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Improving Performance of Cable Robots by Adaptively Changing Minimum Tension in Cables

Saeed Abdolshah[1] and **Giulio Rosati**[1,#]

1 Department of Management and Engineering (DTG), University of Padua, I-35131 Padova, Italy
Corresponding Author / E-mail: giulio.rosati@unipd.it, TEL: +39-049-827-6809, FAX: +39-049-827-6816

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Higher tension in cables of a cable-driven parallel robot is preferable due to increased stiffness, higher disturbance rejection, better trajectory tracking performance and more precise motion; however, cable tension augmentation can result in saturation of actuators and high-energy consumption. This paper is devoted to investigate if dynamically changing the minimum tension in cables can allow achieving an efficient motion in term of power consumption, while preserving good trajectory tracking performance. The proposed method changes the minimum tension on-the-fly according to stiffness, dynamics of the system, and error values as feedback. A simple cable robot prototype has been used to compare traditional fixed minimum tension utilization, and the proposed approach. Experimental results showed that application of our method improves motion accuracy and reduces energy consumption of the robot.

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1. Introduction

In the recent past, the application of cable-driven systems has risen significantly; some examples are Skycam,[1] rehabilitation,[2,3] surgical robot instruments,[4] passive brake mechanism[5] and high speed manipulation.[6] Cable-Driven Parallel Robots (CDPRs) use cables to control the end-effector (EE) pose. High dynamic performances, very light weight, large workspace, reduced manufacturing and maintenance costs, superior modularity and reconfigurability are some of the advantages of such systems.[7] Moreover, CDPRs can be easily shaped and on-line adapted to fit certain application or performance requirements, showing greater flexibility with respect to traditional robot designs.[8,9]

In the case of over-constrained cable robots, where multiple sets of cable tensions can be used to gain the same wrench at the end-effector, many researchers proposed different methods to find optimal tension distributions.[10] The most prevalent approach is based on fixing a constant minimum tension in cables. Then an optimization algorithm is used to find a set of tension in cables that provide the desired wrench, while at least one cable has the minimum tension.[11,12]

Linear programming is commonly used where the objective function is sum of all cable tensions. This method provides optimal solutions, which may not be continuous along a given trajectory.[13-15] Furthermore, quadratic programming approach was employed to minimize the sum of squared tension in cables. The superiority of this method over linear programming lies in providing smooth solutions.[16,17] Application of Gradient projection in[18] led to obtaining continuous and smooth tension in cables. The method was compared with quadratic and linear programming. Moreover, some other approaches such as convex optimization,[19] minimization of p-norm,[20] L1-norm optimization,[21] and using pattern of fingers grasp were proposed.[22] Pott compared various methods and defined weakness of these algorithms, while suggested a modified closed form solution.[10]

These methods are based on a *fixed* minimum tension value in cables. Higher minimum tension results in greater stiffness, less vibration, and superior accuracy of motion; however, power consumption increases. Determining minimum tension through theoretic approaches is very tough.[13] Usually, the minimum tension was chosen through experiments to gain the desired path tracking accuracy of the system, considering capability of actuators at the same time.[23]

Recent studies proposed a lower bound for stiffness to achieve a proper trajectory tracking.[24,25] This method works based on achieving a minimum stiffness level regarding to the eigenvalues of the stiffness matrix besides an optimization method, but a feasible solution may not always exist. More recently, we introduced a method to dynamically changing the minimum tension in cables based on total wrench.[26] We proposed to increase the minimum tension in cables, when the wrench is low and to decrease, in case the wrench value is high.

In this paper, we further develop the concept outlined in[26] by proposing a novel approach for minimum cable tension calculation based on system stiffness, end-effector wrench, position and error as feedback. Cable tension increment can be desirable due to stiffness augmentation, higher trajectory tracking performance, more precise motion and disturbance rejection; however, it can increase power consumption, and saturation in actuators may occur. The proposed method allows running the system efficiently by dynamically controlling the minimum tension in cables considering accuracy and power consumption.

We used a 1-DOF cable-driven test bed to compare the traditional and the proposed approach. Section 2 is dedicated to discuss about the concept of the method, which is called Dynamic Minimum Tension Control (DMTC). The executive algorithm is presented in Section 3 and experimental results are illustrated in Section 4. Finally, conclusions are presented in Section 5.

2. Dynamic Minimum Tension Control (DMTC) Concept

Let us consider an n-DOF cable-driven robot, controlled by m cables. In static conditions, the relationship between the wrench and tension in cables is given by:

$$AT = W, \quad T_{min} \le T_i \le T_{max}, \quad i = 1, 2, \ldots, m \tag{1}$$

where T_{min}, T_{max} are the minimum allowable and maximum feasible tension in cables, $A \in \mathbb{R}^{n \times m}$ is the structure matrix, which is a function of object coordinates, $W=[F \quad M]^t \in \mathbb{R}^n$ is wrench and denotes external force and torque on the end-effector, $T=[T_1, T_2, \ldots, T_m]^t \in \mathbb{R}^m$ is the cables tension vector. To determine the tension in cables, an optimization method can be used to find the best solution within the feasible tension range. Tension distribution of an over-constrained cable-driven parallel robot can be converted to an optimization problem using following equations:[27]

$$\begin{aligned} & Minimize \;\; f, \\ & f = \frac{1}{2}(T - T_{min})^t (T - T_{min}), \\ & s.t. \quad AT = W \quad and \quad T_{min} \le T_i \le T_{max}, \quad i = 1, 2, \ldots, m \end{aligned} \tag{2}$$

Selecting a proper value for T_{min} is a challenging subject.

Generally, the resonant frequencies of the transmission system between the sensor and actuator limits the control bandwidth, which results in the fact that many designers consider as 'Stiffer is better'.[28,29] Some researchers presented stiffness adjustable structures.[30] In different studies of cable-driven robots, higher stiffness is considered completely desirable for motion accuracy and stabilization. Inevitable elasticity of cables reduces the accuracy and bandwidth of the robot, and the stiffness of the system has a direct relation with position accuracy.[31-34]

So, increasing the value of T_{min} is desirable, as it prevents cable slacking, and usually generates higher stiffness, and accuracy. In addition, less vibration, and even better controller tuning are obtained due to higher natural frequency of the cables; however, increasing T_{min} raises norm of tension in cables, and energy consumption enhances. Moreover, increasing T_{min} can result in saturation of actuators, not only when the total wrench W is large, but also when the end-effector pose is close to singular configurations.

In this paper, a new method is proposed to calculate a proper minimum value (T_{min}) for tension in cables dynamically, while employing a tension distribution approach. Unlike traditional methods that a fixed T_{min} is used, we propose to change the value of the T_{min} on-the-fly and within a certain range, to gain a good compromise between performance, energy consumption, and the risk of saturating the actuators

Different aspects must be considered before defining DMTC algorithm.

2.1 Stiffness and resonance

Let us consider a cable-driven parallel robot with n degrees of freedom and m cables. The stiffness matrix of the system can be found by using the following equation:[35]

$$K = A\Omega A^t + \frac{d}{dp}(A)T, \tag{3}$$

$$\Omega = diag[k_1, k_2, \ldots, k_m], \quad k_i = \frac{E_i A_i}{L_i}, \quad i = 1, 2, \ldots, m \tag{4}$$

where $p = (x, y, z, \theta_x, \theta_y, \theta_z)^T$ is the position of the end-effector in the Cartesian space and Ω is a diagonal matrix having spring constants k_i in the main diagonal. E_i, A_i and L_i are the Young's modulus, cross section, and the length of the ith cable. The stiffness matrix is a combination of two parts. The first one is related to the elastic stiffness of the cables, the second part is linked to the tension in cables.

Behzadipour et al.[36] showed that usually, the elastic stiffness is much higher than the stiffness related to the tension in the cables, but for some positions and directions, the stiffness corresponding to the tension in cables can be dominant. High stiffness is desirable at the end-effector for proper position accuracy and load capacity.[37] On the other hand, low stiffness can negatively affect trajectory tracking performance, disturbance rejection and vibrations in the system,[13,38] so the stiffness should be considered as a key parameter in cable-driven systems. Some studies set a minimum value for the eigenvalue of the stiffness matrix (σ_{min}) to guarantee a minimum stiffness within the workspace.[39]

In applications of cable-driven parallel robots with long cables, not only the longitudal vibration but also the transverse vibration can affect trajectory tracking and a very small excitation can produce high transversal vibrations.[40] To this regard, the minimum tension in the cables can play an important role to decrease the vibration and providing motion trajectory tracking with high accuracy.

In fact, the first natural frequency of transversal vibration of a cable[41] can be calculated as

$$\omega_{cable} = \frac{\pi}{L_i}\sqrt{\frac{T_i}{\rho}}, \tag{5}$$

where T_i and ρ are tension and the mass per unit length of the cable. A cable with higher tension has greater natural frequencies allowing for greater control gains, which are profitable in term of more accurate motion. To refuse the resonance, the natural frequency of the actuator is usually chosen to be equal or less than half of the cable natural frequency:[42]

$$\omega_{actuator} \leq \frac{\omega_{cable}}{2} \tag{6}$$

Using Eq. (5), the following constraint for the tension in cables can be defined:

$$T_i \geq \frac{4\omega^2_{actuator} L_i^2 \rho}{\pi^2} \tag{7}$$

2.2 Wrench

Using the norm of the end-effector *Wrench* as an index to change the minimum tension in cables was introduced in our last study.[26] We proposed to decrease T_{min} when the absolute value of the wrench W on the moving platform is large and to increase T_{min} when the absolute value of the wrench reduces. The method is useful to avoid cable slacking in case of low wrench and to prevent the saturation of actuators while the wrench is high.

Obviously, application of this method results in calculating a vector of tension in cables that satisfies the statics equations with reduced norm. As an example, let us consider a planar point-mass cable-driven parallel robot. For a certain desired wrench W, the direction of at least one cable is opposite to the wrench W and the dot product of the cable direction and the wrench is negative. In such condition, the minimum tension decrement results in reducing the tension in all cables and less power consumption.[26]

2.3 Trajectory Tracking Error

The method proposed in[26] guarantees smaller tension in all cables when W is high; however, it does not always guarantee the best efficiency. As an example, let us consider a system working with low total wrench, but also with an acceptable trajectory tracking accuracy; in this case, there is no need to increase T_{min}, which in turn brings higher power consumption. On the other hand, if a system is running with poor trajectory tracking, due to trajectory complexity, noise or improper tuning of controller, stiffness enhancement considering actuators capacity can be an effective solution.[34] Therefore, not only the stiffness is an important issue, but also the accuracy of the system can drive a suitable choice of robot stiffness and minimum cable tension. Trajectory tracking error can be used together with total wrench as feedback to change the minimum tension in cables.

3. Dynamic Minimum Tension Control (DMTC) Algorithm

Based on the considerations above, the DMTC algorithm is proposed as the following equation:

$$T_{min} = T_0 + \Delta T[\alpha g_1(W) + (1-\alpha) g_2(E)] \tag{8}$$

where T_0 and ΔT are the lower bound and the range of variation of T_{min}; $g_1(W)$ and $g_2(E)$ are functions of *Wrench* and *Error* respectively and α is a parameter to determine the weight of the two terms. Functions $g_1(W)$ and $g_2(E)$, and parameter α range between 0 and 1. In this way, the whole term multiplied by ΔT ranges between 0 and 1 itself, so that T_{min} is always between T_0 and $T_0+\Delta T$.

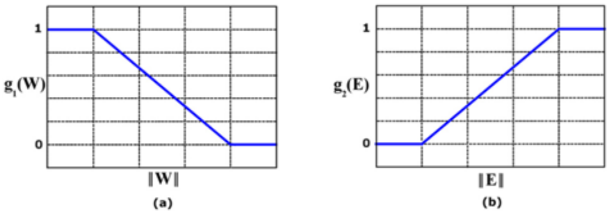

Fig. 1 (a) Mapping function for adjusting the minimum value of tension in cables T_{min} in respect to the absolute desired wrench (W) and (b) absolute position error (E)

To express $g_1(W)$ and $g_2(E)$, two look-up tables (LUTs) are proposed (Fig. 1). As it is shown, $g_1(W)$ increases in case of Wrench reduction, while $g_2(E)$ raises in case of low accuracy (Large error). The slope of the LUTs, and the α value can be chosen, according to the application, to gain a suitable compromise between accuracy and energy consumption. This method can be employed to any kind of cable-driven parallel robots with arbitrary number of cables and DOFs.

Fig. 2 depicts a flow chart showing how to choose the proper T_{min}. Let us call $T_{0,in}$ as initial value of T_0. First, $g_1(W)$ and $g_2(E)$ are estimated considering the total Wrench and Error. In case, the level of motion accuracy is not acceptable ($g_2(E) \geq Q$)[†], we propose to increase T_0 by δT to enhance the tension in cables. δT can either be constant or be calculated considering the system configuration and limitations. If δT is high, T_{min} changes fast, which can be inappropriate if the system overpasses constraints such as hardware limitations, stiffness and resonance requirements. On the other hand, if δT is low, the proper T_{min} cannot be determined in the right moment, which decreases system performance. A moderate value for δT can keep the system working with an acceptable performance level.

By increasing T_0, the motion accuracy enhances. On the other hand, if the level of motion error is acceptable ($g_2(E) \leq Q$), we do not need to increase the tension in cables and the system stiffness. So, if T_0 is greater than the initial value $T_{0,in}$, we decrease T_0. Otherwise, the same value of T_0 is used to estimate T_{min} based on the Eq. (8). Knowing T_{min} and *Wrench*, the tension in cables are calculated.

The proposed method has some advantages over the conventional ones. In the traditional methods, a fixed minimum tension is determined. The value should be high enough to guarantee an acceptable motion accuracy within the whole workspace. On the other hand, high minimum tension increases power consumption and raises the risk of actuators saturation.

Moreover, this value is fixed even if energy consumption and motion accuracy changes severely during the motion; however, using DMTC results in less energy consumption and more precise motion. As an example, if the motion accuracy is more than expectation, high minimum tension is waste of energy and if motion precision is low, increasing the minimum tension is beneficial. The traditional method is incapable of coping with such conditions; however, DMTC can address the issue and change the minimum tension, which shows superiority of

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[†] Q is an arbitrary motion accuracy level

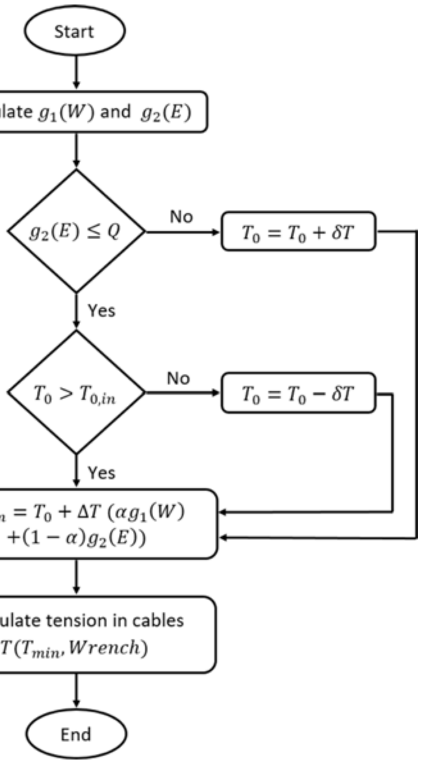

Fig. 2 The algorithm to estimate T_{min} using Dynamic Minimum Tension Control (DMTC)

the proposed method over the traditional ones in terms of motion precision and power consumption.

4. Experimental Setup and Results

A 1-DOF cable-driven robot was employed to test the proposed method. The robot has two cables connected to DC motors and an end-effector (Fig. 3). To measure the position of the end-effector (slider) and the rotation of motors, one linear and two rotational encoders were applied. The robot was controlled by Matlab and Simulink Real-Time Windows Target (RTWT). A PCI Multifunction I/O Sensoray626 board was employed to connect the system to a PC.

A schematic of position control algorithm with the application of the proposed method is illustrated in Fig. 4. The output W consists of feedforward, which is extracted from system inverse dynamics, and feedback, which comes from the controller. In this study, we used PID controller, which is widely used and is easily applicable in industrial systems.

The DMTC block calculates T_{min} according to the proposed algorithm and the tension in cables are determined based on Wrench and T_{min}. In this block, different tension distribution methods such as p-norm optimization can be used. After considering motor dynamics, the output is sent to the drivers. The loop is closed using the position feedback provided by encoders. Lamaury et al. [43] used the similar method and tuned a PID controller without using the DMTC method.

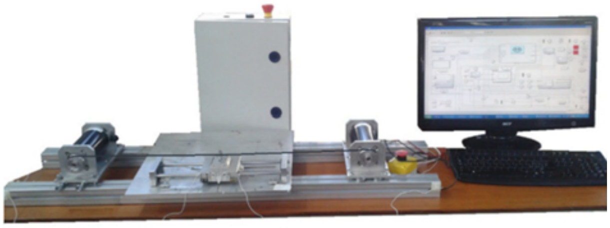

Fig. 3 The 1-DOF prototype for testing the DMTC method

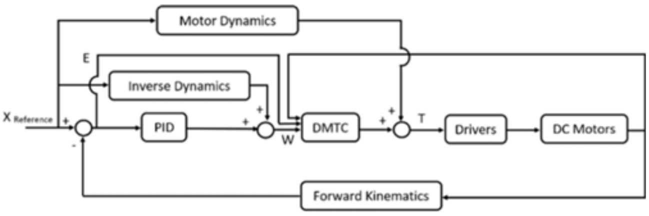

Fig. 4 Position control algorithm with the application of DMTC method

To gain more precise results, slider friction and elongation of cables were considered. The friction was modeled using sum of Stribeck, Coulomb, and viscous components and the related parameters were calculated by experiments. The position of the slider was estimated using the data from rotational encoders, and calculation of cables elongation. Moreover, the accuracy of results were verified using the linear encoder by measuring the actual position of the slider.

The cable tension calculation distribution method calculated the tension in two cables in respect to the direction of the wrench W, which can be written as T_{min} and $W + T_{min}$. A fifth degree polynomial reference with the amplitude of 35 mm was considered and the test was implemented with the reference frequencies of 1 Hz and 0.5 Hz.

To show the efficiency of the new algorithm, we used three different methods to run the system. The first one uses fixed minimum tensions of 4 N, 8 N, and 12 N in cables. The second one uses the DMTC with $\alpha = 1$; the third one, uses the DMTC with $\alpha = 0.5$. As it mentioned before, tuning the LUTs is also dependent on the necessities, but we have generated some LUTs to run the system as accurate as usage of fixed tensions to compare the power consumption of new method with formers.

Results are shown in Table 1. We applied a position error variance and a power-related index to compare the DMTC with the traditional method. The first index was calculated as the variance of the difference between actual and reference positions. Root mean square (RMS) of the wrench is presented as the next index. To calculate the third index, the average current references of the drivers were considered as the power-related index. The error variances and wrenches are almost same in similar cases; however, the power consumption is decreased using LUT method.

The power consumption data are plotted in Fig. 5. Using the proposed formulation with $\alpha = 1$ reduces power consumption (e.g. Average current of drivers); and setting $\alpha = 0.5$ results in more power savage due to application of $g_2(E)$ meanwhile motion accuracy is similar in all conditions. Furthermore, it is clear that in case of higher frequency motions, LUTs have more priority comparing to fixed minimum tension usage. In all cases, DMTC algorithm with $\alpha = 0.5$

Table 1 Comparison of fixed minimum tension with DMTC algorithm for $\alpha = 1$ (Wrench only) and $\alpha = 0.5$ (Wrench, Error)

F (Hz)	Fixed Minimum tension				DMTC ($\alpha = 1$)				DMTC ($\alpha = 0.5$)			
	T_{min} (N)	Error Var. (mm)	Wrench RMS (N)	Current (A)	Error Var. (mm)	Wrench RMS (N)	Current (A)	Cur. Savage	Error Var. (mm)	Wrench RMS (N)	Current (A)	Cur. Savage
0.5	4	0.305	6.96	2.27	0.301	6.83	2.09	%7.93	0.299	6.78	1.97	%13.22
	8	0.261	7.12	5.66	0.259	6.98	5.20	%8.13	0.259	6.89	4.89	%13.60
	12	0.224	7.18	11.23	0.223	7.09	10.24	%8.82	0.222	6.99	9.68	%13.80
1	4	0.156	9.95	2.98	0.154	9.84	2.71	%9.06	0.152	9.81	2.43	%18.46
	8	0.133	10.21	6.87	0.132	10.01	6.24	%9.17	0.132	9.97	5.58	%18.78
	12	0.107	10.32	12.68	0.105	10.20	11.51	%9.23	0.105	10.15	10.19	%19.64

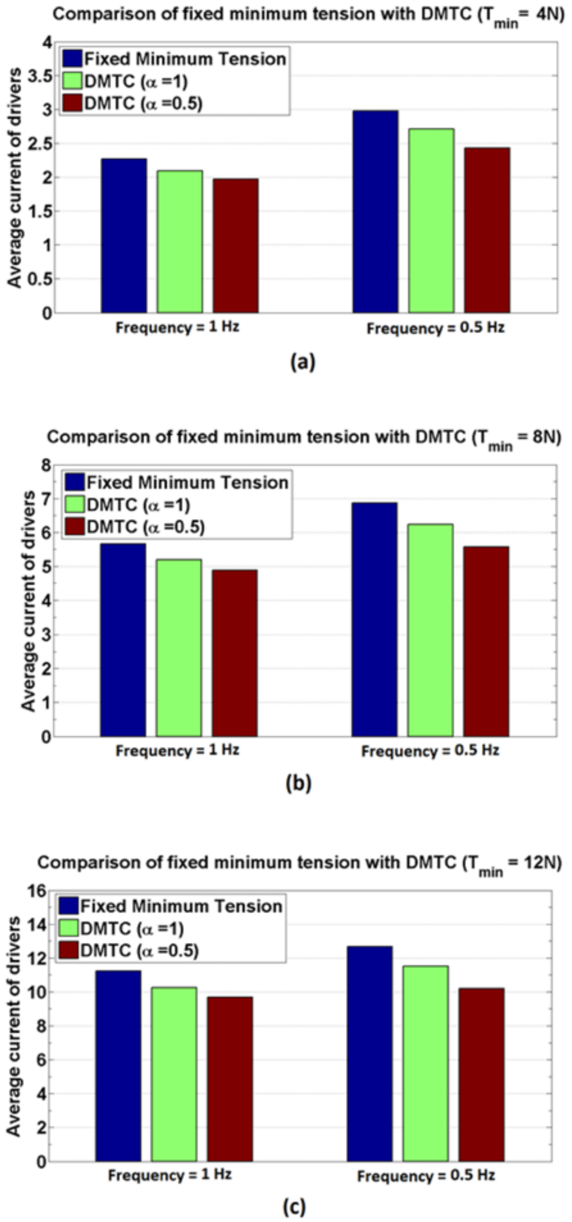

Fig. 5 Comparison of power consumption for fixed minimum tension and DMTC algorithm for $\alpha = 1$ (Wrench only) and $\alpha = 0.5$ (Wrench, Error)

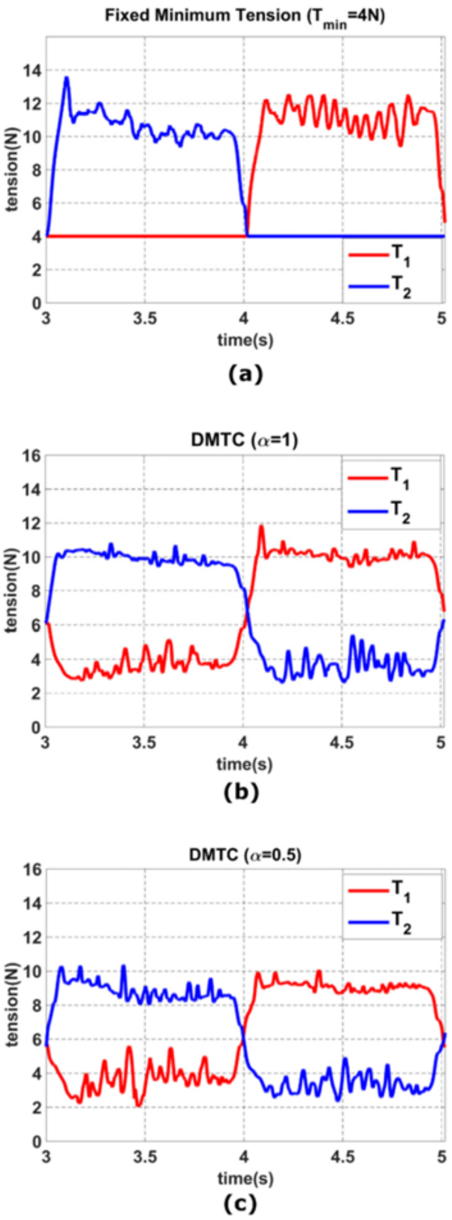

Fig. 6 Comparison of tension in cables between (a) fixed minimum tension (T_{min} = 4 N), (b) DMTC (α = 1), and (c) DMTC (α = 0.5)

has the lowest energy consumption compared to other methods.

Fig. 6(a) shows the tension in cables using fixed minimum tension method in motion frequency of 0.5 Hz and $T_{min} = 4\ N$. T_1 and T_2 are tension in the first and second cables respectively. One of the cables always has a tension of 4 N; however, the second one is changing based on the total wrench. In Fig. 6(b) the tension in cables for $\alpha = 1$ is illustrated. In this case, the minimum tension is continuously changing based on the total wrench, and part (c) dedicates to the condition of $\alpha = 0.5$, where the minimum tension is in a changing mode in respect to the Wrench and Error. The total power, which was used for the same reference in the case of $\alpha = 0.5$ was the least one; while the accuracy of all three experiments were similar.

5. Conclusion

In this paper, a new algorithm to control the minimum value of tension in cable-driven parallel robots was presented and tested on a cable-driven system. Higher tension in cables results in more stiffness, higher trajectory tracking performance, more precise motion and disturbance rejection. On the other hand, there are always hardware limitations. Therefore, in case of increasing the tension in cables, saturation may occur. Furthermore, energy consumption is an important issue in case of robotic applications. We proposed a method to address this challenge.

This method works based on changing the minimum value of tension in cables, according to the stiffness, the system dynamics as a feedforward line, and error value of the system as the feedback. The minimum tension is increased in case of low Wrench, and reduced when Wrench value is high. Also based on the feedback data, minimum tension reduces in case of high accuracy of motion to save energy consumption; however, minimum tension growth is a good option whenever the error value is high. Using the concept, DMTC method was proposed.

We used the stiffness and two Look Up Tables (LUTs) in relation with error and total wrench. We offered the ones capable to achieve the same accuracy with less power consumption to show the superiority of the suggested method.

The application of DMTC algorithm led to large benefits in terms of accuracy and power consumption, which were verified by the experiments. Comparison between the proposed algorithm and the traditional method shows that the DMTC algorithm performs much better to gain the same accuracy with less power consumption. In future studies, we intend to test the DMTC algorithm on more complicated systems with more DOFs.

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