First Experimental Results of Load Carrying Capacity for a Planar Cable-suspended Manipulator

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Abstract: In this paper a performance analysis is presented for a cable-suspended parallel manipulator. Experimental results from some first tests are presented and discussed to validate the theoretical calculation of load carrying capacity. The load-carrying capacity during a given trajectory is obtained. This computational technique is tested on a typical planar cable suspended manipulator. The experiment is performed to compare the calculated maximum load with the actual carrying payload on the path chosen for the comparison.

Keywords: Planar Manipulator, Cable Parallel Manipulator, Dynamic Load Carrying Capacity


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1 INTRODUCTION

Cable-based parallel manipulators are structurally similar to traditional parallel ones but they have some advantages, if compared to them. The large workspace, high payload-weight ratio, transportability and economical construction are the most important characteristics. These machines may be ideally suited for large scale manufacturing applications. This robot consist of a fixed base and a centrally-located end-effector, attached to moving payload, connect to cables whose tension is maintained along the tracked trajectory. An early cable suspended robot is the Robocrane developed by NIST (National Institute of Standards and Technology) for using in shipping ports [1]. The large payload capacity allows application to a large variety of tasks on lift systems. Moreover planar parallel manipulators can be used in haptic devises [2]. The computing Dynamic Load Carrying Capacity (DLCC) of fixed base robotic manipulators [3], elastic manipulators [4], and flexible joints 6UPS-Stewart platform [5] can be seen in the theoretical literature.

The force and/or torque at the mechanical interface which can be exerted along the various directions of motion under specified conditions of velocity and acceleration should be calculated. The load is a function of mass, moment of inertia, and static and dynamic forces supported by the robot. The Kinematics, dynamic modelling and a method for load carrying capacity calculation based on positive cable tensions are presented. A prototype has been built and tests have carried out to verify the feasibility of the robot operation. Theoretical study of a particular cable-suspended robot has been undertaken. This experiment test-bed of a planar robot is fabricated to confirm the theory with experiments.

2 DYNAMIC MODELLING OF A CABLE-SUSPENDED MANIPULATOR

A general model of a cable-suspended parallel manipulator in planar system architecture consists of an end-effector that is connected by m cables to a fixed platform [6]. These two elements are connected by multiple cables that can extend or retract as shown in Fig. 1. For cable-based parallel manipulators, links are constituted by cables and make a closed chain structure, while the end-effector is moved by extending and retracting cables, the joint variables being the cable lengths. The kinematics of this manipulator is referred to the diagram of kinematics parameters.

\[ T_D + C_{xx} x + g(x) = -J^T T \]

Where \( T \) is the cable tensions, \( D(x) \) is the inertia matrix, \( C(x, \dot{x}) \) is the vector of velocity terms, \( g(x) \) is the gravity vector and \( J \) is the conventional parallel manipulator Jacobian.

3 DETERMINING THE LOAD CARRYING CAPACITY

Full load motion of manipulators while carrying a load on a given path can be an important situation in cable suspended manipulators application. The motion is slow and the robotic manipulator is considered on force task. The load carrying capacity of a robot is defined as the maximum load that the robot can carry on a specified path. Since the two end points of motion locate on a given path, the statically positions are considered and the minimum value of static load carrying capacity at all of points can be used to define the upper bound of the dynamic load carrying capacity [3]. The basic idea behind the presented scheme is based on actuators limits.

4 BOUNDS ON THE MANIPULATOR PERFORMANCE

The maximum load carrying capacity which can be achieved by a robotic manipulator during a given trajectory is limited by the actuator torque capacity.
The linear superposition of the actuator torques due to the dynamics of the end-effector and the dynamics of the attached payload to end-effector can achieve the total actuator torques on each grid point [5]. The cable tension due to manipulator motion and the attached end-effector payload mass at each point is computed. The used actuators are limited in the maximum and minimum torque which they can exert. The bound on each actuator torque is a function of the rotor rotational speed referred to as the speed-torque curve for commonly used DC motors. This constraint should be imposed in such a way that the worst case, which corresponds to the least DLCC, is used to determine the maximum. This involves checking the points where the actuator torque would be reached to bound, by maximizing payload. Maximum payload will be obtained from actuator torque within the bounds satisfies on the basis of typical DLCC algorithm on points used for discretizing trajectory [3-4]. It is seen that the load carrying capacity at different end-effector positions is different. The path divides to discrete points. The proposed analysis also provides a description of the worst-case combinations of a manipulator’s load carrying capabilities. In order to determine it is necessary to introduce the concept of load coefficient for each point of a given path.

5 SAMPLE PLANAR MANIPULATOR

The cable suspended planar parallel manipulator with three DOFs is presented in Fig. 2. The position and orientation of the end-effectors’ center of mass (i.e., \( \mathbf{x} = [x, y, \theta] \)) varied when the given trajectory is tracked. The manipulator Jacobian transpose \( \mathbf{J}^T \) is:

\[
\mathbf{J}^T = \begin{bmatrix}
\bar{\lambda}_1 s \\
\bar{\lambda}_2 s \\
\left[ \bar{a}_1 \times \lambda_1 \right] \\
\left[ \bar{a}_2 \times \lambda_2 \right]
\end{bmatrix}
\]

where \( \bar{\lambda}_1, \bar{\lambda}_2, \ldots, \bar{\lambda}_m \) are unit vectors along the cable lengths \( l_1, l_2, \ldots, l_m \). The position vector of connection point of the cable \( i \) on the end-effector is denoted by \( \bar{a}_i \). The rotation matrix about base coordinate frame \( \{B\} \) is

\[
\bar{R}_x = \begin{bmatrix}
\bar{\theta}_x \\
\bar{\theta}_y \\
c \bar{\theta}_z \\
s \bar{\theta}_z
\end{bmatrix} , \quad c \theta_i = \bar{\lambda}_i s ; s \theta_i = \bar{\lambda}_i , (i = 1, 2)
\]

Assuming that friction in joints and gravitational effects on links are negligible, the reaction forces on the end-effector are determined. The Cartesian dynamic model for the end-effector is given in general form Eq. (1) with related planar dynamic model as:

\[
D \mathbf{C}(\mathbf{x}, \dot{\mathbf{x}}) = 0, \quad \mathbf{g} = [0, -mg, 0]^T
\]

Where \( m \) is the mass end-effector are obtained by pulling cables and are applied in unidirectional senses. \( I_{zz} \) is the moment of inertia of the end-effector about its center of mass along \( Z \) axis. The static equilibrium equations of the planar manipulator [7] can be used to obtain the forces in the cables for dynamical model. It is assumed that the cables are idealized massless, straight and perfectly stiff. The cable forces \( T_1 \) and \( T_2 \) can be obtained during motion:

\[
T_1 = \frac{(m \dot{x} s \theta_1 - (m \dot{y} + mg) c \theta_1)}{s (\theta_1 - \theta_2)}
\]

\[
T_2 = \frac{-(m \dot{x} s \theta_1 + (m \dot{y} + mg) c \theta_1)}{s (\theta_1 - \theta_2)}
\]

The cable forces are adapted with moment equation and the following relation should be satisfied:

\[
(T_1 \bar{a}_1 - T_2 \bar{a}_2) (\theta_1 - \theta_2) - I_{zz} \bar{\theta}_1 = 0 ,
\]

Fig. 2 Theoretical model of two-cable suspended planar parallel manipulator

Fig. 3 Experimental setup of two-cable suspended planar parallel manipulator
Substitution of the angle of cables into geometric parameters of model, the cable forces and the moment equation as a constraint condition are simplified.

\[ T_1 = \frac{-(m\ddot{x})l_1(x + ax\dot{\theta} - b)}{2(ax\dot{\theta}_2 - acs\dot{\theta}_2 - by + ab\dot{s}\dot{\theta}_2)} \] (8)

\[ T_2 = \frac{-(m\ddot{x})l_2(y - ax\dot{\theta}) - (m\ddot{y} + mg)l_2(x - ac\dot{\theta})}{2(ax\dot{\theta}_2 - acs\dot{\theta}_2 - by + ab\dot{s}\dot{\theta}_2)} \] (9)

\[ c\dot{\theta}_2(2xy - 2y) + s\dot{\theta}_2(4\dot{x} - 2x^2) - 2ax\dot{\theta}_2s\dot{\theta}_2 - 1a\ddot{\theta}_2 = 0 \] (10)

The motion of the end-effector is assigned by imposing trajectory including the velocity and acceleration of end-effector.

6 EXPERIMENTAL STUDIES

The Two-cable suspended planar parallel manipulator has been conceived. It is composed by a mechanical structure, a controller, a PC for programming and actuator system as shown in Figures 3 and 4.

The problem of finding the load carrying capacity of designed manipulator, operated by limited force or torque actuators, is presented. It can be shown the maximum allowable load on a given load trajectory, is a function of base position. The trajectory is discretised into some grid points, and the base is positioned on each grid point as shown in Fig. 5.

The cable suspended robots have been designed to accommodate the end-effector and payload attached to it. They are inherently low cost and easy to reconfigure. The maximum load carrying capacity is limited by torque actuators. The actuator system parameters including pulleys and motors that used in the simulation are listed in Table 1. The parameters are the same value for all components.

Brushless motors are connected to 3V power and they are found to provide the enough torque and speed for this application. The motors are coupled to the winch drums and the designed encoder (LED) is installed on the pulley. Disk encoder has 12 notches for sensing (see Fig. 4). The end-effector will be moving along the desired path and it is important to the end-effector position is predicted by motor encoder with the effective cable length calculation.

A variety of experiments were performed to ensure that the end-effector was moving correctly whereas carrying the payload. Essentially, the motor saturation is evaluated by changing the payload mass between 200gr and 500gr.

It is more appropriate to solve this problem by a sequential search approach and evaluation of DLCC at each and every grid point until the extreme values are found as a fine discretization technique is applied in MATLAB environment. The motion begins and ends in the same vertical position (Y), but the radius of the curves in the path is important. The given trajectory of the end-effector has the initial position \( x_0 \) and final position \( x_f \) as:

\[ x_0 = [0.1, 0.2, 0.3\pi], x_f = [0.4, 0.2, -0.3\pi]. \] (11)

The chosen end-effector is a moving rod attached to cables. The half distance between base points \( B_1 \) and \( B_2 \) is \( b = 25cm \) and the length of end-effector is divided into equal two parts \( a = 5cm \).

In Fig. 6 by comparison, the maximum load at each point of the trajectory is shown considering the joint torque capacity. In the experimental case, the end point with coordinates \( x = 0.4 \text{ m} \) and \( y = 0.2 \text{ m} \) is the
optimal end-effector position with a maximum load of 0.46 kg, and comparatively in the theoretical case, \( x = 0.34 \, \text{m} \) and \( y = 0.27 \, \text{m} \) is the optimal end-effector position with a maximum load of 0.44 kg.

![Graph of Dynamic Load Carrying Capacity](image1)

**Fig. 6**  Dynamic load carrying capacity on trajectory points

The corresponding actuator torques at the joints is depicted in Fig. 7. The first motor let loose the cable and it contains a minimum tension for holding the end-effector. Unlike the first, the second motor keeps the upper bound with the maximum effort. Cable 2 has the largest tension because the end-effector is pulled upward and the upper bound of motors is achieved by measuring the joint angular velocity. It is seen that in the first motor, the exerted torque on the actuators is comparatively lower than upper bound. The optimum actuator torque do not achieved to upper torque bound of motor but for the second actuator with present the torque bound, the motor is saturated.

![Graph of Torque Motor 1](image2)

**Fig. 7**  a) Torque of first motor, b) Torque of second motor.

An extra simulation study is done by Sim-designer R14 (modeling with catia V5R14 and dynamics analysis with adams2003) due to comparison to two previous approaches. In this simulation, end-effector mass is considered 0.46 kg, that is the maximum Mass calculated through the experimental tests. The final end point of the trajectory is obtained \( x = 0.41 \, \text{m} \) and \( y = 0.18 \, \text{m} \) which is in good agreement with experimental results. Cable robot model designed in Sim-designer software is as Fig. 8. The little observed difference between experimental and simulation results can be explained considering the ignorance of cable mass and motor friction in simulation studies.

![Simulation Model of Cable Robot](image3)

**Fig. 8**  Cable robot model designed in Sim-designer software
Table 1 Simulation parameters for actuators

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulley radius</td>
<td>r=1.59</td>
<td>Cm</td>
</tr>
<tr>
<td>Motor shaft viscous damping</td>
<td>c=73.41</td>
<td>N.m.s</td>
</tr>
<tr>
<td>Lumped actuator rotational</td>
<td>J=71.37</td>
<td>Kg.m^2</td>
</tr>
<tr>
<td>inertia</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum no-load speed</td>
<td>ω_m=246</td>
<td>Rpm</td>
</tr>
<tr>
<td>Stall torque</td>
<td>γ_{stall}=0.021</td>
<td>N.m</td>
</tr>
</tbody>
</table>

7 CONCLUSION

In this work a general approach for determining the load carrying capacity has been presented and experimentally validated. This paper explores a characterization of the dynamic performance of cable-suspended parallel robots.

The performance of these systems was analyzed by extending the concept of load carrying capacity on the given trajectory. The result from the experiment demonstrates the effectiveness of the maximum carrying payload computation. The end-effector moves from start point to an ending point. During the motion all cable tensions are within the allowable range. In this paper, the payload carrying capability while taking into account motor torques as constraints is calculated.

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