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Collision-free and dynamically feasible trajectory of a hybrid cable–serial robot with two passive links

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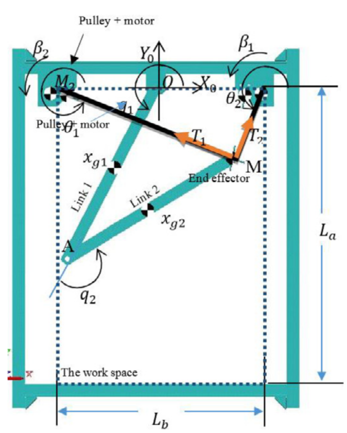
HIGHLIGHTS

- A path planning algorithm avoiding obstacles and taking into account dynamics is applied to a hybrid cable–serial manipulator in order to find the shortest and the fastest path.
- Cable tensions have to be bounded during the motion of the robot in order to ensure stability of the end-effector.
- Two cases were presented and the simulation results proved the effectiveness of our approach.

GRAPHICAL ABSTRACT



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ABSTRACT

In this work, a dynamic path planning algorithm is applied to a hybrid cable–serial manipulator in order to find the shortest and the fastest path while ensuring bounded tensions in the actuators cables. The trajectory is given by a geometric planning method, originally proposed for serial manipulators and adapted to a hybrid cable–serial robot. The obtained trajectory ensures the shortest path between two poses of the robot while avoiding obstacles. The dynamic planning algorithm is then applied to the obtained trajectory, to ensure a maximum velocity and acceleration, while keeping the tensions in the different cables within an allowable interval.

Some simulation results are presented in order to show the effectiveness of the proposed dynamic path planner.

1. Introduction

One major requirement for robotic systems is the capability of handling important masses and high inertia loads. In [1], the goal of the "Robocrane" is lifting, maneuvering and positioning heavy loads with high accuracy in all six degrees of freedom, such capability had revolutionized the way cranes operate. In [2], another robot like crane was suggested to be used for loading ships. Other examples of suggested applications such as the use of cable robot in high speed manipulations, were proposed in [3]. The "WARP" a cable based manipulator can be used for fast assembling

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semiconductors or any lightweight objects, however, this type of manipulators requires a redundant actuation [4].

In the literature, many researchers studied cable robots and tried to classify them [5]. Control strategies were proposed for each type of application. In [6], a helicopter carrying a cable suspended robot is studied. In [7], cable robots are applied in construction. Crane type robot are studied in [8,9]. In [10], translational planar cable robots were studied. The dynamic workspace was studied in [11–13] in order to identify feasible trajectories. More recently, in [14,15] elastic cables were used to design parallel robots. The use of four-bar linkages, along with a spring, is suggested in order to provide static tensioning in the cables and to reduce the need for a continuous actuation.

Some studies addressed the issue of vibration of the end effector in cable robots [16,17], which is one of the main limitations of cable robots.

In order to eliminate the limitations encountered in using cable robots, hybrid cable–serial robots were proposed in the literature [17–19]. The serial robot motion is provided through cables pulling on the end-effector by motors not directly mounted on the joints, which replaces the classical way of actuation. The elimination of the joint actuators yields a robot with low moving inertia. Thus, the dynamic capabilities of hybrid cable robots are enhanced.

The control of such hybrid robots remains challenging and poorly studied, especially when trying to achieve a high velocity and acceleration of the end-effector, while maintaining positive bounded tensions in the cables [20]. In [18], the authors used a hybrid robot for force display. In [21], the authors studied the inverse dynamics of wire-actuated parallel manipulators with a constraining linkage. The proposed robot was redundantly actuated. More recently in [22], the authors proposed a cable suspended walking robot "Spider-Bot" that uses four cables actuated one at the time. In [17] the authors suggested a three link passive serial support cable robot as an extension to the work done in [19].

The issue of the workspace of such robots was addressed in [23]. Some authors showed that the serial manipulator along with the cables have a limited workspace and complicated collision avoidance path planning [24].

One emerging application of these robots is medical rehabilitation. In [25,26], a hybrid serial–cable robot is used for upper limb rehabilitation. In [27] an exoskeleton is used for neural rehabilitation, while in [28] gait and posture were restored using a hybrid cable–serial robot. For this type of applications, the serial structure provides a better accuracy, reduction of the out of plane compliance compared to traditional cable robots.

In this work, a dynamic joint space controller is developed for a hybrid serial–cable robot, along with a feasible trajectory planning algorithm. A feasible trajectory requires obstacle avoidance and bounded cable tensions in the cables. This paper is organized as follows: Section 2 contains the hybrid system description. Section 3 presents the dynamic model of the system. Section 4 contains the joint space controller. Results and discussion are presented in Section 5. Some concluding remarks are then presented in Section 6.

2. System description

The hybrid serial–cable robot studied in this work is a planar, under constrained and fully actuated robot (see Fig. 1). It has two degrees of freedom, and it moves in a vertical plane. The robot includes a serial support composed of two links and two passive joints. The two cables are attached to the end-effector and winds around two pulleys, which are actuated using two motors. The two links undergo the effect of gravity and it is supposed to be the only

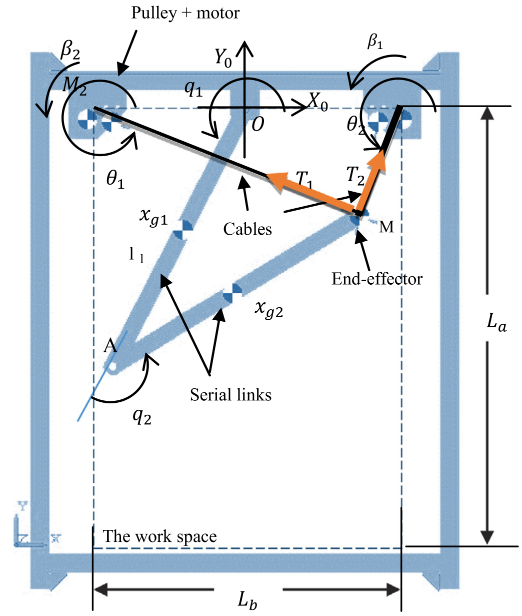

Fig. 1. Hybrid parallel/serial robot.

Table 1
Serial robot characteristics.

Serial robot	Link 1	Link 2
Length	$OA = l_1$	$AM = l_2$
Mass	m_1	m_2
Inertia	J_1	J_2
Center of gravity	x_{g1}	x_{g2}
Mass of the end-effector	m	
Joint parameters	$\mathbf{q} = \begin{bmatrix} q_1 & q_2 \end{bmatrix}^T$	
End-effector position	$\mathbf{x} = \begin{bmatrix} x_1 & x_2 \end{bmatrix}^T$	
Inertia of the end-effector	j	

Table 2
Cable robot characteristics.

Cable robot	Cable 1	Cable 2
Length	$M_1M = L_1$	$M_2M = L_2$
Tension	T_1	T_2
Orientation	θ_1	θ_2
Actuator angles	β_1	β_2
Location	$OM_1 = \frac{L_b}{2}$	$OM_2 = \frac{L_b}{2}$
Inertia of the pulleys and motors 1 and 2	$\mathbf{J} = \begin{bmatrix} j_1 & j_2 \end{bmatrix}^T$	
Pulleys viscous friction	$\mathbf{c}$	
Pulley radius	r	

external force applied to the system along with the two torques of the actuators.

The geometric parameters of the system are presented in Fig. 1. The serial manipulator and the end-effector characteristics are given in Table 1, while the cable robot characteristics are given in Table 2.

3. Cable driven robot modeling and simulation

In this section, the robot model is discussed. The position of the end-effector can be given by either the two angular joints positions of the serial link q_1 and q_2, or by the pulleys angular position β_1 and β_2.

3.1. Kinematics modeling

In this section we present the forward and the inverse kinematics description of the studied cable driven robot. The