First Experimental Testing of a Dynamic Minimum Tension Control (DMTC) for Cable Driven Parallel Robots

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Abstract Cable tension distribution is an important issue in parallel cable-driven robots to obtain high efficiency and accuracy of motion. In this paper, a novel approach is introduced to optimize cable tension distribution of cable-driven parallel robots, which consists in modifying the minimum tension of the cables according to the dynamics of the system. This method has been compared to the traditional, fixed-minimum tension approach on a 2-cable, 1 DOF test bed with different settings of the controller. First experimental results showed that Dynamic Minimum Tension Control (DMTC) can be better than traditional approaches in terms of accuracy and energy consumption.

1 Introduction

Cable-Driven Parallel Robots have a short but growing history. They can be defined as closed loop mechanisms consisting of multiple actuated cables and an end-effector. There are some advantages such as very large workspace and high acceleration due to less mass and inertia, however inaccuracy and necessity of cables to be in tension can be regarded as disadvantages. Cable driven systems have been used widely in different applications. SkyCam [1], rehabilitation [2], and high speed manipulation [3] are the most important applications of such systems.

Recently, there have been major advances in different fields of cable driven robots related to statics, dynamics, control and design [4]. Performance study and cable tension distribution are some of the most significant subjects which were discussed by different researchers. In these studies, a maximum limitation of cable tension has been considered based on cable and actuators properties, and a minimum boundary is usually set to keep cables in tension to reduce control issues and vibrations. Several

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algorithms were proposed to find the most efficient cable tension in this range, to apply the smallest torque values without changing the working condition.

Different solutions have been derived accroding to the level of redundancy of the system being controlled, but all of them employ a fixed value for the minimum allowable tension in the cables. The most common algorithm of CRPMs cable tension distribution consists in finding the set of cable tensions, among those ensuring the desired end-effector wrench, which has at least one cable at minimum tension [5].

In the case of overconstrained cable robots, many researchers investigated on estimation of optimal tension distribution using linear, and quadratic programming. Shiang et al. [6] proposed a standard linear programming to minimize sum of all tensions while maximizing tension on two longest cables in order to refuse any kind of slack on a four-cable array robotic crane. In [7] an analytical solution was suggested based on sum of tensions along cables as small as possible at every pose of platform without violating the controllable workspace condition. The minimum Tension was chosen referring to some experiments for an accurate path tracking in a completely constrained 6-DOF robot.

Pham et al. [8] proposed a recursive algorithm to check the existence of positive torques, and then optimized torque objective function with linear programming. In another study, tension distribution has been implemented by feedback linearization, however some modifications were suggested in case of mathematical constraints or negative force [9]. Necessity of finding a proper starting point and possibility of jump from one extreme point to another between successive computations are problems of LP, however with introducing an optimally safe tension distribution with a slack variable, fast generation of proper starting and optimal point were gained [10]. Moreover, quadratic programming methods for estimation of two-norm optimal tension distributions were applied [11, 12], and Lim et al. [13] proposed a gradient programming method and compared it to linear and quadratic programming.

Furthermore some other methods based on convex optimization for minimization of actuator forces were applied [14]. Minimization of p-norm [15], and L1-norm optimization [16] have been applied for tension distribution, however Mikelsons et al. [17] investigated on safe tension distribution using noniterative method to gain higher robot stifness. Also since the fingers of a grasp are unidirectional, some relationships between planar cable-driven robots and spatial antipodal grasp theorem were studied to achieve proper cable tension distribution [18].

Pott et al. [19] had proposed a closed form solution which has been modified in his recent study [20]. In addition, properties of different cable tension distribution methods were explained and compared regarding to some factors such as computational speed, workspace coverage, capability of real time responses, applicability for different redundancies and force margin. This comparision shows that each of common methods have some kinds of problems and are not capable of controlling all kind of cable driven robots efficiently.

In this paper, we propose a novel approach for cable tension calculation, based on the estimated dynamics of the end-effector, which sets a dynamically variable value for the minimum tension of cables according to the desired wrench. The algorithm has been tested on a 2-cable, 1 DOF prototype, and results were compared

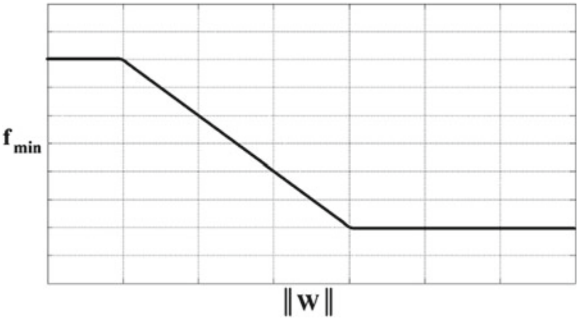

Fig. 1 Sample mapping function used for changing the minimum cable tension $f_{\min}$ according to the absolute desired wrench W

with traditional, fixed minimum tension methods. In Sect. 2, the new algorithm is described. Section 3 presents the experimental setup and the analysis of results.

2 Dynamic Minimum Tension Control

The main idea behind the DMTC control consists in dynamically calculating a suitable minimum value of the lower boundary $f_{\min}$ of cable tension, before applying a standard tension distribution algorithm. The main difference with already existing approaches lies in that the value of $f_{\min}$ is not fixed. On the contrary, it is changed on-the-fly according to the dynamics of the end-effector. More precisely, $f_{\min}$ is increased when the *desired end-effector wrench* W is small, and it is decreased when its absolute value gets greater.[1]

The main reason for adjusting $f_{\min}$ is that, on the one hand, higher values of $f_{\min}$ are preferrable, as they allow to avoid cable slacking and they usually yield higher positioning accuracy [7]; on the other hand, increasing $f_{\min}$ can lead to saturation of actuators, especially when the total wrench W is large. Based on such considerations, we propose to reduce $f_{\min}$ as long as the absolute value of W increases, and to restore higher minimum tensions when it gets close to zero, as qualitatively shown in Fig. 1. Such an approach can be applied to any cable-driven parallel robot, regardless the number of cables and the number of degrees of freedom, as the mapping function converts one scalar quantity (the absolute desired wrench) into another scalar quantity (the minimum tension of the cables). In the implementation presented in this paper, this is obtained using a look-up table (LUT).

It is well known that the static equilibrium of an n-DOF cable driven robot, controlled by m cables, can be expressed by the following linear equation system:

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[1] For such systems with rotational and translational degrees of freedom, the units in the wrench vector W must be normalized before calculating its absolute value, e.g., by dividing the torques by the pulley radius.

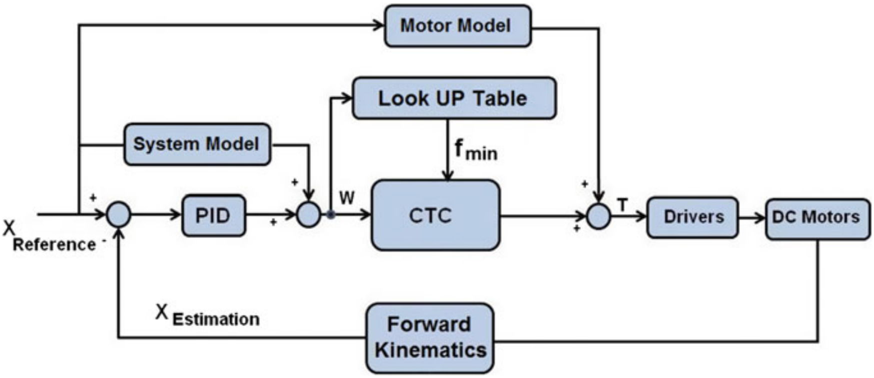

Fig. 2 Schematic of a position control using the Dynamic Minimum Tension Control (DMTC)

$$AT = W \tag{1}$$

where A $\in \mathbb{R}^{n\times m}$ is the structure matrix of the robot, W is the wrench applied to the end-effector, and T is the vector of cable tensions, which can be written as:

$$W = \begin{bmatrix} F \\ M \end{bmatrix} \in \mathbb{R}^n \qquad T = \begin{bmatrix} T_1 \\ . \\ . \\ . \\ T_m \end{bmatrix} \in \mathbb{R}^m \tag{2}$$

It has been demonstrated in [21] that, as long as the end-effector lies in the force-closure workspace, vector T can be calculated by taking the sum of one particular solution T_p of system (1) and one vector belonging to the kernel of the matrix A with all positive components, which we call T_k, whose norm increases with $f_{\min}$:

$$T = T_p + T_k = T_p + N\lambda(f_{\min}) \tag{3}$$

where $N \in \mathbb{R}^{m\times(m-n)}$ is a basis of the kernel of A; $\lambda \in \mathbb{R}^{m-n}$ contains the weights of the linear combination of the columns of N yielding T_k. By properly chosing the vector λ, the vector T will hold at least one cable at tension $f_{\min}$ and all others cables at $f_{\min}$ or greater. Clearly, by reducing $f_{\min}$ we will get a vector T satisfing system (1) with reduced norm. This is particularily clear, for example, in the case of planar point-mass CRPMs, where for a given direction of the desired force W, there will be at least one cable whose direction is opposite to that of W (in the sense that the dot product between the desired force W and the direction of the cable will be negative), so the reduction of its tension ($f_{\min}$) will help reducing the tension in all other cables.

Figure 2 presents a schematic of a position control using the DMTC approach. The output W of the controller, given by the sum of feedforward and feedback actions,

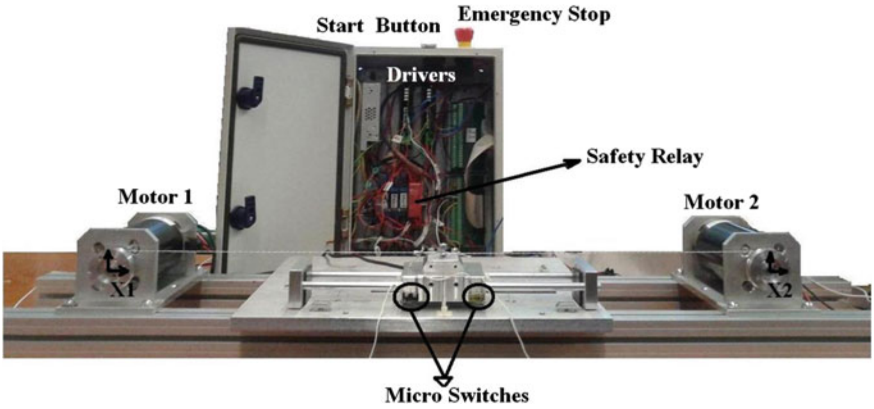

Fig. 3 Experimental setup for testing optimal force distribution

enters the DMTC block which calculates $f_{\min}$. Both W and $f_{\min}$ enter the Cable Tension Computation (CTC) block, which outputs reference to drivers. Position feedback by encoders closes the feedback loop. A similar approach, except from the DMTC, is that presented by Lamaury et al. in [22], where they proposed the PID position control in the Cartesian space of a 6-DOF cable-suspended parallel robot, based on forward kinematics and on a particular PID tuning procedure. Clearly, the DMTC approach can be applied also in the case of joint space position control, provided that also in this case the output of the controller is the end-effector wrench, which is obtained from the motor torques vector by using the pseudo-inverse of the Jacobian matrix.

3 Experimental Setup and Results

To test the new method, a 1 DOF cable-driven robot with two DC motors and a slider (end-effector) was built (Fig. 3). One linear and two rotational encoders were used to measure the position of the slider and of the motors. This plant was connected to a PC via a PCI Multifunction I/O Sensoray626 board to control the system by Matlab and Simulink RTWT.

In the feedforward loop, slider friction was modeled as a function of velocity, based on sum of Stribeck, Coulomb, and viscous components, which were estimated through experiments. In the feedback loop, the position of the end-effetor was estimated using rotational encoder readings, with additional compensation of cable elongation. The linear encoder was used only to measure the actual position of the end-effector for final assesment of controller performance.

The CTC block distributed the force in the two cables by simply imposing their tensions to $f_{\min}$ and $W + f_{\min}$, according to the direction of W. Then, it calculated

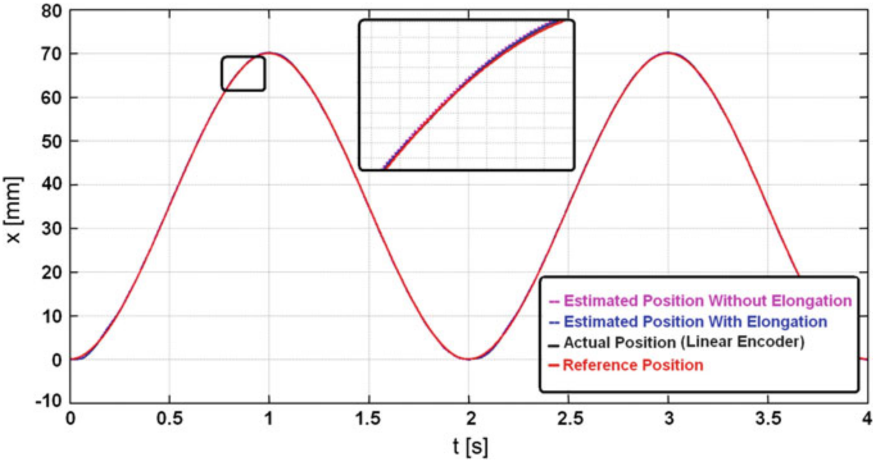

Fig. 4 Comparision of motion reference and position estimation of encoders

the current reference for the drivers in two ways: either proportionally to the desired cable tension (CTC1), or by calculating a position reference for each motor and yielding to the driver a PID control action to track this reference (CTC2). The CTC1 implements a very easy but not accurate controller, which totally neglects actuator dynamics. Such solution can be used only with very slow motion, when actuator dynamics is negligible. The CTC2 implements a more accurate controller, which in turn requires a model of cable elasticity to compute motor position reference and the tuning of a PID controller for each motor.

We used a periodic, third degree polinomial reference (see Fig. 4), with various frequencies (0.5, 1 and 2 Hz) and fixed amplitude (35 mm). Each reference was tested with both CTC algorithms and with four different minimum tensions: LUT, 1, 4 and 7 N. An upper bound of 30 N was used for cable tension. In LUT mode, the minimum tension varied between 1 and 7 N according to the absolute value of W.

To compare the different working conditions, the variance of position error and a power-related index were used. The former was calculated as the variance of the difference between reference and actual (linear encoder) positions. The latter was calculated as the average sum of the squared current references provided to the drivers. Measures were repeated during ten periods (i.e., twenty travels of the slider).

A Comparative Index i_C was also calculated, given by the following expression:

$$i_C = \frac{var_x}{var_{LUT}} * \frac{i_{P,x}}{i_{P,LUT}} \tag{4}$$

where var_x is the variance of error with $f_{\min} = x[N]$, $i_{P,x}$ is the power index in the same condition, whereas LUT values refer to LUT $f_{\min}$. We will consider a value of i_C greater than one as an indicator that the LUT method outperforms the fixed $f_{\min}$ method. In fact, if $i_C > 1$, the ratio between the performance parameters must be

Table 1 Comparison of LUT and fixed minimum tension with different references and CTC1

Frequency (Hz)	Minimum cable tension	Error variance	Power consumption	Comparative index
0.5	Look-Up Table	0.00376	2.77	—
	1 N	0.00498	1.58	0.756
	4 N	0.00399	3.21	1.230
	7 N	0.00358	5.34	1.836
1	Look-Up Table	0.00709	2.87	—
	1 N	0.00839	1.27	0.524
	4 N	0.00759	2.69	1.003
	7 N	0.00677	5.18	1.723
2	Look-Up Table	0.0537	3.67	—
	1 N	0.131	1.58	1.050
	4 N	0.0701	3.64	1.295
	7 N	—	—	—

more than one in at least one case, indicating superiority of LUT for such parameter; on the other hand, the other parameter may yield a ratio lower than one, but with a smaller difference.

Results are summarized in Tables 1 and 2. The LUT method tends to provide better results, as measured by the comparative index, considering a mix of accuracy and power consumption. This result holds especially when the LUT method is compared to a fixed maximum tension mode where $f_{\min}$ equals the maximum value provided by the LUT. In this case, the LUT method yields comparable accuracy with less power consumption with respect to the fixed mode. The greatest difference is obtained with CTC1 (simplest control).

When compared to fixed modes with reduced constant tension, the LUT mode performs better in terms of accuracy, but yields greater power consumption. In such cases, the comparative index may be close to one or even smaller than one. The latter case indicates that the relative (percentage) benefit in terms of accuracy is smaller than the increase in power consumption.

Figure 5 shows the plots of power consumption versus variance of position error for all testing conditions. Each plot refers to a specific CTC and frequency condition, and renders in blue the three fixed modes, in red the LUT mode. Blue points are connected with lines to highlight the trend. The plots in Fig. 5 indicate that an increase in accuracy is usually obtained through greater power consumption. They also show that the LUT method tends to stay below the trend of the fixed modes, although further testing is needed to verify if this holds also for different settings of the LUT.

Table 2 Comparison of LUT and fixed minimum tension with different references and CTC2

Frequency (Hz)	Minimum cable tension	Error variance	Power consumption	Comparative index
0.5	Look-Up Table	0.00173	1.09	—
	1 N	0.00196	1.02	1.060
	4 N	0.00142	1.38	1.039
	7 N	0.00125	2.12	1.406
1	Look-Up Table	0.00591	1.03	—
	1 N	0.00646	0.958	1.017
	4 N	0.00595	1.15	1.124
	7 N	0.00432	1.78	1.263
2	Look-Up Table	0.0674	1.69	—
	1 N	0.0789	1.45	1.004
	4 N	0.0737	1.61	1.042
	7 N	0.00624	2.26	1.238

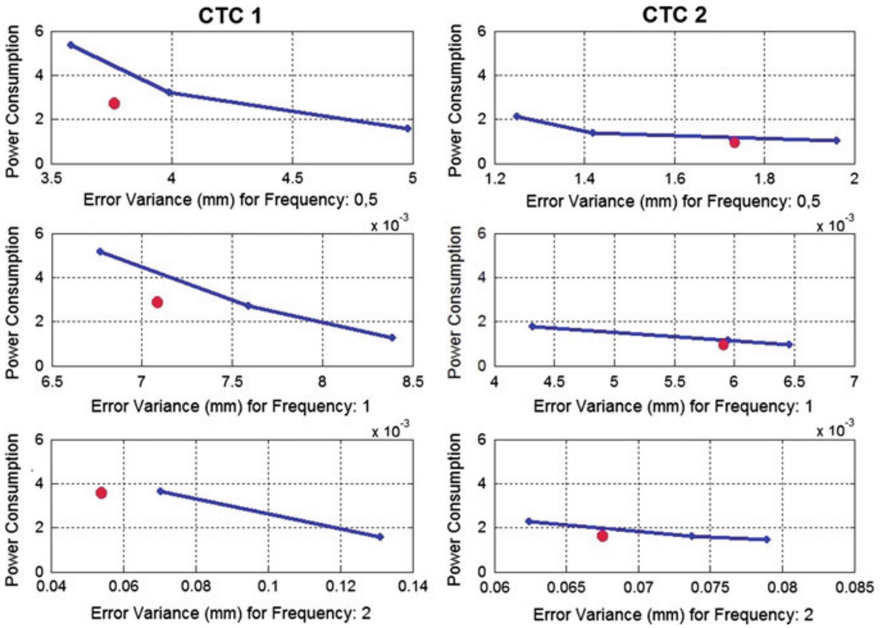

Fig. 5 Prediction of cable tension estimation for constant minimum value and look up table

4 Conclusion

In this paper, a dynamic minimum tension control for cable-driven robots was proposed and tested on a simplified scenario. This method is based on changing the minimum tension of cables according to the dynamics of the system. In particular, minimum cable tension is reduced when the end-effector wrench is large, with the aim of avoiding saturation of actuators and limiting power consumtion.

First experimental results show that this approach yields large benefits in terms of power consumption, although a reduction in accuracy is observed, especially with slow reference. When compared to fixed minimum tension modes with smaller minimum tension, the DMTC control performs comparably to the fixed modes, except when the fixed value becomes extremely small.

One limitation of this study is that the experimental setup included a single-dof system, so further testing is needed to verify if the DMTC concept can be applied succesfully in more complex contexts. Moreover, our system had a quite high friction, due to the coupling of the slider, which may have influenced results, and which is not usually present in cable-driven parallel robots. On the other hand, this setting allowed for precise measurement of end-effector motion. Finally, further investigation is needed to tune LUT parameters with the aim of obtaining the best trade-off between acuracy and power consumption.

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