



Research paper

Trajectory planning for the static to dynamic transition of point-mass cable-suspended parallel mechanisms



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ABSTRACT

This paper presents a trajectory formulation that connects an initial point at rest to a final point to be reached with zero velocity but nonzero acceleration for planar two-dof and spatial three-dof cable-suspended mechanisms with point-mass end-effectors. The trajectory is designed to reach the first of a sequence of target points that can be located outside of the static workspace of the mechanisms. The proposed motion consists of oscillations of progressively increasing amplitude centred at the initial point, whereby an upper bound for the minimum feasible number of oscillations is determined by ensuring positive tension in all cables throughout the trajectory. It is shown that this number of oscillations can be found for any trajectory that is entirely located below the spools. The paper provides novel insight into the dynamics of the three-dof mechanism, and highlights the similarities and differences between the planar and spatial motions. Simulation results of example trajectories are included in order to illustrate the approach, along with a video demonstration of an experimental validation performed using a three-dof prototype.

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1. Introduction

A cable-suspended parallel mechanism consists of a platform that is suspended by cables, and that is put into motion by the winding and unwinding of these cables on their respective servo-controlled winch. Unlike fully constrained cable-driven parallel mechanisms that have more cables than degrees of freedom (dofs) (see for instance [1] and [2] and many others), cable-suspended mechanisms have the same number of cables as dofs and rely on gravity to maintain tension in the cables. Cable-suspended parallel mechanisms can be used in applications that require very large workspaces, such as cranes [3] or camera support systems [4]. Examples of some of the first cable-suspended mechanisms are presented in [5–7].

In most cases reported in the literature, cable-suspended mechanisms are assumed to work in static or quasi-static conditions, which implies that their workspace (called static workspace [8]), is limited by the footprint of the mechanism.

However, using the notion of dynamic workspace [9], it is possible to envision the dynamic control of cable-suspended parallel mechanisms. The dynamic workspace is defined as the set of poses that the platform can reach with a controlled kinematic state (position, velocity and acceleration) while maintaining all cables under tension. Clearly, poses beyond the static workspace can only be reached with a nonzero acceleration, while poses in the static workspace can be reached with either zero or nonzero accelerations.

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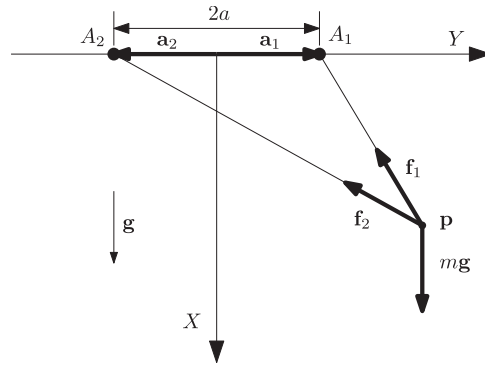


Fig. 1. Planar two-dof cable-suspended mechanism.

In this context, an elementary task that cable-suspended mechanisms must be able to perform consists in connecting two target points that are located outside of their static workspace with a zero instantaneous velocity at each of the points. Dynamic point-to-point trajectory planning aims at developing path-finding procedures that satisfy these boundary conditions while maintaining cable tension throughout the motion.

Trajectory planning techniques for underactuated cable-suspended mechanisms were proposed in [10–13]. These techniques require the online numerical integration of the complex dynamic equations. On the other hand, the trajectory planning of fully actuated cable-suspended mechanisms is much simpler since it can be accomplished using algebraic relationships. Based on such relationships, periodic trajectories were developed in the literature for a two-dof planar mechanism with a point-mass end-effector [14], for a three-dof spatial mechanism with a point-mass end-effector [15], and then for a specific architecture of a planar three-dof mechanism [16]. Notably, the conditions that ensure trajectory feasibility presented in these publications lead to the discovery of a special frequency that can be regarded as the natural frequency of the mechanism, as shown in [17]. This approach was also used to develop dynamic point-to-point trajectories for a two-dof planar mechanism with a pointmass end-effector [18]. The dynamics of cable-suspended parallel mechanisms was also studied in [19–22].

In this paper, a dynamic trajectory planning framework is proposed for fully actuated planar two-dof and spatial three-dof mechanisms with pointmass end-effectors. The trajectory connects an initial point at rest to a final point to be reached with a dynamic state (nonzero acceleration). The proposed motion consists of oscillations of progressively increasing amplitude centred at the initial point, whereby the minimum number of oscillations is determined to ensure positive tension in all cables throughout the trajectory.

This paper is arranged as follows. Section 2 presents, in the following order, the kinematic and dynamic modelling of the two-dof mechanism, the proposed transition trajectory, the condition ensuring its feasibility, the optimized minimum-time trajectory, and the reverse transition trajectory. Section 3 presents the same derivations for the spatial three-dof mechanism and highlights the similarities and differences between the planar and spatial motions. Section 4 addresses the amplitude function, which is an essential component of the proposed trajectory formulation. Section 5 provides simulation results of examples trajectories that illustrate the impact of some parameters on the motion. Finally, a video demonstrating the implementation on a prototype is provided in order to validate the trajectory proposed in this paper.

2. Planar mechanism

2.1. Mechanism modelling

The planar two-dof cable-suspended mechanism addressed in this study is represented schematically in Fig. 1. It consists of two actuated spools mounted on a fixed structure which are used to control the extension of two massless cables with infinite stiffness. The cables are attached to a common end effector which is considered as a point mass. By controlling the extension of the two cables, the position of the point mass can be controlled. The mechanism has two actuators and two dofs and is therefore fully actuated. However, because the cables can only work in tension (they cannot push), constraints must be imposed on the Cartesian trajectory prescribed at the end effector. The static workspace of the mechanism, i.e., the portion of the Cartesian space in which the end effector can be brought to rest, is limited by vertical lines passing through the cable attachment points on the structure.

Referring to the two-dof cable-suspended mechanism of Fig. 1, a fixed reference frame is defined on the base of the mechanism, whose origin is located on the line that connects the spool output points and at an equal distance from these points. The Y axis is defined along this line which is assumed to be horizontal and the X axis is vertical, pointing downward. The distance between the spool output points is noted $2a$. The (constant) position vectors of these points can then be written as $\mathbf{a}_1 = [0 \ a]^T$ and $\mathbf{a}_2 = [0 \ -a]^T$. The position vector of the end-effector point mass m is noted $\mathbf{p} = [x \ y]^T$.

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