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Effect on wrench-feasible workspace of cable-driven parallel robots by adding springs

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ABSTRACT

Cable-driven parallel robots (CDPRs) possess a number of promising advantages over conventional rigid-link robots, such as light weight, large payload handling capacity, considerably large workspace, and simpler dynamics. However, since cables can only pull but not push its attachment point on the end-effector, it is usually challenging for the wrench-feasible workspace (WFW) of CDPRs to meet the design requirements. Therefore, redundant cables or load on the end-effector is used to attain the required workspace. In this paper, springs are added between the end-effector and a base with the goal to modulate the workspace. The effects of different parameters of the spring on CDPR's wrenches are investigated and an optimization is proposed to determine the feasible spring parameters. Workspaces of two planar and spatial examples are presented. A reshaped workspace validation experiment was conducted. These results show that springs, with properly chosen parameters, can increase or reshape the WFW of CDPRs to meet the specified design requirements.

1. Introduction

Compared with traditional parallel robots, cable-driven parallel robots (CDPRs) have the following desirable characteristics – light weight, large payload handling capacity, considerably large workspace, and simpler dynamics – by virtue of the cable actuation. Based on these characteristics, CDPRs have found their way into the following novel designs and applications: Robocrane [1,2], SEGESTA [3–5], IPAnema family [6–9], five hundred meter aperture spherical radio telescope (FAST) [10–12], KNTU [13], Tethered Pelvic Assist Device (TPAD) [14,36,37], Cable-driven arm exoskeletons [15], automated Cable Crane [16,17], MARIONET [18], DeltaBot [19], Spidercam [20], and Skycam [21]. In all these applications, an end-effector is driven in-parallel using cables which are deployed or retracted by actuated winches.

However, for CDPRs, a critical issue is the unidirectional nature of forces exerted by cables, which must remain in tension while performing tasks. Hence, only those reachable points of the end-effector are feasible where cables remain in tension. The feasible workspace of CDPRs can be defined as the set of poses (positions and orientations) for the end-effector where the required wrenches (force and moment) can be delivered with all cables in tension. Usually, if one or more cables become slack unexpectedly in special poses, often called a singular pose, the robot loses its rigidity.

Different workspaces have been identified in the literature: Static Equilibrium Workspace (SEW) (Agrawal et al. [22]) is the set of poses that the end-effector can attain statically, taking into account the gravity loads, with all cables in tension; Wrench-closure Workspace (WCW) [23,24] is defined as the set of poses in which the end-effector can physically maintain equilibrium with all cables in tension; wrench-feasible workspace (WFW) is the set of poses that the end-effector can exert or balance (bounded) wrenches with

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tension in the cables remaining within a prescribed range (usually between the allowable minimum and maximum tension values) [25,26]. Since cables can only pull, the workspace of CDPRs depends not only on the geometry but also on the limits of cable tensions. In order to fully control a CDPR with n degrees-of-freedom (DOFs), a minimum of $n + 1$ cables are needed to guarantee that all cables are in tension at a point in the workspace [29]. Other extra actuated cables lead to additional planning and control methods to keep the desired tensions in the cables.

In order to increase the performance of a cable system, the end-effector mass can be increased to have a larger gravity force or springs can be added. Intuitively, springs may keep cables in tension with properly chosen placement parameters. Russell proposed a CDPR to perform sub-millimeter operations where a compression spring was used to keep cables in tension [27]. Trevisani et al. proposed a planar translational CDPR with a linkage mechanism tensioned with two torque springs to prevent slacking in the cables [28]. It was pointed out that the introduction of springs can increase the workspace of single or multi-body cable-driven robots [29,30]. The use of passively guided compliant subunits and energy-storing elements can increase the application range of wire-driven robots [31–33]. von Zitzewitz et al. described that the eigenmotion of the oscillator consisting of an end effector and the attached springs was capable of reducing wire forces generated by the active components for a given task. A first discussion of optimizing the springs not only for a workspace, but for a defined trajectory was presented in [31]. Gao et al. proposed a cable-driven flexible parallel robot with three cables and a compression spring to mimic a human neck [33]. However, to the best knowledge of the authors, there are only a few studies that have attempted to systematically analyze the impact of adding springs on the workspace of CDPRs.

This paper addresses the workspace of CDPRs by adding springs. The effect on the WFW of general CDPRs with springs is analyzed. Optimal design of spring parameters is investigated to meet the specific design requirements of the workspace. The organization of this paper is as follows: Section 2 presents the kinematic and dynamic model of CDPRs with springs. The effects of different spring parameters on CDPR's wrenches are explored. Additionally, an optimization model to determine the spring parameters is proposed in Section 3. Numerical examples demonstrating the workspace changes with added springs are included in Section 4. A reshaped workspace validation experiment was conducted in Section 5. These are followed by concluding remarks.

2. Kinematic and dynamic model of CDPRs with springs

It is assumed that cables have negligible mass and do not stretch. A general model of a spatial CDPR which consists of a moving end-effector driven by n supporting elements, m (≥ 3) actuated cables and n–m springs, is shown in Fig. 1. A global frame $Oxyz$ is located at O and a local frame $O_1x_1y_1z_1$ is fixed to the end-effector at its center of mass. The direction of gravity is selected to be the negative z-axis of the global frame. The position vector of point B_i is denoted by the vector ${}^1\boldsymbol{b}_i = [{}^1x_{bi}, {}^1y_{bi}, {}^1z_{bi}]^{\mathrm{T}}$ in the local frame and that of point A_i is denoted by $\boldsymbol{a}_i = [x_{ai}, y_{ai}, z_{ai}]^{\mathrm{T}}$ in the global frame. These are fixed points in the two respective frames, where $i = 1, 2, \ldots,$ n. Cables and springs are attached to the fixed points A_i and B_i on the end effector, which correspond to the vectors in the global coordinate system, $\boldsymbol{r}_{Ai}$ and vector $\boldsymbol{r}_{Bi}$, respectively. The cable vector can be kinematically defined as

$$\boldsymbol{l}_i = \boldsymbol{r}_{O1} - \boldsymbol{r}_{Ai} + \boldsymbol{r}_{Bi}. \tag{1}$$

According to Newton–Euler's law, output wrenches (forces and moments) on the end-effector O_1 can be written as

$$\boldsymbol{W} = -J^T\boldsymbol{f} \tag{2}$$

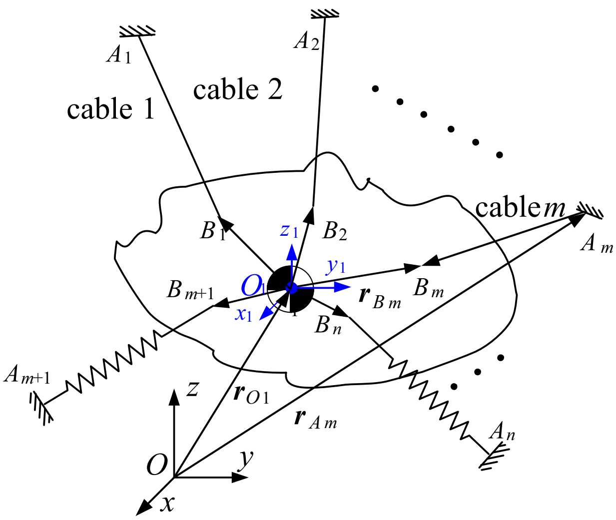

Fig. 1. A spatial CDPR with springs.