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Dual Space Control of a Deployable Cable Driven Robot: Wave Based Approach

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ABSTRACT

Known for their lower costs and numerous applications, cable robots are an attractive research field in robotic community. However, considering the fact that they require an accurate installation procedure and calibration routine, they have not yet found their true place in real-world applications. This paper aims to propose a new controller strategy that requires no meticulous calibration and installation procedures and can handle the uncertainties induced as a result of that. It is well known that kinematic uncertainties can lead to loose cables when one deals with a redundantly actuated robot. The control methodology presented in this paper is a simple yet powerful controller based on wave-based theory that can handle the aforementioned loosened cables. Thus, through applying this novel controller, the applications of cable robots to real-world problems has become more feasible. This paper also investigates the performance of the proposed controller and its effectiveness through some practical experiments. We observed that the proposed controller outperforms conventional cascade topologies in terms of tracking smoothness.

1. Introduction

In a cable driven parallel manipulator the moving platform is connected to the based through a number of cables each connected to an actuator. Known characteristics of these robots are there large workspace, agility and payload capabilities. These unique characteristics have made them great choices for applications such as sport video capturing [1] or large scale radio telescopes [2,3].

In Deployable Suspended Cable-driven Robots (DSCRs), since the kinematic parameters are not accurately available, the mathematical models for the robot are perturbed [4] .In turn, these perturbations of the model leads to many challenges when designing a controller to meet the required performance [5,6,7].

As an example of a DSCRs, we can mention the Spider-cams that are commonly used for the purpose of video capturing in sports fields. shown in the Figure 1, our ARAS-CAM robot is also a DSCR specifically designed for the purposes of imaging and video capturing. Basically, simple installation as the main property of DSCRs makes them an extremely suitable choice for imaging industry.

For controlling CDPMs several topologies have been proposed in the literature [8]. Based on where the feedbacks are taken from theses controllers can be categorized into two groups; the first group takes the feedback from the cable length measurements and the second group measures the end-effectors position as the feedback. The former is joint space controlling and the later is controlling in task space [8,9,10]. In what follows, these two general topologies are briefly

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discussed and based on their properties their potential applications are introduced.

When the measured end-effector position [11] is taken as the feedback signal, the forward kinematics of the robot should be utilized as the map between cable quaneties and workspace measurements.

In this case, the position error in the workspace is applied to the controller [12,13]. Then the output of the controller which is in the form of a Cartesian force, is asserted to the end-effector by mapping it to the desired cable tensions. This mapping is achieved using the Jacobian matrix. Often in practice, for implementing this strategy a cascaded system is employed. In this system, an inner-loop controller is implemented for controlling the tension of the cables and an outer-loop controller is employed for producing the desired force references for their inner-loop counterparts. A ramification of this method is that the cable tensions must be measured. Hence, as a major drawback for this method, we can mention the fact that the force measurements are noisy and utilizing them in a high gain inner-loop controller would lead to amplified deteriorations of the performance.

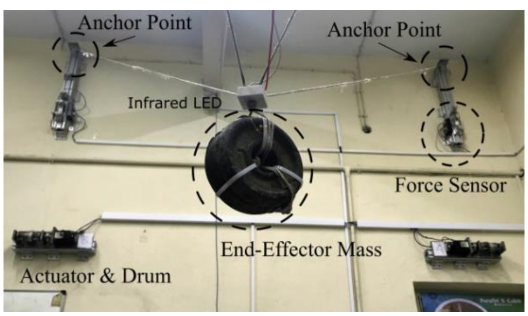

Figure 1. Prototype of a deployable suspended cable driven robot called ARASCAM

On the other hand, joint space controllers map the desired trajectory from the workspace to the cable lengths. Next, the main objective is to enforce these desired lengths by controlling each actuator individually. As simple as this method might appear, there are some major problems with it. First, the exact kinematic parameters are unknown in most deployable cases and this leads to a non- vanishing error in the position of the end-effector. Second, in the case of redundant systems, this strategy leads to loosened cables. When it comes to deployable DSCRs though, measuring the precise location of the end-effector is not feasible. Because it would require high-end sensors such as laser trackers witch contradicts with the nature of easy deployability [7]. Therefore, for this type of applications we are bound to the second controlling strategy discussed above [9,11].

As mentioned before, in deployable scenarios the kinematic parameters are not exactly known. Therefore, this paper aims to propose a control architecture that is robust to force measurement noises and that can grantee a smooth tracking performance without any loosened cables. To achieve this, we exploit concepts presented in wave-based control theory.

Wave Based Control (WBC) is a relatively new method for accounting for flexible links and damping vibrations in the system [14,15]. Moreover, these controllers are applied to the join space variables. The main idea of this method is that the actuator emits a wave toward controlling the system and absorbs the reflection as it returns back [16,17,18].

Our work is the extension of the method proposed in [19,20] where the authors have introduces a conceptual framework to control DSCRs. We have extended this method to be applicable in real-world applications. Moreover we compare its performance with other conventional cascade methods through some practical experiments. Our controller is simple and reliable and can simultaneously control the cable forces and lengths. This is done while a trade-off between these two is maintained. Furthermore, since in our topology the force measurements are passed through an integral operator, its high frequency contents are filtered out. Thus in our method the noise related problems are mitigated. In fact our method relies on the length measurements coming from the digital encoders which are immune to noise. Therefore, we can employ high gain controllers that in turn provide us with smooth operation. Finally, the particular method we propose avoids loosened cables despite uncertain kinematic parameters which is an unavoidable phenomenon in conventional joint-space controllers. The paper is structured as follows; first we briefly introduce the WBC method. Next, the kinematic model of the robot is introduced in section 3. In section 4, we propose our control strategy. Finally, after presenting our experimental setup in section 5, we present the experimental results in section 6 and the paper is wrapped up by concluding remarks in section 7.

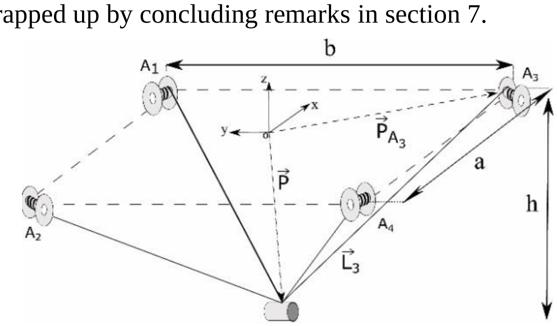

Figure 2. Kinematic schematics of deployable suspended cable robot.

2. Wave Based Control Theory

In this section, we briefly introduce the WBC method. A WBC for controlling a flexible system with a lumped spring-mass model is proposed in [17,18]. Furthermore, [14,15] proposes utilizing WBCs for attenuating vibrations in various robotic and gantry crane applications.

Here we describe the key idea behind this method without getting into details of the formulations involved. Imagine a string of n masses each connected to the other through a spring and controlled by a single actuator at the end of the chain [19]. Now the goal here is to control the n^{th} mass in this chain by applying an appropriate input by moving the first mass using the actuator. To do so, the actuator launches a wave and absorbs it as its reflection returns. In this paper, the term wave is used to describe temporal and special disturbance propagated in the flexible system.

As shown in the reference [14], the movement applied to the first mass is comprises of half the reference displacement and a measured returned displacement. In order to dampen the reflection coming back to the motor, it should simulate the impedance of the medium that it sees. Hence, the process is as follows. First, the wave is created by the actuator. The created energy propagates in the medium and reaches the n^{th} node. Part of the energy influences the object under control connected at the end of the chain and the rest returns back toward the actuator. At the actuator side, since it mimics the impedance of the medium, the wave is dampened. In fact, theoretically we look at this wave as if it was passed into a virtual end-less medium of springs and masses never reflecting back again.

3. Robot Kinematics

In this section, we drive the kinematic equations of our DSCR. This consists deriving the inverse kinematics and next the Jacobian matrix from it.

Our DCR is illustrated in Fig. 2. As it can be seen form this figure, our DSCR is actuated by four cables. The loop closure for this robot is given as follows:

$$(l_i)^2 = \left(P - P_{A_i}\right)^T (P - P_{A_i}) \quad (1)$$

where l_i is the length of i'th cable. Rewriting this equation in a component-wise fashion leads to:

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

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

3.1. Inverse Kinematic Solution

In solving the forward kinematic problem, one aims to calculate the position of the end-effector given the cable length measurements. Here for our redundant robot, there are four equations relating the cable lengths to the end-effector position. While the solution for the inverse kinematic is unique and one-to-one, calculating the position from length measurements is an over constrained problem. One might easily take three equations from Eq. (2) for $i = 1,2, \ldots ,4$, and find a solution for the position. For example, if equations for $i = 1,2,3$ are selected, the forward kinematic can be expressed as follows:

$$x = \frac{1}{2a}(l_2^2 - l_1^2),\ y = \frac{1}{2b},\ z = \mathrm{h} \pm \sqrt{\mathrm{l}_1^2 - \left(\mathrm{x} - \frac{a}{2}\right)^2 - \left(\mathrm{y} - \frac{b}{2}\right)^2} \quad (3)$$

In the above, there are two solutions for z while based on the physical structure of the robot, only the negative one is valid.

It is important to note that in the above equations the length measurement for the forth cable dose not contribute to the solution. On the other hand, the kinematic parameters a and b in the equations are not accurately available. This brings us to the better strategy toward solving the forward kinematic. The better approach is to take all the equations and construct a least square (LS) problem whose solution utilizes all the information available.

Next, we need to calculate the Jacobian matrix. Jacobian matrix is an important tool that relates important quantities from joint space and work space. It relates the cable length's rate of change to the workspace speeds. In addition, it maps the tensions of the cable to the Cartesian force applied to the end-effector [8]. Another important application for the Jacobean matrix is performing singularity analysis which is an important tool for finding the feasible workspace and designing the trajectory of the robot. Thus, in what follows, we calculate this matrix.

Let l denote the cable length from end-effector to its corresponding anchor point and x the position vector for the end-effector. Thus, the kinematic of the robot can be expressed as a function of these two states: $f(l, x) = 0$. Calculating the Jacobian of this function with respect to x and l *relates* $\dot{x}$ *and* $\dot{l}$ quantities as follows:

$$J_x \dot{x} = J_l \dot{l} \quad (4)$$

$$J_x = \frac{\partial f}{\partial x},\ J_l = -\frac{\partial f}{\partial l} \quad (5)$$

Finally the robot's Jacobian J is defined as:

$$\dot{l} = J\dot{x} \quad (6)$$

$$J = J_L^{-1} J_x \quad (7)$$

The analytical form of Jacobian matrix of our robot shown in Fig. 2 is as follows:

$$J = \begin{bmatrix} \frac{x-x_1}{l_1} & \frac{y-y_1}{l_1} & \frac{z-z_1}{l_1} \\ \frac{x-x_2}{l_2} & \frac{y-y_2}{l_2} & \frac{z-z_2}{l_2} \\ \frac{x-x_3}{l_3} & \frac{y-y_3}{l_3} & \frac{z-z_3}{l_3} \\ \frac{x-x_4}{l_4} & \frac{y-y_4}{l_4} & \frac{z-z_4}{l_4} \end{bmatrix} \quad (8)$$

4. A Different Approach Toward Controlling CDPMS

In this section two model independent controllers are investigated. Similar to [9,12], the first control system has a cascade structure and is comprised of an inner-loop controller for controlling the cable forces and an outer-loop for controlling the position of the end-effector. The second control system is designed based on (WBC) theory and is extended to be better compatible with deployable cable driven robots.

4.1. The Cascade Controller

The structure of the cascade controller described in this section is illustrated in Fig.3. The control input u shown in the figure is governed by the following equation:

$$U = K_{p\tau} \times (\tau_d - \tau) + K_{i\tau} \times (\int_t \tau_d - \tau \ \ dt) \quad (9)$$

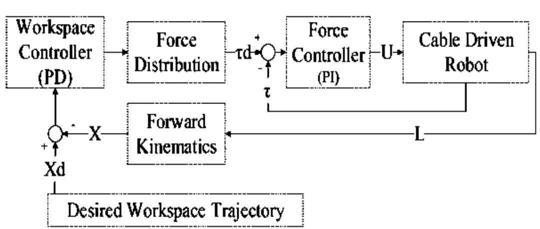

Figure 3. Block diagram of using wave based control in cable driven parallel manipulators.

In the above equation, τ is the cable tension which is measured using the force sensors. Furthermore, $K_{p\tau}$ and $K_{i\tau}$ are the gains for the PI controller and τ_d is the .desired cable tensionThis desired tension is mapped from the workspace desired force through the Jacobian matrix as follows:

$$\tau_d = J^{\dagger} f_d + Q \quad (20)$$

Here, Q is a vector from the null-space of the Jacobian matrix and f_d is the desired Cartesian force. The Q term here, does not effect the applied force in the Cartesian space but it created an internal force in the joint space cable tensions which can be leveraged as a parameter for maintaining a positive tension in the cables. The Cartesian force f_d is calculated by the outer-loop controller as follows:

$$f_d = K_{px} \times (x_d - x) + K_{vx} \times (\dot{x}_d - \dot{x}) \quad (31)$$

where x represents the end-effector position and x_d is the desired reference for the position. Moreover, K_{px} and K_{vx} are the gains for the PI controller.

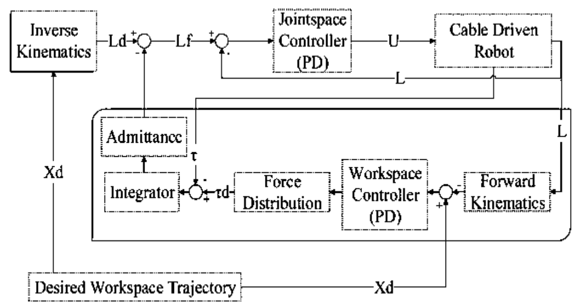

Figure 4. Block diagram of WBC control in cable driven parallel manipulators.

4.2. The Wave Based Controller

The block diagram of the proposed wave-base controller is illustrated in figure 4. Here, the control input u shown in the figure is governed by the following equation:

$$U = K_{pl} \times (L_f - L) + K_{vl} \times (\dot{L}_f - \dot{L}) \quad (42)$$

where the desired cable length L_f is calculated as follows:

$$L_f = L_d - L_\tau \quad (53)$$

In the above equation L_d is the ideal desired cable length calculated using the inverse kinematics and L_τ is governed by the following equation:

$$L_\tau = Y \int_{t=0} \tau_d(t) - \tau(t) dt \quad (64)$$

Here, Y is admittance of the cable and τ_d is the desired cable tension which is calculated through the force distribution rule as follows:

$$\tau_d = J^{\dagger} f_d + Q$$

(75)

Furthermore, f_d is the desired Cartesian force and is calculated using the following PD control law:

$$f_d = K_{px} \times (x_d - x) + K_{vx} \times (\dot{x}_d - \dot{x}) \qquad (86)$$

The major advantages of the WBC controller Compared to other conventional cascade controllers is highlighted as follows:

1) Since the controller is designed in joint space, it is safer. This is because the feedbacks are taken from joint space variables which are more reliable in nature.

2) The integral operator applied on the force measurements, greatly attenuates the high frequency noise contents of the force sensors.

3) Because of using a high gain controller and low noise measurements, the robot operates smoothly. In other words, the proposed structure mitigates the impacts of kinematic uncertainties and brings us smooth and repeatable operation performance.

4) Due to the wave based structure of the proposed controller, the vibration suppression of end effector is automatically provided.

It should be noted that cables are not rigid bodies and in many applications, their mass and flexibility could not be ignored. In these cases, vibration and swaying behaviors should be accounted for. We hypothesize that the proposed (WBC) controller can alleviate these phenomena.

5. EXPERIMENTAL SETUP

The ARAS-CAM is a 3-DOF robot equipped with four actuators. The presence of one extra actuator with respect to the degrees of freedom means that the robot is redundantly actuated and can handle the problem of cable force distribution throughout a larger workspace. The physical parameters for the robot are shown in the table 1. As stated earlier, this robot has a redundancy in actuators which leads to a better force distribution. The calibration procedure of the robot is carried out without any complex and expensive equipment. Since this CDPM is a fast deployable robot, it has up to 5 dimensional uncertainties in its kinematic parameters. In addition to this kinematic uncertainty, the end-effector mass is considered to be known with a 1kg uncertainty bound ($4.5 \pm 0.5\, kg$) . This robot is equipped with sensors cable of measuring cables lengths, end-effector's position and cables tensions. These low cost sensors include four encoders for cable length measurement, four force sensors for measuring cable torsion and a camera for position feedback. The camera used in this robot is a stereo camera capable of providing accurate position feedback at a rate of 120Hz. It should be noted that in this work, the data obtained from the vision system is not utilized for controlling the robot. Here, these data are as a ground truth for comparison purposes. In the following sub--sections, a brief overview of these constituent parts are presented.

Table 1. Kinematic and Dynamic Parameters of the ARAS--CAM

Parameter	unit	value
End effector mass	kg	4.5
End effector inertia (kg)	kg m^2	≅ 0
Gear ratio	-	1
Drum radius	cm	3.5
Number of pulleys	-	4
Parameter a in figure	m	3.56
Parameter b in figure	m	7.05
Parameter h in figure	m	4.23

5.1. Cable Winch System

For controlling the cable length, a special cable winch is designed such that the drum moves along its axis as it rotates. As the pitch of the screw is equal to the cable width, the cable cluttering is prevented using this system. Moreover, Since the cluttering is prevented, that cable's length change can be accurately inferred from the encoders attached to the drum. This design is illustrated in the figure 5. As a consequence of using incremental encoders, determining the absolute lengths of the cables is not possible. Therefore, measuring the value of the cable lengths is mandatory. For this purpose, an off-the-shelf laser length measuring device is employed.

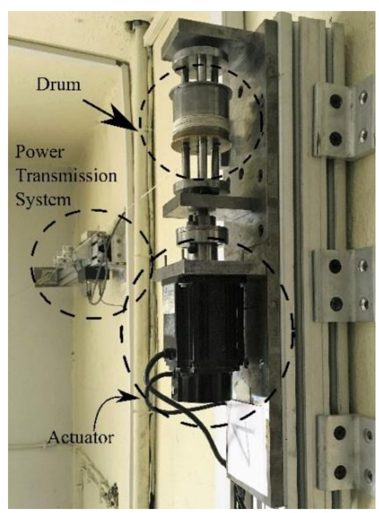

Figure 5. Cable winch system.

5.2. Force Sensors

Each cable tension is measured by a load-cell sensor places in a structure comprised of three pulleys. Our current approach toward measuring the cable tensions is the new version of our previous system described in [9]. In the old system, small load-cells were attached in between the cables and the end-effector. The downsides of this approach was twofolded. First, the weight of the load-cells directly affected the models of the robot. Second, the signal wires hanging out from these sensors curbed the application of the robot in many practical scenarios. However, compared to this old model the new system does not impose any weights on the cables and since it is installed within the structure on the anchor points, its wires do not hamper the operation of the robot.

Figure 6. Force sensor system designed to measure cable force

5.3. Vision Sensor

The stereo camera used in the robot act as a marker tracker system for providing the end-effector's position in space. With a resolution of 640×480 pixels, the comprising camera sensors in the stereo rack is capable of capturing images at a rate of 120 Hz. As a marker, an IR LED is attached to the end-effector. On the other hand, a visible light filter is placed in front of both cameras rendering them incapable of capturing ambient light and letting just the light emitted from the LED to pass through. Therefore, what is seen by the cameras is a white circle in a black background. Finally, to find the 3D coordinate of the LED, the pixel coordinates of the detected light from the two cameras are fed into camera undistortion and stereo tracking algorithms. In the Figure 7 the infrared LED and its place on the end-effector is shown. In the Fig.7 the designed stereo vision rack is illustrated.

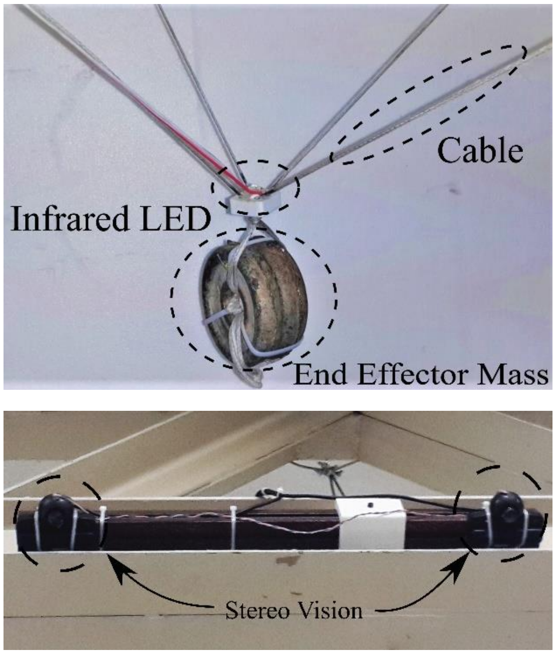

Figure 7. Stereo vision sensor designed to measure the position of end-effector.

5.4. Real-Time Control System

The architecture of the control system is illustrated in Fig. 8. The host computer as the place where the controller developed acts as a master to another PC running Matlab Simulink Real-time kernel. This PC is equipped with the required data acquisition cards for commanding the motors and reading the encoders. Moreover, the data provided by the vision system is fed into the target system through UDP communication. When the controller is ready and designed, the Matlab coder converts it to a C code that after compilation, is run on the target PC. This workflow accelerates the design-test iterations making the development workflow easy and tractable.

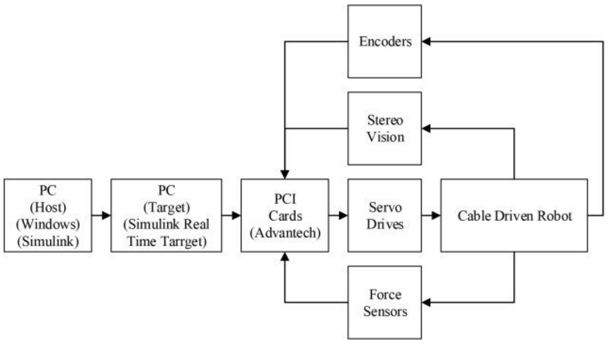

Figure 8. Real-time control system.

6. EXPERIMENTAL RESULTS

The characteristic parameters of our deployable cable driven parallel manipulator are presented in the Table 1. These kinematic parameters are the same as those depicted in figure 2. In order to investigate the proposed algorithms, we designed a circular trajectory. Then, we observe the tracking performance robot after applying the proposed controllers. Figure 9 shows the designed desired trajectory and the tracking behavior of the robot under WBC control. In addition, the tracking errors are depicted in Figure 10. A comparison of the desired and the measured cable lengths during this maneuver is performed in Figure 11. Furthermore, the desired and measured cable tensions during the maneuver is shown in figure 12.

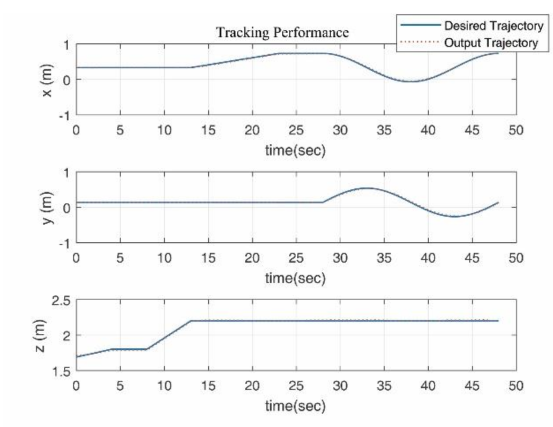

Fig. 9. The desired and final trajectory of the end-effector.

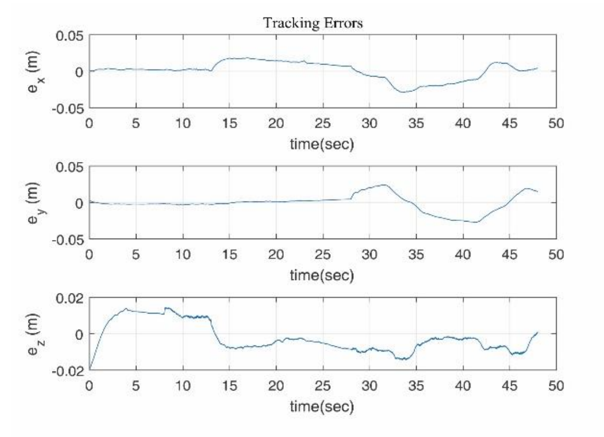

Fig. 10. The tracking error using WBC.

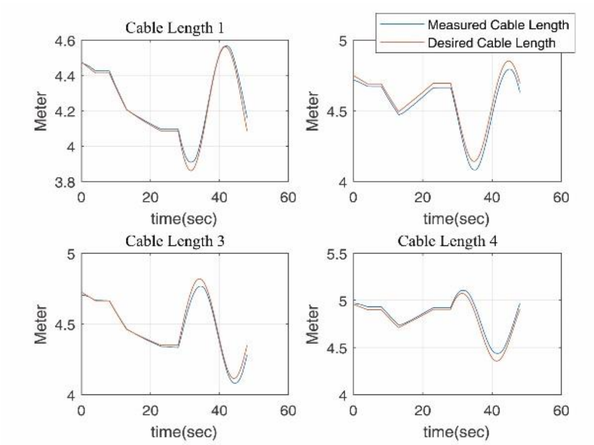

Fig. 11. The desired and measured cable lengths during robot movement.

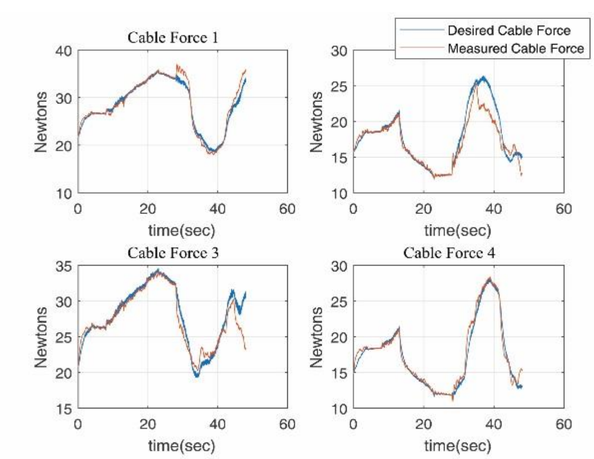

Fig. 12. The desired and measured cable tensions during robot movement.

Finally, the desired circular trajectory in x-y plane and the performance of the robot under control of (WBC) and Cascade controls are illustrated in figure 13.

As it can be seen in figures 10 and 13, when the wave based control law is applied, the tracking of force and cable length have some errors. That is due to the fact that the proposed controller tunes the dynamic relation between force and motion variables instead of controlling them independently.

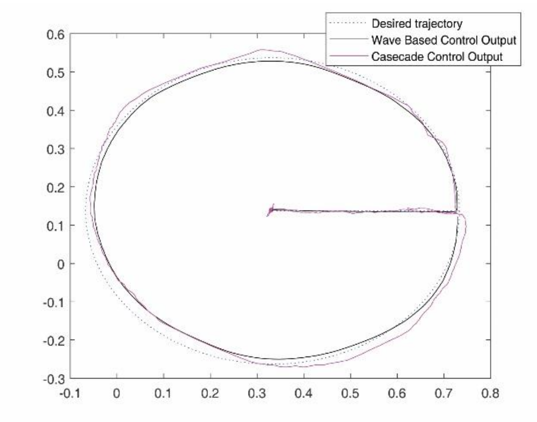

Fig. 13. The desired path and the trajectory of the end-effector after applying WBC and cascade controllers.

7. CONCLUSIONS

For cable driven parallel robots, we have proposed a simple and effective controller capable of attenuating the impacts of kinematic uncertainties. Controlling the end-effector's position while damping undesirable vibrations is the main novelty of this work. The effectiveness of the proposed method was then explored through some practical experiments on ARAS-CAM which illustrated improved performance and stable tracking. Furthermore, through these experiments we also showed that our controller can effectively ameliorate vibration rejection in the system. Hence, this paper provides a simple and easily applicable method for controlling cable driven robots aimed for real-work applications.

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8. Biography

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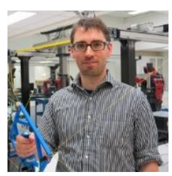

Philippe Cardou received the B.Eng. degree in mechanical engineering from the Université Laval, Quebec City, QC, Canada, in 2003, and the Ph.D. degree from McGill University, Montreal, QC, in 2008. In 2007, he joined the Department of Mechanical Engineering, Université Laval, where he has been an Assistant Professor since 2008. His research interests include kinematics and optimization, with an emphasis on two specific applications: the measurement of rigid-body displacements from accelerometers and the dimensional synthesis of mechanisms. He is a member of the American Society of Mechanical Engineers. Since 2008, he has been an Associate Editor of the Transactions of the Canadian Society for Mechanical Engineering