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Physically based real-time interactive assembly simulation of cable harness

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ABSTRACT

In this paper, we designed and developed an interactive assembly simulation system of cable harness. First, we establish a real-time physical model of cable harness based on an extension of the mass–spring model. We use various kinds of springs to describe the different properties of the cable harness: linear springs for stretching, bending springs for bending, and torsion springs for geometrical torsion and material twisting. The constraints of connectors and clips on cable harness are both considered. We also associate the elastic coefficients of various springs with the material parameters of the cable. Moreover, we use spherical bounding volume hierarchy and triangular facets for collision detection of cable harness during the assembly simulation. By applying contact forces to both ends of the cable links that collide with the surrounding environment, we obtain the real-time contact response of cable harness. Finally, we apply the proposed model to a cable assembly task. The results show that the proposed model successfully expressed the deformation of the cable harness and the interactive manipulation is computationally efficient.

Introduction

Cable harnesses are used to connect electrical components, equipment, or control devices in complex products. They play important roles in transferring power and signals. The rationality of layout design and the reliability of cable assembly directly influence the performance of these products. In recent years, with the development of computer-aided design (CAD) and virtual reality (VR) technology, the routing design and assembly simulation of cable harness in virtual environment [1–8] has gradually attracted attention. For example, Ritchie et al. [4–6] developed an immersive VR system to design and plan the assembly and installation of cable harness. Valentini [7] and Liu et al. [8] implemented the interactive design of cable harness in augmented reality. Through simulation, we can verify the design rationality and assembly reliability of cables, then predict and solve the possible problems in their practical assembly in advance.

Modeling is the foundation of assembly simulation of cable harness in a virtual environment [9]. Any model of a cable must fulfill the demands of reality and real-time. On the one hand, it needs to express the real configurations and physical properties of cable harness. On the other, the calculation of the model needs to be sufficiently fast to keep up with assembly manipulation during the simulation process. The cable is a kind of deformable linear object (DLO). Recently, many researchers have developed models to simulate DLOs.

The dynamic spline model was first introduced to simulate deformable objects by Terzopoulos [10]. They combined the geometrical features of the spline with physical properties, such as mass and deformation energies. Lenoir et al. applied the idea of dynamic spline model to the manipulations of catheter and guidewire [11], as well as adaptive simulations [12]. Theetten et al. [13] provided geometrically exact dynamic splines and described a virtual system for cable positioning. Valentini et al. deduced a detailed dynamic spline formulation [14], and applied it to the interactive cable harnessing in augmented reality [7]. However, the computational time of this kind of model is relatively high when accounting for all of the physical properties.

The articulated link chain model [15] describes the DLO as consecutive rigid cylinder links connected by ball joints. Redon et al. [16] presented an adaptive algorithm for computing the forward dynamics of articulated bodies. Hergenröther et al. [17] equipped the joints with springs to express the bending behavior of cables, while Servin et al. [18] used a new type of "angular constraint." This kind of model is usually computed using inverse kinematics [19] or a minimal energy method [17]. However, because it con-

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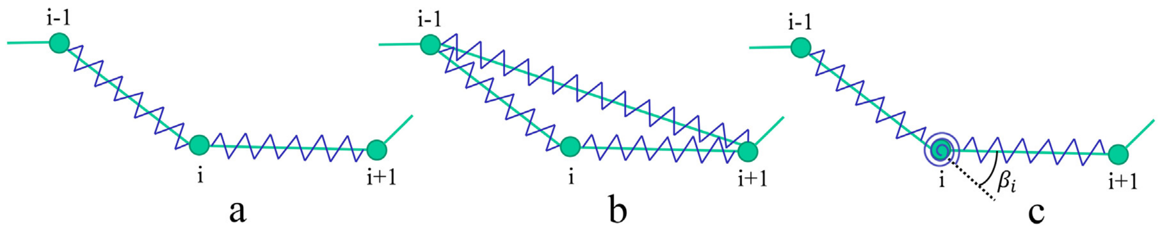

Fig. 1. Various mass-spring models in existing studies.

tains too few physical properties, the results provide only a limited description.

The finite element method (FEM) [20,21] can accurately express the deformations of cables, but the solving process is generally too complex and time-consuming to be usable for the real-time simulation of cables.

In recent years, several researchers have used an elastic rod model, which regards the DLO as a thin elastic rod. Two common methods are the Kirchhoff rod model and the Cosserat rod model. In 1859, Kirchhoff [22] proposed the dynamic analogy theory of an elastic thin rod. Bertails et al. [23] used the Kirchhoff equations to simulate human hair strands. Bergou et al. [24] and Bretl et al. [25] used the Kirchhoff elastic rod model to calculate the equilibrium configurations of DLOs under various manipulations. Cosserat's theory improved the Kirchhoff model by taking into account the axial linear strain and bending shear strain of the elastic rod, establishing more accurate equilibrium equations. Pai [26] first applied the Cosserat theory to the modeling of thin elastic solids. Spillmann et al. [27] and Grégoire et al. [28] used the Cosserat elastic rod model to simulate the bending and twisting behavior of one-dimensional flexible parts. The elastic rod model involves more comprehensive physical properties, but real-time simulation becomes a problem for high-complexity rods. It is also difficult to combine constraints with this model.

As a simple and real-time physical model, the mass–spring model is widely used in the simulation of flexible bodies, such as cloth [29,30], tissue [31], hair [32], and cable. This model was initially proposed by Haumann and Parant [33]. They described a behavioral simulation test-bed using particles connected by linear springs, as shown in Fig. 1(a). Provot et al. [29] improved the mass–spring model by adding "flexion springs," which are linear springs linking the masses i–1 and i+1, as shown in Fig. 1(b) and obtained good results in the simulation of the bending behavior of cloth. However, the disadvantage of the flexion spring is that for small angles, its length is almost constant, making the restoring force too small. To overcome this, Loock et al. [34] improved the model by using "torsion springs" attached to masses instead of the flexion springs, as shown in Fig. 1(c). They simulated the configuration of several cables with different material parameters under gravity and obtained a better bending effect of cables. However, existing mass-spring models did not consider the torsion deformation of the cable, which is very important to realistically express the deformation of a cable harness.

In this paper, we improved the usual mass–spring model by adding torsion springs to describe the twisting behavior of cable harness. We associated the elastic coefficients of springs with the material parameters of the cable for the first time. The practical constraints of connectors and clips on cable harness were also considered. Moreover, based on collision detection, we determined the real-time contact response of cable harness. Finally, based on the model, we developed an interactive assembly simulation system of cable harness and carried out an assembly task. The model successfully expressed the deformation of the cable harness and interactive manipulation was computationally efficient.

The paper is organized as follows. In Section 2, we introduce the real-time physical model of the cable harness. The collision detection and contact response of the model are introduced in Section 3. Section 4 presents the simulation results. Finally, the conclusions and future work are summarized in Section 5.

2. Physical modeling of cable harness

Previous mass–spring models only describe the gravity, stretching, and bending behaviors of cable harness. In this study, we added torsion springs to the model to describe twisting behavior, considered the constraints of connectors and clips on cable harness, and associated the elastic coefficients of springs with the material parameters of the cable. We then calculated the model based on quasi-static equilibrium conditions.

2.1. Description of the proposed model

The proposed model is shown in Fig. 2. The cable harness is modeled as a sequence of cable links consisting of discrete mass points and different springs. The various springs describes different physical properties of the cable harness. The linear springs connect every two adjacent mass points, expressing the stretching or compression behavior of the cable harness. Bending springs are attached to mass points that are not endpoints, to express the bending behavior of the cable harness. Additionally, we added torsion springs to the cable links to account for the geometric torsion and material twisting of the cable harness.

The basic notations are as follows:

(1) The cable harness is composed of n cable links (1,2,3...n) and n+1 mass points (0,1,2...n).
(2) m^0 is the total mass of the cable harness, and m_i is the mass of the point i. Each point has an equal mass, so $m_i = m^0/(n+1)$.
(3) l^0 is the initial total length of the cable harness and $l_i{}^0$ is the initial length of the cable link i. We assume that the initial length of each link is the same, so $l_i{}^0 = l^0/n$. l_i is the current length of cable link i.
(4) $\boldsymbol{x_i} = (x_i{}^1, x_i{}^2, x_i{}^3)^T$ is the three-dimensional coordinate of the mass point i in space, and ψ_i is the torsion angle of the cable link i.

2.2. Forces of the mass points

According to Newton's second law, we can determine the motion law of the mass points:

$$m_i \frac{\partial^2 \boldsymbol{x_i}}{\partial t^2} + k^d \frac{\partial \boldsymbol{x_i}}{\partial t} = \boldsymbol{F_i} = -\frac{\partial E}{\partial \boldsymbol{x_i}} + \boldsymbol{F_i^e}, \tag{1}$$

where k^d is the damping coefficient, preventing the excessive vibration of the mass points in the calculation process; $\boldsymbol{F_i}$ is the force acting on the point i; $\boldsymbol{F_i^i} = -\frac{\partial E}{\partial \boldsymbol{x_i}}$ and $\boldsymbol{F_i}^{\boldsymbol{e}}$ are the internal and exter-

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