Study on Cable-Driven Parallel Robot with Adaptive Velocity Controller in Distribution Warehouse

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I. Introduction

The advent of robotics in industrial automation has marked a significant shift in how operations are conducted in various sectors. Robotic arms, with their diverse degrees of freedom and workspace capabilities, have been at the forefront of this revolution, offering precision, efficiency, and reliability. However, as the demand for larger workspace and more versatile operations increases, the limitations of conventional robotic arms have become more apparent. These limitations include increased weight and volume, as well as restricted range of motion, especially in expansive industrial environments like distribution warehouses.

A. Prior Works

In addressing these challenges, prior research has largely focused on cable-driven parallel robots. These systems stand out due to their ability to operate over large workspace and at high speeds. Previous studies have primarily concentrated on enhancing the positioning accuracy of these robots. For instance, one research introduced a hybrid control method that significantly improved positioning accuracy by separating upper and lower-level controls [1]. Another study proposed a vision-based control method, utilizing multiple cameras to enhance the robot's positioning accuracy by continuously comparing the current state with desired outcomes [2].

However, these studies predominantly focus on positioning performance, often overlooking the critical aspect of velocity control. They present a limitation, especially in scenarios where speed and adaptability are crucial for handling different types of objects efficiently.

B. Motivation and Novelty

The motivation behind our project stems from the need to adopt cable-robotic systems in large workspace and to address the limitations of existing cable-driven robotic systems, particularly in terms of velocity control. While current solutions excel in positioning accuracy, they fall short in dynamically adjusting the robot's speed based on the varying physical characteristics of the objects being handled. This limitation is particularly pertinent in industrial settings where efficiency, energy consumption, and adaptability are key considerations.

Our novel approach introduces an adaptive velocity controller for a cable-driven parallel robot. This innovation is not just about enhancing the speed of operations but about intelligently adapting to the task at hand. By incorporating an adaptive velocity controller, our solution can fine-tune the robot's movements, ensuring optimal efficiency and precision when handling objects of different shapes, sizes, and rigidity. This approach marks a significant departure from existing solutions, which are largely static in their speed and motion control.

II. System Design

A. Hardware

In designing a 3D model of a cable-driven parallel robot, specific aspects regarding the working environment must be considered. Typically, minimum of n+1 number of cables are required to provide a gripper with n degrees-of-freedom (DoF). However, a higher number of cables increases the likelihood of collisions with existing obstacles in the environment and complicates the design. This complexity makes finding kinematic solutions more challenging. In a distribution workplace, where only 3-DoF translations are required, reducing the number of cables from seven (for 6-DoF motion) to four can significantly simplify the parallel robot system. This reduction potentially avoids collision issues and facilitates easier and more efficient resolution of kinematic problems, compared to a system with seven cables. From these considerations, the four cable-driven parallel robot is designed as shown in Figure 1.

B. Software

To analyze the motion of the cable-driven robot, we conducted a 3D simulation using MATLAB. This involved calculations for inverse kinematics and implementing the cubic polynomial equation for adaptive velocity control. The simulation, as shown in Figure 2, demonstrated smooth motion and adaptive speed changes in the robot. This observation validates the possibility of fine-tuning the robot's velocity, enabling the 4-cable-driven robot system to be effectively used for handling even fragile objects.

III. System Analysis

To solve the inverse kinematics equations, a few constraints must first be defined so that we can determine the end position in the workplace. We define the motors' coordinates as (x_i, y_i, z_i), where i is the ith motor. Then define the workspace length and width as L_{ws} and W_{ws}, respectively. We can then apply the constraint of the following:

$$x_1 + x_3 = x_2 + x_4 = L_{ws} \tag{1}$$

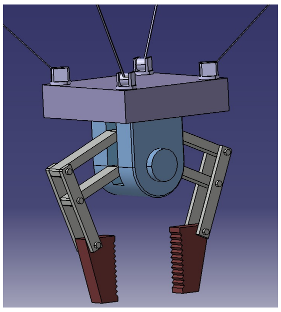

Fig. 1. 3D design of the 4 cable-driven parallel robot

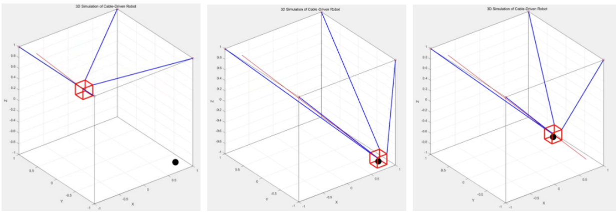

Fig. 2. 3D simulation of the 4 cable-driven parallel robot in Matlab

$$y_1 + y_3 = y_2 + y_4 = W_{ws} \tag{2}$$

With the constraints defined, by knowing the length of each cable, we can determine the position of the end effector in the workspace. We can draw spheres at the center point of each motor as potential cable attachment points, with their cable's length as the radius. The four spheres that are on the same plane would overlap and have 2 common intersection points. One is outside of the workspace, while the other one is inside the workspace, which is our end effector coordinate.

With the inverse kinematics of the cable-driven gripper, the cable's total length is defined as L_i, where i is the ith motor. To calculate the total length, we can use the distance formula by plugging in the motor's coordinate to the end effector's coordinate, $(x_E,\ y_E,\ z_E)$. This will give us the following formula:

$$L_i = \sqrt{(x_i - x_E)^2 + (y_i - y_E)^2 + (z_i - z_E)^2} \tag{3}$$

The cable length on the motor can be calculated with the arc-length formula, θ_i multiplied by r. θ_i is the angle of the ith's motor and r is the radius of the motor. The cable's initial length is defined as l_i, where i is the ith motor. We can create the following relationship:

$$\theta_i r + l_i = L_i \tag{4}$$

Substituting (3) into (4):

$$\theta_i r + l_i = \sqrt{(x_i - x_E)^2 + (y_i - y_E)^2 + (z_i - z_E)^2} \tag{5}$$

Rearrange (5) and solve for θ_i:

$$\theta_i = \frac{1}{r}[\sqrt{(x_i - x_E)^2 + (y_i - y_E)^2 + (z_i - z_E)^2} - l_i] \tag{6}$$

Equation (6) gives us the inverse kinematics of the angle of the motor.

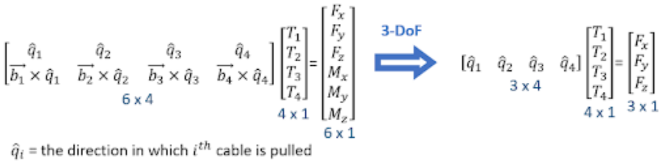

Fig. 3. Jacobian matrix for providing optimized force to the end effector

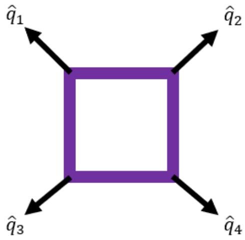

Fig. 4. Directions of the cable pulling the end effector

Figure 3 shows the Jacobian matrix for providing optimized force to the end effector. The force and moment applied to the end effector can be characterized by an equation JT = F, where J is the 6-by-4 Jacobian matrix, T is the 4-by-1 matrix of the tension of each cable, and F is the 6-by-1 matrix of the force and moment applied to the end effector. Since we are only considering 3 DoF translations of the end effector, J,T and F can be reduced down to 3-by-4, 4-by-1, and 3-by-1 matrix, respectively.

In the J matrix, q_i denotes the direction in which the ith cable is pulling the end effector as shown in Figure 4. By multiplying xyz-terms of q_i with the total tension of the cable, we can find the resultant force that is applied to the end effector in xyz terms.

For the velocity control, by implementing the cubic polynomial equation, we could find the smooth trajectory of both moving toward the object and backward. From the trajectory equation, we could gain the velocity graph of the robot and adaptively control the speed of the robot. In the simulation, the speed of moving toward the object and backward changes smoothly so that the gripper can move fast but carefully approach and convey the object.

From Figure 6, we can see that the end effector starts from rest and accelerates to a top velocity of 4.45 units per second, and decelerates to rest when the end effector is at the location of the object. Once the object is picked up by the end effector and accelerates to a top velocity of 2.25 units per second and decelerates to rest when the end effector reaches its destination. The benefit of controlling the speed of the end effector allows us to save a lot of time. From Figure 5, we can see that the end effector took 1 second to travel 3 units when the end effector was not gripping any object. It took the end effector 2 seconds to travel 3 units when the end effector was gripping the object. This is a 100% difference in time spent to travel the same distance and overtime can save a significant amount of time.

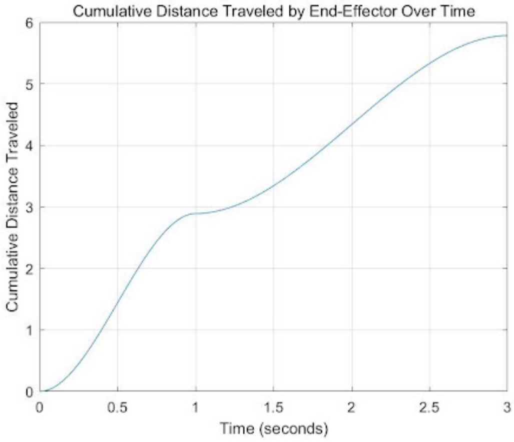

Fig. 5. Cumulative distance traveled by end effector over time

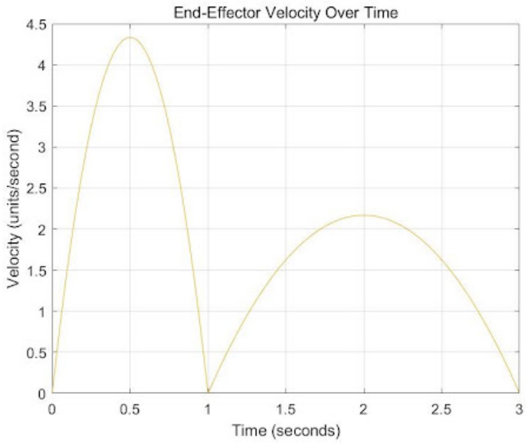

Fig. 6. End effector velocity over time

IV. Discussion

The cable-driven parallel robot has several advantages over rigid robotic arms, one of which is its suitability for usage in expansive workspace. Rigid robotics arms, as compared to cable-driven robots, grow exponentially in size and mass with increasing workspace. For cable-driven robots, the size and mass of the device remain nearly constant with increasing workspace despite the increasing mass of the cables, which is negligible compared to their rigid counterparts.

When coupled with the novel adaptive velocity controller, the cable-driven parallel robot can unlock its full potential across various applications. While most prior works on cable-driven parallel robots primarily focused on accurate position control, the novel controller allows for adaptive velocity control, enhancing the robot's versatility. In industrial settings such as distribution warehouses, the simulation has proved that the controller can optimize completion time while reducing the need for labor, including human and rigid robotic arms. Furthermore, the velocity controller enables the robot to treat materials of varying fragility. The robot can proficiently handle various objects, from rigid metal frames to soft items like tofu.

The adaptive velocity controller is critical to unlocking various ranges of the robot's potential applications. However, it is crucial to integrate this research with the concurrent advancement of robotic grippers. The parallel robot needs the flexibility to adapt to various robotic grippers that have different actuation types and forms to suit the specific characteristics of different objects it handles. Also, implementing such a robot for practical applications requires a redesigned environment to accommodate its inherent limitations.

Despite reducing the number of actuated cables from seven to four to mitigate certain drawbacks, the need for a customized environment remains partially unresolved. The entire environment above a certain height should be obstacle-free to prevent collision with the cables. Furthermore, since reducing the number of cables limits the degree of freedom of its motion, the robot can only conduct simple tasks such as stacking. Such limitation leads to difficulty in conducting complex tasks such as positioning the object at the desired angle. Nevertheless, in tailored settings where the robot can operate without errors, the research marks a significant breakthrough in velocity control for cable-driven parallel robots.

V. Conclusion

The adaptive velocity control, implemented with the cubic polynomial equation, has found its potential usage through simulation. Besides distribution warehouses, the device could be applied in other scenarios requiring large workspace, such as building construction or stadium maintenance. However, several factors should be considered for this controller, when used along with the physical robotic device.

The first factor is to minimize the position errors that may arise from inaccurate measurements, cable elasticity, and other sources. Since the adaptive velocity controller relies on inverse kinematics, even minor measurement errors could seriously impact the device's position. This issue can be addressed by incorporating a motion capture system or camera sensors to provide accurate positional feedback. The second factor is to control the vibration of the cables. Controlling the vibration of the cable poses a significant challenge in developing cable-driven robotic systems. Strategies such as dampers or springs can be employed to suppress cable vibrations. The third task is to incorporate a controller that minimizes the effect of the mass and elasticity of the cable. As the robotic device occupies a larger workspace, the cable's mass and elasticity would also become more extensive. The increasing mass of the cable could affect the force controller of the device, necessitating the modification to ensure taut cables. The elasticity of the cable may lead to discrepancies between the cable length derived from the encoder and the actual length of the cable. The last factor involves the development of an optimized force controller capable of lifting objects with varying weights. Based on the Jacobian matrix that maps the net force applied on the end effector, applying an optimized amount of force would be possible depending on the object's weight. Addressing these issues is imperative for successfully implementing the cable-driven system in real-world applications.

References

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