CALIBRATION OF A 6-DOF CABLE ROBOT USING TWO INCLINOMETERS

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ABSTRACT

This paper focuses on the accuracy enhancement of a six degree-of-freedom (DOF) cable robot through kinematic calibration. This cable robot comprises of six variable-length cables that connect a fixed base to the moving platform and the construction of this cable robot is such that it is kinematically equivalent to the 3-3 Stewart platform. The fundamental difference between the two being the cables can only pull the moving platform but not push it. Since kinematic errors, especially assembly errors are likely to be introduced in the construction; kinematic calibration becomes particularly important to enhance the positioning accuracy of such cable robots.

In this paper we have reviewed various kinematic calibration methodologies that have been used with parallel manipulators. A methodology for kinematic calibration of the Stewart platform using two inclinometers is examined in detail. This methodology is extended for use with the said cable robot under the assumption that the orientation of the moving platform of this cable robot can be measured by using two inclinometers. The calibration process relies on the estimation of geometric parameters and it requires the solution of a nonlinear optimization problem. Cost function for the prescribed optimization being the norm of the errors of the measured and computed inclinometer values. Simulation results are presented towards the end of the report. The calibration methodology can be modified to accommodate calibration using other measurement devices in addition to the inclinometers.

Keywords: *Intelligent system design, Cable robot, Kinematic modeling, optimization*

1. INTRODUCTION

Although calibration of parallel manipulators has been an area of active research within the robotics engineering community, the calibration of cable robots has not received much attention. A large number of methods/algorithms designed for the calibration of parallel robots rely either on fixing a few passive joints or placing sensors on them to measure the joint variable values. Although a 6-DOF cable robot such as the NIST mini tetra is kinematically equivalent to a 6-DOF parallel manipulator such as the Stewart platform, it is not possible to fix one of the spherical joints in a particular limb of the cable robot as can be done for the Stewart platform. Hence, parallel robot calibration methods that rely on fixing or measuring such passive joint variable values cannot be used for the purpose of calibrating a cable robot. Thus, there is a need for investigating alternative calibration methods which will work with the type of instrumentation that can be made available with a cable robotic system in general. In this report we present an extension of a Stewart platform calibration methodology, developed by Besnard and Khalil [1], for the kinematic calibration of a 6-DOF parallel cable manipulator.

The objective of this effort was to conduct case study on how automatic on-line calibration can be used in cable robots where traditional one-time or periodic calibration methods do not provide adequate measures of performance. Hence, from the standpoint of intelligent system design and performance metrics, through this example, we demonstrate the need for automated on-line calibration of intelligent systems (cable robots) so that repetitive manual calibration can be minimized. A flowchart summarizing our approach is shown in Figure 1. Starting out from the governing kinematic equations of the cable robot, a set of kinematic parameters is selected for identification. It is well known that for some calibration methods, all the kinematic/geometric parameters cannot be identified: some of them have no effect on the calibration model, and some others are grouped together [2]. Hence, a parameter identifiability analysis is performed to make sure that all geometric / kinematic parameters can be identified uniquely. Once the parameter identifiability is ascertained, a set of configurations to be used for calibration and validation are selected. Note that the kinematic parameter identifiability Jacobian can also be used for the purpose of optimal pose selection in calibration of the cable robot. The calibration problem is then set up as a nonlinear optimization problem and is solved by using the *lsqnonlin* function of Matlab. The corrected kinematic model obtained from the optimization procedure is then validated using experimental data.

The 6-DOF cable robot, whose calibration we have studied in detail in this report is a closed-chain mechanism in which the mobile platform is connected to the fixed base by six variable length cables. Such cable robots offer the advantages of a larger workspace and low weight with the disadvantage that the cables can apply forces only when in tension. The join of each of these cables with the fixed and the moving platforms are kinematically equivalent to and are modeled as passive spherical joints. Whereas the cable can be modeled as a prismatic joint that can apply forces in one direction only. A typical control strategy for such cable robots is to specify the pose of the moving platform in some world coordinate frame and then to use the inverse kinematics relationship to solve for the cable lengths. The accuracy of the moving platform location critically depends upon the kinematic model of the cable robot that resides in the robot controller. The kinematic calibration of such parallel mechanisms improves the accuracy of the moving platform through modification of the manipulator kinematic model.

Calibration of a general parallel manipulator normally encompasses the following tasks:

1. Kinematic modeling of the platform to account for major error sources.
2. Measurement of platform poses
3. Identification of the kinematic error parameters of the platform by use of the measurement data.
4. Accuracy compensation of the platform by use of the identified error parameters.

In what follows, we will briefly review various methods used for the calibration of parallel manipulators in general and then show how one of these techniques can be extended for the calibration of cable robots. The classical methods for parallel robot calibration require external sensors to measure the position and orientation of the moving platform and the values of the motorized joint variables. The calibration problem is then formulated in terms of a measurement residual that is the difference between the measured and computed variables such as the "moving platform orientation" or the "motorized" joint variables etc [1, 2, 3, 4, 9, 10, 11]. The self-calibration methods of parallel manipulators generally make use of extra sensors on the passive joints of parallel robots. Some self-calibration methods for parallel manipulators have been presented in [5, 6, 7, 8]. Both calibration methods adjust the values of kinematic/geometric parameters in order to minimize a residual between the measured and calculated values of the passive joint variables. The disadvantages of self-calibration approaches are that high accuracy is needed of the sensors and also it may not be possible to mount sensors on all passive joints. Since it is not possible to mount any sensors on the passive joints in a cable robot it is difficult to extend such self-calibration methods to cable robots directly. Also, calibration methods such as those presented by Besnard and Khalil [7] in which they lock the Spherical joint of one limb and then proceed with the generation of residuals for the purpose of calibration cannot be extended to cable robots since the passive joints in a cable robot cannot be locked as such.

Kinematic calibration of a Stewart platform using two inclinometers was studied by Besnard and Khalil [1]. The calibration procedure presented in this paper can be classified as a classical calibration technique. It does not need the measurement of or locking of any of the passive joints of the Stewart platform and is amenable to the calibration of cable robots. In this report we will present the application of this inclinometer based approach for the purpose of calibration of the 6-DOF cable robot shown in Figure 2. The method of kinematic calibration needs measurement of the moving platform orientation using two inclinometers and measurements of the motorized prismatic joints.

Besnard and Khalil [1] consider the following geometric parameters in their calibration: coordinates of the Ball Joint centers on the fixed and moving platforms (36 parameters), offsets of the motorized prismatic joints (6 parameters) and error on the perpendicularity of the two inclinometers (1 parameter). However, the coordinate systems on the base and moving platforms are placed in such a fashion that 8 out of the 36 geometric parameters are equal to 0. Remaining 28 parameters are constant and may not be equal to zero in general. Aim of the calibration process is to compute the exact values of these 28 parameters, those of the 6 offsets of the prismatic joints, and the error angle on the perpendicularity of the two inclinometers.

Besnard and Khalil [1] use a numerical method that solves the forward kinematics of the Stewart platform (Direct Kinematic Model or DKM) based upon the measured prismatic joint variable values and the nominal kinematic model. From the direct kinematics solution they compute the theoretical inclinometer values and hence compute the residual which is the difference of actual inclinometer values as measured and those computed from the nominal kinematic model at k different moving platform poses. A nonlinear optimization problem in then setup to compute the real values of the kinematic parameters.

The organization of the technical part of this paper is as follows: In the next section we present the required kinematics of the 6-DOF cable robot followed by a description of the calibration and the optimization problems. Finally we describe the nonlinear optimization procedure needed for the purpose of calibration and present some preliminary results from simulations.

2. KINEMATIC MODELING

A schematic of the 6-DOF cable robot studied in this report is shown in Figure 2. A coordinate system A: *xyz* is attached to the fixed platform and another coordinate frame B: *uvw* is attached to the moving platform. The inverse kinematic model (IKM) which calculates the leg lengths vector for a given T_r , which is the homogeneous transformation matrix from frame B to frame A, is easy to obtain. On the contrary, the direct kinematic model (DKM), which calculates the moving platform location T_r as a function of given cable lengths vector, is difficult to obtain analytically. A numerical iterative method based on the inverse Jacobian matrix of the cable robot is used to find a local solution to the direct kinematics problem. For the purpose of solving the direct kinematics problem we will use a general purpose algorithm which can solve the direct kinematics of any general robot manipulator. This algorithm converges rapidly and can be summarized as follows:

1. Input the actuated joint variable values, $\mathbf{q}_a$, the initial guess values on the moving platform location, T_r, and the passive joint variable values, $\mathbf{q}_p$.
2. Solve the kinematic constraints for the manipulator to compute the actual passive joint variable values, $\mathbf{q}_p$.

3. Calculate the corresponding moving platform location by solving the forward kinematics of any limb of the parallel manipulator and update the initial guess on the moving platform location.

Where T_r is a homogeneous matrix which defines the location of the moving platform with respect to the base coordinate frame and $\mathbf{q}_a$ is the given vector of cable lengths.

3. CABLE ROBOT CALIBRATION MODEL

By making use of the direct kinematic model of the cable robot we can calculate the orientation of the moving platform with respect to some coordinate frame A: *xyz* as a function of cable lengths and the nominal values of the geometric parameters. In this work we will demonstrate an approach to calibrate this 6-DOF cable robot using two inclinometers mounted on the moving platform of the cable robot. This calibration procedure follows the approach proposed by Besnard and Khalil [1] for the calibration of Stewart Platform using two inclinometers.

Following Besnard and Khalil [1] we consider that there is an error angle γ on the perpendicularity of the two inclinometers. Hence then inclinometer angle values are:

The angle γ is unknown and it can be included in the

$$\alpha_1 = \sin^{-1}(\mathrm{T}_r(3,1))$$
$$\alpha_2 = \sin^{-1}(\mathrm{T}_r(3,2) - \mathrm{T}_r(3,1)\sin\gamma) \quad (3)$$

parameters to be calibrated. In the calculations presented in this paper we have assumed the two inclinometers to be perfectly perpendicular and hence γ is identically equal to zero.

4. OPTIMIZATION

The inclinometer values are calculated for each of the *k* robot

$$\Phi_m^n = f(q^n, \zeta_m) \quad (4)$$

manipulator configurations using Equation 3 as function of the nominal geometric parameters and the cable lengths:

where $\Phi_m^n = [\alpha_1^n, \alpha_2^n]^T$ is the vector of computed inclinometer values at the n^{th} moving platform location, ζ_m is the 35x1 vector of nominal values of the robot geometric parameters.

Similarly we define the vector Φ_r^n of the measured inclinometer values (real) for the n^{th} manipulator pose. If the

$$\left\| \Phi_m^i - \Phi_r^i \right\| = 0 \quad \textit{for } i = 1, 2, \ldots\ n \ldots\ k \quad (5)$$

model is exact, the angles calculated and measured must have the same values at any arbitrary moving platform pose:

Using *k* configurations, the geometric parameters are identified such that $\|F\| = \min$, with

$$F = \begin{bmatrix} \Phi_m^1 - \Phi_r^1 \\ \vdots \\ \Phi_m^k - \Phi_r^k \end{bmatrix} \quad (6)$$

This least squares estimation based nonlinear problem was solved by *lsqnonlin* function of Matlab.

5. SIMULATION PROCEDURE AND RESULTS

We simulated the calibration method on a cable robot whose nominal parameter and real parameters are given in Table 1 through Table 4. At present we do not any consistent (real) sensor data to validate our calibration model. We hope to acquire some field data in the near future. This will enable us to check the accuracy of calibration and also validate the calibration procedure.

The procedure used to generate the simulation configurations can be summarized as follows:

1. Generate *m* random sets of cable lengths.
2. Select *n* sets of cable lengths from the *m* for which the moving platform lies within the manipulator workspace. Further, select *k* sets of cable lengths from the *n* that have that lowest condition numbers for the Identification Jacobian matrix.
3. Compute the inclinometer values using the forward kinematics solution.
4. Add some random numbers on the nominal inclinometer values to generate a set of data that we would term as the real sensor readings.
5. Compute the objective function for the purpose of optimization using these sets of the so-called real and computed inclinometer values.
6. Solve the nonlinear optimization problem using the Matlab optimization toolbox.
7. Compute the real geometric parameters for the robot under consideration.

Table 1 Nominal values of cable attachment points at the Base platform in the Base platform coordinate frame.

	x	**y**	**z**
$^{base}A_1$	0	0	0
$^{base}A_2$	0	0	0
$^{base}A_3$	0.8189	0	0
$^{base}A_4$	0.8189	0	0
$^{base}A_5$	0.4095	0.7092	0
$^{base}A_6$	0.4095	0.7092	0

Table 2 Real values of cable attachment points at the Base platform in the Base platform coordinate frame.

	x	y	z
${}^{base}A_1$	0	0	0
${}^{base}A_2$	0.01	0	-0.009
${}^{base}A_3$	0.8312	-0.01	0.0043
${}^{base}A_4$	0.7989	0.03	0.0147
${}^{base}A_5$	0.4275	0.6792	0.004
${}^{base}A_6$	0.3858	0.7302	-0.03

Table 3 Nominal values of cable attachment points at the Moving platform in the Moving platform coordinate frame

	x	y	z
${}^{moving}B_1$	0	0	0
${}^{moving}B_2$	0.2572	0	0
${}^{moving}B_3$	0.2572	0	0
${}^{moving}B_4$	0.1286	0.2228	0
${}^{moving}B_5$	0.1286	0.2228	0
${}^{moving}B_6$	0	0	0

Table 4 Real values of the cable attachment points at the Moving Platform in the Moving platform coordinate frame.

	x	y	z
${}^{moving}B_1$	0	0	0
${}^{moving}B_2$	0.2770	0	-0.052
${}^{moving}B_3$	0.2472	0.05	0.02
${}^{moving}B_4$	0.1716	0.2028	0.1
${}^{moving}B_5$	0.1076	0.2398	-0.03
${}^{moving}B_6$	0.04	-0.03	-0.05

6. SUMMARY

In summary, we present a case study to illustrate an automatic kinematic calibration method that allows intelligent systems to precisely manipulate their surroundings. This approach can be implanted on-line and hence it obviates the need for an operator to move the robot end-effector to its home position, for calibration, every time the robot is turned on. This continuous on-line calibration approach provides performance improvement over the conventional periodic calibration methods as it continuously compensates for mechanical changes to the system. This improved system behavior provides quantitative measures of performance improvement.

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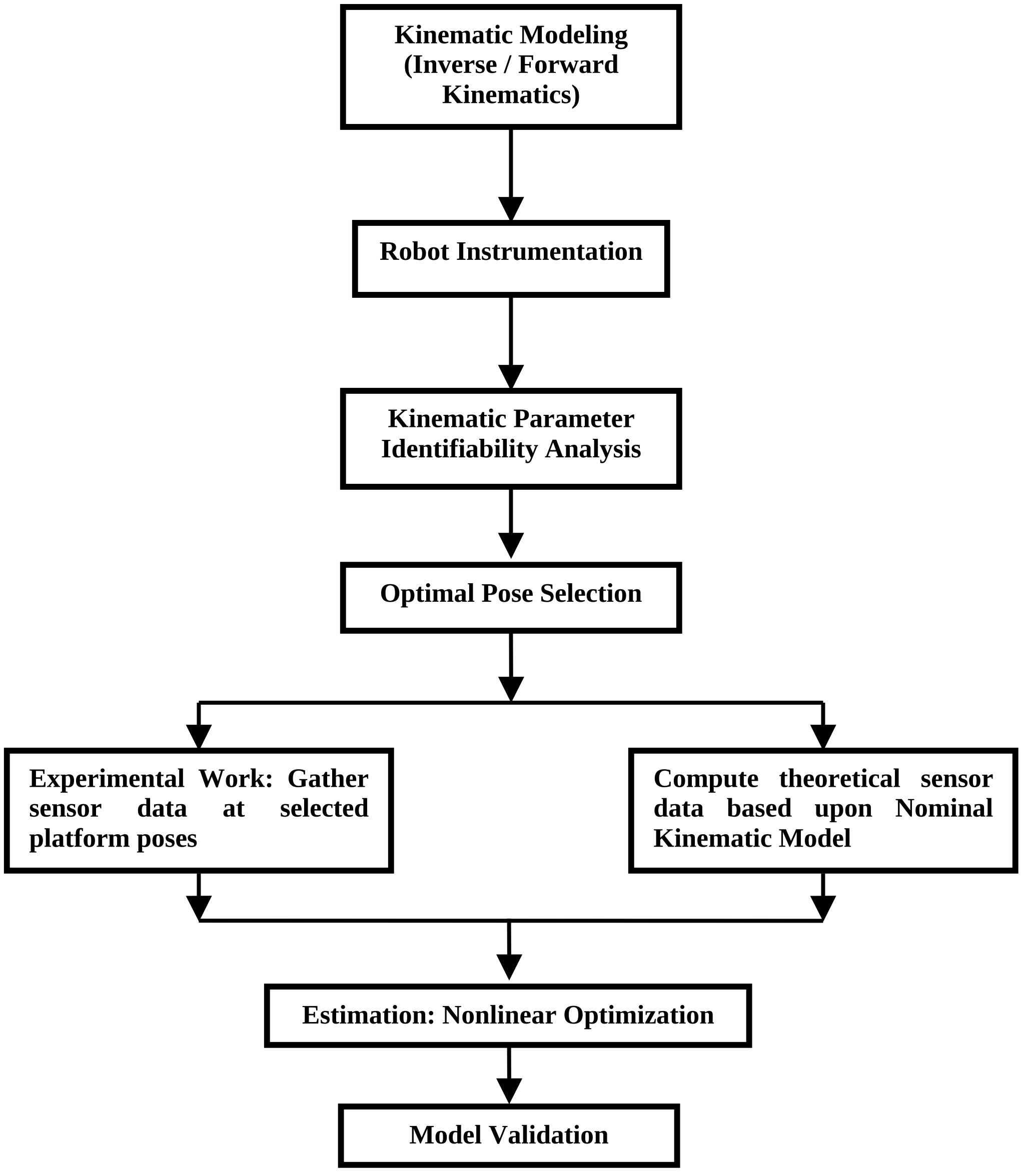

Figure 1: Cable robot calibration process

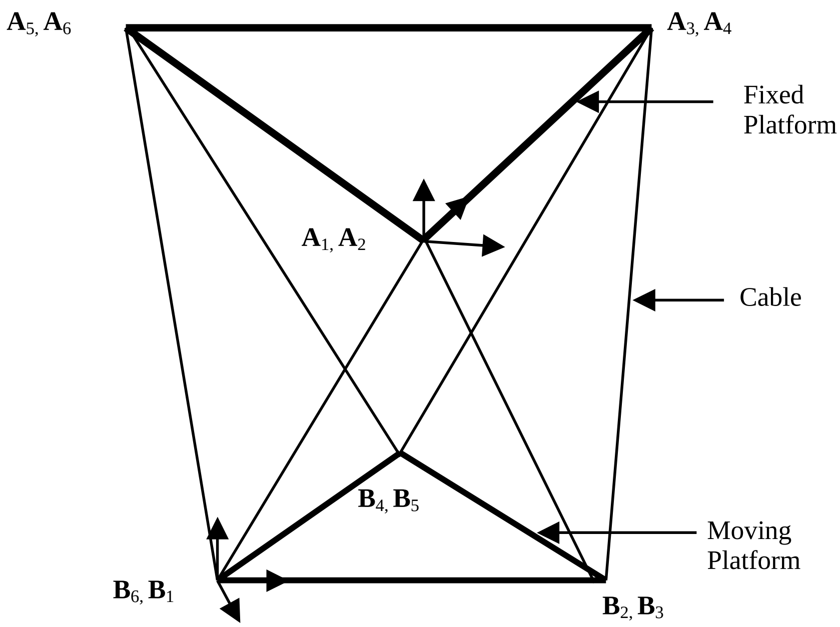

Figure 2: A six degrees-of-freedom cable robot.