A Novel Calibration Algorithm for Cable-Driven Parallel Robots with Application to Rehabilitation

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Featured Application: This paper proposed a novel auto-calibration method for redundantly actuated cable-driven parallel robots. This method does not need any extra sensor, while only using the inner encodes of the driving motors. Thus, it is convenient for a wide range of applications where auto-calibration is required.

Abstract: Cable-driven parallel robots are suitable candidates for rehabilitation due to their intrinsic flexibility and adaptability, especially considering the safety of human–robot interaction. However, there are still some challenges to apply cable-driven parallel robots to rehabilitation, one of which is the geometric calibration. This paper proposes a new automatic calibration method that is applicable for cable-driven parallel rehabilitation robots. The key point of this method is to establish the mapping between the unknown parameters to be calibrated and the parameters that could be measured by the inner sensors and then use least squares algorithm to find the solutions. Specifically, the unknown parameters herein are the coordinates of the attachment points, and the measured parameters are the lengths of the redundant cables. Simulations are performed on a 3-DOF parallel robot driven by four cables for validation. Results show that the proposed calibration method could precisely find the real coordinate values of the attachment points, with errors less than $10^{-12}$ mm. Trajectory simulations also indicate that the positioning accuracy of the cable-driven parallel robot (CDPR) could be greatly improved after calibration using the proposed method.

Keywords: self-calibration; rehabilitation; parallel robots; cable robots

1. Introduction

A cable-driven parallel robot (CDPR) is a new kind of parallel kinematic machine system that is driven by flexible cables [1]. The main structure of CDPRs consists of a base frame, a moving platform, a certain number of driving cables, and winch modules. Such a simple structure makes CDPRs convenient for quick assemblage and reconfiguration. Therefore, CDPRs become more flexible than other kinds of robots in changing themselves to adapt to new tasks and environments. Moreover, CDPRs also have some common characteristics of traditional parallel robots made by rigid links, such as fast moving speed, large payload capacity, high precision, and good structural stiffness [2–4]. In addition, CDPRs also have their own advantages such as low moving mass, large workspace, and low manufacturing cost. Because of these superior characteristics, CDPRs are widely used in disaster rescues, large space motion, microgravity simulation, flight simulator, virtual reality, rehabilitation, etc. [5–13].
Geometric calibration is obligated for any robot to improve the kinematic accuracy. Generally, geometric calibration methods can be classified into two types, i.e., with and without external measurements. The previous ones should use extra sensors or measuring systems, such as the inclinometer and the laser tracker to obtain the required measuring data [14–16]. The later ones do not need any external sensor or measuring equipment, while only using the internal information to complete the calibration; thus, these methods are also called auto-calibration or self-calibration methods [17–20].

For traditional rigid-link robots including both serial and parallel ones, calibrations are usually done by manufacturers before the robots leave their factories. Once calibrated, these robots do not need calibration again for normal use. However, this is totally different for CDPRs. Since most CDPRs are assembled at the users’ places and need reconfiguration for different tasks, calibration of CDPRs is usually needed in daily use. Therefore, auto-calibration/self-calibration methods are especially significant for CDPRs.

A variety of methods have been proposed on the calibration of CDPRs. For example, Joshi et al. proposed a kinematic calibration methodology by using two inclinometers for 6-DOF CDPRs [14]. Xuechao Duan et al. used a triple-level spatial positioner to obtain measuring data for calibration [15]. An interval-based approach has been reported in [21], and measurements were achieved according to external equipment similarly. There are also some auto-/self-calibration method that have been proposed. Philipp Miermeister and Andreas Pott presented an auto-calibration method for overconstrained CDPRs using internal position and force sensors to achieve measurements [17]. A differential kinematic and force-based forward kinematics for CDPRs were introduced in [22]. Per Henrik Borgstrom et al. presented two novel self-calibration methods, based on incremental displacement and cable tension, respectively [18]. Some researchers have proposed a number of calibration methods for CDPRs. However, most of them need to be done with external measuring equipment, like laser trackers, inclinometers, spatial positioners, etc. [14,15,21]. For some self-calibration methods [17,19], they are only proposed for some specific mechanism CDPRs, such as 6-DOF CDPRs driven by eight or seven cables. There is no general automatic self-calibration method that has been proposed for all kinds of redundant CDPRs so far.

This paper proposes a general self-calibration method that is applicable for redundantly-actuated CDPRs (both suspended and non-suspended configurations). The encoders of the servo motors are used to obtain the driving cable lengths that are required by the calibration model. Compared to traditional calibration methods with external measurements, the proposed method uses the internal sensors of CDPRs to generate measuring data. Therefore, the proposed auto-calibration method is convenient for the field calibration of CDPRs and also quite useful for reconfigurable CDPRs.

This paper is organized as follows. The kinematic derivation of CDPRs is detailed in Section 2. The automatic calibration method for general redundantly-actuated CDPRs is proposed in Section 3. In Section 4, a numerical example is presented through a 3-DOF CDPR driven by four cables to validate the proposed method. Finally, conclusions are made in Section 5.

2. Kinematic Modeling

2.1. General Structure of CDPRs

Most CDPRs have a similar composition, mainly consisting of a base body, a moving platform, and a number of driving cables. The schematics of general CDPRs are shown in Figure 1. There are m attachment points $B_i (i = 1, ..., m)$ on the fixed base, m end points $A_i (i = 1, ..., m)$ located at the moving platform, and m driving cables connecting the moving platform and the fixed base. The moving platform could change its positions and orientations by changing the cable lengths. According to the arrangements of the cables, two kinds of CDPRs could be considered: suspended CDPRs where all the driving cables are above the end-effector and non-suspended CDPRs where at least one driving cable is below the end-effector. In addition, according to the relationship between the driving cable
number $m$ and the controllable DOF of the moving platform $n$, CDPRs could be classified into two groups, i.e., redundantly—($m > n$) and non-redundantly—($m \leq n$) actuated CDPRs. In this paper, the proposed automatic calibration method aims at redundantly-actuated CDPRs (i.e., $m > n$) and is applicable for both suspended and non-suspended CDPRs.

2.2. Inverse Geometrics

In this section, the inverse geometric model of CDPRs is presented. Firstly, two coordinate systems are defined, i.e., the local frame $R_e \{O_e,x_e,y_e,z_e\}$ fixed on the moving platform and the global frame $R_G \{O_G,x_G,y_G,z_G\}$. Then, the homogeneous transformation matrix $T$ from $R_e$ to $R_G$ could be defined as a function of the pose of the moving platform $p_j (j = 1, \ldots, n)$. For example, when $n = 6$, $P = [x, y, z, \alpha, \beta, \gamma]^T$, where $x, y, z$ represent the position of the end-effector in Cartesian space and $\alpha, \beta, \gamma$ represent the orientation of the end-effector using Euler angles.

$$
T = \begin{bmatrix}
\cos \beta \cos \gamma & -\sin \beta \sin \gamma & \cos \gamma \\
-sin \beta \cos \gamma + \cos \beta \sin \gamma & \cos \beta \cos \gamma - \sin \beta \sin \gamma & -\cos \gamma \\
-sin \beta \cos \gamma & \cos \beta \cos \gamma - \sin \beta \sin \gamma & \cos \gamma \\
0 & 0 & 1
\end{bmatrix}
$$

(1)

Then, any attachment point on the moving platform $A_i$ could be expressed in the global frame:

$$
^G A_i = T \cdot ^e A_i
$$

(2)

Finally, the inverse geometrics of CDPRs could be formed as:

$$
l_i = \left\| ^G A_i - ^G B_i \right\|, (i = 1, \ldots, m)
$$

(3)

It should be noted that the driving cable lengths are usually controlled by winches and motors. Therefore, it is necessary to introduce a simple equation to substitute the cable length $l_i$ with the winch rotatory angle $\theta_i$.

$$
l_i = \theta_i \cdot d_i / 2
$$

(4)

where $d_i$ is the winch diameter. Then, the inverse geometric model can be reformed as:

$$
f_i(p_1, p_2, \ldots, p_n, ^e A_i, ^G B_i, \theta_i, d_i) = 0 \ (i = 1, \ldots, m)
$$

(5)
3. Calibration Method

In this section, the automatic calibration method is detailed for general redundantly-actuated CDPRs with \( n \) DOFs and driven by \( m \) cables.

3.1. Differential Kinematics

Firstly, the differential kinematics of CDPRs is presented. Through making total differentiation on the inverse kinematic equation by Equation (5), we can obtain:

\[
\frac{\partial f_i}{\partial p_1} dp_1 + \frac{\partial f_i}{\partial p_2} dp_2 + \cdots + \frac{\partial f_i}{\partial p_n} dp_n + \frac{\partial f_i}{\partial \theta_i} d\theta_i + \frac{\partial f_i}{\partial \theta_{i+1}} d\theta_{i+1} + \cdots = 0
\]

(6)

Noting \( dX = [dp_1, dp_2, \ldots, dp_n]^T \), the above differential equation can be reorganized as:

\[
J \cdot dX = B
\]

(7)

where \( J \) is the classical Jacobian matrix and \( B \) is a column vector, which can be expressed as:

\[
J_{ij} = \frac{\partial f_i}{\partial p_j}, (i = 1, \ldots, n; j = 1, \ldots, n)
\]

(8)

\[
B_i = - \left( \frac{\partial f_i}{\partial \theta_i} d\theta_i + \frac{\partial f_i}{\partial \theta_{i+1}} d\theta_{i+1} + \cdots \right)
\]

(9)

3.2. The Calibration Model

Since the proposed calibration method aims at redundantly-actuated CDPRs, i.e., the driving cable number \( m \) is larger than the robot DOF \( n \), the differential equations Equation (7) can be separated into two parts: one part is an \( n \) by \( n \) square matrix, and the other part is an \( (m - n) \) by \( n \) matrix, specifically expressed as follows:

\[
J_C dX = B_C,
\]

(10)

\[
J_M dX = B_M,
\]

(11)

where:

\[
J_{Cij} = \frac{\partial f_i}{\partial p_j}, (i = 1, \ldots, n; j = 1, \ldots, n),
\]

(12)

\[
J_{Mij} = \frac{\partial f_i}{\partial p_j}, (i = n + 1, \ldots, m; j = 1, \ldots, n),
\]

(13)

\[
B_{Ci} = - \left( \frac{\partial f_i}{\partial \theta_i} d\theta_i + \frac{\partial f_i}{\partial \theta_{i+1}} d\theta_{i+1} + \cdots \right), (i = 1, \ldots, n),
\]

(14)

\[
B_{Mi} = - \left( \frac{\partial f_i}{\partial \theta_i} d\theta_i + \frac{\partial f_i}{\partial \theta_{i+1}} d\theta_{i+1} + \cdots \right), (i = n + 1, \ldots, m).
\]

(15)

It is worth noting that the winch diameters \( d_i, (i = 1, \ldots, m) \) are constant. Thus, the \( dd_i \) in Equation (11) is zero. However, two cases should be considered for the motor rotary angles \( \theta_i \).

For angles \( \theta_1 \sim \theta_n \), they are controlled by the robot controller. Assuming the control error is negligible, \( d\theta_1 \sim d\theta_n \) in Equation (11) should be zeros. \( d\theta_{n+1} \sim d\theta_m \) are approximate instead of the difference between the theoretical length of cables and the real length of measuring cables measured by internal motor encoders. However, for angles \( \theta_{n+1} \sim \theta_m \), they are the measuring data obtained by the encoders of these corresponding motors. Thus, the \( \theta_{n+1} \sim \theta_m \) in Equation (11) must remain. Therefore, \( B_C \) and \( B_M \) can be simplified to:
where \( J \) parameter can be obtained from the calibration model.

Applying using the least squares optimization method. Then, \( k \) different poses should be collected. If \( r \) of the CDPR in its workspace. Since there are \( \theta \) represents the vector of motor angles used for measurement, which consists of \( (m-n) \) components.

Finally, the calibration model can be obtained from Equation (19):

\[
J_{err} \cdot \Delta q \approx \Delta \theta
\]

where \( \Delta q \) = \([\Delta^t A_1, \Delta^t A_2, \Delta^t A_3, \cdots, \Delta^t A_m, \Delta^G B_1, \Delta^G B_2, \Delta^G B_3, \cdots, \Delta^G B_m]^T\), \( \Delta \theta \) is the error vector consisting of \( (m-n) \) components, which are the differences of the motor rotary angles between the theoretical values and the measured counterparts.

In fact, according to Equation (20), \( (m-n) \) equations can be obtained from each collection pose of the CDPR in its workspace. Since there are \( r \) unknown parameters to be solved, at least \( r/(m-n) \) different poses should be collected. If \( k \) different poses are used for calibration, there are in total \( k(m-n) \) equations, which can be written as:

\[
\begin{bmatrix}
J_{err1} \\
J_{err2} \\
\vdots \\
J_{errk}
\end{bmatrix} \cdot \Delta q =
\begin{bmatrix}
d\theta_1 \\
d\theta_2 \\
\vdots \\
d\theta_k
\end{bmatrix}
\]

Noting \( I_{clbr} = \begin{bmatrix} J_{err1} \\ J_{err2} \\ \vdots \\ J_{errk} \end{bmatrix}, d\theta_{clbr} = \begin{bmatrix} d\theta_1 \\ d\theta_2 \\ \vdots \\ d\theta_k \end{bmatrix} \), the \( (m-n) \) equations can be written as:

\[
I_{clbr} \cdot \Delta q = d\theta_{clbr}
\]

Then, the error of the difference between the real structure parameter and the theory structure parameter can be obtained from the calibration model.

\[
\Delta q = I_{clbr}^{-1} \cdot d\theta_{clbr}
\]

It is obvious that \( I_{clbr}^{-1} \) is the core of calibration model. In this paper, this problem is solved by using the least squares optimization method. Then, \( \Delta q \) can be obtained.
4. Numerical Example

In order to verify the proposed automatic calibration method, a numerical example is detailed on a 3-DOF CDPR driven by four cables. The structural diagram of the CDPR is shown in Figure 2.

As shown in Figure 2, the moving platform was a rectangle whose length and width were respectively 120 and 80 mm. The local coordinate frame $R_c\{O_cx_cy_c\}$ was fixed on the center of the rectangular platform. The origin of the global coordinate frame $R_G\{O_Gx_Gy_G\}$ coincided with the attachment point $B_4$, which means that the global coordinates of $B_4$ were zero. The nominal values of the other three attachment points $B_1 \sim B_3$ are listed in Table 1.

As shown in Equation (20), both $B_i$ and $A_i$ can be calibrated by the proposed method. However, generally, the attachment points on the moving end-effector ($A_i$) are known after being fabricated. $A_i$ will not change for reconfigurable CDPRs. Thus, the coordinates of the attachment points $A_1 \sim A_4$ were assumed to be accurate, which did not need calibration. Moreover, the global frame was set on point $B_4$. Therefore, the unknown parameters remaining to be calibrated were the coordinates of $B_1 \sim B_3$. According to the proposed method, in the calibration procedures, the servo motors for the driving cables $l_1 \sim l_3$ worked in position mode, while the motor of cable $l_4$ worked in torque mode. Thus, the cable lengths $l_1 \sim l_3$ were controlled by the servo motors, and the length $l_4$ could be measured by the encoder of the corresponding motor.

At the beginning of the simulation, a group of random deviations (range: $\pm 20$ mm) were added to the nominal values of the coordinates of the attachment points $B_1 \sim B_3$, and the results were taken as the real positions of these attachment points, which are listed in Table 1. Then, 200 poses of the moving platform were randomly generated in the workspace of the CDPR. For each pose, an independent equation can be calculated according to Equation (20). Thus, $\Delta q$ could be obtained through the 200 linear equations according to Equation (23). After that, the coordinates of the attachment points were revised according to $\Delta q$ obtained in the previous step. Then, iterations were made to recalculate $\Delta q$ based on the revised coordinate values, until $\Delta q$ was small enough, which was $10^{-6}$ mm in this simulation. Finally, the calibrated coordinates of the attachment points are listed in Table 1, which shows that the difference between the real coordinate values and the calibrated ones was quite small, i.e., less than $10^{-12}$ mm.
Table 1. Nominal, real, and calibrated coordinate values of the attachment points.

| Attachment Point | Nominal Value (mm) | Real Value (mm) | Calibrated Value (mm) |
|------------------|--------------------|-----------------|-----------------------|
| B₁               | x −850            | −861.69 −0.341 × 10⁻¹² | −861.69 −0.341 × 10⁻¹² |
|                  | y 0               | −18.38          | −18.38 −0.277 × 10⁻¹² |
| B₂               | x −850            | −856.23 −0.114 × 10⁻¹² | −856.23 −0.114 × 10⁻¹² |
|                  | y −770            | −751.43 −0.227 × 10⁻¹² | −751.43 −0.227 × 10⁻¹² |
| B₃               | x 0               | −13.97          | −13.97 −0.011 × 10⁻¹² |
|                  | y −770            | −787.36         | −787.36                |

In order to further examine the proposed calibration method, two typical trajectories of the moving platform were performed by simulation. The first trajectory was a straight line, and the second was a circle. Figures 3 and 4 show the simulation results, where the red solid lines represent the ideal trajectories and the blue dashed lines represent the trajectories obtained by the initial coordinate values before calibration, while the green dot lines represent the trajectories obtained by the corrected coordinate values after calibration. As is shown in Figures 3 and 4, the trajectories obtained by the calibrated coordinates were much closer to the ideal trajectories. These trajectory errors are further shown in Figures 5 and 6. As we can see, the positioning errors of the moving platform have been greatly reduced after calibration by the proposed calibration method.

![Figure 3](image-url)  
Figure 3. Trajectories of the moving platform: circular case.

![Figure 4](image-url)  
Figure 4. Trajectories of the moving platform: linear case.

![Figure 5](image-url)  
Figure 5. Trajectory errors relative to ideal situation: circular case.
5. Conclusions

This paper presented a new automatic calibration method for CDPRs with application to rehabilitation. This proposed method used the length information of the redundant driving cables, which can be easily obtained by the encoder of the servo motors, and did not need any extra measuring equipment. Therefore, this method brings great convenience to the calibration of CDPRs, especially for reconfigurable CDPRs. Simulation results showed that this method could find the real coordinate values of the attachment points with extremely small errors, i.e., less than \(10^{-12}\) mm. Results also proved that the positioning error of the CDPR along given trajectories could be greatly reduced after calibration using the proposed method. In future work, a prototype of the CDPR will be fabricated, and the proposed calibration method will be further verified by experiments.

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