Mechatronics 49 (2018) 26–35

Contents lists available at ScienceDirect

Mechatronics

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

Research on the dynamic trajectory of spatial cable-suspended parallel manipulators with actuation redundancy☆

Zhufeng Shao[a,b], Tiemin Li[a,b], Xiaoqiang Tang[a,b,*], Lewei Tang[c,*], Hao Deng[d]

[a] State Key Laboratory of Tribology, Tsinghua University, Beijing 100084, China
[b] Beijing Key Lab of Precision/Ultra-precision Manufacturing Equipments and Control, Beijing 100084, China
[c] State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, College of Mechanical and Vehicle Engineering, Hunan University, 410082 Changsha, China
[d] Department of Precision Instrument, Tsinghua University, Beijing 100084, China

ARTICLE INFO

Keywords:
Cable-driven
Dynamic trajectory
Actuation redundancy
Parallel manipulator

ABSTRACT

A cable-driven parallel manipulator (CDPM) adopts flexible cables instead of rigid limbs, connecting the base and the end effector. When gravity is considered as a virtual cable, the cable-suspended parallel manipulator (CSPM) takes shape. Due to various advantages, i.e. large workspace, high speed and low cost, the CSPM has drawn the attention of both academia and industry. Dynamic trajectories of the CSPM are deduced by considering the dynamic model instead of the traditional quasi-static or static assumption, which further expands the motion range of the CSPM. Our previous work revealed that redundant actuation helps to improve the dynamic capability of the planar CSPM in terms of the feasible frequency. In this paper, dynamic trajectories of the redundantly actuated spatial CSPM are investigated. By considering the inertial force of the end effector as an additional gravitational force, equivalent gravitation and equivalent projection are proposed, which bridge the gap between static and dynamic workspaces. Feasible frequency ranges of typical dynamic trajectories for 4-cable CSPM are analytically deduced with the three-cable theorem, giving an insight into the problem. The stable and promising pendulum-like frequency is confirmed with physical experiments. Methods established in this paper could be conveniently adopted for the dynamic trajectory analysis of other spatial CSPMs with actuation redundancy.

1. Introduction

A cable-driven parallel manipulator (CDPM) is a subclass of the parallel mechanism [1–3], whose base and end effector are connected by flexible cables instead of rigid limbs. Compared with conventional rigid parallel manipulators, cables imbue the CDPM with some significant qualities such as lightweight, high speed, efficiency, and large workspace [4–6]. CDPMs have attracted a great amount of academic attention, and intensive efforts have been made to study the associated fundamental issues i.e. configuration, workspace, and stiffness [7–11]. Besides, applications of CDPMs expanded into realms such as medical rehabilitation equipment [12,13], material delivery [14,15] and positioning devices [16,17]. Due to the unilateral tension requirement of cables, a CDPM with n degrees of freedom (DoFs) should be actuated by at least $n+1$ cables [18]. When the number of drive cables is $m>n+1$, the CDPM is recognized as the manipulator with actuation redundancy. On the contrary, when $m<n+1$, the CDPM is under-actuated [19]. Gravity could be considered as a virtual cable keeping cables tensioned, and this type of CDPM is usually called the cable-suspended parallel manipulator (CSPM), which possesses simpler configuration and less energy consumption with a reduction in drive cable and cable tension [14,20,21].

In most studies, the trajectory and workspace of the CSPM are limited in the space defined by fixed/mobile actuators [12,13,18–22]. Thus, the support frame needs to be larger than the required trajectory/workspace, which results in a bulky and complicated structure. A novel solution was proposed by considering the inertial forces of the end effector during the motion instead of assuming in a traditional quasi-static or static condition [14,23]. Dynamic workspace and trajectory of CSPM [24,25] inspire a novel approach to realize a huge range of motion with a relatively small support structure, and put forward a new topic that requires further study.

☆ This paper was recommended for publication by Associate Editor Prof. Feliu Vicente.
* Corresponding authors at:
E-mail addresses: shaozf@mail.tsinghua.edu.cn (Z. Shao), litm@tsinghua.edu.cn (T. Li), tang-xq@mail.tsinghua.edu.cn (X. Tang), leweitang@hnu.edu.cn (L. Tang), haodeng@mail.tsinghua.edu.cn (H. Deng).

https://doi.org/10.1016/j.mechatronics.2017.11.001
Received 22 December 2016; Received in revised form 1 October 2017; Accepted 1 November 2017

Redundant actuation is a well-known method to enhance the capability to apply force to the end effector for parallel manipulators. According to Hamid (2011), redundant drive cables are adopted to decrease motion time and reduce the cable force for the planar CDPM [26]. In our previous work, it was revealed that redundant actuation helps to improve the dynamic capability of planar CSPM in term of the feasible frequency region. In this paper, dynamic trajectories of redundantly actuated spatial CSPM are analyzed. Adopting 4-cable spatial CSPM as an example, feasible frequencies and amplitude ranges of dynamic trajectories are deduced with analytic approach, and illustrates insight into the problem. The remainder of this paper is organized as follows: In the next section, spatial CSPM is introduced briefly and a general dynamic model is established. Then, in Section 3, the basis theorem to carry out the analytic method is introduced. Typical spatial trajectories are studied, and feasible frequency regions for the 4-cable CSPM are obtained in Section 4. Physical experiments are carried out in Section 5 and finally, conclusions are outlined in Section 6.

2. System descriptions and dynamic modeling

The redundantly actuated spatial CSPM considered in this study is illustrated schematically in Fig. 1. Drive cables C_i ($i = 1, 2, \ldots, m$) are applied in this spatial manipulator, which are usually actuated by the servo motors through transmission spools/pulleys. One end of each cable is attached to the moving platform at B_i point and the other end is located at respective vertex A_i of the fixed horizontal convex polygon base. When the spatial CSPM is of 3 DoFs, the moving platform changes into a point mass P, and there are m-3 redundant cables. The base frame $\{\boldsymbol{G}\}$: O-XYZ is attached to the base, X and Y axes are located in the base plane, and the Z axis is oriented vertically downward. The end-effector frame $\{\boldsymbol{P}\}$ is attached to the mass center of the end effector as shown in Fig. 1.

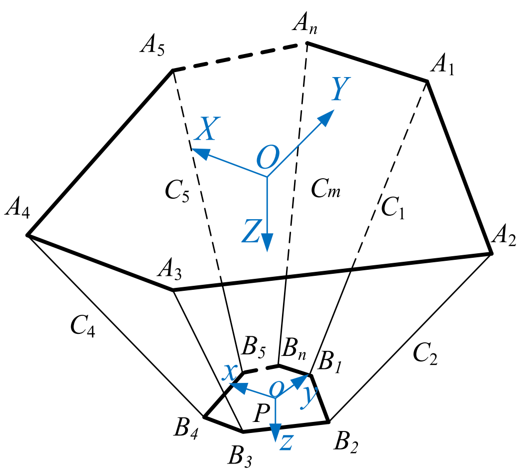

Fig. 1. Redundantly actuated spatial CSPM.

In the subsequent theoretical analysis, it is assumed that cables are straight without sagging effect. In other words, mass and elasticity of the cable are ignored. Under this assumption, length of the ith cable can be denoted as

$$\rho_i = \sqrt{({}^{\mathrm{G}}\mathbf{b}_i - \mathbf{a}_i)^T({}^{\mathrm{G}}\mathbf{b}_i - \mathbf{a}_i)}, \tag{1}$$

where ${}^{\mathrm{G}}\mathbf{b}_i$ is the position vector of point Bi in the base frame, and ${}^{\mathrm{G}}\mathbf{b}_i = \mathbf{p} + \mathbf{R}\,{}^{\mathrm{P}}\mathbf{b}_i$. $\mathbf{R}$ is the rotation matrix of the end effector, $\mathbf{p} = [x, y, z]^{\mathrm{T}}$ is the position vector of the end effector, and $\mathbf{a}_i$ is the position vector of point Ai.

Without considering the cable mass and elasticity, the simplified dynamic model of the spatial CSPM can be deduced with the Newton–Euler method, which can be expressed as

$$\begin{cases} \sum_{i=1}^{\mathrm{n}} \frac{-f_i({}^{\mathrm{G}}\mathbf{b}_i - \mathbf{a}_i)}{\rho_i} + m\mathbf{g} = m\ddot{\mathbf{p}} \\ \sum_{i=1}^{\mathrm{n}} {}^{\mathrm{G}}\mathbf{p}_i \times \frac{f_i({}^{\mathrm{G}}\mathbf{b}_i - \mathbf{a}_i)}{\rho_i} = \mathbf{I}\ddot{\theta} \end{cases}, \tag{2}$$

where f_i is the tension of the ith cable, $\mathbf{g} = [0, 0, g]^{\mathrm{T}}$ (the gravitational acceleration vector), m is the mass of the end effector, $\ddot{\mathbf{p}}$ is defined as $[\ddot{x}, \ddot{y}, \ddot{z}]^{\mathrm{T}}$ which is the translational acceleration of the end effector, $\mathbf{I}$ is the moment of inertia of the end effector with respect to the mass center, and $\ddot{\theta}$ is the angular acceleration of the end effector.

When dealing with the dynamic trajectory planning of redundantly actuated spatial CSPMs, the geometric constraints of Eq. (1), the dynamic equation of Eq. (2) and non-negative tension requirement should be taken into account together. For a completely constrained CSPM whose DoFs number n equals the cable number m, the dynamic equation can be readily solved since the tension of cables is unique and straightforward for every pose throughout all trajectories. By contrast, redundantly actuated CSPMs have the potential to attain a pose with infinite different cable tension solutions due to the redundant drive cables. In this paper, an analytic method is illustrated in detail to determine the feasible motion frequency and amplitude range.

3. Basic theorem of the analytic method

The three-cable theorem for the CSPM with a point moving platform is proposed under the static assumption [21]. In this section, this theorem is extended to analyze the dynamic workspace. The object 4-cable CSPM is shown in Fig. 2(a). The distance between A_1 and A_2 equals $2c$. Based on this architecture, the potential motion space (i.e. the entire 3-dimensional space below the base square $A_1A_2A_3A_4$) is divided into nine regions by four vertical planes containing two adjacent actuators A_i ($i = 1, 2, 3, 4$) namely A_1A_2, A_2A_3, A_3A_4, and A_4A_1, and the central one is the static workspace.

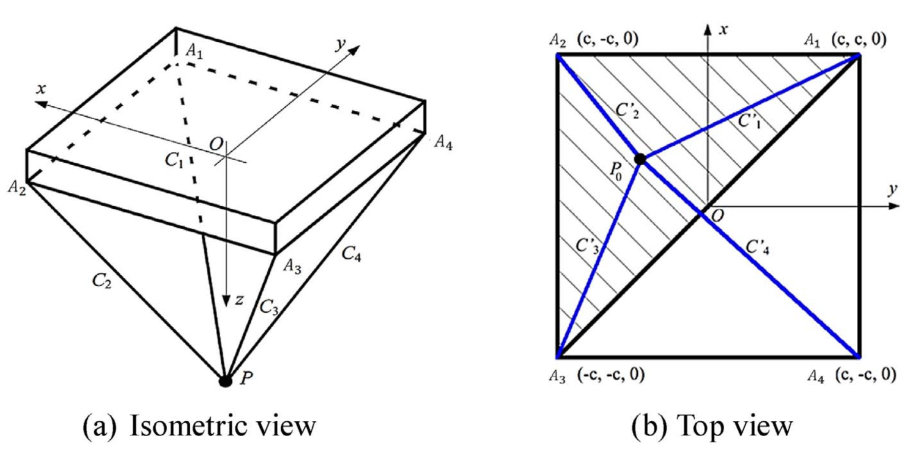

Fig. 2. Redundantly actuated 4-cable CSPM.