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Dynamic trajectory planning study of planar two-dof redundantly actuated cable-suspended parallel robots

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ABSTRACT

This paper analyzes a set of dynamic trajectories for planar two-dof redundantly actuated cable-suspended parallel mechanisms. In recent literature, the global dynamic trajectory planning problem of cable-suspended mechanisms was addressed and some of the characteristic properties of such robots were revealed. In this paper, actuation redundancy is introduced and the dynamic trajectory planning is addressed using a series of periodic trajectories (i.e. straight line and circular periodic trajectories) and the application of the antipodal theorem. The experimental results obtained show that introducing actuation redundancy increases the dynamic capabilities of the robots. Also, cable tensions acquired via tension sensors confirm that cables always remain taut during all experimental verifications at feasible frequencies and that they are consistent with the tension variations predicted by theory. Furthermore, special frequencies are specified that are similar to those encountered with non-redundant mechanisms. Additionally, an alternative architecture is proposed to deal with cable interferences and it is shown that the novel architecture leads to improved dynamic capabilities when compared to the original architecture.

1. Introduction

Cable-driven parallel manipulators are of considerable importance in some applications, including motion over large workspaces [1–4] or with high acceleration/velocity [5] (see [6,7] for a literature review). To control the movement of end-effectors, cables in parallel replace extensible rigid linkages to form cable-driven parallel robots. According to the number of cables and degrees of freedom (dofs), cable-driven parallel robots are divided into three types: redundantly constrained robots (i.e. the number of cables is larger than the dofs [8]), statically determined robots (i.e. the number of cables is equal to the dofs) and underactuated robots (i.e. the number of cables is smaller than the dofs). When gravity is used to keep the connected cables taut, this special kind of cable-driven parallel manipulators is also referred to as a cable-suspended parallel robot [9,10].

To design a cable-suspended parallel robot, the first crucial issue is to determine whether a pose can be produced with positive cable tensions, i.e., feasible workspace determination. Noting that cables can only yield tensions, equilibrium equations should be included in the workspace determination algorithm together with geometric constraints in order to satisfy the positive cable tension requirements. In the recent literature [11–14], several workspace determination methods were proposed including numerical and analytical approaches. However, static or quasi-static assumptions were used in most of the aforementioned methods, and thus the workspace obtained is referred to as the static workspace. An alternative definition of the workspace of cable-driven robots is defined as the dynamic workspace considering the kinematic states (i.e. velocity and acceleration) [15]. In [16,17], the dynamic workspaces of planar two-dof and spatial three-dof cable-suspended robots were studied and the results demonstrated that the end-effectors can controllably move beyond the corresponding static workspaces. Now, it is worth noting that the difference between the planar cable-suspended mechanism studied here and the robots discussed before [16,17] is that the cable-suspended robots that this paper focuses on are redundantly actuated instead of being completely actuated.

Referring to [16,17], the dynamic trajectory planning is addressed using parametric trajectories and inequality constraints based on positive tension requirements as shown in Fig. 1. In summary, two conclusions are drawn namely: (1) cable-suspended

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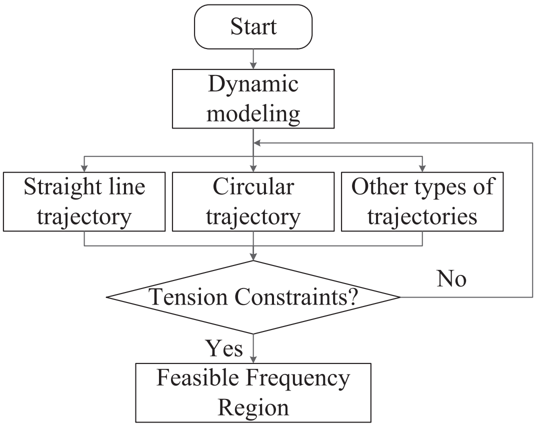

Fig. 1. Flow chart of dynamic trajectory planning.

parallel robots can be manipulated beyond the static workspace, and (2) a special frequency similar to the natural frequency of a pendulum-type robot can be used to simplify trajectory planning of such cable-suspended robots.

In this paper, the dynamic trajectory planning of a planar redundantly actuated four-cable-suspended parallel robot is studied. Compared with two-cable planar robots, redundantly actuated cable robots bring more challenges for dynamic trajectory planning but may also offer more potential. A similar analysis of redundantly actuated planar cable-suspended robots is also presented in [18], but which focuses on the trajectory tracking with optimal time based on tension and velocity constraints.

Additionally, interferences between cables or/and actuators should be carefully considered for redundantly actuated cable-suspended robots, especially in trajectory planning. Some techniques can be found in the literature for the determination of potential interferences on cable-driven robots (the reader is referred to [19] for more details). However, for the robots considered in this paper, interferences along certain trajectories are obvious and hence two distinct cases are considered to avoid them. Then, an alternative two-cable robot with similar features is applied to study the dynamic characteristics in simulation and experiments, and thereby shed some light on the properties of redundantly actuated cable-suspended robots.

Based on similarities between cable-driven robots and grasping hands regarding unilateral forces, the antipodal theorem was used in [20,21] to simplify the static workspace determination process. Here, the antipodal theorem is exploited to solve the dynamic trajectory planning problem of a planar two-dof redundantly actuated cable-suspended parallel robot, which is expected to apply in other redundantly actuated cable-suspended manipulators as well.

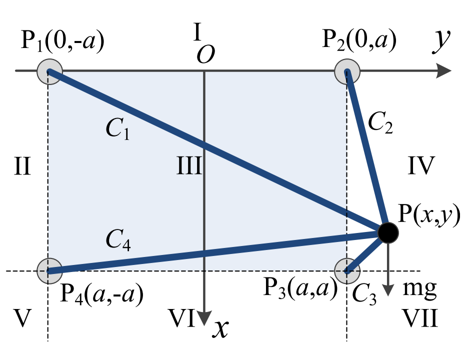

Fig. 2. Planar 2-dof redundant cable robot.

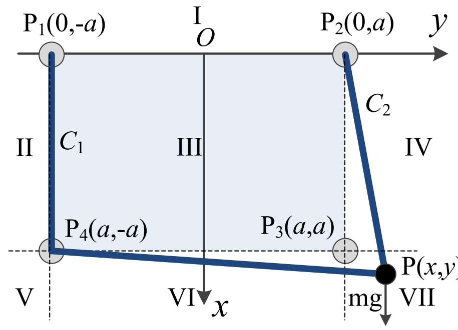

Fig. 3. Alternative planar cable robot.

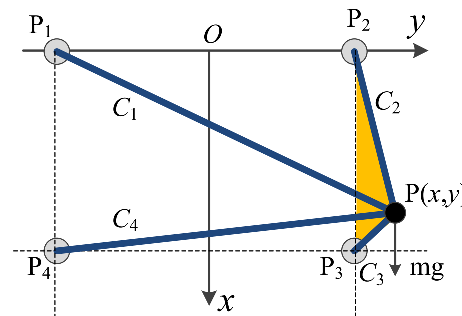

Fig. 4. Antipodal theorem applied to the redundantly actuated cable-suspended robot.

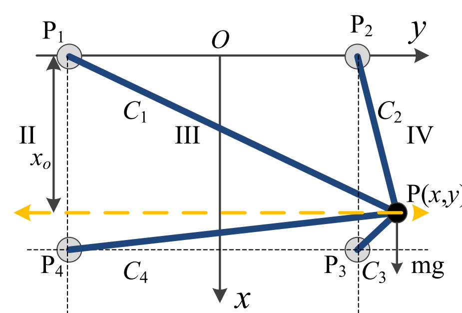

Fig. 5. Horizontal trajectory *A* in areas II, III and IV.

This paper is organized as follows. Section 2 presents a planar two-dof redundantly actuated cable-suspended robot architecture. In Section 3, the kinematic and dynamic modelling of redundantly actuated cable robots is described. Then, the antipodal theorem is used to investigate positive tension constraints when dynamically performing periodic Cartesian trajectories in Section 4. Straight line and circle trajectories planning simulations are performed and the feasible frequency regions are presented in Section 5. Next, experimental verifications are accomplished with various frequencies in Section 6. Finally, Section 7 concludes this paper and discusses ongoing future work.

2. Robot description

The planar two-dof redundantly actuated cable-suspended parallel robot considered in this study is illustrated schematically in Fig. 1. Four cables C_i $(i = 1, 2, 3, 4)$ are included in this robot, where one end of each cable is attached to a common point mass P and