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Research Paper

Networking of Bennett linkages and its application on deployable parabolic cylindrical antenna

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A B S T R A C T

In this study, the networking method of Bennett linkages is investigated, and a deployable parabolic cylindrical antenna is constructed based on the network. The alternative form of Bennett linkage has excellent performance in terms of deployment and folding. Using the alternative form as basic units, a networking method of Bennett linkage is proposed. In the network, the units are parallel in one direction and have an included angle in the vertical direction. Thereafter, the mobility of the mechanical network is analyzed through screw theory. Results show that the network has one degree of freedom, and that the included angle has no effect on network mobility. According to this property, a method of constructing parabolic cylindrical antennas is proposed. The parameters of units in the network are then analyzed. A parabolic cylindrical antenna is designed, and a prototype is constructed. The parabolic cylindrical antenna proposed in this study can be folded completely and can be deployed to the predetermined profile. This study provides a novel industrial application of the classical Bennett linkage.

1. Introduction

Single-loop overconstrained spatial linkages (SOSLs) have been the focus of research in the field of mechanisms for many years. The first SOSL was proposed by Surrus in 1853 [1]. In 1903, Bennett proposed the classical Bennett linkages with four links and four joints whose axes are not parallel or concurrent to each other [2]. Since then, many scholars have investigated SOSLs, and many theoretical achievements have been obtained. Baker analyzed the properties of various linkages, such as Bennett [3–5], Goldberg, Bricard [6], and Altmann linkages [7,8]. Huang analyzed the mobility of Bennett linkage [9]. Yu [10] as well as Chen and You [11,12] synthesized several new SOSLs based on Bennett linkages. However, SOSLs are rarely applied in the industry because of their complicated configuration and motion path. Schatz invented the Turbula using the Schatz linkage, and this linkage is the only SOSL with mass application in the industry; it is particularly applied in the spatial blender [13]. Despite this rarity, several scholars focused on the application of SOSLs. Racila presented a one degree-of-freedom (DOF) parallel manipulator based on Bricard linkage [14]. Zeng designed several parallel hybrid-loop manipulators with Bennett and Bricard linkages [15].

Deployable mechanisms are those mechanisms that can be folded into a compact form for storage and transportation and can be deployed to a predetermined form in orbit. Deployable mechanisms are typically constructed by planar linkages. Given their special geometric configurations, SOSLs have a higher deployment ratio than planar linkages. Thus, deployable mechanisms have become the new application field of SOSLs. Many researchers have focused on this field. Gan and Pellegrino proposed several SOSLs that can be folded completely and can be deployed to planar polygons [16,17]. Chen and You presented the alternative form of the Bennett

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linkage and proposed a networking method of Bennett linkages to construct large-scale deployable networks [18–22]. Chen and You also proposed a networking method of Myard linkages [23]. Huang and Li synthesized SOSLs by the Lie group and investigated the networking method of SOSLs [24,25]. Ding proposed a deployable mast by connecting eight-bay linkages [26] and a network constructed by type III Bricard linkages [27], he also proposed a cylindrical network composed of Bennett linkages [28].

With a large-scale and complicated geometric profile, deployable mechanisms cannot be implemented by only one SOSL; therefore, they are always constructed by connecting the SOSLs as modules. At present, the application of SOSLs on deployable mechanisms is still hindered by various problems. For example, one problem is the lack of a theoretical method to verify the networking of SOSLs. Another problem is the lack of research on the network profile. For the networking method, Chen and You presented that in a mobile assembly, each loop of connected rigid bodies must be a mobile mechanism and that the geometry of these mechanisms are retained in the motion of the assembly [29]. Huang and Li proposed a virtual chain approach, which uses the equivalent motion of open-loop virtual kinematic chains to replace the links of single-loop units in a multi-loop mechanism, thereby allowing the multi-loop mechanism to be considered as an equivalent single-loop mechanism and deriving the mobility of the multi-loop mechanism [30]. These methods are intuitive and depend on the personal experience of researchers. They are appropriate for networks with unitary and repeated connections. A strict theory used to verify the feasibility of the networking is still lacking. In this study, we use screw theory to verify the feasibility. First, the mobility of the network is analyzed through screw theory. Second, the network is judged according to the result, the method of the mobile network is feasible. For the mobility analysis of the multi-loop mechanism by screw theory, Dai presented that mobility is determined by the rank of the null space of the constraint screw matrix for the mechanism [31,32]. He also proposed the method to solve the null space of the constraint screw matrix [33]. Using this approach, Wei and Dai analyzed the mobility of a complex and articulated ball [34], the Hoberman Switch-Pitch Ball [31], and the mechanisms inspired by origami [35]. Sun also analyzed the mobility of a deployable structure of scissor-like elements using this approach [36]. However, the null space matrix and its rank were solved straightforwardly in these studies. We cannot obtain the specific role of one parameter in the mechanical network. When we construct a modular mechanical network through SOSLs, we formulate the concept design first. In this step, the effects of parameters of each module and their connections on the mobility of the network are analyzed. Therefore, we need a modified approach to analyze the mobility in which these parameters' roles can be shown entirely. As the difference between the column number of the constraint matrix and its column rank indicates the mobility of the network, we proposed an approach to calculate the column rank through elementary column transformation. The elements in the constraint matrix indicate the parameters of each module and their connections. In this approach, we can determine their effects on the mobility through analysis, thereby providing a theoretical base for the design of a deployable mechanical network. Using this approach, we have analyzed a mechanical network constructed by Altmann linkages [37]. For the other problem, given the complicated configuration of SOSL and the lack of a theoretical networking method, the network profile constructed by SOSLs is confined to planar and ruled surfaces, it cannot meet the requirements of profiles of deployable mechanisms.

A satellite antenna is an application of the deployable mechanism. The profiles of satellite antennae mainly include planar antennae, cylinder antennae, parabolic antennae, and parabolic cylindrical antennae. Combining the properties of the reflector antenna and the array antenna, the parabolic cylindrical antenna can conduct line focusing and can transmit radial signals. Thus, this type of antenna is commonly used as the satellite antenna [38–41]. At present, the parabolic cylindrical antenna is constructed by panels or membranes. The panels and membranes are connected by planar linkages and can thus be folded in only one direction and cannot be folded completely. Based on the alternative form of Bennett linkage, a networking method to connect the Bennett linkages is presented in this study. The mobility of the mechanical network is first analyzed by using screw theory. Then a parabolic cylindrical antenna is constructed, and a prototype is manufactured. The resulting mechanical network can achieve the fully folded state and can be deployed to the parabolic cylindrical profile. In addition, the mobility analysis process presented in this study provides a reference for verifying the feasibility of other deployable mechanisms constructed by SOSLs.

The remainder of this paper is organized as follows. In Section 2, screw theory is introduced briefly. In Section 3, the Bennett linkage and its alternative form are presented. In Section 4, a networking method of Bennett linkages is proposed and the mobility of the mechanical network is analyzed. In Section 5, the parameters of the Bennett linkages are obtained through the analysis of the connectivity between units. In Section 6, the profile parameters of the mechanical network are investigated, a specific parabolic cylindrical antenna is designed, and a prototype is provided. Finally, a conclusion is given.

2. Preliminary theory

2.1. Screw theory

In screw theory, a screw is defined by six components [42,43]. The first three components represent the direction of the screw axis, defined as $\boldsymbol{S}$; the last three components are defined as $\mathbf{S}_0$, where $\boldsymbol{r}$ is the position vector of any point on the screw axis and p is called the pitch of the screw.

$$\$ = (\mathbf{S};\ \mathbf{S}_0) = (\mathbf{S};\ r \times \mathbf{S} + p\mathbf{S}) = (lmn;\ pqr) \tag{2-1}$$

For $\$ = (\mathbf{S};\ \mathbf{S}_0)$, if $\mathbf{S}\cdot\mathbf{S}_0 \neq 0$, then we refer to \$ as a screw. The pitch h of screw \$ is defined as$h = \mathbf{S}\cdot\mathbf{S}_0/(\mathbf{S}\cdot\mathbf{S})$; thus, $\mathbf{S}_0 = \mathbf{r} \times \mathbf{S} + h\mathbf{S}_0$. When $\mathbf{S}\cdot\mathbf{S} = 1$, \$ represents a unit screw. When h=0, we have $\mathbf{S}\cdot\mathbf{S}_0 = 0$ and call \$ a line vector. Expressed as $\$ = (\mathbf{S};\ \mathbf{r} \times \mathbf{S})$, a line vector represents a force or rotation with the direction represented by $\mathbf{S}$. When $h = \infty$, we call \$ a couple. Expressed as $\$ = (0;\ \mathbf{S})$, a couple represents a couple or a translation with direction $\mathbf{S}$ [44].

For screws $\$_1 = (\mathbf{S}_1;\ \mathbf{S}_{01})$ and $\$_2 = (\mathbf{S}_2;\ \mathbf{S}_{02})$, their reciprocal product is defined as follows: