Mechanism and Machine Theory 79 (2014) 64–79

Contents lists available at ScienceDirect

Mechanism and Machine Theory

journal homepage: www.elsevier.com/locate/mechmt

Approximate static balancing of a planar parallel cable-driven mechanism based on four-bar linkages and springs

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ARTICLE INFO

Article history:
Received 6 February 2013
Received in revised form 4 April 2014
Accepted 15 April 2014
Available online 9 May 2014

Keywords:
Static equilibrium
Cable-driven parallel mechanism
Design optimisation
Four-bar linkage
Nonlinear spring
Static balancing

ABSTRACT

In parallel cable-driven mechanisms (PCDMs), the unilaterality of force transmission requires a minimum level of tension in the cables in order to preserve their geometry. As a result, the driving electrical motors need to produce continuous torques to keep the cables taut. We propose to use nonlinear springs to generate these minimum torques, while altering as little as possible the PCDM neutral equilibrium over its workspace. The design of the required nonlinear springs couples a four-bar linkage with commercially available springs. By our approach, the electrical motors only need to produce additional forces, i.e., those forces needed to generate accelerations and balance external forces applied to the end effector. This paper reports the method used to choose the optimum tension profile and the design of the ensuing nonlinear spring. An experimental verification is also performed, where the external forces that must be applied on the end effector to move it across the workspace are measured and compared with those predicted by the kinetostatic model.

1. Introduction

Mechanical static balancing of mechanisms has received sustained interest from researchers, since it allows one to significantly decrease the size of actuators for equivalent displacements of the end effector. Indeed, the actuators do not have to produce the required input energy to counter balance the usual variations of the potential energy of the system between each pose of the end effector. This role is generally rather fulfilled by springs, counterweights, pneumatic or hydraulic cylinders, and even by electromagnetic devices.

Springs are widely used since they do not affect much the mechanism's inertia as counterweights do. For this reason, many researchers have chosen springs in order to statically balance their mechanism. As examples, let us cite the work of Nathan [1,2], which has designed constant force generator mechanisms using springs for an adjustable seat application, and the work of Arakelian et al. [3] and Lin et al. [4], who has worked on the balancing of a leg orthosis and a mobile arm support, respectively. Other authors such as Herder [5], Tuijthof and Herder [6], Streit and Shin [7], Shin and Streit [8], Laliberté et al. [9], Deepak et al. [10], which have worked on the static balancing of different planar mechanisms, have also used springs as fundamental components of their analyses. Other research has focused on the exact balancing of spatial mechanisms [11–13,5,14–16] as well as on their partial gravity compensation [17] in adding either compression, extension, and torsion springs.

Even if, in general, counterweights add inertia to the original system, they have been extensively used as a mean to statically balance mechanisms. From the literature, we can cite, as examples, the work of Russo et al. [18] and Baradat et al. [19], who both combined counterweights with pantograph linkage in order to reach their goal. Also, more recently, Lacasse et al. [20] proposed the design of a statically balanced serial robot by using remote counterweights connected to the robot via a low-pressure

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http://dx.doi.org/10.1016/j.mechmachtheory.2014.04.008
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hydraulic transmission. More generally, other research groups have also used counterweights to statically balance planar and spatial mechanisms [21–24].

If springs or counterweights are not sufficient or practical for a specific application, the use of pneumatic or hydraulic cylinders may be considered. Indeed, some researchers have chosen to rather include these technologies into their design, such as Idan et al. [25] and Windenberg [26], who directly connected these additional components to the moving platform of their mechanism for partial static gravity balancing. Similarly, Segawa et al. [27] proposed the use of permanent magnets attached on the base and on the moving platform of a given mechanism in order to statically equilibrate its weight.

On the other hand, parallel cable-driven mechanisms (PCDMs) are interesting candidates for several robotic applications, because of advantages they hold over conventional robots. Indeed, the low inertias of their moving parts, due to the use of cables instead of rigid links, allows for larger accelerations. Also, the fact that cables are wound on reels leads to the possibility of covering a larger workspace [28]. The modularity and the potential portability of this kind of mechanisms are also additional benefits inherent to their use. Many applications take advantage of PCDM, e.g., the RoboCrane from Bostelman et al. [29], a cable-suspended haptic interface from Williams II [30], the robot Falcon from Kawamura et al. [31], and recently, a very large radiotelescope from Bouchard and Gosselin [32] and a locomotion interface from Perreault and Gosselin [33]. Unfortunately, there are non-negligible drawbacks, which must be taken into account when designing such a mechanism. The main one is the unilaterality of the force transmission in cables, i.e., their inability to push on the end effector. Hence, many researchers have worked on this problem, which is summarised by determining the reachable workspace of the PCDM where a set or all of the possible wrenches can be generated at its end effector by tightening a combination or all of the cables [34–37]. An important result is that $m \geq n + 1$ cables are necessary to suitably constrain an n-degree-of-freedom PCDM [38]. This conclusion leads to the second important disadvantage, which is the possibility that mechanical interferences occur between a pair of cables or between a cable and the end effector of the PCDM while it is moving. Recent work includes a symbolical analysis of this phenomenon [39,40].

However, even if static balancing of mechanisms and PCDMs have been widely studied separately, to our best knowledge, no attention has been given to the static balancing of PCDMs. The proper application of static-balancing principles to PCDMs could lead to better safety and lower power consumption. Indeed, even with partial static balancing, a sudden shortage in electrical power would be less dangerous, as the resulting variation in potential energy would be reduced. Moreover, the maximum torques required from the motors would be smaller, thus reducing their size and weight, and more importantly, their inherent risk for user safety. Currently, the driving electrical motors are used to generate the prescribed accelerations and to balance out the external forces applied at the end effector while maintaining a minimum level of tension in each cable. In this case, continuous torques must be produced by the actuators even if no motion or applied wrench is required. These constant torques may be considered as an unnecessary expenditure of electrical energy. Hence, a conservative, purely mechanical subsystem that could passively generate the required cable tensions would significantly reduce the wasted energy and improve safety.

This paper first proposes a method of designing a nonlinear spring to maintain a given minimum tension in the cables of a PCDM, while approaching neutral static equilibrium over its workspace (see Fig. 1), a method akin to those proposed by Herder [5]. Thence, the desired nonlinear springs are approximated by combining commercial springs with four-bar linkages. More specifically, we report the methodology used to choose the optimal tension profile in the cables and the geometry of the nonlinear springs. An experimental verification of the theoretical results is also presented.

Section 2 describes the three-cable, two-DOF, planar PCDM (PPCDM) used as the experimental testbed for this work. Section 3 presents the optimisation process followed to determine the cable tension profile that best balances the PPCDM. Section 4 reports on the optimisation of the design parameters of the chosen nonlinear springs, namely, the dimensions of the four-bar linkage, the properties of the springs, and the assembly specifications of the subsystem. Finally, Section 5 contains the experimental verification of the theoretical results.

2. Description of the geometry

The geometry of the mechanism used throughout this paper is described such as a three-cable two-DOF PPCDM and its kinematic modeling is presented with Fig. 2. The vector $\mathbf{a}_i$ represents the position of the base-fixed eyelet A_i of cable i in the base frame, vector $\mathbf{p}$ represents the position of the reference point P of the end effector from the origin point O, vector $\mathbf{b}_i$ represents the

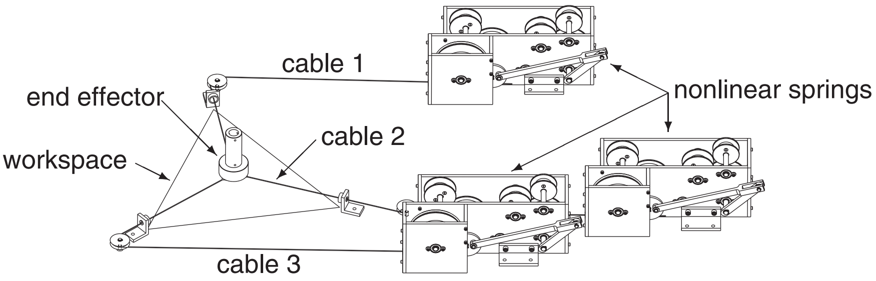

Fig. 1. Computer-assisted design (CAD) 3D model of the two-DOF PPCDM devised benchmark.