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Wave Based Control of A Deployable Cable Driven Robot

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Abstract—**Cable driven parallel manipulator are known by their low costs and numerous applications. However despite of all research interests and developed methods they are not yet vastly used in action. The reason for this, is their limiting requirements for accurate assembly and installation process. The main goal of this paper is to propose a suitable control method by which the robot could appropriately be controlled, requiring no accurate calibrations or precise sensors. As it is well known, uncertainty in kinematics equations can lead to loose cables in redundant robots controlled through joint space controllers. In this paper a simple but very effective joint space controller is proposed that addresses the problem of loose cables by a wave based control method by employing a novel force feedback scheme. Indeed, a new conceptual framework for controlling deployable cable driven parallel manipulators is introduced by which such robots are greatly empowered at real-world scenarios. Finally, the performance of the proposed controller and its effectiveness is verified through some practical experiments showing that the proposed controller outperforms conventional cascade topologies in terms of much smoother tracking performance.**

I. Introduction

Cable driven parallel manipulators (CDPMs) consist of a moving platform connected to the base by means of actuated cables. Large workspace, high acceleration, and high velocity are remarkable features of such mechanisms. Considering their great advantages, this family of robots are appropriate choices for online video capturing in stadiums [7] or building a large radio telescopes [8], [14] which can take up to 500 meters of space. It should be noted that achieving such a large workspace is not feasible by most other common robots.

In Deployable Suspended Cable-driven Robots (DSCRs), the kinematic parameters are not accurately measured, and as a result, characteristics of the robot model is perturbed [4]. This, in turn, introduces many challenges in terms of controller design and meeting the required performance [3], [5], [6]. Nowadays, a family of cable driven robots known as Spider-cams is commonly used for video capturing of sports games. As shown in the Figure 1, ARAS-CAM robot is an example of a DSCR which is specifically designed for the purposes of imaging and video capturing. Simplicity of installation is the main characteristic of DSCR that makes it an extremely suitable choice in the field of the imaging industry.

Toward the control of CDPMs, there have been several topologies introduced in the literature [19]. Some of these

Fig. 1. Prototype of a deployable suspended cable driven robot called ARAS-CAM.

controllers are applied in joint space and others are defined in Cartesian workspace [9], [13], [19]. In what follows, these two general methods are briefly discussed, pros and cons are compared and recommendations for DSCRs applications are given.

In the case of workspace controller topologies, by utilizing the forward kinematics relations [13] or an accurate position sensor [1], the position of end-effector is derived. The achieved position is then compared to the desired location of end-effector and as a result, the control signal which is the desired cable tension is applied to the actuators. Toward the implementation of this method, often a cascade structure is employed in which the task of the inner loop is to control

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the cable forces and the outer loop is tasked to control the position. As a result of that, utilization of cable force sensors is inevitable. The major drawback of such a topology is that the presence of measurement noise in the force sensors thwarts utilization of high gain controllers for the inner loop portion.

In the case of joint space topologies, the transformation of the desired workspace path to the desired cable length variables are accomplished through inverse kinematics formulation. Then the task of designed controller is to enforce cable lengths to their desired values. This strategy could provide proper performance if the exact kinematic parameters were known. However, for DSCRs due to rapid loss of stiffness caused by kinematic uncertainties, this approach is not recommended. In other words, as the desired cable lengths are not accurately derived some cables become loose. Moreover, the existence of force measurement noise causes complications in implementing this first approach.

In deployable robots like DSCRs, employing precise position sensors such as laser tracker systems for measuring the end-effector position is too expensive or not technically feasible [5]. Therefore, the only option for achieving the end-effector position is to utilize forward kinematics equations and cable length measurements [12], [13]. As mentioned before, the exact value of kinematic parameters are not available. Hence, development of the second method to DSCRs would also lead to loose cables. Thus, the main focus of this paper is to propose a new control method which can tolerate force measurement noise and despite of uncertainty in kinematic parameters, guarantee a smooth end-effector motion without any undesirable vibration.

Wave Based Control (WBC) is a relatively new method developed in joint space controller topologies, which encounters for flexible manipulators and suppresses the vibrations in under-actuated flexible systems [2], [16]. In this method, the actuator concurrently emits a wave toward controlling the system and absorbs it when it's reflection is returned [15], [17], [18].

The authors in [11], have introduced a new conceptual framework for controlling DSCRs based on WBC theory. In this paper, the proposed method is modified to be applicable to the real world robot and then its performance is compared with cascade control method. In this topology, using a simple and safe controller, forces and lengths of the cables are simultaneously controlled. Moreover, an integral term in the proposed control law acts as a low pass filter which eliminates the high-frequency noise in the force measurements. As a result, knowing that the encoder measurements of cable length are digital and immune to noise, high gain controllers may be appropriately implemented. Finally, in spite of uncertain kinematic parameters in DSCRs, all the cables will remain in tension which is impossible to achieve when it comes to conventional joint space controllers.

The paper is structured as follows; first WBC strategy is reviewed and primary concepts are introduced. Then kinematic modeling of suspended CDPM is studied and the derivation of inverse and forward kinematics are presented. Finally, experimental results of implementing the WBC controller is illustrated and the paper will be wrapped up by concluding remarks.

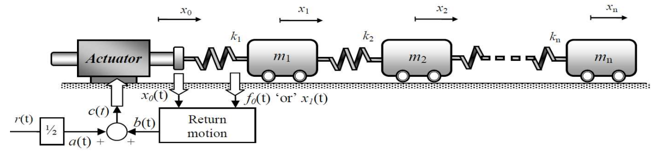

Fig. 2. A flexible system controlled by wave based method [10].

II. Wave Based Control Theory

The literature concerning WBC theory is reveiwed in this section. A WBC based method for controlling flexible systems with lumped mass-spring dynamic models has been proposed in [15], [17]. Moreover, [2], [16] have proposed using WBC in order to vitiate the effect of vibration in various robotics and gantry crane applications. To describe the idea behind this method without getting into the intricate details of the matter, one may image a string of n lumped mass-springs where the string itself is controlled by a single actuator, which an example of can be seen in 2. While the goal of the system is to achieve the desired postion of the n^{th} mass without vibration, WBC law states how actuator should move the first mass. In this paper, the actuator is expected to launch a wave into the system and also to absorb the wave coming from the system. To avoid confusion with regards to the meaning of term wave, in this paper, this term is used to describe a propagating disturbance, usually both in space and time, as it moves through the flexible system. In the control system shown in 2, the input to the actuator equals the sum of two signals, i.e. the sum of half the reference displacement and a measured return displacement mentioned above. To avoid the vibration of the system, the input impedance presented by the actuator to the returning wave should be equal to the returning wave impedance or to the output impedance of the flexible system. In such a situation, the launch wave enters the system at the actuator, travels to the tip through the flexible joints, returns and leaves again through the actuator, similar to an infinite mass- spring system going leftwards, never to return but leaving behind a system at rest in the correct new position.

III. Robot Kinematics

In this section, the kinematic relations of the DSCR is derived. At first, the inverse kinematic relations of a cable robot with four actuators are derived. Then the Jacobian matrix of the robot is calculated. Fig. 3 illustrates a DSCR with four cables. The loop closure relationship for the robot as shown in Fig. 3 is given as follows.

$$\overrightarrow{L_i} = \overrightarrow{P} - \overrightarrow{P_{A_i}}, \quad i = 1, 2, \ldots, 4. \tag{1}$$

In what follows, inverse and forward kinematic relations are derived.

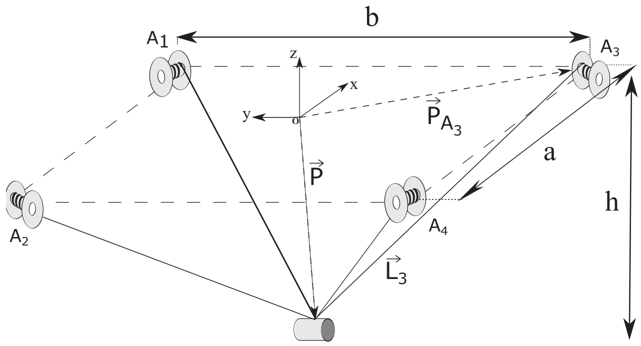

Fig. 3. Kinematic schematics of deployable suspended cable robot.

A. Inverse Kinematic Solution

Rewrite the loop closure relation algebraically as follows:

$$(l_i)^2 = (P - P_{A_i})^T (P - P_{A_i}) \tag{2}$$

where l_i is the length of i'th cable. One may rewrite this equation componentwise as:

$$l_i = \sqrt{(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2} \tag{3}$$

in which, x, y, z and x_i, y_i, z_i denote the position of the end-effector and the attachment points of the i'th cable, respectively.

B. Forward Kinematic Solution

In order to solve the forward kinematic of the ARAS–DSCR, from the set of four equations of (3) for $i = 1, 2, \ldots, 4$, one may select three of them, and directly calculate the position of the end-effector. If equations related only to the cable one to three are selected, DSCR forward kinematic solution may be written as follows:

$$\begin{aligned} x &= \frac{1}{2a}(l_2^2 - l_1^2),\ \ y = \frac{1}{2b}(l_3^2 - l_1^2), \\ z &= h \pm \sqrt{l_1^2 - (x - \frac{a}{2})^2 - (y - \frac{b}{2})^2} \end{aligned} \tag{4}$$

where z has two solutions and according to the work space specifications of the suspended robot, the negative solution is correct. It should be noted that in the above relation the loop closure equation of the fourth cable is not used. Regardless of the length of the forth cable, by using the first three equations the end-effector position may be found. Furthermore, based on equation 4, for the forward kinematics to be solved, the exact values of parameters a and b are to be known.

C. Jacobian matrix

The Jacobian matrix plays an important role in the kinematics problem analysis due to the fact that it reveals important relationships between the work and joint space. In other words, Jacobian matrix performs a mapping between the joint and task space variables. The jacobian matrix constructs a transformation which maps the actuator forces to the forces and moments acting on the moving platform [19]. Furthermore, an important kinematic problem, the singularity analyses, can be studied through the Jacobian matrix. So considering the it's importance, in what follows, the Jacobian matrix of DCSR is derived.

Letting l denote the vector of joint coordinates containing the lengths of the cables and x, the vector of end-effector motion variables, the kinematics equations can be derived as $f(l,x) = 0$, an implicit function of vectors x and l. Through derivative of $f(l,x)$, the relation between the joint space and work space velocities $\dot{l}$, $\dot{x}$ is achieved:

$$J_x \dot{x} = J_l \dot{l} \tag{5}$$

$$J_x = +\frac{\partial f}{\partial x}, \qquad J_l = -\frac{\partial f}{\partial l} \tag{6}$$

So the jacobian matrix can be derived as follows:

$$\dot{l} = J \dot{x} \tag{7}$$

$$J = J_L^{-1} J_x \tag{8}$$

Finally, The analytical form of Jacobian matrix of the robot shown in Fig. 3 is as follows:

$$J = \begin{bmatrix} \frac{(x-x_1)}{l1} & \frac{(y-y_1)}{l1} & \frac{(z-z_1)}{l1} \\ \frac{(x-x_2)}{l2} & \frac{(y-y_2)}{l2} & \frac{(z-z_2)}{l2} \\ \frac{(x-x_3)}{l3} & \frac{(y-y_3)}{l3} & \frac{(z-z_3)}{l3} \\ \frac{(x-x_4)}{l4} & \frac{(y-y_4)}{l4} & \frac{(z-z_4)}{l4} \end{bmatrix} \tag{9}$$

IV. Different Approach To Control CDPMS

In this section, two model independent control methods are investigated to control the deployable cable driven robots. In the first method, a cascade structure simiular to what described in [1], [13] is used in which an inner loop controls the cable tensions and outer loop controls the end-effector position. The second controller proposed in this paper is based on WBC theory which is extended to be used for the control of the deployable cable driven parallel robots.

A. Cascade Control of CDPM

Figure 4 shows the block diagram of cascade controller for deployable CDPM. As shown in figure 4, the control commands, u, which are applied to the motors are as follows:

$$u = K_{p_\tau} \times (\boldsymbol{\tau}_d - \boldsymbol{\tau}) + K_{i_\tau} \times (\int_t \boldsymbol{\tau}_d - \boldsymbol{\tau} dt) \tag{10}$$

where $\boldsymbol{\tau}$ is the cable tensions measured using force sensor. Also, Kp_τ and K_{i_τ} are the coefficients of Proportional derivative (PD) controller and $\boldsymbol{\tau}_d$ is the desired cable force which are determined by controller and have the following relation:

$$\boldsymbol{\tau}_d = J^\dagger f_d + Q \tag{11}$$

in which, Q stands for null space of the Jacobian matrix and f_d is:

$$f_d = K_{p_x} \times (x_d - x) + K_{v_x} \times (\dot{x}_d - \dot{x}) \tag{12}$$

where x represents the end-effector position and x_d is the desired position of end-effector. Also, K_{p_x} and K_{v_x} are the coefficients of Proportional Integral (PI) controller.

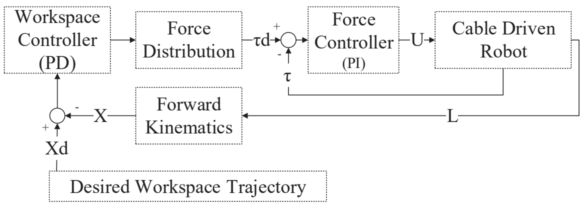

Fig. 4. Block diagram of cascade control in cable driven parallel manipulators.

B. Wave Based Control of CDPM

The block diagram of figure 5 shows how to apply wave base control to cable driven parallel manipulators. As shown

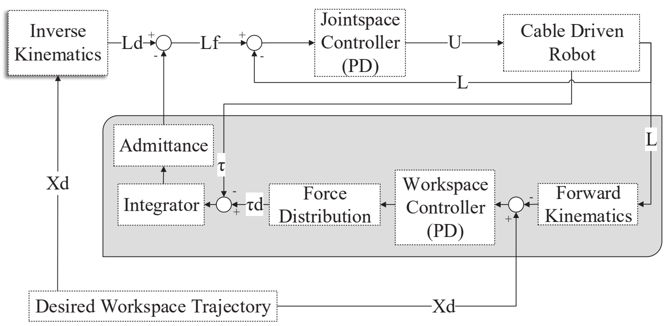

Fig. 5. Block diagram of using wave based control in cable driven parallel manipulators.

in Figure 5, the control inputs of the actuators are determined as follows:

$$U = K_{p_l} \times (L_f - L) + K_{v_l} \times (\dot{L}_f - \dot{L}) \tag{13}$$

where the L_f is obtained as:

$$L_f = L_d - L_\tau \tag{14}$$

$$L_\tau = Y \int_{t=0} \boldsymbol{\tau}_d(t) - \boldsymbol{\tau}(t) dt \tag{15}$$

in which, Y stands for admittance of cable and τ_d denote the desired cable forces which are derived as follows:

$$\boldsymbol{\tau}_d = J^\dagger f_d + Q \tag{16}$$

$$f_d = K_{p_x} \times (x_d - x) + K_{v_x} \times (\dot{x}_d - \dot{x}) \tag{17}$$

The outstanding points of the WBC separating it from other cascade topologies could be highlighted as follows:

1) Due to the fact that the controller is designed in joint space, the robot operates safely.
2) The integral term in force measurement output can reduce the high frequency noises.
3) Because of using high gain controller and low noise measurements of cable lengths, the proper tracking performance of cable length can be achieved.
4) According to wave based structure of the proposed controller, the vibration suppression of end effector is automatically provided.

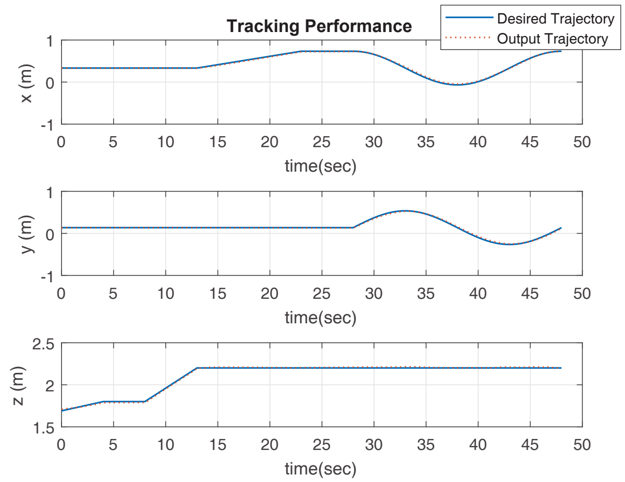

Fig. 6. The desired and final trajectory of the end-effector.

It should be noted that in fact cables are not rigid body and in many applications, their mass and flexibility cannot be ignored. These types of robot suffer from vibration and swaying behavior resulting from low stiffness of sagging cables.

V. Experimental Results

The characteristics of deployable cable driven parallel manipulator built in ARAS group are denoted in the Table I. The kinematic parameters stated in this table are the same as depicted in figure 3. In order to invsetigate the proposed algorithms, a circular trajectory is designed for the desired path and the robots behavior under application of the controls law are investigated. Figure 6 shows the desired trajectory designed in Cartesian workspace alongside the results obtained utilizing the WBC control law. Also the tracking error is depicted in Figure 7. A comparison of the desired and measured cable lengths during this maneuver are illustrated in Figure 8. Also, the desired and measured cable tension during robots maneuver is shown in figure 9. Finally, the desired circular trajectory in xy plane and the robot position under control of the WBC are depicted in figure 10. In order to illustrate the effectiveness of the proposed method, the tracking error for the case of cascade controller is also shown in the Figure 10. As it can be seen in figures 9 and 8, when the wave based control law is applied, the force and length tracking express the some errors. That is due to the fact that the proposed controller tunes the dynamic relation between force and motion variables instead of controlling each one of them alone.

TABLE I
THE KINEMATIC AND DYNAMIC PARAMETERS OF CDPM.

$a(m)$	$b(m)$	$h(m)$	end effector mass(Kg)
3.56	7.05	4.25	4.5

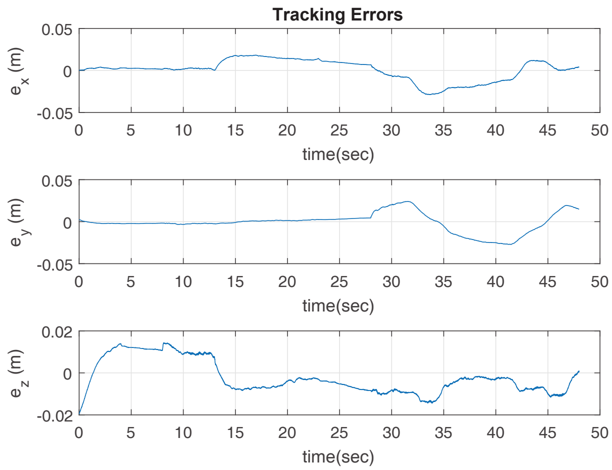

Fig. 7. The tracking error using WBC.

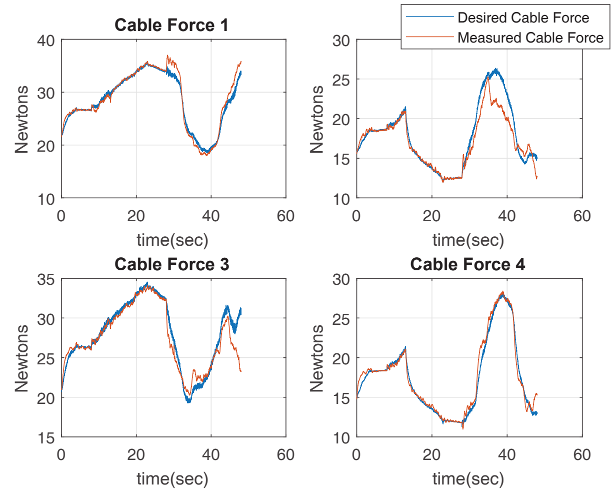

Fig. 9. The desired and measured cable tension during robot movement.

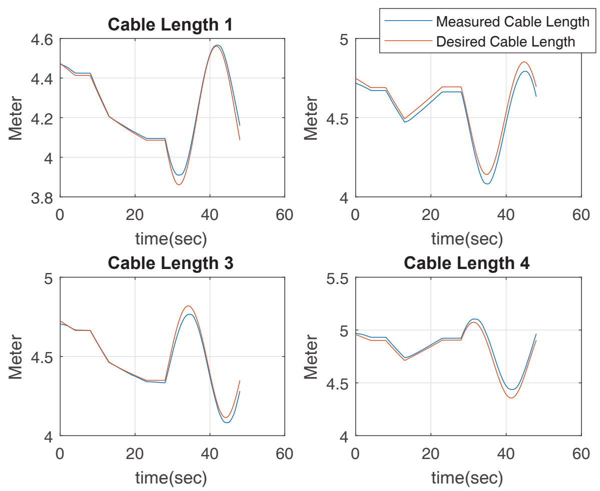

Fig. 8. The desired and measured cable length variation during robot movement.

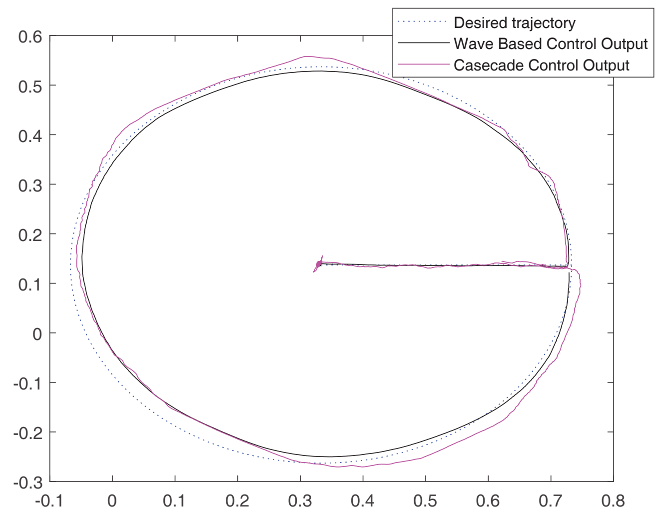

Fig. 10. The desired path and final trajectory of the end-effector using WBC and cascade control.

VI. Conclusions

This paper proposed a modified wave based approach adapted to the deployable cable driven parallel robots with kinematic uncertainties. The main novelty of this work is to simultaneously combine position control and active vibration damping by emitting and absorbing motion waves in a controlled way. For the related experiments, a deployable cable driven robot, called ARAS-CAM was used to show the performance of the proposed algorithm. The experimental results manifest how well a modified version of WBC performs at both end effector position control and vibration damping.

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