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Design of a large-scale cable-driven robot with translational motion

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ABSTRACT

The design of a new cable-driven robot for large-scale manipulation is presented with focus on the tension condition in the cables. In this robot, the arrangement of the cables is such that the moving platform has three translational motions. The robot has potentials for large-scale robotic manipulations, machining of large parts and material handling. The design analysis presented here is towards the synthesis of the robot as well as the sizing of the actuators and cables. The synthesis of this robot is dependent on the results of the tensionable workspace analysis previously published by the Alikhani et al. [6]. The analysis of the cable forces is presented in detail, which is then used to size the actuators. For this purpose, a geometrical approach is used to represent the capability of the end-effector for applying forces and moments as convex polyhedra. The design problem is then reduced to the sizing of these polyhedra according to the design requirements and manufacturing limitations. A prototype is also designed and fabricated, which is presented at the end to further elaborate on the proposed approach.

1. Introduction

Cable-driven robots, referred to as cable robots in this paper, are categorized as a type of parallel manipulator. They have recently attracted interest for large-scale manipulation tasks. Cable robots are relatively simple in form, with multiple cables attached from one end to a mobile platform or end-effector and to motorized winches at the other end as illustrated in Fig. 1. The end-effector is moved by the winches that extend or retract the cables. These winches may be in fixed locations or mounted on mobile bases. The end-effector may be equipped with various attachments, including hooks, cameras, electromagnets or robotic grippers.

Cable robots possess a number of desirable attributes, which make them well-suited for a variety of applications. Since the motors may reel out a large amount of cable, they can have very large workspaces [1]. In addition, the motors do not need to be mounted near the end-effector and therefore they are suitable for operating in hazardous environments [2]. Also, their load capacity can be very large, in some cases comparable to construction cranes [3]. Their high payload-to-weight has been utilized in high-speed manipulation tasks [4]. The simple design makes them inexpensive, modular, transportable and reconfigurable. On the other hand, a major challenge in the design and operation of these manipulators is that cables can exert unilateral force (tensile only). The complexities resulted from this constraint are the central issues in the literature pertaining to this type of manipulator. There are several works on the fundamental topics related to cable robots. For example, kinematics [5,22,7], workspace [8–13], singularity [8], stiffness [8,14], statics [22,15], dynamics [16,22,17,18] and control [22,17,18,19,20,21] are extensively investigated.

There are relatively less published works on the optimal design of these manipulators, which is the main contribution of this work. This is perhaps due to the fact that the design of parallel robots is already a complex problem, which becomes rather hard by adding the cable tension constraints. An optimal workspace design of two planar cable robots for global dexterity index is carried out in [23]. In [24], the optimal design of a planar cable robot with respect to tension and stiffness conditions is performed by resorting to a simplex search method. In another attempt, the optimization of a planar cable robot for a maximal dexterous workspace under several load conditions is undertaken [10].

Most of the available works propose numerical search methods for finding design parameters under different assumptions and conditions. As a result, they are computationally expensive and may not find the optimum solution. For cable robots with fewer degrees of freedom and/or translational motions, where the motion has a simpler geometry, line geometry may provide a more powerful tool for analysis and design. The main focus of the present work is to develop and apply a geometrical approach for the design of a large-scale cable-driven robot (LCDR), which possesses three translational motions.

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The most essential issue in cable-driven robots is maintaining positive (tensile) forces in the cables. Landsberger defined tensionability [25] as a property for these manipulators, which indicates whether tensile force can be maintained in all cables while the end-effector undergoes an arbitrary loading.

In [6], the authors introduced LCDR, which is a reduced degree of freedom cable-driven manipulator. LCDR has three pure translational motions. In Fig. 2a, a schematic design of the LCDR is shown. The middle plate is the moving platform (end-effector) and the lower and upper ones are the bases. Three pairs of parallel cables are attached to the moving platform and collected by three spools mounted on the upper base after passing through guide holes on the spool frames. The spool shafts are connected to motors (not shown in the figure) to change the cables lengths. The spools and their frames are attached to the upper base, and their configurations with cables and moving platform form three parallelograms, such as *abcd* shown in Fig. 2b. This is a particular realization of the Delta mechanism [29], which ensures translational motion for the moving platform as long as the cables are taut. To read more about the Delta mechanism, the reader is referred to the extensive literature on this mechanism such as [28,30–32].

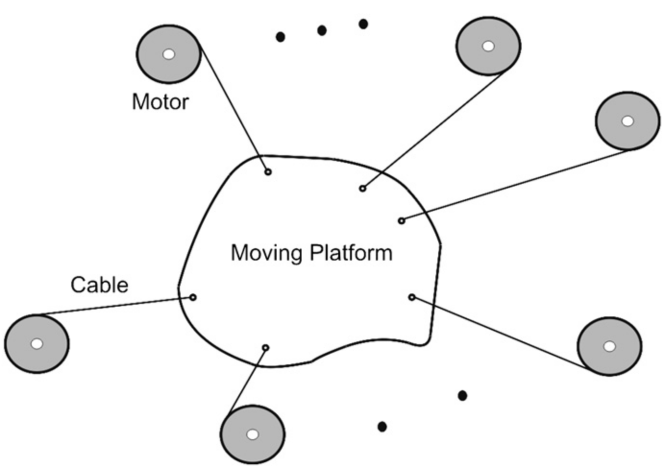

Fig. 1. Cable-driven parallel manipulator.

The lower cables, which consist of three cables and the corresponding motorized spools, are used to maintain tension in the mechanism. Therefore, the robot needs six rotary actuators, such as electrical motors: three motors on the upper base each of which drives one pair of parallel cables and three motors on the lower base to drive the lower cables. It is shown that LCDR is tensionable inside a polyhedron formed by the lower and upper bases [6]. Therefore, as long as the moving platform stays inside this polyhedron, tensile force can be developed in all cables to maintain the rigidity of the manipulator under arbitrary loading. This condition is assumed to be met all the time in the present work whose focus is the development of a design approach for LCDR.

This article presents the design problem of LCDR and the approach that is followed to satisfy the design requirements. The design of LCDR is performed in two stages:

1. Geometrical synthesis of the manipulator in order to fulfill the kinematic requirements, such as the workspace and footprint. Using the results of the previous work on the workspace analysis of the LCDR, and due to its relatively simple geometry, this stage is relatively straightforward as will be briefly discussed in Section 3.
2. Design or sizing of the cables and actuators. In this part, we analyze the required force in the cables in order to perform the given task as well as maintaining tensile force for the rigidity of the robot. As a result of this analysis, the maximum cable forces and hence actuators' torques are found, which are used to size them. The approach can be also used in the operation and control of the robot by finding the cable forces. This is detailed in Section 4.

The design requirements of LCDR are assumed to be given by the following parameters:

1. the footprint of the manipulator,
2. the geometrical workspace,
3. the maximum magnitude of the force to be produced by the end-effector at any position and any arbitrary direction in the workspace,
4. the maximum magnitude of the moment to be produced by the end-effector at any position and any arbitrary direction in the workspace.

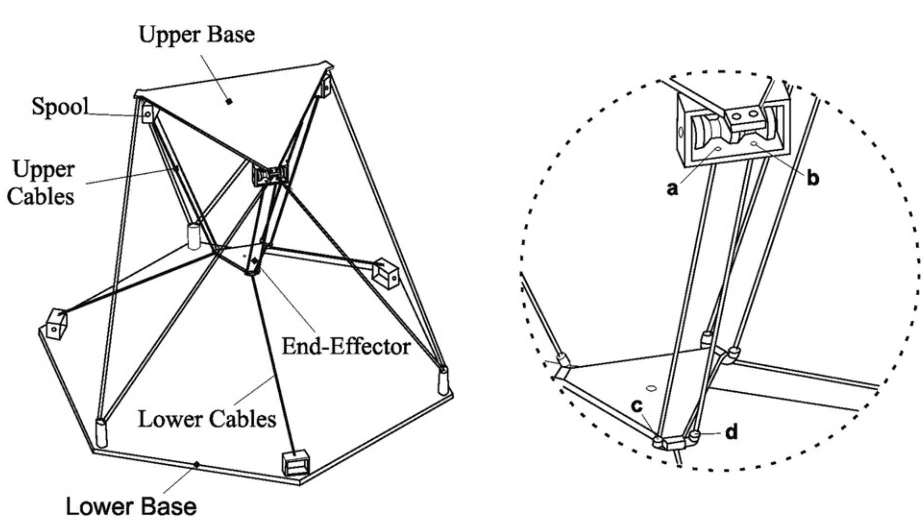

Fig. 2. (a) The general structure of LCDR, (b) parallelogram *abcd* formed by a pair of parallel cable.