2017 17th International Conference on Control, Automation and Systems (ICCAS 2017)
Oct. 18–21, 2017, Ramada Plaza, Jeju, Korea

Black-Box Accuracy Compensation for a Cable-Driven Parallel Robot

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Abstract: This paper presents the findings of experiments done to increase the accuracy of a fully constrained cable-driven parallel robot with 8 cables and 6 degrees of freedom. Measurements were conducted using a Laser Tracker in 3 dof and the position accuracy mapped. Measurements were performed in a grid with 1920 points. From the measurement data distortion to the actual desired position is measured and using a linear approximation subsequent trajectories are compensated for any systematic errors. On an example robot, this black box correction brought an average improvement from 10.6 mm distance to the desired point to 2.47 mm distance from the desired point. This is a significant improvement in accuracy.

Keywords: Selected keywords relevant to the subject.

1. INTRODUCTION

The first cable robots appeared around thirty years ago, an aerial camera device first built around 1985 [1]. Many prototypes have been implemented which make use of the cable-driven principle [2], [3], [4].

There are a unique set of challenges for this technology. Cables are non-rigid links which need to be kept under tension at all times which has significant impact on workspace and stiffness [5].

It is well known that to achieve n DOF, a cable robot needs $n+1$ cables. Then a robot can be considered *fully constrained*. A construction which does not fulfill this criterion is said to be *underconstrained*, which has important implications for the stability of such a system.

There are many factors which have an effect on accuracy which have been discussed in literature. The include components such as pulleys [6], cable mass and elongation [7], or further geometrical properties [8]. Additionally, ovalisation has been shown to cause highly force dependent transmission ratio of winches [9]. From experience, it can also be said that the initial geometry also has a great impact on how accurate or inaccurate a system is. Firstly, determining the actual physical geometry is difficult. If CAD-Data exists, it does not reflect the actual robot as manufacturing methods on such large scale are not so precise. Also the measurement of these requires some expert skill and sophisticated tools which are inherently inaccurate. Further, the geometry has an impact on stiffness which in turn effects accuracy. It is easy to visualize a singular geometry having very low accuracy and thus expected.

Apart from modeling the factors affecting accuracy in the kineamtic calculation, other methods of improvement have also been suggested. Methods include continuous calibration and inclinometers [10], general geometric calibration [11], and external sensors such as an expensive non-contact laser scanning system for Cartesian metrology used by the NIST Robocrane [12].

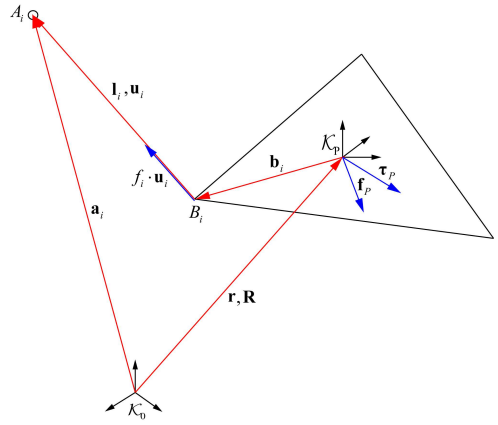

Fig. 1: Kinematic Parameterization

In this paper a very simple method based on a black box correction. A very accurate 3 dof measurement tool was used and a corrective grid calculated. An example trajectory then shows the improvements gained through this method. To conduct the accuracy measurements a Lasertracker AT901-MR was used. This device can measure the three dimensional position of a reflector in a workspace of 18 m radius and with a precision of 5 μm [13].

2. GEOMETRY AND PARAMETERIZATION

For reference, the basic kinematic algorithms are quickly introduced. On figure 1 the position of anchor points on the base and the robot platform are described by vector $\mathbf{a_i}$ and $\mathbf{b_i}$ respectively, and give the rope vector $\mathbf{l_i}$ for a given pose. The platform vectors $\mathbf{b_i}$ are in the coordinate system of the platform which is defined by

the Cartesian vector $\mathbf{r}$ and rotation matrix $\mathbf{R}$. Since the length of the cables in the standard kinematic model is $l_i = \|\mathbf{l_i}\|_\mathbf{2}$ simple vector algebra yields

$$\mathbf{a_i} - \mathbf{r} - \mathbf{R}\mathbf{b_i} = \mathbf{l_i} \quad (1)$$

$$\|\mathbf{a_i} - \mathbf{r} - \mathbf{R}\mathbf{b_i}\|_\mathbf{2} = l_i \quad (2)$$

for $i = 1, ..., m$.

This suffices for the general computation of inverse kinematics under the assumption that all cable connections are ideal points. This is also the basis for the standard forward kinematics used in [14].

As such very important parameters describing the geometry of a cable robot are the vectors $\mathbf{a_i}$ and $\mathbf{b_i}$. An example for a fully-constrained 8 cable robot is given in table 1. This is also the geometry used in the experimental evaluation.

Table 1: Geometrical Properties of the new Geometry

Cable i	Frame vector $\mathbf{a_i}$ [m]	Platform vector $\mathbf{b_i}$ [m]
1	$[\ 3.73\ 5.13\ 2.42]^\mathrm{T}$	$[\ 0.15\ 0.25\ -0.65]^\mathrm{T}$
2	$[\ 4.01\ -5.63\ 2.40]^\mathrm{T}$	$[\ 0.14\ -0.25\ -0.65]^\mathrm{T}$
3	$[-4.07\ -5.81\ 2.42]^\mathrm{T}$	$[-0.14\ -0.25\ -0.65]^\mathrm{T}$
4	$[-4.37\ 4.98\ 2.41]^\mathrm{T}$	$[-0.15\ 0.25\ -0.65]^\mathrm{T}$
5	$[\ 3.16\ 5.55\ -1.33]^\mathrm{T}$	$[\ 0.25\ 0.14\ 0.65]^\mathrm{T}$
6	$[\ 4.05\ -5.84\ -1.36]^\mathrm{T}$	$[\ 0.24\ -0.17\ 0.65]^\mathrm{T}$
7	$[-3.84\ -5.99\ -1.35]^\mathrm{T}$	$[-0.24\ -0.14\ 0.66]^\mathrm{T}$
8	$[-4.02\ 5.19\ -1.34]^\mathrm{T}$	$[-0.24\ 0.14\ 0.66]^\mathrm{T}$

3. BLACK BOX METHOD

As already mentioned, there are many factors which can affect the accuracy of such a robot system. Not all of these factors are deterministic, but there is a large enough number of systematic errors which can be combated using by simply measuring the difference between desired and achieved position and correcting for it.

So at first a grid within the workspace is defined. This regular grid is then measured using our measurement tool. In this particular case a grid of 1920 points was set up. The grid was not evenly spaced across each axis as evident from the grid parameters shown in table 2. The z-axis was spaced the least, while the x-y plane had many more points. This corresponds to the geometry and workspace of the robot.

Each of these points is approached and a corresponding measured point evaluated. The measured points are referred to as the distortion. Figure 2 shows that there must be systematic distortions which can be corrected. The ideal planes are perfectly flat, and measured distortion grids show distinct repeated patterns. When a trajectory is now programmed, for each point in the trajectory the inverse distortion is computed. A linear approximation is done for points which lie in between points in the measured grid.

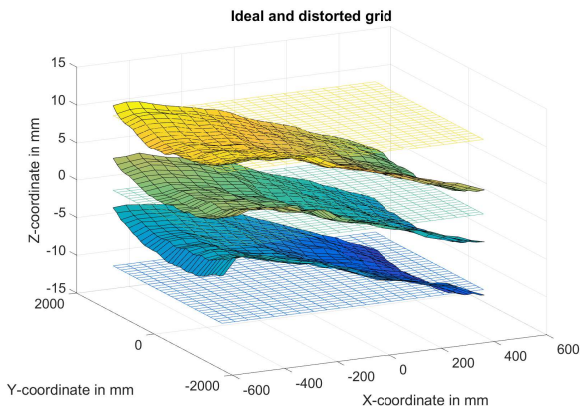

Fig. 2: This plot shows a 3-layered grid and the distorted layers as they were measured.

Since most useful trajectories of the particular tested robot involve little vertical movement (z-axis), the correction approach can select either none or all x-y planes. From table 2 it should be evident that there are four of these planes.

4. EXPERIMENTAL RESULTS

Test of the black-box method were conducted on the IPAnema 3 robot [15]. This uses Dyneema (UHMWPE) cable of type LIROS D-Pro 01505-0600 with an elastic modulus of 55000 - 172000 MN/mm. To further improve the accuracy, systematic distortion was measured and used to further improve the accuracy of the cable robot.

The measured distortion from the grid can be seen in Figure 2. From this grid several closest points are chosen to calculate an average offset. The number of points chosen and whether points in a separate plane are considered are part of the grid compensation parameters.

Table 2: Grid Parameters

Axis	**Min [mm]**	**Max [mm]**	**Increment**
X-Axis	-550	450	50
Y-Axis	-1400	1400	100
Z-Axis	-10	10	5

Using this distortion grid, new trajectories are calculated which contain an offset according to the measurements. These trajectories are then evaluated to obtain an improved accuracy.

The results of these measurements are shown in Table 3. For comparison the same trajectories without compensation previously evaluated are also included in the table. It can be seen that a substantial accuracy improvement is achieved. At first only the x-y plane in which the trajectory is taken into account. This is referred to as the single grid. When considering all x-y planes

It should be noted that for the three trials different grid

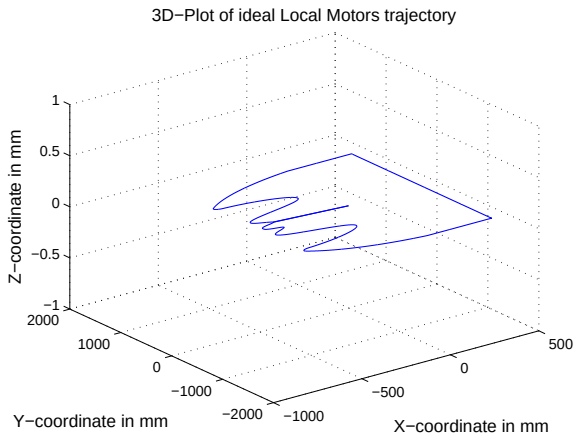

Fig. 3: 3D-Plot of the tested trajectory

compensation parameters are used. As the implementation is very new, the optimal parameters are currently unknown and cannot be transfered from one trajectory to the next. This means that the expected performance using the grid compensation for other trajectories will be the average of the values in the second two rows of Table 3.

Table 3: Average Accuracy Comparison of Grid improvement (all values in mm)

Compensation	**T1**	**T2**	**T3**	**Average**
Without	10.83	10.48	10.57	10.63
With Single Grid	5.20	2.30	4.10	3.87
With All Grids	4.10	1.65	1.66	2.47

The difference in trajectories with and without the compensation can be seen in the figures 4 and 3.

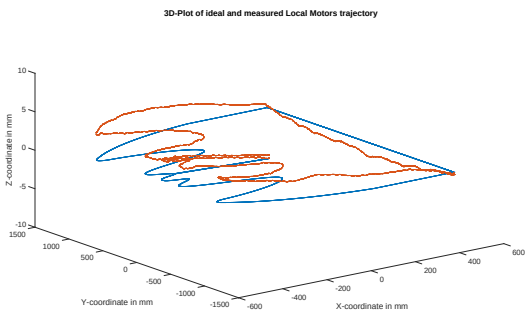

Fig. 4: 3D-Plot of the tested trajectory without correction

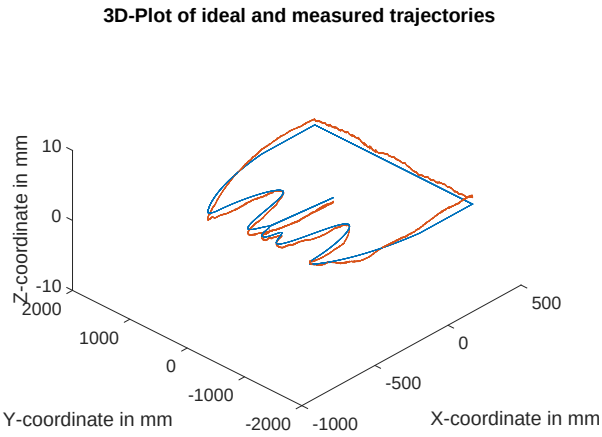

Fig. 5: This Plot shows the best measurement for the Local Motors trajectory with an error of 1.65 mm. It was achieved using the grid correction with all grid levels and 1218 nearest points.

5. CONCLUSION

It is shown that a black box method can increase the accuracy of a robotic system. These methods have not been applied to cable robots frequently although calibration is common in the robotics industry. On the particular cable robot, the accuracy improvement from applying a black box correction was significant. The improvement was almost a factor of four. This shows that there are significant systematic errors which can be accounted for.

Acknowledgements This research was supported by Leading Foreign Research Institute Recruitment Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science and ICT (MSIT) (No. 2012K1A4A3026740).

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