CALIBRATION PROCEDURE FOR A GEOMETRICALLY RECONFIGURABLE 3-DOF CABLE-DRIVEN PARALLEL ROBOT

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ABSTRACT
Cable-driven parallel robots offer certain advantages in terms of dynamics and flexibility. They differ significantly in their structure from industrial, serial robots. In this paper we introduce a novel procedure for calibration for a geometrically reconfigurable 3-DoF cable-suspended robot based on inverse kinematics including a pulley for each cable. For that we use a laser tracker with interferometric measurement in combination with local 3D positioning. This is a new approach because of measuring relative laser beam lengths and cable lengths only. In addition the paper introduces a validation procedure.

KEY WORDS
Cable-Driven Parallel Robot, Modelling, Calibration, Identification

1 Introduction
Cable-driven parallel robots are growing in popularity – making their way from research prototypes into industrial applications. The first commercial application was introduced in 1985, the Skyacam presented in [1] used for tracking shots in stadiums and became very popular. One of the first large research projects which was sponsored by Japanese shipbuilders to develop a cargo crane is presented in [2]. Since then, many other commercial applications as presented in [3] or [4] as well as research projects as presented in [5] or [6] were implemented.

Cable-suspended parallel robots provide several advantages over widely used serial robots. Due to the low weight of these robots – particularly in most cases negligible cable weight or low endeffector weight – they are able to move with high dynamics. Another asset is a very large workspace in comparison to serial robots. But there are also disadvantages. For example, if anchor points for the cables are mounted on both bottom and top of the workspace there is a problem in terms of accessibility because cables pass through workspace. Because of that, the robot of University of Augsburg uses only anchor points on the top of the workspace. In that way an human-robot interaction is conceivable.

Our robot has a strictly modular design and can be geometrically reconfigured at any time. A module – consisting of an engine, a winch, a pulley at the suspension point and one cable – can be shifted in a few minutes in order to adapt to a new environment like a novel workspace or a different endeffector. Fig. 1 shows our system consisting of aluminium profiles and three modules. Reconfigurability is necessary in an industrial environment, for example, when production environment has to changed frequently in order to meet the demands of a flexible production. In this case the modules can easily be mounted in new positions and thus, for example, provide a larger working area. The robot can also be mounted over a workstation to assist people in handling tools (see Fig. 2). But, geometrical reconfiguration necessitates a fast and automated calibration of the robot modules. In order to obtain a sufficient precision in trajectory planning, system parameters have to be identified with high precision. This set of system parameters to be identified will be specified in Section 2. Moreover, this is important for a model-based controller design.

The problem of identification of geometric system parameters is well known. In [7] Hayati et al. addresses this problem with the goal of an accurate positioning of an endeffector for a serial kinematic chain. Also for parallel robots the determination of geometric parameters is subject of investigations [8]. In the context of parallel kinematic chains, the research object is often a Stewart gough platform [9]. This publication also shows a way to record measurement data using a camera system.

The calibration procedure to be presented here uses internal measurements like evaluation of incremental rotary encoders of the engines similar to [10] to fulfill its task. In contrast to this work our robot is not overconstrained but fully constrained. However, the problem is similar, as we also focus on the determination of the pulley positions. In addition, we use laser trackers similar to [11] or [12] determining system parameters. Unlike [11] or [12], we use a laser tracker with a relatively measuring interferometer and include these measurements in the optimization presented later instead of using an absolute measuring laser tracker for validation. The use of an interferometer has already been proposed in [8], but without the combination with a laser tracker and in the context of a different kinematic chain.

In the next section we will introduce the model of the 3-DoF cable-driven parallel robot including geometric robot.
and laser beam path modelling, respectively. Section 3 will present the calibration scenario and will introduce both procedure and solution of calibration problem using known optimization algorithms. In addition we will present results for a real scenario. In section 4 we will show a validation procedure. Conclusions and future work are discussed in section 5.

2 Modelling

2.1 Cable-Driven Parallel Robot Modelling

For the calibration process we need a kinematic model. That means we consider only equilibrium positions of the endeffector. If we now look at the specific case of a 3-DoF cable-driven robot our model consists of 3 suspension points $X_{S,i}$, $i = 1 \ldots 3$ which are described by a junction point and a detachment point (see Fig. 4). In addition we include $N$ measurements of the endeffector position $X_{E,k}$ with $k = 1 \ldots N$ for calibration. For cables $i = 1 \ldots 3$ we need to solve the inverse kinematics for the cable lenghts from junction point $X_J$ to $X_E$.

$$\hat{L}_{i,k} = f(X_{S,i}, X_{E,k}, \gamma, r).$$

In contrast to [5] cables of the presented robot are guided by a pulley. We do not assume the pulley positions as geometrical points as described in e.g. [13]. As a result – because the cable runs over a pulley – the equations of inverse kinematics do not only consist of trigonometric calculation including endeffector position and suspension point. We also have to include an angle $\gamma_k$ describing the detachment point $X_{D,k}$ and radius of the pulley $r$ which are emphasized in Fig. 3.

For reasons of clarity, the following modelling is shown for one pulley or cable and a corresponding endeffector position. We do not include indices for cable $i$ and endeffector position $k$. The angle $\gamma$ results from sum of angles $\alpha$ and $\beta$ depicted Fig. 4. For that, we have to take into account angle $\alpha$ occurs in a mathematical negative sense.

$$\gamma = \pi - (\alpha + \beta)$$

with

$$\alpha = \arctan(\frac{d_z}{d_x})$$

and

$$\beta = \arccos\left(\frac{r}{d_{xz}}\right)$$

Figure 1. Cable-robot configuration with three cables or modules respectively

Figure 2. Cable-robot mounted over a workstation in a flexible production

Figure 3. Variation of detachment point
To assume angles $\alpha$ and $\beta$ as presented in Fig. 4 we have to rotate the pulley to x-z-plane. After calculating the following steps of inverse kinematics we have to rotate the pulley back to the native frame.

To calculate the detachment point we need $\gamma$, center of an arbitrary pulley $X_S$ and the corresponding junction point $X_J$ described by angle $\gamma$.

$$X_D = X_S + \begin{pmatrix}
\sin(\gamma - \frac{\pi}{2}) \cdot r \\
\cos(\gamma - \frac{\pi}{2}) \cdot r
\end{pmatrix}$$  \hspace{1cm} (5)

If the endeffector is moving not only the detachment point but also the length of rolled and unrolled cable respectively will vary.

$$l_a = r \cdot \gamma$$  \hspace{1cm} (6)

$$l_f = \sqrt{d_{xz}^2 - r^2}$$  \hspace{1cm} (7)

Now, sum of these lengths $l_a$ and $l_f$ is the actual cable length $\hat{L}$ belonging to endeffector position $k$. The inverse kinematics of one cable and an arbitrary endeffector position is

$$\hat{L}_k = l_{a,k} + l_{f,k}.$$  \hspace{1cm} (8)

This actual cable length is unknown because we cannot measure it precisely after reconfiguration. We only know current cable lengths differences between last and current endeffector position measured by incremental rotary encoder, which provides a very exact method of measuring changes in angle of the engine with a standard deviation of 0.95 $\mu$m with regard to cable length measurement, but has no capability of measuring the initial cable length offsets.

The absolute cable lengths result from

$$L_k = L_{off} + \Delta L_k.$$  \hspace{1cm} (9)

Where $L_{off}$ is an unknown cable length offset or the initial cable length after reconfiguration respectively and $\Delta L_k$ is a measured cable length variation dependent on current endeffector position in measurement $k$.

In summary, for calibration we need to find the junction points $X_J$ because these points do not vary while rotating the pulleys and are as a consequence - fixed after reconfiguration of the cable robot. To find all junction points we have to solve equation (1). To do that, we need to find all detachment points resulting from equation (5) to calculate rolled and unrolled cable lengths $l_a$ and $l_f$.

### 2.2 Laser Beam Path Modelling

During calibration the endeffector will be tracked by a laser beam. The absolute length of this beam is unknown because we do not use a laser tracker with absolute interferometric measurement. We only can reset laser beam length measurement and measure laser beam length variation as a result. Therefore, the laser beam path is given by

$$S_{j,k} = S_{off} + \Delta S_{j,k}$$  \hspace{1cm} (10)

Figure 4. Modelling of inverse kinematics with pulley

\[ \text{Figure 4. Modelling of inverse kinematics with pulley} \]

\[ \text{similar to equation (9). Where } j \text{ is the current position in the so-called reference frame because the laser tracker can be shifted in position by the positioning system (stage) and } k \text{ is the current endeffector position index. This procedure will be explained later in more detail. Overall, there are } j = 1, \ldots, P \text{ positions within the reference frame. The variation } \Delta S \text{ we can measure with a standard deviation of } 0.138 \mu m. \]

Now, the laser beam path will be modelled as Euclidian distance between laser source and retroreflector attached to the endeffector.

$$\hat{S}_{j,k} = \|X_{E,k} - X_{L,j}\|.$$  \hspace{1cm} (11)

We will use equation (8) – (11) in the next section in order to optimize a cost function.

### 3 Calibration

#### 3.1 Procedure

For calibration we use the system configuration depicted in Fig. 5. The system presented in section 1 will be extended by the laser tracker introduced by [14] which is mounted on a 3D positioning unit with a working area of 0.2 m for each single cartesian axis. The presented calibration procedure consists of a number of preparatory steps followed by two basic steps. The first one is determination of endeffector positions relative to reference frame. The second one is, finally, determination of the pulley positions. Achieving these goals we have to pass through the state machine depicted in Fig. 6.

Preparatory steps – At the beginning, we have to move the endeffector into its first position. At this position we must ensure that cable lengths do not change until we have to move in a new endeffector position. Now, the laser tracker needs to find the retro reflector mounted on the endeffector. When the retroreflector is tracked, from that moment on, the laser tracker have to keep contact to the retroreflector for the rest of calibration procedure. In addition, for the first endeffector position the interferometric measurement
has to be reset to zero. From now on, the laser tracker measures laser beam path variations very precisely.

Now, that we have accomplished all preliminary actions and reached the first end effector position, we can proceed further with next state and evaluate interferometric measurement. For that, the laser tracker is moved into the reference frame. This arrangement of positions in reference frame \( X_{R,j} \) is shown in Fig. 7. Fig. 8 visualizes this shifting, as an example. For the first position of course laser beam path measurement will result zero. But, for any other position in reference frame we will get variations in beam path.

Step 1 – We calculate the end effector position in reference frame related to shifted positions. For each of these \( P \) shifts in reference frame laser beam length will change and we are able to determine the end effector position with respect to the stage. With these measurements we can continue with the optimization step, see 3.2. In addition, in order to calculate the pulley positions in the next step, we measure all three cable lengths one particular position in reference frame and repeat the cycle for the whole set of \( N \) end effector positions \( X_{E,k} \).

Step 2 – For the second basic step we need a sufficient number of end effector positions. For example, we use \( N = 16 \) different positions. In addition we have to ensure that cable lengths variations from one position to another differ significantly. That means for each new position we vary the cable lengths by several centimeters up to decimeters. After finishing a complete cycle of determination of a set of end effector positions and measurements of cable lengths belonging to that positions we can optimize the pulley positions.

3.2 Optimization

Refering to Fig. 6 we have to solve two optimization problems. The first one includes laser beam length variations at specific positions of the laser tracker in reference frame. The result of this optimization is an end effector position in the reference frame. At this time, we ignore cable lengths. The goal is to find a set of \( N \) end effector positions with
reference to a known frame. The object function to be minimized is

$$\text{min } J_S = \min \sum_{k=1}^{N} \sum_{j=1}^{P} (\hat{S}_{j,k} - S_{j,k})^2. \quad (12)$$

Where \(\hat{S}_{j,k}\) is model-based laser beam length for \(k\)-th endeffector position and \(j\)-th position in reference frame (see equation (11)). \(S_{j,k}\) is a measured laser beam length consisting of an offset and a variation for the same positions of endeffector and laser tracker, respectively (see equation (10)).

For \(k\) endeffector positions and \(j\) positions in reference frame we aspire to find the squared difference between model-based laser beam length \(\hat{S}_{j,k}\) and measured laser beam length \(S_{j,k}\). According to equation (10), it is important to mention that we do not measure absolute laser beam lengths but relative. As a result we find a laser beam offset length corresponding to the first measured laser beam length in reference frame. This offset is constant for all measurements concerning this endeffector position. For optimization we use a Levenberg-Marquardt Algorithm.

After we have identified relative endeffector positions we are able to calculate pulley positions. We can reutilize the structure of equation (12) as shown below.

$$\text{min } J_L(k) = \min \sum_{i=1}^{3} \sum_{k=1}^{N} (\hat{L}_{i,k} - L_{i,k})^2. \quad (13)$$

Where \(\hat{L}_{i,k}\) is the model-based cable length for \(i\)-th pulley position and \(k\)-th endeffector position (see equation (8)). \(L_{i,k}\) is the measured cable length also consisting of an offset and a variation (see equation (9)). Now, endeffector positions are known and these positions can be used in order to identify pulley positions with relative cable lengths measurements. Equivalent to the first step, we also find an initial cable length offset equivalent to cable length in the first endeffector position and inverse kinematics, respectively.

### 3.3 Implementation and Results

For simulation and optimization we use Matlab. The laser tracker and the cable robot are actuated by a modular real-time system from the company dSPACE. In this way, a rapid control prototyping is feasible. After interferometric measurement of laser beam path variation and measurement of cable lengths variations we can identify three pulley positions. Fig. 9 shows the result of calibration process in different views. The blue circle is the first of the laser tracker positions and the center of 3D positioning system, respectively. Without loss of generality, this position is \(X_{R,1} = [0 \ 0 \ 0]\). The blue crosses are 16 different endeffector positions relative to reference frame of the laser tracker and the red circles, finally, are identified pulley positions. As Fig. 9 shows, identified pulley positions are tilted with respect to x-y-plane. This is a fact we also become aware of as a result of calibration.

### 4 Validation

After calibration we need both, a validation of first and the second step presented in section 3.1. For the first step – calculating endeffector positions – we can determine a lower bound of quality concerning repeatability of procedure. We can mount the reflector on same breadboard that carries the laser tracker. In that way we ensure the reflector does not swing as a result of suspending it by cables. Now we can determine the position of a fixed retroreflector. If we do that 20 times in sequence, identify the position of reflector and, after that, calculate a mean position we get

$$X_{E,\text{val}} = \begin{pmatrix} -0.0499 \\ 0.7114 \\ -0.0299 \end{pmatrix} \text{m}. \quad (14)$$

However, much more interesting than the position of reflector is the variance or standard deviation which results from these 20 iterations. The standard deviation for component \(x\), \(y\) and \(z\) condensed in one vector is

$$\sigma_{E,\text{val}} = \begin{pmatrix} 4.909 \\ 80.472 \\ 6.129 \end{pmatrix} \cdot 10^{-6} \text{m}. \quad (15)$$

That means, with the presented optimization we are able to determine an unknown position of a reflector at the given distance of approximate 0.7 m with a standard deviation of \(80.472 \cdot 10^{-6}\) m for worst sensitive dimension. Following the theorem of intersecting lines, the distance influences the result linearly. That means, for distances of \(2.5\) m up to \(3.5\) m there should be a standard deviation of about \(0.4 \cdot 10^{-5}\) m up to \(0.5 \cdot 10^{-5}\) m.

Now, if we identify a reflector – now suspended by cables – in the addressed distance range 20 times we get a mean position vector

$$X_{E,\text{val}} = \begin{pmatrix} -0.3468 \\ 2.6872 \\ 0.3154 \end{pmatrix} \text{m}. \quad (16)$$

with a standard deviation vector

$$\sigma_{E,\text{val}} = \begin{pmatrix} 0.299 \\ 2.343 \\ 0.276 \end{pmatrix} \cdot 10^{-3} \text{m}. \quad (17)$$
The standard deviation of calculated positions is significantly larger than expected. The reason for this is the oscillation of the endeffector connected with cables. Keeping this uncertainty in mind, we identify pulley positions. In this scenario the reflector is mounted on the endeffector. Now, we use one of the endeffector positions of the first step presented in section 3 as a basis for validation of the whole procedure. We know the vector from reference frame to this position. That means, we are also able to generate additional positions of the endeffector in reference frame which have the same distance to the laser tracker. Of course, all these positions are located on a sphere. Moreover, if we adjust the cable lengths reaching these positions and, simultaneously, track the reflector mounted on the endeffector while driving to the positions the laser beam lengths should be zero in all positions.

To validate this, we generate 25 endeffector positions on a grid which should have the same distance to the laser tracker as the middle position given by the identification procedure. In each position there is an error in laser beam length. These errors are depicted in Fig. 10. The deviations of laser beam lengths are emphasized by colored circles for each validation position. The unit of the colored bar is millimeters. As it can be seen, there are deviations in laser beam lengths in a range of $-10 \cdot 10^{-3} \text{m}$ up to $15 \cdot 10^{-3} \text{m}$.

5 Conclusion

This paper presented a novel calibration procedure of a 3-DoF cable-driven robot based on relative, interferometric measurements of a laser tracker. This procedure involves two steps which are based on the same optimization principle. As a novel approach should be pointed out the relative positioning of the laser tracker in a reference frame. In this way, the tracker generates relative endeffector positions for calibration. After presentation of modelling of the cable-suspended robot and laser beam path an approach identifying system parameters was introduced. This procedure includes formulation and subsequent optimization of a cost function with real data. In addition, a validation strategy was introduced using the existing configuration of components. The validation considers both validation of the first and the second step of calibration. Finally, results of validation were presented.

The objective of the presented method is comparable to [10]. We also use internal measuring systems of the motors. In addition, however, we have introduced local positioning of the laser tracker in order to aggregate the measured relative interferometer values. With this positioning, we compensate for the fact that [10] uses an overconstrained system in order to use the additional cables available for measuring. With our method we achieve a repeatability of a few millimeters. It is very robust and independent of the initial value of the winch positions before optimization.

The procedure can be applied to an arbitrary number of cables. It does not matter if anchor points for the cables are mounted on both bottom and top of the workspace or not. Moreover, the method is not limited to cable-suspended or parallel robots, respectively. With the presented approach, geometric parameters of serial robots can also be identified. This requires kinematic modelling of the robot. The procedure remains the same. In addition to the presented calibration procedure we found a new way of determining the accuracy of a 3-DoF cable-driven robot by using relative, interferometric measurements which was also addressed in [15]. This validation can also be applied to other robots.

For the future we aspire including rigid body considerations and validating results with absolutely interferometric measurements. We will also apply the procedure to a serial robot to prove the generalizability of the method.

References


Figure 10. Experimental results of calibration procedure


