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From modeling to control of a variable stiffness device based on a cable-driven tensegrity mechanism

Quentin Boehler [a,*], Salih Abdelaziz [b], Marc Vedrines [a], Philippe Poignet [b], Pierre Renaud [a]

[a] ICube, University of Strasbourg, CNRS, 1 place de l'Hôpital, 67000 Strasbourg, France
[b] LIRMM, University of Montpellier, CNRS, 161 rue Ada, 34090 Montpellier, France

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ABSTRACT

Cable-driven tensegrity mechanisms are now considered for various applications in which their reconfiguration capacities are required together with their inherent lightness. Moreover, they can exhibit interesting variable stiffness capacities through the modification of their level of prestress when composed of deformable cables. Control schemes that deal with both reconfiguration and stiffness variation have however not been developed in the literature yet.

This paper presents two control strategies for that purpose to transform a cable-driven tensegrity mechanism into a variable stiffness device. The mechanism is a planar tensegrity mechanism allowing us to control an angular position and the associated stiffness. Relying on the properties of the mechanism models, the proposed control strategies allow a modulation of the stiffness or of its first time derivative. The interest of both propositions is outlined and an experimental investigation of their characteristics is performed. Encouraging results are obtained in terms of reconfiguration capabilities and stiffness variation.

1. Introduction

1.1. State of the art

Tensegrity mechanisms are a class of self-stressed systems defined as a set of compressed bars in a set of tensioned elements [1] that can be either rigid or elastic cables. Large reconfiguration of such mechanisms can be obtained through the actuation of the bars or the cables. Moreover, high dynamics are usually achievable thanks to their parallel architecture and their structural lightness [1]. For these reasons, the use of tensegrity mechanisms has appeared of great interest in various applications ranging from mobile robotics [2–4], to manipulators [5,6] and deployable systems [7,8].

Besides, the stiffness of a tensegrity structure composed of elastic cables can be drastically modified along specific directions through a modification of the level of prestress within the cables [9]. This interesting property has been successfully exploited in [10] to design a variable stiffness component. Such use is motivated by the interesting results obtained with

* Corresponding author.
E-mail address: q.boehler@unistra.fr- (Q. Boehler).

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similar strategies in the context of variable stiffness actuators [11]. In this case, the stiffness comes from the deformation of a compliant part within the system, such as a spring or a tendon, and a modification of its level of prestress provides a variation of the internal passive stiffness of the mechanism.

Fully exploiting tensegrity mechanisms should allow the modification of the position and the stiffness with a single robotic system. Such capabilities have however not yet been exploited, due to the absence of adequate control strategy. The goal of the paper is therefore to develop such control scheme.

The control of cable-driven tensegrity mechanisms is tedious as cables need to be constantly tensioned. They indeed impose *unidirectional* constraints, contrary to classical parallel manipulators in which the kinematic redundancy can be managed through *bidirectional* constraints [12]. Some prior works have been focused on the configuration control of cable-driven tensegrity mechanisms. For applications in mobile robotics such as [13], the main concern is the generation of a gait pattern to move the system center of mass regardless of an accurate configuration tracking. Positive tensions are then ensured by bounding the actuators range of motion. In more complex mechanisms as the ones assessed in [4,14], this constraint is managed in a quasi-static state using the equilibrium matrix of the system. This aims at finding the actuator states compatible with admissible cable tensions for a stable target configuration. Interestingly, similar constraints are encountered when considering cable-driven robots. A platform is then connected to the ground by cables whose lengths are coordinately modified to control the platform pose. In this case, the problem of unidirectional constraints is generally solved using tension distribution algorithms [15]. Until now, such algorithms aimed at finding the most suitable cable tensions within an admissible positive range [16,17]. The only goal is then to avoid negative tensions in the cables by discarding the non-compatible actuators state. A modulation of tension within its compatible range is of interest in our context, in order to bring a stiffness variation to the system.

1.2. Contributions

Our objective is to introduce control strategies for position and passive stiffness control of tensegrity mechanisms. To do so, the case study of a planar cable-driven tensegrity mechanism is used. Such a mechanism is interesting for the achievable control of an angular position and the associated stiffness. Its modeling properties are identified and control schemes built from them.

Our contributions include the development of two adapted control strategies that are shown to fulfill our objectives, while being complementary. Both are dealing with the system redundancy, and they provide a modulation of the system stiffness or of its first time derivative. The first strategy exploits a tension distribution algorithm inspired from those implemented in cable-driven robots. The second one proposes a novel velocity distribution algorithm. An implementation and an evaluation of these developments are achieved through the control of the considered planar cable-driven tensegrity mechanism. Their characteristics and their relative performances are experimentally assessed and discussed.

The modeling of the considered mechanism is first developed in Section 2. The two control strategies are then presented in Section 3. An experimental validation of our approach on a dedicated setup is presented in Section 4 and results are discussed in Section 5. Conclusions and perspectives in terms of generalization are finally given in Section 6.

2. System modeling

2.1. Description of the mechanism

The tensegrity mechanism under study is depicted in Fig. 1. It is a planar mechanism composed of three moving bars and one bar linked to the base, all of equal length L. The four bars are considered as perfectly rigid and articulated by four pin joints in A, B, C and D. The obtained parallelogram linkage is actuated by two inelastic cables attached in C and D, passing respectively through A and B. It is a class-2 tensegrity mechanism [18] as the bars are compressed by the two tensioned actuated cables. It is considered as a 1-DOF mechanism whose end-effector is the bar BC, and its configuration is described by the angle θ. Such a mechanism can for instance be integrated in medical applications [19,20]. Two linear springs of stiffness k are integrated along each cable to bring compliance to the linkage when the cables are tensioned. The end-effector angular stiffness is denoted K_θ. The distances AC and BD are respectively denoted l_1 and l_2 and can be computed as

$$\begin{cases} l_1 = 2L\cos(\theta/2) \\ l_2 = 2L\sin(\theta/2) \end{cases} \tag{1}$$

The two lengths will be noted with the compact form $\mathbf{l} = [l_1, l_2]^T$. Cables are actuated by two actuators whose angular positions are described by the vector $\boldsymbol{\alpha} = [\alpha_1, \alpha_2]^T$ (Fig. 1). Pulleys of radius R are mounted on the actuators so that $\mathbf{q} = [q_1, q_2]^T = -R\boldsymbol{\alpha}$ describes the cable displacement. The springs are the only compliant elements in the system, structural elements and actuators being considered rigid. They reach their free length for $\mathbf{q} = \mathbf{l}$ as each length q_i, $i \in [1, 2]$ is measured from the cable take-off point on the actuated pulley to the actuator-side end of the i-th spring. In the following, $\mathbf{q}$ is designated as the *articular variables*, and the configuration of the system is represented by the *operational variable* θ.