

Integrated Controller For An Over-Constrained Cable Driven Parallel Manipulator: KNTU CDRPM

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Abstract—This paper presents an approach to the control of the KNTU CDRPM using an integrated control scheme. The goal in this approach is achieving accurate trajectory tracking while assuring positive tension in the cables. By the proposed controller, the inherent nonlinear behavior of the cable and the target tracking errors are simultaneously compensated. In this paper asymptotic stability analysis of the close loop system is studied in detail. Moreover, it is shown that the integrated control strategy reduces the tracking error by 80% compared to that of a single loop controller in the considered manipulator. The closed-loop performance of the control topology is analyzed by a simulation study that is performed on the manipulator. The simulation study verifies that the proposed controller is not only promising to be implemented on the KNTU CDRPM, but also being suitable for other cable driven manipulators.

I. INTRODUCTION

Increasing performance requirements necessitates design of new types of manipulators working in a larger dexterous workspace with higher accelerations. Parallel manipulators can generally perform better than serial manipulators in terms of stringent stiffness and acceleration requirements [1] [2]. However, limited workspace and existence of many singular regions inside the workspace of a typical parallel manipulator, limit the use of parallel manipulators in various applications. In the case of *cable driven redundant parallel manipulators* (CDRPM), the conventional linear actuators of parallel manipulators are replaced with electrical powered cable drivers. This novel engineering design idea leads immediately to a wider workspace, and higher accelerations of the moving platform due to the fact of using lighter moving parts [3]. However, forward kinematics of parallel manipulators such as CDRPM's are very complicated and difficult to solve [4]. Cables are sagged under compression forces [5], and therefore, to achieve tension forces in the cables throughout the whole *dexterous workspace*, the moving platform must be designed over-constrained [6]. In this case $m = n + 2$ cables are proposed to be used in order to *dextrously* move the redundant actuated end-effector in an n -dimensional space [7]. Redundancy resolution is needed to assure tension force along each cable, however, this is usually computationally expensive [8]. The KNTU CDRPM uses a novel design to achieve high stiffness, accurate positioning for high-speed maneuvers.

This research is supported by K.N.Toosi University of Technology under Grant MP1853.

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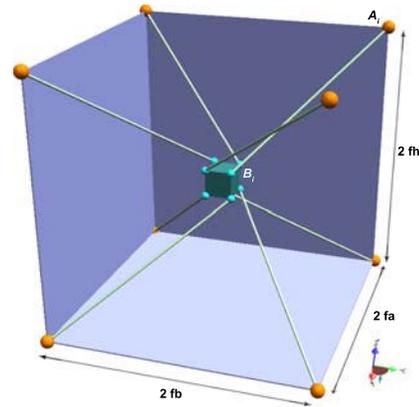


Fig. 1. The KNTU CDRPM, a perspective view

This paper presents an approach to the control of the CDRPMs using an integrated control scheme to achieve a stringent tracking performance while all the cables are in tension for such maneuvers. Control schemes for parallel manipulators are grouped in two classifications in the literature. The first one classifies the control methodologies in two frameworks. One is to design a controller based on the leg space or joint space coordinates and the other is based on the workspace or task space coordinates [9], [10]. Most of the controllers are designed based on the joint space coordinates [11], [12]. The other framework is based on the workspace coordinates [10], [2]. The second classification sets the schemes in two categories: model-based and non model-based schemes [11], non model-based controls such as *Proportional-Integral-Derivative* (PID) control [11], [13], fuzzy logic control [14] and neural network control [15]; and model-based controls such as impedance control [16] and adaptive control [17], etc. Nevertheless, there are few researches focused on the position control of Cable Driven Redundant Parallel Manipulators (CDRPM). There are two general schemes in this field; The first one works on the joint space coordinate, the length of the cables are measured and then controlled to reach the desired cable length corresponding to a desired position of an end-effector [18], [19]. Kawamura et al. proved that such a controller can guarantee the convergence of the motion of the end-effector to a desired trajectory. However, as studied in the control section, the joint space controller confronts some problems in the tracking performance [19], [5]. On the other hand, the second scheme controls the pose of the end-effector based on the dynamics described by a feedback from a 6DOF position or acceleration sensor in the task space or

workspace coordinates. For instance, a workspace controller is proposed which uses the position of the end-effector to acquire the pose of the moving platform [20] for an under-constrained suspended CDRPM.

This paper presents a different control topology examined for possible implementation on KNTU CDRPM using an integrated control scheme. The proposed controller structure guarantees fully tension forces on the cables, in a more trusted fashion, and is capable to fulfill the stringent positioning requirements for these type of manipulators. This paper is organized as follows. In section II the inverse kinematics and the Jacobian is derived first. Subsection II-C recalls dynamic modeling of the KNTU CDRPM. The integrated control with on-line gravity compensation is introduced in section III-A accompanying with the proof of stability and simulation analysis. The proposed redundancy resolution scheme is examined in section III-B, and finally, the concluding remarks and contributions of this work are enlightened in the last section.

II. KINEMATICS AND DYNAMICS

A. Kinematics

The KNTU Cable Driven Redundant Parallel Manipulator is illustrated in figure 1. This figure shows a spatial six degrees of freedom manipulator with two degrees of redundancy. This robot has eight identical cable limbs. The cable driven limbs are modeled as spherical-prismatic-spherical (SPS) joints, for cables can only bear tension force and not radial or bending force. Two cartesian coordinate systems $A(x, y, z)$ and $B(u, v, w)$ are attached to the fixed base and the moving platform. Points A_1, A_2, \dots, A_8 lie on the fixed cubic frame and B_1, B_2, \dots, B_8 lie on the moving platform. The origin O of the fixed coordinate system is located at the centroid of the cubic frame. Similarly, the origin G of the moving coordinate system is located at centroid of the cubic moving platform. The transformation from the moving platform to the fixed base can be described by a position vector $\vec{g} = \overrightarrow{OG}$ and a 3×3 rotation matrix ${}^A R_B$. Consider that \vec{a}_i and ${}^B b_i$ denote the position vectors of points A_i and B_i in the coordinate system A and B , respectively. Although in the analysis of the KNTU CDRPM, all the attachment points, are considered to be arbitrary, the geometric and inertial parameters given in table I are used in the simulations. Similar to other parallel manipulators, CDRPM has a complicated forward kinematic solution [4]. However, the inverse kinematic analysis is sufficient for dynamic modeling. For inverse kinematic analysis of the cable driven parallel manipulator, it is assumed that the position and orientation of the moving platform $x = [x_G, y_G, z_G]^T$, ${}^A R_B$ are given and the problem is to find the joint variable of the CDRPM, $\mathbf{L} = [L_1, L_2, \dots, L_8]^T$. From the geometry of the manipulator as illustrated in figure 2 the following vector loops can be derived:

$${}^A \overrightarrow{A_i B_i} + {}^A \vec{a}_i = {}^A \vec{g} + \mathbf{E}_i \quad (1)$$

in which, the vectors \mathbf{g} , \mathbf{E}_i , and \mathbf{a}_i are illustrated in figure 2. The length of the i 'th limb is obtained through taking the

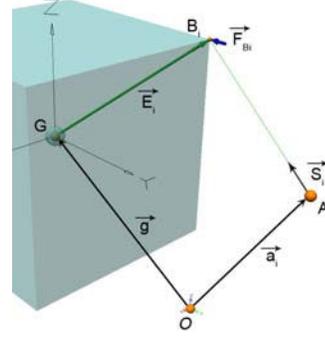


Fig. 2. i th Attachment point on the moving platform and related vectors

dot product of the vector $\overrightarrow{A_i B_i}$ with itself. Therefore, for $i = 1, 2, \dots, 8$:

$$L_i = \{[\mathbf{g} + \mathbf{E}_i - \mathbf{a}_i]^T [\mathbf{g} + \mathbf{E}_i - \mathbf{a}_i]\}^{\frac{1}{2}}. \quad (2)$$

B. Jacobian

Jacobian analysis plays a vital role in the study of robotic manipulators [21]. Let the actuated joint variable be denoted by a vector \mathbf{L} and the location of the moving platform be described by a vector \mathbf{x} . Then the kinematic constraints imposed by the limbs can be written in the general form $\mathbf{f}(\mathbf{x}, \mathbf{L}) = 0$ by differentiating with respect to time, we obtain a relationship between the input joint rates and the end-effector output velocity as: $J_x \dot{\mathbf{x}} = J_L \dot{\mathbf{L}}$ where $J_x = \frac{\partial \mathbf{f}}{\partial \mathbf{x}}$ and $J_L = -\frac{\partial \mathbf{f}}{\partial \mathbf{L}}$. The derivation above leads to two separate Jacobian matrices Hence the overall Jacobian matrix J can be written as:

$$\dot{\mathbf{L}} = \mathbf{J} \cdot \dot{\mathbf{x}} \quad (3)$$

where $\mathbf{J} = J_L^{-1} J_x$. Jacobian matrix not only reveals the relation between the joint velocities $\dot{\mathbf{L}}$ and the moving platform velocities $\dot{\mathbf{x}}$, but also constructs the transformation needed to find the actuator forces $\boldsymbol{\tau}$ from the forces acting on the moving platform \mathbf{F} . When J_L is singular and the null space of J_L is not empty, there exist some nonzero $\dot{\mathbf{L}}$ vectors that result zero $\dot{\mathbf{x}}$ vectors which called serial type singularity and when J_x becomes singular, there will be a non-zero twist $\dot{\mathbf{x}}$ for which the active joint velocities are zero. This singularity is called parallel type singularity [22].

TABLE I
GEOMETRIC AND INERTIAL PARAMETERS OF THE KNTU CDRPM

Description	Quantity
f_a : Fixed cube half length	1 m
f_b : Fixed cube half width	2 m
f_h : Fixed cube half height	0.5 m
C : The moving platform cube half dimension	0.1 m
M : The moving platform mass	5 Kg
I : The moving platform moment of inertia	0.033 Kg · m ²
ρ : The limb density per length	0.007 Kg/m

as joint space controller [26]. The controller based on the workspace coordinates should compensate the nonlinear dynamic behavior of the cables arising from projecting the parameters in cable coordinates onto work space coordinates, so it's apparent that a joint space controller can achieve a better performance in this area. Therefore, in order to achieve a high tracking performance, the advantages of both workspace and joint space controllers must be incorporated. Based on this idea, an integrated control scheme is proposed in this section. In the following subsections first the topology proposed for the integrated controller is elaborated, and then, controller stability is analyzed. Finally, simulation results and their analysis are presented in detail.

A. The Integrated Control

The block diagram of the integrated control is shown in figure 3. In this control scheme, two control loops are used, namely, the internal loop, which is based on decentralized PD controller in joint space and the external loop, which is based on a decentralized PD controller in workspace. Inherent nonlinear behavior of the cable manipulator is controlled by the internal loop, while external loop can effectively reduce the target tracking errors of the end-effector in the presence of disturbance force/torques. The gains of each controller are tuned such that the required tracking performance is achieved. Note that in this topology the redundancy resolution block is elaborated in section III-B.

Assume that the desired path of the manipulator in 3D is cylindrical as shown in figure 4. As illustrated in figure 3 the vector force, \mathcal{F} , in the external loop is determined by:

$$\mathcal{F} = \mathcal{F}_w + \mathcal{F}_{IDC} \quad (12)$$

Where \mathcal{F}_w is the created vector force by PD controller $\mathcal{F}_w = K_{pw}e(t) + K_{vw}\dot{e}(t)$. Where $e(t) = x_d(t) - x(t)$ is the trajectory tracking error and K_{pw}, K_{vw} are appropriate position and velocity gain matrices, whose values in the simulations are $10^4 \times I_{6 \times 6}$ and $10^3 \times I_{6 \times 6}$ respectively. \mathcal{F}_{IDC} is the generated vector force by the IDC [27]. Inverse dynamics generated force, preserves the end-effector current state of acceleration and obtains required force in the external loop in the form of a feedback linearization:

$$\mathcal{F}_{IDC} = \hat{M}\ddot{x}_d + \hat{G} \quad (13)$$

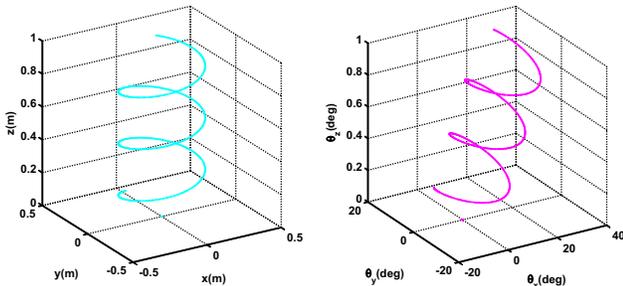


Fig. 4. Desired path in the workspace

Where, $\hat{M}\ddot{x}, \hat{G}$ are the computed inertia and gravity forces of the end-effector represented in task coordinate. In the internal loop, the cables length L are measured and its time derivative \dot{L} are either measured or estimated. Let L_d, \dot{L}_d denote the desired cable length and its velocity which can be easily obtained through computing the inverse kinematics. In this part, the control efforts are directly applied through the cable driver units. In this loop, the control law is as follows:

$$\tau = \tau_j + \tau_r \quad (14)$$

In which, τ is an 8×1 tension force vector along each cable, τ_r is redundancy resolution distributed forces vector and τ_j is part of the tension force in the joint space coordinate that is provided by PD controller by $\tau_j = K_{pj}e + K_{vj}\dot{e}$. The values of K_{pj} and K_{vj} which is used in the simulations are $2 \times 10^5 \times I_{8 \times 8}$ and $2 \times 10^4 \times I_{8 \times 8}$, respectively. These gains are tuned such that the required tracking performance is achieved. Let $e(t) = L_d - L$ and $\dot{e}(t) = \dot{L}_d - \dot{L}$ denote the error of actual cable length to that of the desired one and its derivative.

The tracking performance of the CDRPM using the proposed integrated controller is illustrated in figure 5. As seen in this figure, the proposed control topology is capable of reducing the tracking errors less than $4\mu m$ in position and less than 4×10^{-5} degrees in orientation. In order to compare the tracking performance of this control topology to that of a single loop controller, consider the two and infinity norms of the tracking performance as shown in figure 7, and notice the logarithmic scale that is used to represent the errors. As it is seen from this chart this proposed topology can significantly improve the tracking error norms in all the translational and rotational degrees of freedom. This significant improvement is due to the fact that the internal loop has a linearizing effect on the system, while the external loop ensures better tracking of the robot manipulator.

B. Redundancy Resolution

Actuator redundancy of CDRPMs is an inherent requirement in order to move the end-effector by tension forces of the cables. Redundancy resolution is an essential tool to optimally project a desired wrench in the cartesian space on the cable forces into the joint space. The KNTU CDRPM uses 8 actuators in a 6 dimensional motion. Therefore, there

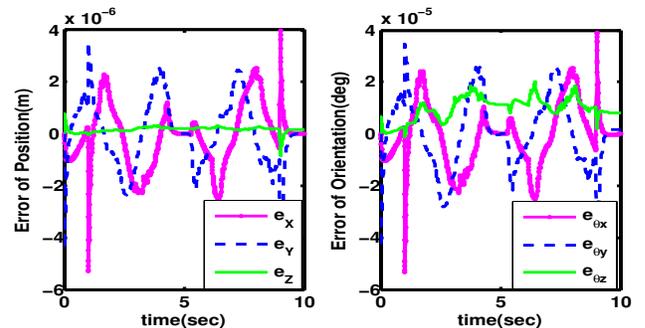


Fig. 5. The tracking error in the cascade controller

are infinitely many solutions for the eight actuators forces to solve the six dynamic equations. Let us denote the resulting cartesian force/torque applied to the manipulator moving platforms \mathcal{F} . In this definition \mathcal{F} is calculated from the summation of all inertial, and external forces *excluding the actuator torques* τ in the dynamic equations 10. Due to the projection property of the Jacobian matrix [21], $\mathcal{F} = \mathbf{J}^T \tau$ is the projection of the actuator forces onto the moving platform, and can be uniquely determined from the dynamic equations by excluding the actuator forces from them. If the manipulator has no redundancy in actuation, the Jacobian matrix, \mathbf{J} , would be squared and the actuator forces could be uniquely determined by $\tau = \mathbf{J}^{-T} \mathcal{F}$, provided that \mathbf{J} is nonsingular. For redundant manipulators, however, there are infinity many solution for τ to be projected into \mathcal{F} . The simplest solution is a minimum norm solution, which can be determined by the pseudo-inverse of \mathbf{J}^T , through:

$$\mathbf{J}^{T\dagger} = \mathbf{J}^T (\mathbf{J} \mathbf{J}^T)^{-1} \quad (15)$$

By this means, $\tau_0 = \mathbf{J}^{T\dagger} \mathcal{F}$ determines the minimum required force of each cable to generate the corresponding force, \mathcal{F} . However, this solution can result into positive or negative tensions of the cables. Since the cable forces must be kept in tension in all maneuvers, a constrained optimization technique is proposed in here to resolve the redundancy. Note that all the solutions of the projection can be determined using the null space of the Jacobian matrix by:

$$f_\tau(\gamma) = \tau_0 + (\mathbf{I}_{m \times m} - \mathbf{J}^{T\dagger} \mathbf{J}^T) \gamma \quad (16)$$

in which, \mathbf{I} is the identity matrix and γ is an m dimensional vector in the joint space. $f_\tau(\gamma)$ determines an affine hyperplane as an intersection of n subspaces of linear equality constraint defined by Jacobian transpose. To achieve a solution for the actuator forces of the CDRPM, the constrained optimization is numerically solved in order to find an optimum value for $f_\tau(\gamma)$ by finding an appropriate value for γ vector in the equation 16. In this optimization the norm of actuator efforts are minimized subject to:

$$\tau = f_\tau(\gamma) \Rightarrow (\forall i, i \in \{1, 2, \dots, m\} \Rightarrow \tau_i > \tau_{min}) \quad (17)$$

where, τ_{min} is the lower bound of the actuator forces. Other optimization techniques can be used to find the actuator forces projected from, \mathcal{F} which can minimize another user defined cost function [8].

The simulation result for the cascade controller using the proposed redundancy resolution scheme is shown in figure 6. As it is seen the proposed redundancy resolution scheme is capable to keep the actuator forces of the CDRPM always positive.

C. Stability Analysis

In this subsection, the stability of CDRPMs under the integrated control law is proved by Lyapunov stability theorem. First, the dynamic equation of error is derived. Regarding

dynamic equation of the manipulator from 11 and the control law from 14, we have:

$$\mathbf{M} \ddot{x} + \mathbf{H} + \mathbf{G} = K_{pw}(x_d - x) + \mathbf{M} \dot{x}_d + \mathbf{G} + \mathbf{J}^T (K_{pj}(l_d - l) + K_{vj}(\dot{l}_d - \dot{l})) \quad (18)$$

or,

$$\mathbf{M} \ddot{e} + K_{pw}e + K_{vw}\dot{e} + \mathbf{J}^T K_{pj}e_l + \mathbf{J}^T K_{vj}\mathbf{J}\dot{e} + \mathbf{H} = 0 \quad (19)$$

which results in:

$$\mathbf{M} \ddot{e} + (K_{vw} + \mathbf{J}^T K_{vj}\mathbf{J})\dot{e} + K_{pw}e + \mathbf{J}^T K_{pj}e_l + \mathbf{H} = 0 \quad (20)$$

in which, $e = x_d - x$ and $e_l = l_d - l$ and $(\cdot)_d$ is a notation for desired values. Now, consider the following Lyapunov function:

$$\mathbf{V} = \frac{1}{2} \dot{e}^T \mathbf{M} \dot{e} + \frac{1}{2} e_l^T K_{pj} e_l + \frac{1}{2} e^T K_{pw} e \quad (21)$$

Where \mathbf{M} , K_{pw} and K_{pj} are positive definite matrices. The time derivation of Lyapunov function \mathbf{V} is given by

$$\dot{\mathbf{V}} = \dot{e}^T \mathbf{M} \ddot{e} + \frac{1}{2} \dot{e}^T \dot{\mathbf{M}} \dot{e} + \dot{e}_l^T K_{pj} e_l + \dot{e}^T K_{pw} e \quad (22)$$

By substituting $\mathbf{M} \ddot{e}$ from the dynamic equation of error in equation 20, we have:

$$\dot{\mathbf{V}} = \dot{e}^T \left(-(K_{vw} + \mathbf{J}^T K_{vj}\mathbf{J})\dot{e} - K_{pw}e + \mathbf{J}^T K_{pj}e_l - \mathbf{H} \right) + \frac{1}{2} \dot{e}^T \dot{\mathbf{M}} \dot{e} + \dot{e}_l^T K_{pj} e_l + \dot{e}^T K_{pw} e \quad (23)$$

$$\dot{\mathbf{V}} = -\dot{e}^T (K_{vw} + \mathbf{J}^T K_{vj}\mathbf{J})\dot{e} + \frac{1}{2} \dot{e}^T (\dot{\mathbf{M}} - 2\mathbf{H})\dot{e} \quad (24)$$

$$\dot{\mathbf{V}} = -\dot{e}^T (K_{vw} + \mathbf{J}^T K_{vj}\mathbf{J})\dot{e} \quad (25)$$

where, $\mathbf{J}^T K_{vj}\mathbf{J}$ is a positive definite matrix, because K_{vj} is positive definite and:

$$y^T (\mathbf{J}^T K_{vj}\mathbf{J}) y = y^T (\mathbf{J}^T K_{vj}^{\frac{1}{2}} K_{vj}^{\frac{1}{2}} \mathbf{J}) y = z^T z > 0$$

Therefore, $K_{vw} + \mathbf{J}^T K_{vj}\mathbf{J}$, the sum of two PD matrices, is a PD matrix; Then we can conclude that $\dot{\mathbf{V}} \leq 0$. Thus, the motion converges to a maximum invariant set which satisfies $\dot{\mathbf{V}} = 0$. In this case, $\dot{\mathbf{V}} = 0$ means that $\dot{e} = 0$. Therefore, due to the equation 20, the maximum invariant set is:

$$(K_{pw} + \mathbf{J}^T K_{pj}\mathbf{J})e = 0 \quad (26)$$

From positive definiteness of $(K_{pw} + \mathbf{J}^T K_{pj}\mathbf{J})$, this leads to $e = 0$. Hence, we conclude: $x = x_d$ as time t tends to infinity as long as the motion is within the wrench closure workspace [7] and without any collision [28] parallel or serial type singularity.

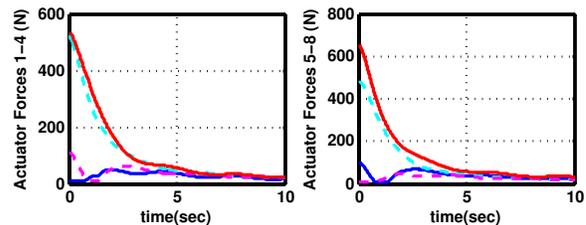


Fig. 6. The actuator forces in the cascade controller

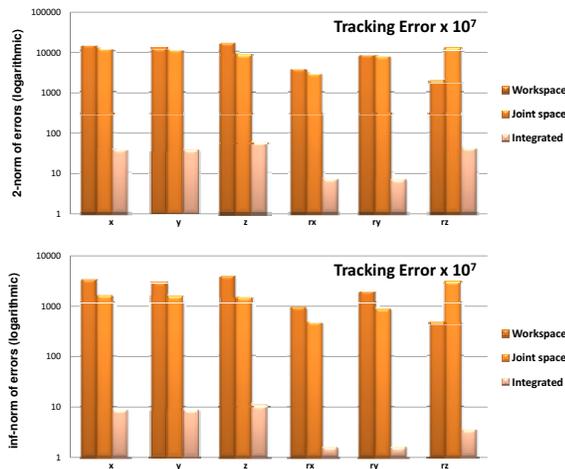


Fig. 7. Comparison of norms between three control topologies

IV. CONCLUSION

An integrated control strategy is proposed to improve the overall tracking performance of a cable driven redundant parallel manipulator while system nonlinear behavior is remedied and sensitivity of the external loop to nonlinearity of the cables dynamics is decreased. The main idea in this controller algorithm is the integration of two control loops, namely the internal loop, which is based on decentralized PD controller in the joint space and the external loop, which is based on a decentralized PD controller in the workspace. Inherent nonlinear behavior of the cable manipulator is significantly reduced by internal loop, while the external loop can effectively reduce the tracking errors of the end-effector in the presence of disturbance force/torques. The work presented here represents an effective attempt to use two control loops for performance improvement in trajectory-following tasks of this type of robot manipulators. The simulation analysis presented on the KNTU CDRPM verifies the expected theoretical claims and demonstrated that the proposed algorithm can significantly improve the overall tracking performance while keeping the cables under positive tension. As shown in figure 7 the cascade strategy can decrease the tracking error by 80% with respect to the previously advised inverse dynamic control. The investigated control topologies can be carefully implemented for the other cable parallel redundant manipulators in real-time applications.

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