Four-cable-driven parallel robot

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Abstract: This paper presents design and kinematic analysis for a cable-driven parallel robotic (CDPR) manipulator with four cables. The CDPR manipulator produces a planar motion including two translational and one rotational degrees of freedom. To move the end-effector of CDPR, its kinematic structure is analyzed and the inverse kinematics is formulated in the closed-form solution. The experimental tests using an implemented prototype have shown the feasibility of the system design and its operation.

Keywords: Winches, Forward kinematics, Parallel manipulators, Cable-driven manipulator.

1. INTRODUCTION

Parallel robots are defined as robots that have closed kinematic chains. It means several actuators meet at one end-effector or joint. Cable-driven parallel robots (CDPR) are a type of parallel manipulators wherein the end-effector is supported in parallel by multiple cables that are controlled by multiple tensioning actuators. As for classical parallel robots, motion of an end-effector may be generated either by changing lengths of cables or modifying the locations of attachment points when the actuators’ lengths are fixed. In this paper, cable lengths are controlled by using coiling winches that act as linear actuators with long stroke.

CDPRs are structurally similar to parallel robots, but they have additional merits, such as large workspace, if compared with the workspace of classical parallel manipulators. Moreover, their actuators are fixed on the frame, thus they have a few moving parts, resulting in small inertial properties, high payload-weight ratio, transportability, and economical construction. In the last decade, a lot of research has been carried out to study the related theory [2, 3, 4] and/or implementation of these robots [1, 5].

Cable-driven parallel manipulators can be classified into “fully constrained” and “under constrained” based on the extent to which the end-effector is constrained by the cables. Figure 1 shows an example of the two types of cable robots. This paper concerns about cable robots of the fully constrained type. We present design and kinematic analysis of a four-cable-driven parallel manipulator. A prototype has been built and experimental tests show the feasibility of the cable system design and its operation for planar tasks.

![Fig.1 Example of the two types of parallel cable robots.](image)

(a) Fully-constrained cable robot, (b) Under-constrained cable robot

2. MECHANICAL DESIGN OF A FOUR-CABLE-DRIVEN PARALLEL ROBOT

In this paper, we explain a four-cable-driven planar parallel robot, whose specifications are given as in Table 1. The prototype presented in this work is used to verify the algorithms such as inverse/forward kinematics, workspace analysis, tension control and so forth.

<table>
<thead>
<tr>
<th>Table 1 Specification of a four-cable-driven planar parallel robot</th>
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<tr>
<td><strong>Size of Frame</strong></td>
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<td><strong>Speed</strong></td>
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<td><strong>Payload</strong></td>
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<td><strong>DOF</strong></td>
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<td><strong>Settling Time</strong></td>
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2.1 System Configuration

The four-cable-driven parallel manipulator is composed of a rigid frame, four winches that control the cable lengths, a low-level position controller, a PC for a high-level control, an end-effector that contains a laser scanner, as shown in Fig. 2.
2.2 Design of Winches

Figure 3 shows assembly of the winch, whose basic concept is same as the winch explained in [10]. A main shaft is supported by two bearings at both ends for reducing lateral deflection. The discrepancy between the pitch of the ball screw and that of the drum was corrected by using the pitch of the ball screw and the reduction ratio of timing pulleys. The reduction ratio between two timing pulleys is thus chosen as 1:2. Due to equal pitch of the drum and the spindle the relative direction of the coiled cable is constant allowing for reliable coiling and uncoiling of the cable. This is especially important since the velocities and accelerations of the cables are very high for cable robots. The tension of each wire is measured by a load cell. The mechanical design of the winches is derived from crane winches where some additional requirements have to be taken into account to control and operate cable-driven parallel robots as in [11]. A first requirement for lasting operation of cable robots without excessive wear of the cables is that the maximum curvature of the cable’s route in the winch should be significantly smaller than the minimum curvature of the cables themselves. Secondly, the direction of the cables changes continuously during operation of the cable robot. Therefore, it is necessary to include an omnidirectional guidance mechanism into the winch. The manufactured cable-driven parallel robot and its winches are shown in Fig. 4.

2.3 Choice of the Motors and Cables

A static analysis has been carried out in order to decide properly the size of actuators and cables of the proposed manipulator. In particular, two cables are connected to one point at the end-effector, as shown in the simplified scheme of Fig. 5, where \( m \) is the mass of the end-effector plus the payload. The simplification is done since the upper cables support most of load in the static situation.

For these conditions, each cable is loaded by a tension \( F \) whose direction is inclined by an angle \( \alpha \), with respect to the horizontal plane. Thus, one can write

\[
2F \sin \alpha = mg + ma. \tag{1}
\]

A maximum required force \( F_{req} \) can be calculated as in (2) to satisfy the specification in Table 1. The required torque for the actuator can be calculated as in (3), considering the drum radius and the gear reduction.

\[
F_{req} = \frac{m(g + a_{max})}{2i\alpha_{min}} \tag{2}
\]

\[
T_{req} = \frac{F_{req}}{r_{drum}} \cdot (i - 1) \tag{3}
\]
\[ \tau_{req} = \frac{F_{req} \cdot r}{G} \quad (3) \]

The maximum acceleration \( a_{\text{max}} \) and the maximum payload are assumed to be 2.5m/s\(^2\), and 5kg, respectively. The drum radius and gear reduction ratio are selected to \( r=0.004\text{m} \) and \( G=5 \), respectively.

It is worth noting that if \( \alpha \) becomes 0 the actuation torque becomes infinite. In fact, the configuration where all cables are horizontal is singular, in which all the tensions of the cables are orthogonal with respect to the force given by gravity (mg). Assuming \( a_{\text{max}} = 20 \) degrees, we can get \( F_{req} = 90\text{N} \) and \( \tau_{req}=0.072\text{Nm} \).

Thus, for the above-mentioned considerations each cable should yield a force higher than about 90 N and each actuator has a nominal torque of about 0.1 Nm. These properties can be achieved, for example, by using commercial cables and motors PANASONIC MSMD012S1T001 with 5:1 reduction ratio.

2.3 2-D Laser Scanner

![LMS400 Laser Scanner](image)

Fig. 6 LMS400, SICK

The LMS400 manufactured from SICK provides a measurement solution with high scanning rates, comprehensive process reliability and improved measurement resolution for close range applications. The laser scanner can measure up to 3 m, with high angular and distance resolution which satisfy with our application. The LMS400 will be integrated with our cable robotic system.

3. Kinematics

3.1 Inverse Kinematics

Figure 7 shows the kinematic structure of our four-cable-driven parallel robot. Black dotted arrows indicate position vectors from the attachment points, where the cables are connected to the end-effector, to anchor points of the rigid frame. A vector describing 4th single cable is shown using a red solid arrow. The world coordinate system \( K_w \) and the end-effector coordinate system \( K_p \) are assigned as shown in Fig. 7.

\[ \begin{bmatrix} x \\ y \end{bmatrix} = r + R \begin{bmatrix} a_i \\ l_i \end{bmatrix} \]

where \( r = \begin{bmatrix} x \\ y \end{bmatrix} \) and \( R = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix} \).

\[ a_i - r + Rb_i = l_i \quad (4) \]

3.2 Forward Kinematics

Finding the Cartesian position of the end-effector when joint variables are given is called forward kinematics. The problem of forward kinematics of CDPR is one of highly complicated issues and cannot be solved in a closed form. It is also an area of consistent research for parallel manipulators in general. In fact, for the general case with 6 degrees of freedom up to 40 solutions may exist for the forward kinematic problem [6]. Husty proposed a method using a univariate polynomial of degree 40 finding all these solutions [7]. This would be very impractical to implement. In this research, the cables tension forces is used as an extra sensory data in the solution of forward kinematics. Since only the inverse kinematics is needed for a position control, the forward one is not performed in this work.

4. SIMULATION

4.1 Interpolation

We design a smooth curve using cubic-spline interpolation to guide CDPR along a vertical cycle assuming that the end-effector leaves the home location, moves the object to a release location, and returns to the home location. We use the inverse algorism to calculate...
the cable lengths to control CDPR using MATLAB. Figures 8 and 9 show the simulation results of the cable lengths to produces the circular motion.

Fig. 8 Generated circular path with 100mm of radius

Fig. 9 Generated cable lengths for circular motion

4.2 Workspace

The wrench feasible workspace for CDPR is governed by the fundamental requirement that all cables must be under tension. This means, that for a given wrench (forces and moments acting on the end-effector) there must exist such a distribution of forces in the cables, where all cables are under sufficient tension. For planar cable robots there exists a closed form method illustrated in [8]. The unit vector along the tension becomes $u_i = l_i |P|^{-1}$. For force equilibrium it holds that [5, 9]

$$Af - w = 0 \quad (5)$$

It is constructed through the unit vectors $u_i$ of each cable and the distal attachment points on the end-effector $p_i$, which are described with respect to the world coordinate system. The relation between the structure matrix $A$ and the vector of cable forces $f$ and the external wrench $w$ applied on the end-effector. For a given pose we now check whether there exists a vector $f$ with only positive values so that Eq. (5) holds true. If this is not the case, the pose is considered to be outside of the workspace.

5. FURTHERWORK

Increasing the accuracy through a better structural kinematic model is one of important issues of investigation. This may include modeling of cable sag, cable tension, or the geometric effects of winch pulleys.

Another very important issue is the lack of constraint normal to the plane. Thus any acting force in this direction will result in vibrations and inaccuracies in position and control due to deflections on this normal. It was observed that increasing cable tension improved this behavior. A detailed experimental and theoretical examination is needed in order to generalize these observations and add validity to this claim. This is an important area of research which can be experimentally verified using the laser scanner to calibration.

6. CONCLUSION

A suitable kinematics analysis of four-cable-driven parallel architecture has given the possibility to conceive an easy-operation design of a cable manipulator. Basic performances have been simulated for design purposes and they have been experienced in successful tests for validation purposes. The proposed four-cable driven parallel manipulator has been used in laboratory tests both for under constrained and fully constrained applications that have outlined the possibility to extend, and also can combine with laser scanner application in the future, the design concepts for a general 8-cable parallel manipulator.

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REFERENCES


