Estimating Inertial Parameters of Suspended Cable-Driven Parallel Robots – Use Case on CoGiRo

Philipp Tempel[1], Pierre-Elie Herve[2], Olivier Tempier[3], Marc Gouttefarde[3], and Andreas Pott[1]

***Abstract*— Model based open-loop and closed-loop control systems make use of the system's inertial parameters. Unfortunately, not all of these values can be determined analytically nor can they be obtained from simple measurements. Established experiments for inertial parameters estimation have been applied to serial and parallel rigid-link manipulators, yet in very few cases to cable-driven parallel robots. Due to their kinematic properties and their unique setup, cable robots are more sensitive to incorrect estimates of the inertial parameters making it important to obtain such quantities through experiments. In this work, we assess the topic of inertial parameter identification of a parallel flexible-link manipulator exemplified by the suspended cable-driven parallel robot CoGiRo. Identification equations are derived from Newton-Euler equations of motion of an arbitrary point fixed to a rigid-body. Laboratory experiments for identification of the inertial parameters are then introduced and results are presented. Within the limitations of the sensors and data acquisition methods, reasonable results have been obtained, thereby validating the procedure for suspended cable-driven parallel robots.**

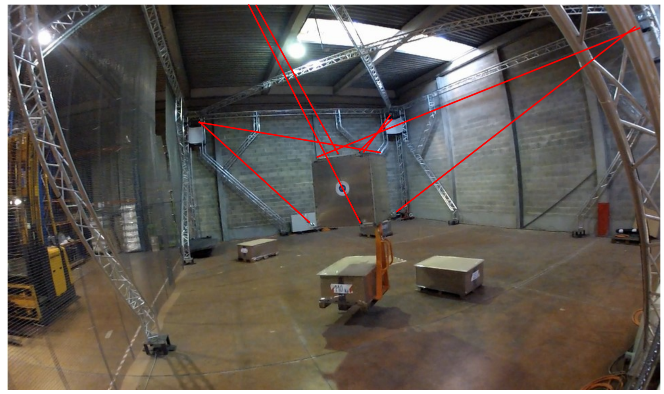


Fig. 1: Picture of cable-driven parallel robot CoGiRo with its cuboid platform and an attached forklift; the cables are highlighted in red.

I. Introduction

Simulation of technical processes is a powerful tool to examining system properties and dynamics under certain conditions or given task requirements. Furthermore, simulation may be used in quality control or to implement and test sophisticated linear or non-linear feedback control loops without requiring or harming process hardware. The more complex and challenging these tasks become, the more process model parameters are required for them to work robustly. Such parameters may be velocities or accelerations, process forces or torques, or payload, though inertial parameters of the components of such mechanical systems play a pivotal role. While there are model parameters that may be quantified by gauging physical properties of the mechanical system e.g., geometric parameters, others may not be easily identified or are unknown in practice–such as the exact material coefficients. Among these are combined parameters such as the overall mass, center of gravity, and the moments and products of inertia.

Combining different rigid-bodies into a multi-body mechanism makes determining the inertial parameters more important as the bodies are interacting with each other. This becomes especially significant when several bodies with largely varying stiffness are combined, such as cables attached to a cuboid body. Here, uncertainties in the mechanical properties of only one body can lead to deviation between model and reality. In the case of cable-driven parallel robots [1], uncertainties in the inertial parameters of the mobile platform can lead to both static and dynamic errors due to the very low flexural rigidity of the cables. Therefore, both online and offline identification of these inertial parameters is of vital importance to better model and simulate cable-driven parallel robots, but also for improved operational stiffness and accuracy.

A. Cable-Driven Parallel Robots

Cable-driven parallel robots, cable robots in brief, are a special implementation of the well-known Gough-Stewart platform with the force transmitting elements realized by means of cables (see Fig. 1). However, cable robots differ from conventional parallel manipulators in the number of actuators needed: since cables can only exert tensile forces and thus cannot be used to push, cable robots need to satisfy the constraint of having at least one cable more than number of degrees of freedom (DOF). Mathematically speaking, this can be expressed by the constraint equation $m \geq n+1$, where n is the number of degrees of freedom and m is the number of cables. It is worthwhile mentioning that cable robots can be implemented with $m = n$ cables, if gravity is used to keep the cables tensed.

In general, a cable robot consists of a mobile platform, cables, and winches mounted to the surrounding robot frame.

[1] Institute for Control Engineering of Machine Tools and Manufacturing Units (ISW), University of Stuttgart, 70174 Stuttgart, Germany, philipp.tempel@isw.uni-stuttgart.de, andreas.pott@isw.uni-stuttgart.de

[2] Tecnalia France, Batiment 6 - Centre Spatial Universitaire Montpellier-Nîmes, 34090 Montpellier, France, pierre-elie.herve@tecnalia.com

[3] Laboratoire d'Informatique, de Robotique et de Microèlectronique de Montpellier (LIRMM, UM - CNRS), 34095 Montpellier cedex 5, France, marc.gouttefarde@lirmm.fr, olivier.tempier@lirmm.fr

This deliberate reduction of mass and inertia of the mobile parts makes the joints more compact and allows for higher dynamics and bigger workspace yet still allows for surprisingly large payloads. While conventional industrial robots present a payload to total weight ratio of 1:3.4 (see KUKA LBR iiwa: payload 7 kg; total mass 23.90 kg), cable robots can reach ratios of up to 20:1 [2].

Since cables can be bend with small radii, it is possible to store very long pieces of cable occupying a comparatively small space. All these properties give cable robots a competitive edge over their conventional, rigid-actuator counterparts. However, reduced flexural rigidity of the joints has an ineluctable impact on the performance of cable robots especially with motion in directions perpendicular to the cables' neutral axes. Additionally, both longitudinal and transversal vibrations of the cables impact performance and accuracy of cable robots more predominantly than they affect parallel manipulators with rigid joints.

B. *Inertial Parameter Estimation*

Different identification techniques can be used to obtain the actual robot inertial parameters. With regards to serial manipulator, inertial parameter identification is a well-known topic and several systematic procedures exist for experimental identification e.g., [3]–[8]. Taking advantage of the open kinematic chain, load parameters of serial manipulators can be obtained by motion of a single link. A common estimation procedure is based on direct measurements of data during motion along specifically designed trajectories. For parallel robots, making use of single link motion is usually not applicable because the n-DOF end-effector is connected to the base by at least $m = n$ independent kinematic chains [8]. Hence, different approaches have been developed to determine the inertial parameters, despite most of these providing solutions to only a subset of all ten parameters [5], [9]–[13]. These techniques have been equally applied to serial and parallel rigid-link systems, yet only seldomly to flexible-link manipulators.

With regards to cable robots, exact knowledge of the inetial parameters is important due to the reduced lateral stiffness of the cables which cannot compensate for (slightly) incorrect values. Moreover, estimation of inertial parameters becomes more involved for large-dimension cable robots for which cable lengths, elongations, and tensions are difficult to measure directly. To the best of the authors' knowledge, only few research has been conducted. In [14], the authors estimate the mass and center of gravity of the mobile platform of a redundantly-restrained cable robot using a circular trajectory. The work is limited to translational motion and angular motion is omitted as the orientation workspace of the assessed cable robot is relatively small. Thus, estimation of only the mass and center of gravity is performed yielding results with error margins of 5 % to 200 %. Determination of the inertia matrix is not performed, which may be applicable to fully-restrained cable robots, but is not sufficient for suspended cable robots like CoGiRo [15]. A similarly set-up cable robot, yet smaller in its footprint, was subjected to

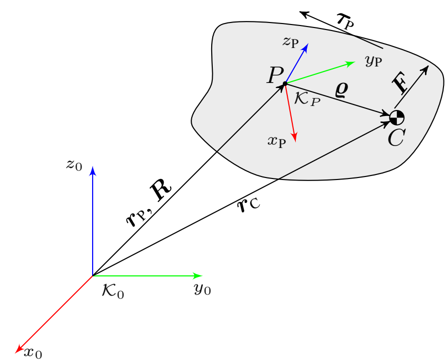


Fig. 2: Free floating rigid body in space with forces and torque acting about body-fixed point P located at ϱ with respect to the body's center of gravity C.

an offline parameter identification methodology [16]. Here, the authors first identified kinematic parameters, followed by dynamic parameters including those of the drive trains. The estimation was performed by minimizing a non-linear least squares problem formulated in the joint space. A set of infrared cameras was used for kinematic parameter identification but not for estimating the dynamic parameters.

C. *Contribution*

In this paper, the inertial parameters of suspended cable-driven parallel robot CoGiRo are estimated using methodologies derived for inertial parameter estimation of parallel rigid-link manipulators. The identification equations are obtained from the operational space dynamic model and formulated as linear equations in the inertial parameters to be identified. An inertial measurement unit on board the mobile platform, cable force sensors at the cable attachment points on the platform, and a laser tracker are used as measurement sources.

The paper is organized as follows: in Section II, the equations of motion are rewritten to yield linear equations for the identification process. Section III then discusses the laboratory setup used for experimental identification while Section IV presents the results of experimental identification. The paper closes with a discussion of the findings in Section V and conclusions presented in Section VI.

II. Model Dynamics Equation

The equations of motion of a rigid body written for point P not coinciding with the body center of gravity are ([17], [18])

$$\begin{bmatrix} \boldsymbol{F} \\ \boldsymbol{\tau}_{\mathrm{P}} \end{bmatrix} = \begin{bmatrix} m_{\mathrm{P}} \boldsymbol{I}_3 & -m_{\mathrm{P}} \left[\boldsymbol{\varrho}\right]_\times \\ m_{\mathrm{P}} \left[\boldsymbol{\varrho}\right]_\times & \boldsymbol{J}_{\mathrm{C}} + m_{\mathrm{P}} \left[\boldsymbol{\varrho}\right]_\times \left[\boldsymbol{\varrho}\right]_\times \end{bmatrix} \cdot \begin{bmatrix} \boldsymbol{a}_{\mathrm{P}} \\ \dot{\boldsymbol{\omega}} \end{bmatrix} + \dots$$
$$+ \begin{bmatrix} m_{\mathrm{P}} \left[\boldsymbol{\omega}\right]_\times \left[\boldsymbol{\omega}\right]_\times \boldsymbol{\varrho} \\ \left[\boldsymbol{\omega}\right]_\times \left(\boldsymbol{J}_{\mathrm{C}} + m_{\mathrm{P}} \left[\boldsymbol{\varrho}\right]_\times \left[\boldsymbol{\varrho}\right]_\times\right) \boldsymbol{\omega} \end{bmatrix} . \tag{1}$$

with the sum of external forces $\boldsymbol{F}$ and external torque $\boldsymbol{\tau}_{\mathrm{P}}$ about P, respectively, where m_{P} is the rigid body's mass, $\boldsymbol{I}_3$ the 3×3 identity matrix, the location $\boldsymbol{\varrho} = [\varrho_x, \varrho_y, \varrho_z]^{\mathsf{T}}$ of the center of gravity expressed in body-fixed frame $\mathcal{K}_{\mathrm{P}}$, $\boldsymbol{J}_{\mathrm{C}}$ the inertia matrix about the center of gravity, $\boldsymbol{\omega}$ and

$\dot{\boldsymbol{\omega}}$ the angular velocities and accelerations, respectively, and $\boldsymbol{a}_{\mathrm{P}}$ linear acceleration of point P. The cross-product skew-symmetric matrix of any vector $\boldsymbol{x} = [x, y, z]^{\mathsf{T}}$ is defined by $[\boldsymbol{x}]_{\times}$ such that

$$[\boldsymbol{x}]_{\times} \equiv \begin{bmatrix} 0 & -z & y \\ z & 0 & -x \\ -y & x & 0 \end{bmatrix} \tag{2}$$

holds.

The orientation of the platform is given by the Tait-Bryan angles tuple $\eta = \langle \varphi, \theta, \psi \rangle$ such that the rotation matrix $\boldsymbol{R}$ from $\mathcal{K}_{\mathrm{P}}$ to $\mathcal{K}_0$ reads (cf. Fig. 2)

$$\boldsymbol{R} = \boldsymbol{R}(\eta) = \boldsymbol{R}_z(\psi)\boldsymbol{R}_y(\theta)\boldsymbol{R}_x(\varphi). \tag{3}$$

The Tait-Bryan angles tuple and its time derivatives $\dot{\eta}$ and $\ddot{\eta}$ can be related to the body-fixed angular velocities $\boldsymbol{\omega} = [p, q, r]$ and accelerations $\dot{\boldsymbol{\omega}}$ expressed in the world frame by satisfying the kinematic differential equations ([19], [20])

$$\underbrace{\begin{bmatrix} p \\ q \\ r \end{bmatrix}}_{\boldsymbol{\omega}} = \underbrace{\begin{bmatrix} C_\theta C_\psi & -S_\psi & 1 \\ C_\theta S_\psi & C_\psi & 0 \\ -S_\theta & 0 & 0 \end{bmatrix}}_{\boldsymbol{P}^{-1}(\boldsymbol{\eta})} \cdot \dot{\boldsymbol{\eta}} \tag{4a}$$

$$\begin{aligned} \underbrace{\begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix}}_{\dot{\boldsymbol{\omega}}} &= \underbrace{\begin{bmatrix} 0 & -\dot{\varphi} S_\theta C_\psi & -\dot{\varphi} C_\theta S_\psi - \dot{\theta} C_\psi \\ 0 & -\dot{\varphi} S_\theta S_\psi & \dot{\varphi} C_\theta C_\psi - \dot{\theta} S_\psi \\ 0 & -\dot{\varphi} C_\theta & 0 \end{bmatrix}}_{\frac{\mathrm{d}}{\mathrm{d}\boldsymbol{\eta}}(\boldsymbol{P}^{-1}(\boldsymbol{\eta})\cdot\dot{\boldsymbol{\eta}})} \cdot \dot{\boldsymbol{\eta}} + \dots \\ &+ \boldsymbol{P}^{-1}(\boldsymbol{\eta}) \cdot \ddot{\boldsymbol{\eta}} \end{aligned} \tag{4b}$$

where $S_{\{\cdot\}} := \sin\{\cdot\}$, $C_{\{\cdot\}} := \cos\{\cdot\}$.

A. Parameter Identification Equations

The goal of this work is to estimate the following robot inertial parameters:

- Platform mass m_{P} (i.e., combined mass of platform and possible on-board manipulators, loads, or other equipment such as sensors);
- Location of center of gravity $\boldsymbol{\varrho}$ w.r.t. P;
- Inertia matrix $\boldsymbol{J}_{\mathrm{C}}$ (moments and products of inertia).

To this end, we rewrite Eq. (1) such that the inertial parameters are given in an implicit form. First, we split the forces $\boldsymbol{F}$ and torques $\boldsymbol{\tau}_{\mathrm{P}}$ such that

$$\boldsymbol{F} = \boldsymbol{F}_{\mathrm{c}} + m_{\mathrm{P}}\boldsymbol{F}_{\mathrm{g}} = \sum_{i=1}^{m} \boldsymbol{F}_{\mathrm{c},i} + m_{\mathrm{P}} \cdot \begin{bmatrix} 0 \\ 0 \\ -g \end{bmatrix} \tag{5a}$$

$$\begin{aligned} \boldsymbol{\tau}_{\mathrm{P}} = \boldsymbol{\tau}_{\mathrm{c}} + m_{\mathrm{P}}\boldsymbol{\tau}_{\mathrm{g}} &= \sum_{i=1}^{m} [(\boldsymbol{R}\boldsymbol{b}_i) \times \boldsymbol{F}_{\mathrm{c},i}] + \dots \\ &+ m_{\mathrm{P}} \cdot [(\boldsymbol{R}\boldsymbol{\varrho}) \times \boldsymbol{F}_{\mathrm{g}}] \end{aligned} \tag{5b}$$

holds, where $\boldsymbol{F}_{\mathrm{g}}$ is gravitational force with $g = 9.81\,\mathrm{m/s^2}$, $\boldsymbol{F}_{\mathrm{c},i}$ are cable forces, and $\boldsymbol{b}_i$ are the location of cable attachment points given in body-fixed frame $\mathcal{K}_{\mathrm{P}}$. Furthermore, assume angular velocities and accelerations $\boldsymbol{\omega}$ and $\dot{\boldsymbol{\omega}}$, respectively, linear accelerations $\boldsymbol{a}_{\mathrm{P}}$, to be given as measured quantities. Angular position and velocities are measured by an inertial measurement unit (IMU) placed on the mobile platform; measurements of cable forces are given directly by means of force sensors placed between the cable and the platform while cable force generated torques are to be calculated as a function of the current pose as well as cable force directions and magnitudes.

On the one hand, we can then use the conservation of linear momentum from Eq. (1) and rewrite it such that it yields

$$\underbrace{\begin{bmatrix} -\boldsymbol{F}_{\mathrm{c}}, & [\dot{\boldsymbol{\omega}}]_{\times} + [\boldsymbol{\omega}]_{\times}[\boldsymbol{\omega}]_{\times} \end{bmatrix}}_{=:\boldsymbol{\Phi}_{1,j}} \cdot \underbrace{\begin{bmatrix} \frac{1}{m_{\mathrm{P}}} \\ \boldsymbol{\varrho} \end{bmatrix}}_{=:\boldsymbol{k}_1} = \underbrace{\boldsymbol{F}_{\mathrm{g}} - \boldsymbol{a}_{\mathrm{P}}}_{=:\boldsymbol{Y}_{1,j}} \tag{6}$$

in which we now have a linear expression of the force components $\boldsymbol{\Phi}_{1,i}$, the to-be-estimated inertial parameters $\boldsymbol{k}_1$, and the nominal external accelerating forces $\boldsymbol{Y}_{1,i}$. From this equation, platform mass m_{P} and position $\boldsymbol{\varrho}$ of its center of gravity can be determined.

On the other hand, determination of the moment and products of inertia of the cable robot platform, given by the vector of unknown parameters $\boldsymbol{k}_2 = \left[J_{\mathrm{C}_x}, J_{\mathrm{C}_y}, J_{\mathrm{C}_z}, J_{\mathrm{C}_{yz}}, J_{\mathrm{C}_{xz}}, J_{\mathrm{C}_{xy}}\right]^{\mathsf{T}}$, can be done using the conservation of angular momentum from Eq. (1). The parallel axis theorem provides the relationship between the inertia matrices $\boldsymbol{J}_{\mathrm{P}}$ and $\boldsymbol{J}_{\mathrm{C}}$ with

$$\boldsymbol{J}_{\mathrm{P}} = \boldsymbol{J}_{\mathrm{C}} + \underbrace{m_{\mathrm{P}}[\boldsymbol{\varrho}]_{\times}^{\mathsf{T}}[\boldsymbol{\varrho}]_{\times}}_{\boldsymbol{J}_{\mathrm{PC}}}. \tag{7}$$

Accordingly, we can rewrite Eq. (1) as

$$\underbrace{\boldsymbol{\tau}_{\mathrm{P}} - m_{\mathrm{P}}[\boldsymbol{\varrho}]_{\times}\boldsymbol{a}_{\mathrm{P}} - \boldsymbol{J}_{\mathrm{PC}}\dot{\boldsymbol{\omega}} - [\boldsymbol{\omega}]_{\times}\boldsymbol{J}_{\mathrm{PC}}\boldsymbol{\omega}}_{=:\boldsymbol{Y}_{2,i}} = \boldsymbol{\Phi}_{2,i} \cdot \boldsymbol{k}_2, \tag{8}$$

with

$$\begin{bmatrix} \dot{p} & -qr & qr & q^2 - r^2 & \dot{r} + pq & \dot{q} - pr \\ pr & \dot{q} & -pr & \dot{r} - pq & r^2 - p^2 & \dot{p} + qr \\ -pq & pq & \dot{r} & \dot{q} + pr & \dot{p} - qr & p^2 - q^2 \end{bmatrix} = \boldsymbol{\Phi}_{2,i}.$$

Assuming a set of N data samples, we obtain Eqs. (6) and (8) for each of these samples with different $\boldsymbol{\Phi}_{i,j}$ and $\boldsymbol{Y}_{i,j}$ $(i \in \{1,2\}, j = 1,\dots,N)$ allowing us to reformulate these equations to estimate platform mass and its center of gravity over all measurements, finally yielding

$$\boldsymbol{\Phi}_1 \cdot \boldsymbol{k}_1 = \boldsymbol{Y}_1, \qquad \boldsymbol{\Phi}_2 \cdot \boldsymbol{k}_2 = \boldsymbol{Y}_2, \tag{9}$$

where $\boldsymbol{\Phi}_1 \in \mathbb{R}^{3N\times 4}$ and $\boldsymbol{\Phi}_2 \in \mathbb{R}^{3N\times 6}$ are the vertical concatenation of all $\boldsymbol{\Phi}_{i,j}$, and $\boldsymbol{Y}_i \in \mathbb{R}^{3N}$ are the vertical concatenation of all $\boldsymbol{Y}_{i,j}$, respectively, $(i \in \{1,2\}, j = 1,\dots,N)$.

B. Parameter Estimation Procedure

With Eq. (9) at hand, we can analyze the data acquired from force sensor reading, laser tracker (LT) data, and IMU recording. Table I shows the mapping of measurement data to the data required for identification.

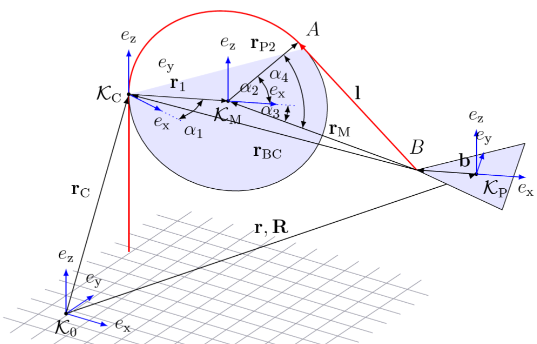


Fig. 3: Kinematic loop of a cable robot at pose $\boldsymbol{y} = \langle \boldsymbol{r}, \boldsymbol{R} \rangle$ where the cable length l splits into the segment on the pulley l_{r} and the part in the workspace l_{ws}. Roller orientation γ and roller wrapping angle β are functions of the current pose $\boldsymbol{y}$.

Fig. 4: Close-up picture of the CoGiRo cable robot mobile platform with the attached forklift.

TABLE I: Mapping of required identification data and available measurement sources.

Parameter	Source
$\boldsymbol{f}_{\mathrm{c},i}$	Cable force sensors
$\boldsymbol{\tau}_{\mathrm{c}}$	Calculation from Eqs. (5b) and (11)
$\boldsymbol{a}_{\mathrm{LT}}$	Laser tracker (LT)
$\boldsymbol{a}_{\mathrm{P}}$	Inertial measurement unit (IMU)
η	IMU
$\boldsymbol{\omega}$	IMU
$\dot{\boldsymbol{\omega}}$	IMU

To determine the cable force-generated torque, we make use of the inverse kinematics including pulleys, which states for a mobile platform pose $\boldsymbol{y} = \langle \boldsymbol{r}, \boldsymbol{R} \rangle$ (see Fig. 3 and [1])

$$\boldsymbol{l}_i = \boldsymbol{a}_{i,\mathrm{corr}}(\boldsymbol{y}) - (\boldsymbol{r} + \boldsymbol{R}\boldsymbol{b}_i) \tag{10}$$

$$\boldsymbol{F}_{\mathrm{c},i} = f_{\mathrm{c},i} \frac{\boldsymbol{l}_i}{\|\boldsymbol{l}_i\|_2} \tag{11}$$

where $f_{\mathrm{c},i}$ is the nominal force of cable i as read by the force sensor and $\boldsymbol{a}_{i,\mathrm{corr}}(\boldsymbol{y})$ is the location of the cable leave point on the pulley as a function of the pose. From these equations, we can determine the direction of each cable's force giving us the directed total cable force $\boldsymbol{F}_{\mathrm{c}}$ and its corresponding moment $\boldsymbol{\tau}_{\mathrm{c}}$.

In a forward dynamics computer simulation, we used Eq. (1) and known inertial parameters to validate our identification algorithm and implementation. The results were used to verify our implementation of the algorithms using ideal i.e., consistent, data.

III. Laboratory Setup

For experimental validation, identification of inertial parameters is performed for CoGiRo, a suspended cable-driven parallel robot with $n = 6$ degrees of freedom and $m = 8$ cables (see Fig. 1 with the dimensions of the robot frame and platform given in Table II, [15]). The cables in use are steel cables of $4\,\mathrm{mm}$ in diameter which are assumed non-elastic thus not elongating in the range of tensions used in this work. Furthermore, cable mass is not considered thus cable sag is not being accounted for in this contribution.

During experimental identification of the inertial parameters, data are acquired through multiple data acquisition interfaces. Absolute linear position data are tracked using a laser tracker T3 by API (operational space accuracy: $3\,\mathrm{mm}$, maximum tracking speed: $4\,\mathrm{m/s}$, maximum tracking acceleration: $2\,\mathrm{m/s^2}$) with data acquisition running at $f_{\mathrm{LT}} \approx 238\,\mathrm{Hz}$. Angular position and velocity, linear acceleration, and force sensor data was acquired autonomously at $f_{\mathrm{IMU}} = 25\,\mathrm{Hz}$ on the mobile platform. Commanded position was recorded in the B&R control system at $f_{\mathrm{cmd}} \approx 833\,\mathrm{Hz}$. All measurement systems were synchronized on the rising edge of the control command and the sampling rates were adjusted before analysis to satisfy one common sampling rate.

IV. Identification of Robot Inertial Parameters

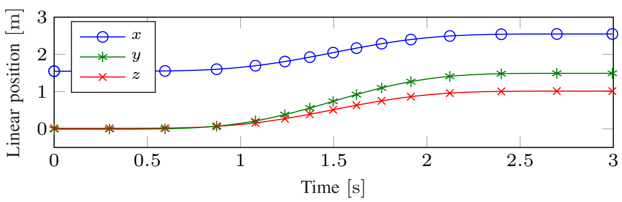
To perform identification of the robot inertial parameters, we first performed simulative checks of correctness of the derived and implemented equations of estimation (cf. Eq. (9)). Afterwards, an input trajectory was defined to excite all of the parameters to be estimated.

A. Design of Excitation Trajectory

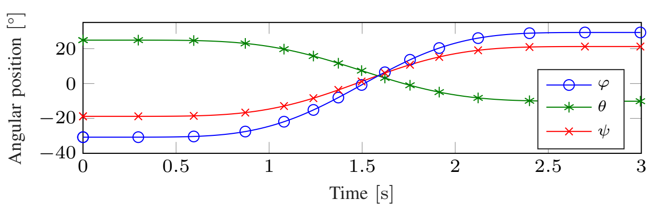
Designing good trajectories for experimental identification is crucial to obtaining good results. Two key features need to be fulfilled by the input trajectory, the first being necessity of angular motion, the second being relatively quick accelerations. Requirement of providing angular motion can be deduced from the equations of motion (cf. Eq. (1)) and the equations for estimation of the center of gravity and platform mass (cf. Eq. (6)): the center of gravity $\boldsymbol{\varrho}$ is read from the angular motion $\boldsymbol{\omega}$, thus cannot be estimated without these values. Additionally, satisfying large accelerations can be read from the latter equation as well: Exciting the system with large amplitudes of acceleration leads to more accurate estimation of the center of gravity as its estimate depends on a linear combination of angular velocity and acceleration. Furthermore, from Eq. (8), angular velocity and acceleration

TABLE II: Positions of cable outlet points $\boldsymbol{a}_i$ of CoGiRo given in world reference frame $\mathcal{K}_0$ and cable attachment points $\boldsymbol{b}_i$ on the platform of CoGiRo given in body-fixed reference frame $\mathcal{K}_P$.

Cable #	$\boldsymbol{a}_{i,x}$ [m]	$\boldsymbol{a}_{i,y}$ [m]	$\boldsymbol{a}_{i,z}$ [m]	$\boldsymbol{b}_{i,x}$ [m]	$\boldsymbol{b}_{i,y}$ [m]	$\boldsymbol{b}_{i,z}$ [m]
1	−7.1967	−5.4398	5.3928	0.5032	−0.4928	0.0000
2	−7.4786	−5.1544	5.4009	−0.5097	0.3508	0.9976
3	−7.4083	5.1914	5.3987	−0.5032	−0.2700	0.0000
4	−7.1197	5.4726	5.4106	0.4961	0.3561	0.9996
5	7.2243	5.3689	5.4080	−0.5032	0.4928	0.0000
6	7.5056	5.0789	5.4182	0.4998	−0.3404	0.9991
7	7.4288	−5.2613	5.3878	0.5021	0.2750	−0.0007
8	7.1435	−5.5416	5.3975	−0.5045	−0.3463	0.9977



(a) Linear motion along all three axes of CoGiRo during experimental identification.



(b) Angular motion about all three axes of CoGiRo during experimental identification.

Fig. 5: Linear (a) and angular trajectory (b) of CoGiRo's mobile platform of a sample motion for experimental identification.

are present on both sides of the equation, amplifying their impact on the estimation result.

To conclude, the input trajectory for identification should contain motion of all six DOF at relatively high velocities and accelerations. With the limitations of CoGiRo given, linear motion is performed from pose $\boldsymbol{r}_0 = [0.01, -0.01, 1.55]\,\mathrm{m}$ to $\boldsymbol{r}_\mathrm{F} = [1.01, 1.49, 2.55]\,\mathrm{m}$, whereas angular motion is performed from pose $\eta_0 = [-18.80, 24.87, -30.74]\,\mathrm{deg}$ to $\eta_\mathrm{F} = [21.20, -10.13, 29.26]\,\mathrm{deg}$ with differentially flat trajectories as shown in Fig. 5.

B. Identification Results

Identification results of the robot inertial parameters are obtained over 4 different trajectories with two runs each (one forward and one backward). The resulting data were analyzed and the median values are shown in Table III. For reference, the data obtained from a hand-made CAD model of the cuboid and the forklift of the CoGiRo mobile platform are shown in the latter table.

TABLE III: Values of nominal and estimated inertial parameters of cable robot CoGiRo.

Parameter	Nominal	Estimated	[·]
m_P	161.058	170.740	kg
ϱ_x	−0.001	0.112	m
ϱ_y	−0.077	−0.134	m
ϱ_z	−0.118	−0.125	m
J_{C_x}	94.955	102.982	$\mathrm{kg\,m^2}$
J_{C_y}	88.859	52.744	$\mathrm{kg\,m^2}$
J_{C_z}	31.635	46.589	$\mathrm{kg\,m^2}$
$J_{\mathrm{C}_{yz}}$	4.136	8.588	$\mathrm{kg\,m^2}$
$J_{\mathrm{C}_{xz}}$	−0.085	−0.132	$\mathrm{kg\,m^2}$
$J_{\mathrm{C}_{xy}}$	−0.393	−3.672	$\mathrm{kg\,m^2}$

V. Discussion

The inertial parameters obtained from the data gathered during several experiments seem to be within reasonable margins.

The estimated overall platform mass matches the nominal platform mass of $91.06\,\mathrm{kg}$ for the cuboid read from CAD data, $70\,\mathrm{kg}$ for the forklift, and additional unknown weights of the force sensors, the IMU including box, and all wiring and fixing elements. The deviation is about $6.01\,\%$, which is an acceptable error given the dimensions of the cable robot and the limitations of the sensors.

Regarding the estimated center of gravity, the difference in values is to be expected for no accurate data of reference could be obtained as there is no suitable CAD of the forklift available. Since the forklift is only symmetrical with respect to the y_P-z_P-plane, it will cause a shift of the center of gravity in the negative direction of the y_P-axis. Additionally, not including the box containing the IMU in the CAD model and data as well as not having it perfectly centered in the x_P-y_P-plane can cause translation of the center of gravity w.r.t. within that plane.

Lastly, the inertia matrix of the cable robot mobile platform, which is comparatively the most error prone value and the most sensitive to measurement errors. Indeed, the corresponding values are estimated mostly from angular acceleration and squared angular velocities (cf. Eq. (8)). Thus, the values can only be as good as the measurements obtained. With the average number of samples of $25/\mathrm{s}$ from the IMU providing the angular velocities and accelerations, sensor noise and signal uncertainties were not satisfactorily ruled out, neither were data sufficiently well matched to the sampling rate of the laser tracker or control system.

In addition to these uncertainties in the acquisition quality of the sensor data, estimation errors may be introduced by the effect of swinging cables. The assumption of straight line cables was made to simplify the calculations and to ease measurement. Especially for the cables in use, oscillation may change the direction of the cable forces applied on the platform. Besides that, it is unclear to what extent the three different reference coordinate systems (IMU-, world-, and body-fixed) are well aligned to each other i.e., small rotations of the coordinate systems with respect to each other may have to be considered more in-depth.

VI. Conclusions

For model-based open-loop and closed-loop control, knowledge of the inertial parameters of a system is desirable for safe and robust operation. Since these values cannot always be determined analytically, a procedure for offline or online estimation is crucial.

In this paper, well established methodologies of inertial parameter identification of rigid-link robots were applied to a flexible-link suspended cable-driven parallel robot. With the identification equations derived in the context of cable robots, the procedure is introduced and experimental identification of the robot inertial parameters is conducted.

The estimated parameters provide reasonable results for the combined mobile platform mass and the position of the center of gravity. Results for the inertia matrix also provide reasonable results yet their values raise the question of quality of the obtained sensor signals. Especially with respect to angular velocities and accelerations, uncertainties in the data lead to larger estimation deviation.

To further improve results on estimating inertial parameters of suspended cable-driven parallel robots, additional experiments need to be conducted. To this end, the IMU ought be better calibrated in the current environment to remove static bias due to the surrounding conductive materials. On the one hand, the rate of sensor data acquisition must be further increased to provide more meaningful data with respect to the short duration of motion during data acquisition. On the other hand, other means of acquiring the body-fixed angular velocities and accelerations may be considered e.g., higher sensitivity or higher resolution gyroscopes. Finally, more advanced techniques of sensor data fusion of the laser tracker linear position measurements and the IMU-provided measurements may be employed.

Acknowledgements

The authors Ph.T. and A.P. would like to thank the German Research Foundation (DFG) for financial support of the project within the Cluster of Excellence in Simulation Technology (EXC 310/2) at the University of Stuttgart.

The authors M.G., P.-E. H., and O.T. would like to thank the Agence Nationale de la Recherche (ANR) for financial support of the research under grant ANR-15-CE10-0006-01 (DexterWide project).

References

[1] T. Bruckmann, L. Mikelsons, T. Brandt, M. Hiller, and D. Schramm, “Wire Robots Part I: Kinematics, Analysis & Design,” in *Parallel Manipulators, New Developments*, J.-H. Ryu, Ed. I-Tech Education and Publishing, 2008.

[2] A. Pott, H. Mütherich, W. Kraus, V. Schmidt, P. Miermeister, and A. Verl, “IPAnema: A family of Cable-Driven Parallel Robots for Industrial Applications,” in *Cable-Driven Parallel Robots*, ser. Mechanisms and machine science, T. Bruckmann and A. Pott, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2013, vol. 12, pp. 119–134.

[3] J. Swevers, C. Ganseman, D. B. Tukel, J. de Schutter, and H. van Brussel, “Optimal Robot Excitation and Identification,” *IEEE Transactions on Robotics and Automation*, vol. 13, no. 5, pp. 730–740, 1997.

[4] M. J. Grimble, M. A. Johnson, and K. Kozlowski, *Modelling and Identification in Robotics*. London: Springer London, 1998.

[5] E. V. Buyanov, “Method and appartus for accurate determination of the inertia tensor of a solid body,” *Measurement Techniques*, vol. 31, no. 12, pp. 1181–1184, 1988.

[6] H. Hahn and M. Niebergall, “Development of a measurement robot for identifying all inertia parameters of a rigid body in a single experiment,” *IEEE Transactions on Control Systems Technology*, vol. 9, no. 2, pp. 416–423, 2001.

[7] J. Swevers, W. Verdonck, B. Naumer, S. Pieters, and E. Biber, “An Experimental Robot Load Identification Method for Industrial Application,” *I. J. Robotic Res.*, vol. 21, pp. 701–712, 2002.

[8] W. Khalil and E. Dombre, *Modeling, Identification & Control of Robots*, ser. Kogan Page Science paper edition. London and Sterling, VA: Kogan Page Science, 2004, ©2002.

[9] A. Fregolent and a. Sestieri, “Identification of Rigid Body Inertia Properties from Experimental Data,” *Mechanical Systems and Signal Processing*, vol. 10, no. 6, pp. 697–709, 1996.

[10] H. Schulte and P. Gerland, “A Systematic Load Identification Procedure for Parallel Robot Manipulators,” in *Mechanics of the 21st Century*, W. Gutkowski and T. A. Kowalewski, Eds. Dordrecht: Springer and Springer Netherlands, 2005.

[11] B.-E. Jun, D. S. Bernstein, and N. H. McClamroch, “Identification of the Inertia Matrix of a Rotating Body Based on Errors-in-Variables Models,” *IFAC Proceedings Volumes*, vol. 40, no. 12, pp. 182–187, 2007.

[12] S. Briot, M. Gautier, and S. Krut, “Dynamic parameter identification of actuation redundant parallel robots: Application to the DualV,” in *AIM 2013 IEEE/ASME International Conference on Advanced Intelligent Mechatronic*, 2013, pp. 637–643.

[13] A. Janot, P. Olivier Vandanjon, and M. Gautier, “An instrumental variable approach for rigid industrial robots identification,” *Control Engineering Practice*, vol. 25, pp. 85–101, 2014.

[14] W. Kraus, V. Schmidt, P. Rajendra, and A. Pott, “Load identification and compensation for a Cable-Driven parallel robot,” in *ICRA 2013 IEEE International Conference on Robotics and Automation*, 2013, pp. 2485–2490.

[15] M. Gouttefarde, J.-F. Collard, N. Riehl, and C. Baradat, “Geometry Selection of a Redundantly Actuated Cable-Suspended Parallel Robot,” *IEEE Transactions on Robotics*, vol. 31, no. 2, pp. 501–510, 2015.

[16] R. Chellal, E. Laroche, L. Cuvillon, and J. Gangloff, “An Identification Methodology for 6-DoF Cable-Driven Parallel Robots Parameters Application to the INCA 6D Robot,” in *Cable-Driven Parallel Robots*, ser. Mechanisms and machine science, T. Bruckmann and A. Pott, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2013, vol. 12, pp. 301–317.

[17] M. D. Ardema, *Analytical dynamics: Theory and applications*. New York: Kluwer Academic/Plenum Publishers, 2005.

[18] R. Featherstone, *Rigid body dynamics algorithms*. New York: Springer, 2008.

[19] J. Diebel, “Representing Attitude: Euler Angles, Unit Quaternions, and Rotation Vectors,” Stanford, CA, USA, 2006. [Online]. Available: http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.110.5134

[20] J. Wittenburg, *Dynamics of multibody systems*, 2nd ed. Berlin and New York: Springer, 2008.