Journal of Manufacturing Systems 45 (2017) 201–211

Contents lists available at ScienceDirect

Journal of Manufacturing Systems

journal homepage: www.elsevier.com/locate/jmansys

Technical Paper

Assembly simulation of multi-branch cables

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ARTICLE INFO

Article history:
Received 17 February 2017
Received in revised form
24 September 2017
Accepted 26 September 2017

Keywords:
Assembly simulation
Multi-branch cable
Physically based modeling
Cosserat theory
Elastic rod model

ABSTRACT

Cable assembly simulation is a key issue in the computer-aided design (CAD) of products with complex electrical components. In this study, an assembly simulation method is developed to simulate the assembly process of multi-branch cables. First, based on the Cosserat theory of elastic rods, a novel scheme is introduced to model the joints of multi-branch cables. The potential energy of joints is calculated by taking the topology and anatomical features into consideration. Various physical properties are considered. Various constraints, including connectors, collars, and handles are analyzed, based on which the initial conditions of assembly simulation are determined. The configuration of the cable is then calculated by minimizing its potential energy. To increase computational efficiency, GPU acceleration is introduced, which makes the simulation run at interactive rates even for a cable with resolution up to 1000 discrete points. Finally, the proposed algorithm is integrated into the commercial assembly simulation system, DELMIA. Several simulations were performed with our system. It was demonstrated that the proposed method is able to handle cables with complex topologies. In addition, the proposed method is about four times as efficient as a previous method, and it is able to generate realistic configurations of multi-branch cables at interactive rates. Thus, the proposed method is helpful in the assembly process planning of cables.

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1. Introduction

Cables are widely used to transport electrical power and signals in many mechatronic products. For these products, assembly of cables is an important issue that should be taken into account from the initial design stage. For example, in modern airplanes, a large number of cables with different roles must be installed in a densely packed space. This makes the assembly of cables a very difficult task. In recent decades, assembly simulation in virtual environment has shown great advantages in assembly planning [1], verification [2] and training [3] comparing with traditional ways. In particular, in order to facilitate the assembly of cables, much research effort has been devoted to the physically based assembly simulation of cables [4–6]. Since no real prototypes need to be built and the potential problems can be predicted at early stages, it is able to increase the efficiency and decrease the cost of manufacture.

To obtain a visually satisfying object behavior with low computational cost and simulate the deformation of cables in interactive rates, mass spring model [7], inverse kinematics [8] and elastic rod model [9] have been introduced. Robinson et al. [10] conducted the assembly simulation of cables in a virtual reality environment and the results showed that the route design and assembly planning of cables can effectively benefit from the simulation work. Roussel et al. [11] explored the automatic manipulation planning of cables, by which the assembly paths of cables can be automatically determined. Mikchevitch et al. [12] discussed the input data (such as CAD models, material properties of cables and input data defined by operators) required for realistic simulations of cables. Despite the remarkable progress that has been made, existing studies were mostly limited to unbranched cables, and the assembly simulation of multi-branch cables has not been well addressed. Most of the commercial computer-aided design (CAD) systems for assembly simulation are incapable of depicting the physical properties of multi-branch cables. As one of the popular systems for assembly simulation, DELMIA, could only simulate the configuration of multi-branch cables based on geometric curves without considering any physical properties.

In this study, we sought to simulate the assembly of multi-branch cables using a physically based model which can ensure the fidelity of simulation. Specifically, a novel scheme is introduced to model the joints of multi-branch cables, considering their topology and anatomical features. Thus, the proposed model can provide realistic simulations of the deformation of multi-branch cables. To

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https://doi.org/10.1016/j.jmsy.2017.09.007
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support the simulation of assembly processes, several constraints are analyzed to generate initial conditions for solving the cable's configuration. Because the cable typically moves at a slow speed during the assembly process, the dynamic behavior of the cable is negligible and a quasi-static simulation is sufficient. The cable's static configuration is finally obtained by minimizing its potential energy. In this study, we also sought to increase the computational efficiency to realize an interactive simulation. Specifically, a GPU acceleration technique is applied to obtain the real-time solution for complex assembly cases.

The remainder of this article is organized as follows. Section 2 briefly surveys prior research on approaches for modeling flexible objects that have common features with multi-branch cables: that is, deformable linear objects and branched structures. In Section 3, we provide some geometry descriptions, based on which the configuration and strains of a cable can be described effectively. In Section 4, we develop a model for simulating the deformation of multi-branch cables. Specifically, we briefly introduce the concepts of the Cosserat theory of elastic rods, then extend the model to enable the modeling of joints. The effects of various constraints are also discussed to support the assembly simulation. In Section 5, the potential energy is calculated and an energy minimizing algorithm is applied to obtain the static configuration of a cable. GPU acceleration is used to assist in the calculation, increasing the efficiency of computation tremendously. Finally, the effectiveness and efficiency of the proposed method are demonstrated in several examples in Section 6.

2. Related work

As the foundation of assembly simulation, the physically based deformation model of multi-branch cables is an important issue. Since the multi-branch cable is a type of branched structure and each branch can be regarded as one deformable linear object. Thus, it is helpful to briefly review related research work on the physically based models of deformable linear objects and branched structures.

2.1. Deformable linear objects

Deformable linear objects have been modeled using flexible elements. The mass-spring system, composed of particles and various springs, is one example [13]. This method can be implemented readily; thus, has been used widely in computer graphics. However, the traditional mass-spring system is limited in reality because it lacks the ability to simulate the effects of torsion applied to the deformable objects, as well as any theoretical basis for determining the stiffness of the springs [14]. To address these shortcomings, some research efforts have been made. Choe et al. [15] modified the mass-spring system by connecting the rigid rods with springs; thus, the effects of torsion can be simulated. Nguyen et al. [16] proposed another method with a chain of flexible elements. By replacing the springs with flexible beams, torsion can be applied to the model and the stiffness of elements can be determined based on the material properties of the simulated objects. However, Nguyen el al.'s method is computationally intensive, which has limited its application. Furthermore, all methods using flexible elements have a common problem that the computational efficiency decreases tremendously when the stiffness of elements is high enough. Thus, they are not suited for applications where the exact length of deformable objects should be preserved.

In contrast, exact length preservation can be achieved readily with a rigid multi-body serial chain, which consists of rigid rods instead of flexible elements. The position of the rods was first solved using an inverse kinematics method, originating from robot theory [8]. However, the inverse kinematics method is limited in reality because the physical properties considered are incomplete. To produce realistic motion of the linear objects, the accurate positions of the rods have been solved using multi-body dynamics. Common methods in this category include the constraint-based method [17] and the impulse-based method [18].

Each method discussed above is implemented with a chain of discrete elements. They are usually categorized as discrete models. It is known that the results from these discrete models lack accuracy [19]. Another class of approach, based on continuous curves, makes up for this deficiency. The dynamic NURBS model falls into this category [20], by simulating the deformable linear objects as NURBS curves, and vesting the NURBS curves with physical properties, such as mass and stiffness. However, using dynamic NURBS curves, only the geometric torsion of the curve is modeled, rather than the material torsion of the linear objects. Additionally, the center line of a real deformable linear object is not necessarily a NURBS curve.

To increase the reality of simulating linear objects, elastic rod models derived from continuum mechanics have been applied. This type of model can accurately reflect the continuity of linear objects, give a precise description of the relationship between stress and strain, and exactly simulate the effects of material torsion; this makes these models more realistic than those mentioned above. Most deformable linear objects in nature and engineering can be approximately modeled with elastic rods. In earlier times, the Kirchhoff theory of elastic rods was used in modeling motional cables [21] and the animated simulation of hair [22]. In the 19th century, the Kirchhoff theory was enhanced by the Cosserat brothers, taking into account axial linear strain and bending shear strain. The Cosserat theory is more accurate and has now become the basic method to solve the problems of non-linear elastic mechanics. The Cosserat theory was first used for modeling deformable linear objects by Pai in 2002 [23]. In Pai's work, the equilibria of elastic thin rods were obtained by numerically solving the differential equations with a shooting method. However, Pai's strategy had difficulty in determining the initial conditions of the numerical solution and dealing with contact and self-contact. Later, Grégoire and Schömer [24] proposed a modified mass-spring system incorporating the Cosserat theory. In this method, the equilibrium of a linear object is obtained by minimizing its potential energy. The contact and self-contact can be handled readily due to the explicit description of the cable's configuration. Spillmann and Teschner [25] further extended Grégoire and Schömer's work to a dynamic model, in which the dynamic evolution of the rod is calculated by numerical integration of the resulting Lagrange equations of motion. However, the numerical computation may fail to converge if the time step size is improper.

2.2. Branched structures

Few studies about the modeling of branched-structure deformation have been reported. Zhao and Barbič [26] used a finite-element method to solve the large deformation of complex plants. This method needs complicated preprocessing and user intervention, making it less attractive for use in cable simulations. Other researchers have tried to extend the models of deformable linear objects to simulate the deformation of branched structures. For example, Theetten and Grisoni [27] added a fusion constraint to a traditional rigid multi-body model to simulate the deformation of several branched structures. They solved the model using a constraint-based method. Bergou et al. [28] simulated tree-like structures by coupling Kirchhoff rods with rigid-bodies. The joint in their method is modeled by a rigid body. Every rod attaching to the rigid-body has constant position and orientation relative to other rods at the same joint. The similar method was used by Hermansson et al. [29] in their study of assembly path planning of

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