes a long time. This paper presents a parallel algorithm for motion simulation of the TSS and representation of this algorithm in the form of a graph model in graph-symbolic programming technology. The speedup of a parallel program that implements the proposed algorithm is evaluated for shared memory and distributed memory computer systems. This evaluation is compared with the results of experiments made on computer cluster. The advantages of using graph models of algorithms for modeling the motion of the TSS are discussed.

Keywords: Parallel Computing; Tethered Satellite Systems; Simulation; Visual Programming

1. Introduction

Application of tethered satellite systems (TSS) opens up new possibilities in the use of outer space: the creation of artificial gravity, transport operations in space, return-ing payloads from orbit, the launch of small satellites from the

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main spacecraft, the use of the Earth's geomagnetic field for orbital maneuvers, creating orbiting power stations, atmospheric probing, study of geomagnetic and gravitational fields, removal of space debris, etc. [1].

Despite the presence of a large number of works, considering various aspects of the space tether systems design, at the present time there is a certain lack in research on the development of methods of analysis and synthesis of controlled and free movement of space tethers of great length. Long tethers are characterized by ununiform distribution of mass characteristics of the system and the parameters of the environment in space. It determines the use of mathematical models with distributed parameters. The apparatus of partial differential equations is used with complex boundary conditions. The complexity of the boundary conditions is caused by the presence of the end-bodies that perform spatial fluctuations, and by the variable length of the tether. All this leads to considerable time needed for the mathematical modeling of tethered system on the computer. Large systems of ordinary differential equations (ODE) are used for modeling. The number of equations is measured in tens of thousands. Direct numerical solution of such systems is difficult, even for the up to date computing resources.

Existing approaches to the solution of large systems of equations can be divided into two main classes. The first class focuses on parallelization of the known numerical methods (often without changing the methods themselves). However, the results of solving ODE systems using this method on cluster systems are not impressive, because they do not take into account the features of the problem to be solved.

The second class comprises the methods that reduce the computational costs due to special heuristic techniques, which usually use the physical features of the problem. Less attention is paid to the accuracy of the solution. The improvement of the calculation speed is gained by decrease in the accuracy of numerical methods without lowering the quality of the results.

We will consider the application of these approaches to the problem of motion simulation of space tether systems.

2. Mathematical Model of Tether Dynamics in Space

The widely used mathematical model of tethered system motion is a model in which tether is described by a system of partial differential equations. In this case, the mathematical models of continuum mechanics are used to describe the motion of tether in which the tether is considered as extensible (or inextensible) slim body, most often of great length [1]. Derivation of equations of motion of such a system is quite simple. It involves the consideration of the stretched differential element of the tether with the length ΔS and the application of Newton's second law to it:

$$\rho(S)\frac{\partial^2 r}{\partial t^2} = \frac{\partial T}{\partial S} + q\,, \qquad (1)$$

where $\rho(S)$ is the linear mass density of the tether, r is the position of the stretched differential element, t is the time, T is the tension force, q is the resultant force acting on the differential element divided by the length of the element.

For a flexible tether, which does not accept transverse loads, tension force is directed tangentially to the tether line, so

$$T = T\tau\,,\ \tau = \frac{1}{\gamma}\frac{\partial r}{\partial S}\,,\ \gamma = \left|\frac{\partial r}{\partial S}\right|, \qquad (2)$$

where τ is tangent unit vector.

The tether tension in the simplest case obeys Hooke's law

$$T(\gamma) = EA(\gamma - 1)\,, \qquad (3)$$

where E is the modulus of elasticity, A is the cross-sectional area of tether, $\gamma - 1$ is the elongation.