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Research paper

Dynamic trajectory planning for a spatial 3-DoF cable-suspended parallel robot

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ABSTRACT

This paper deals with continuous path motion planning of a spatial 3-DoF cable-suspended parallel robot considering the robot's dynamic constraints. First, based on the analysis of the algebraic and geometric properties of cable tension constraints, we present the sufficient and necessary conditions for the end-effector to pass through parallel singularities along straight line paths. Then, a piecewise linear interpolation method is introduced, showing that any target points above cable exit points can be connected in sequence via some intermediate points in the static workspace of the mechanism. The intermediate points are properly selected to avoid collisions between cables and obstacles, and the resulting trajectory is modified using quintic polynomials to enhance the performance. Afterwards, conditions for a general planar curve determined by three points to be feasible are given, and a general curve interpolation method is presented. Finally, three types of periodic trajectories are designed. Using the proposed trajectory planning method, not only can the positive cable tension constraints be satisfied, but the safety and the continuity of tensions can also be ensured. The effectiveness of the method is examined through simulations and experiments.

1. Introduction

For many large workspace industrial applications, conventional rigid-link parallel robotic manipulators are too inefficient to justify their use economically due to the large inertia of the rigid links. Cable-suspended parallel robots (CSPRs) are a new generation of parallel robots whose end-effectors are driven by a number of flexible cables instead of rigid links. The high load carrying capability, modular construction, and energy-efficient properties of CSPRs make them superior to conventional parallel robots and good candidates for a variety of challenging large workspace tasks such as astronomical observation systems [1], automated construction structures [2], camera systems for stadiums [3], and so on.

The kinematic and the dynamic models of CSPRs are similar to their counterparts with rigid links. However, the correctness of them can be ensured only when the unilateral cable tension constraints are satisfied (cables can only pull but cannot push the moving platform). Therefore, to produce a desired motion, the dynamic constraints of CSPRs must be taken into account, which makes the trajectory planning of CSPRs a difficult problem to resolve. It is interesting to note that the trajectory planning strategies for CSPRs are closely related to their workspace classification. When the end-effector moves in the wrench-closure workspace (the set of poses at which the cables can create any wrench on the end-effector) [4] of

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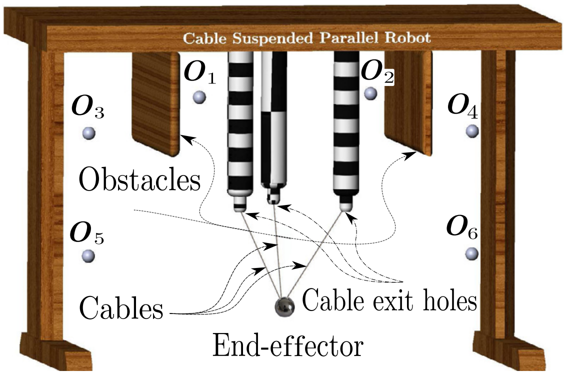

Fig. 1. Spatial 3-DoF CSPR.

the robot, the slackness of cables can be easily avoided by applying optimal tension distribution [5] or safe tension distribution algorithms [6]. This indicates that the trajectory planning for CSPRs in the wrench-closure workspace is similar to that for rigid-link parallel/serial robots, which has already been extensively studied (e.g., [7–11]). However, the wrench-closure workspace does not exist for CSPRs whose cables are not attached below the end-effector, in which case, the wrench-feasible workspace (the set of poses at which the cables can create a given set of wrenches on the end-effector with all tensions lying in a given interval) [12] is suggested to be used to maintain cables in tension. In [13], the wrench-feasible configuration space was placed in correspondence with a smooth manifold, then a continuation strategy is defined to search the space systematically from one configuration until another configuration is found or path nonexistence is verified by exhaustion of the search. Intuitively, if a path lies in the static workspace (abbreviated as SW; the set of poses at which the end-effector can stay at rest) of the robot, then the positive cable tensions can be easily satisfied by setting a sufficiently large duration. The trajectory planning in the SW was studied in [14–17], where the duration was selected as a local minimum to avoid the discontinuity of cable tensions. It should be noted that the global time optimal trajectory planning [18–20] for CSPRs is not suitable for practical use since the discontinuity of cable tensions may cause undesirable vibrations and large trajectory tracking errors. Instead of using local/global time-optimal index (the cables can easily become slack when performing such types of trajectories), in practice, it would be more appropriate to determine the range of the trajectory parameters and find the relationship between the parameters and the performances of the trajectory (e.g., the duration/smoothness of the trajectory and the safety of cable tensions), then make a trade-off [21,22].

The concept of planning trajectories beyond the SW was first presented in [23,24], where a special frequency (called natural frequency) was used to plan periodic trajectories for a 2-degree-of-freedom (2-DoF) CSPR. It was demonstrated that the natural frequency is also suited for designing dynamically feasible periodic trajectories for a planar 3-DoF CSPR [25,26] and a spatial 3-DoF CSPR [27–29]. In [27,30], the transition trajectories are designed to make the end-effector start from rest and blend into the periodic trajectories. The point-to-point dynamic trajectory planning of a 2-DoF and a spatial 3-DoF CSPRs were addressed in [31,32] respectively, where an algebraic method was adopted to cope with the positive cable tension constraints. The method may fail to find a feasible trajectory that connects the prescribed target points and is difficult to be used to avoid obstacles since the path geometry is unpredictable. For spatial 3-DoF CSPRs, the method also requires extensive numerical computations for non-horizontal point-to-point trajectories.

In [21,33], a geometric approach was introduced to avoid the failure of connecting prescribed points, where the tension constraints were expressed in $s-\ddot{s}$ (position-acceleration) plane and dynamic trajectories were designed directly in the feasible areas in the plane. The geometric approach always yields analytical results but a major disadvantage is that the trajectory designed is too special (limited to linear interpolation). Moreover, [21,33] did not deal with the problem regarding whether the end-effector can move above the cable exit points or not. It should be noted that allowing CSPRs to operate above the cable exit points is not only helpful in enlarging the workspace of the mechanism, but also can find some specific applications. Fig. 1 shows an example application of a spatial 3-DoF CSPR that requires trajectories extending above the cable exit points. Suppose the cable exit points of the robot are mounted above the two target points $\boldsymbol{O}_1$ and $\boldsymbol{O}_2$, then the end-effector cannot move to $\boldsymbol{O}_i$ ($i \in \{3, 4, 5, 6\}$) due to the collision between the cables and the obstacles. But if the end-effector has the ability to move above the cable exit points, the height of the cable exit points can be lowered (see Fig. 1) such that all the target points are reached successfully.

The principal purpose of the present work is to design general dynamically-feasible trajectories for a spatial 3-DoF cable-suspended parallel robot. First, a rigorous mathematical proof is provided to show that the end-effector can pass through parallel singularities [34,35] along straight line paths, ensuring positive and continuous cable tensions. Then a trajectory is designed in $s-\ddot{s}$ plane to connect a target point lying above the plane (called singular plane) formed by the three cable exit points to a point in the SW. It is demonstrated that any target points above the singular plane can be connected in sequence via some intermediate points in the SW. To avoid obstacles, the intermediate points are properly selected by using an intuitive geometric technique. The resulting piecewise straight line trajectory is then modified using quintic polynomials,