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On the effects of the design of cable-Driven robots on kinematics and dynamics models accuracy☆

A. Gonzalez-Rodriguez[a], F.J. Castillo-Garcia[b,*], E. Ottaviano[c], P. Rea[c], A.G. Gonzalez-Rodriguez[d]

[a] School of Industrial Engineering, University of Castilla-La Mancha. Av. Camilo Jose Cela SN, 13071, Ciudad Real, Spain
[b] School of Industrial Engineering, University of Castilla-La Mancha. Av. Carlos III SN, 45071, Ciudad Real, Spain
[c] DICeM, University of Cassino and Southern Lazio, Via G. Di Biasio 43, 03043 Cassino, Italy
[d] Department of Electric Engineering and Automation, University of Jaen, Campus Las Lagunillas SN, 23071 Jaen, Spain

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ABSTRACT

This paper tackles the problem of improving the connection between the fixed frame and the end-effector of planar and spatial cable-driven robots. A new design concept is detailed, which consists in adding pulleys to the attachment between the cables and the end-effector. These reflective pulleys must have the same radius as the ones at the frame in order to compensate their geometry. Without this modification in the end-effector, the usual simplification of the point-to-point method used to model the connection between frame and end-effector leads to significant errors in the Kinematics and Dynamics of the system due to the fact that the geometry of the frame pulleys is disregarded. By adding the reflective pulleys in the end-effector, the equations of the Kinematics and Dynamics of the real system are equivalent to those of the point-to-point model, and therefore, this simplified method can be used without inherent errors. This solution may be of great importance for computational issues because it leads to codes that may run at real time. An analytical proof of the equivalence of both models is presented. Finally, experimental results have been conducted for both, planar and spatial cable-robots, in order to illustrate the advantages of using this novel design concept for the connection between the end-effector and the fixed frame.

1. Introduction

Cable-driven robots are a class of parallel manipulators [1] that consist of a moving end-effector connected to a fixed frame by means of cables [2,3]. The main components are the fixed frame (or structure), the end-effector, cables, and the actuation and transmission system. A cable-based manipulator can operate the end-effector by changing the lengths of cables while preventing any cable of becoming slack.

During the last decade, several planar and spatial versions of cable-driven manipulators have been proposed [4–10]. In all these prototypes and design solutions, cables are commanded by electrical actuators, mainly DC-motors due to the necessary application of a torque control [11] to properly regulate the position/orientation of the end-effector [12]. The usual solution to connect DC-motors and end-effector by means of cables is to use winches that roll each cable in and out, as in [9]. They are attached at the motor shaft and they require the so called guiding pulleys to change the direction of the cables and to transmit force [13]. While the guiding pulleys are used in all cases for guiding cables from the winch to the end-effector, in most of the works the cable attachments on the mobile platform is found in the form of cable attachment pegs, ideally represented by a single point [3,4,7–10,12–14]. Although guiding pulleys are always used, few works describe their influence [15,16], or reduce the positioning error by taking them into account in the kinematic model (e.g. [17]).

A second way to connect a cable at the fixed frame is the rail-based system in which cables are considered as links of constant length, driven by a skid-rail system. Although in most of proposed designs of this type [18] each two skids share a common rail, every skid is separately operated by a DC motor through a drive belt. This makes this design solution similar to a linear drive [19].

On the other hand, most of the published works present cable manipulator designs assuming that no sensor is available for a direct measurement of the end-effector position owing to the fact that this kind of sensors (which provide a precise real time mea-

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* Corresponding author.
E-mail addresses: antonio.gonzalez@uclm.es (A. Gonzalez-Rodriguez), fernando.castillo@uclm.es (F.J. Castillo-Garcia), ottaviano@unicas.it (E. Ottaviano), ottaviano@unicas.it (P. Rea), agaspar@ujaen.es (A.G. Gonzalez-Rodriguez).

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surement) are expensive [20]. Therefore, the most extended solution consists in estimating the end-effector pose by means of the position of the motor/gearbox or pulleys [21,22] and/or the cables tensions [16,23]. Hence, a very accurate kinematic relation between end-effector position and actuator position is needed to estimate the end-effector pose. Depending on the demanded accuracy, two kinds of approaches can be found:

(a) Works in which the kinematic and dynamic effects of the pulleys are neglected and they are only taken into account to calculate the relation between the motor torque and the cable tension, and to estimate cables length variation [24,25]. In this case, these modeling assumptions may cause errors in the estimation of the end-effector pose (which is used as a reference in the control loop) and inherent errors will appear.
(b) Works in which the kinematic effects of the pulley inclusion is assumed and included into the model [17,26]. In this case, the reference error described in a) is highly reduced, although the model complexity considerably increases.

It is less frequent to find works focused on improving mechanical designs in order to reach more accurate models (e.g. [27,28]). In this line, this paper introduces a new design concept that overcomes the problems described in a) and b), without increasing the complexity of such models. It consists in including pulleys in the end-effector that compensates the geometry of the pulleys in the frame. This way, the point-to-point model can be used to obtain an accurate relationship between end-effector pose and joints angles without introducing complex equations that take into account the non-punctual geometry of the pulleys/drums/winches in the frame. Preliminary results were presented in [29].

The remaining of the paper is organized as follows: Section 2 details the conventional modeling for cable robots and the Kinematics and Dynamics errors that originate. Section 3 presents the new design concept for the connection between frame and end-effector, which allows using the simplified models without affecting to Kinematics and Dynamics estimation. Section 4 supports the novel proposal by means of experimental results for both, a planar and a spatial case. Finally, Section 5 summarizes the main conclusions obtained in this work.

2. Problem statement

2.1. Conventional point-to-point model: spatial case

This subsection is devoted to detail the conventional point-to-point model for spatial cable robots. This model assumes that cables connect the frame (from fixed points placed at pulleys centroid) to fixed points at the end-effector, neglecting the effects of the pulley radius.

In a first stage let's assume the planar n cable robot of Fig. 1, in which every cable go from a winch/drum attached to the actuator (Fig. 1 detail 1), then to a pulley (detail 2), and, finally, to a fixed point at the end-effector (detail 3). The lengths of the cables are denoted by L_i, and the elevation angles by θ_i. The rotation angle of each actuator is designed as α_i. Positive values originate negative changes in the cables length, ΔL_i, that can be expressed as $\Delta L_i = -\alpha_i r$, being r the radius of the winches. Therefore, actuators angles can be obtained as

$$\boldsymbol{\alpha} = -\frac{1}{r}\Delta\mathbf{L} \tag{1}$$

In the case of a spatial robot (see Fig. 2), the end-effector pose is defined as $\mathbf{Q} = [x, y, z, \varphi_x, \varphi_y, \varphi_z]^T$, being φ_x, φ_y and φ_z the Tait-Bryan angles used to express the end-effector orientation [30]. Cables connect the frame at [x_{fi}, y_{fi}, z_{fi}] to the end-effector at [x_{ei}, y_{ei}, z_{ei}]. In the same way, the orientation of cables is expressed in spherical coordinates by means of angles θ_i and ϕ_i, where θ_i is the angle between the cable i and its horizontal projection, and ϕ_i is the angle between this horizontal projection and the x axis. In a similar way, and for the segment i linking the end-effector centroid to the attachment point i, the angle ζ_i is the angle between this segment and the horizontal projection, and δ_i is the angle between this horizontal projection and the x axis.

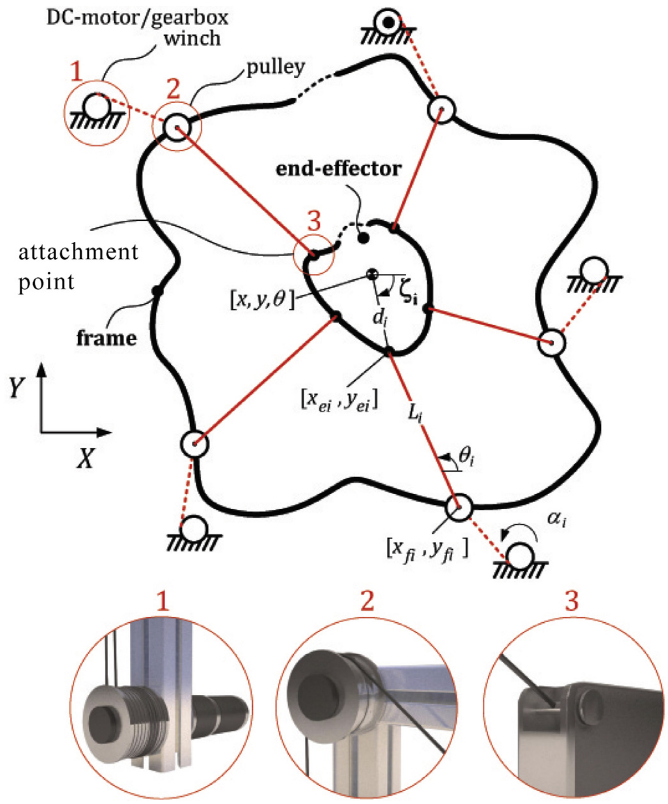

Fig. 1. Conventional planar point-to-point model for n cable-driven robot.

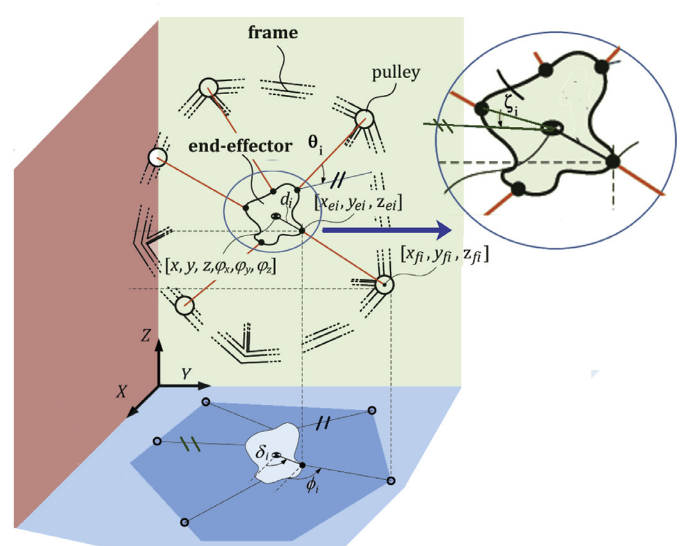

Fig. 2. Spatial cable robot: frame/end-effector connection for point-to-point modeling.