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Dynamic Parameter Identification for Cable-Driven Parallel Robots [★]

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Abstract. This paper presents an initial work of identifying the dynamic parameters for cable-driven parallel robot (CDPR), *CRAFT* with a rigorous protocol. An orbital trajectory of the platform is designed in order to get a pure translation movement of the platform. This trajectory evolves in a plane and allows the identification of four dynamic parameters, the mass of the platform and the first three moments along the three main axes. The identification results obtained respectively from the data from the experimental measurements of the moving platform, and from the experimental measurements treated with the application of a semi-implicit homogeneous differentiator, show that in spite of the complexity of *CRAFT* an identification of all its essential dynamic parameters is possible. Moreover, in the long term, an online identification of *CRAFT* during handling tasks is envisaged.

Keywords: Cable-Driven Parallel Robots · Inverse Dynamic Model · Dynamic Parameter Identification · Least-squares estimator · Semi-Implicit Euler Homogeneous Differentiator · Experiments

1 Introduction

The objective is to initiate a scientific approach in order to identify the essential dynamic parameters of a cable-driven parallel robot (CDPR). A CDPR consists of a moving-platform (*MP*) that is connected to a rigid frame by means of cables and actuators, the latter being generally mounted on the ground. These robots are very attractive for handling tasks [16] because of their low inertia, a higher

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payload to weight ratio and a large workspace compared to conventional manipulator robots with articulated rigid limbs. Their possible application fields can be industrial, or dedicated to search-and-rescue operations. To deal with various restrictions on cable tensions, cable elasticity, collisions and obstacle avoidance, over-actuation of the *MP* is actually a challenging scientific problem [5], [7].

The control of a CDPR is complex because, among other things, whatever its movement, the tension of its cables must always be positive. There are still open problems in the control of CDPRs. One key example of an open problem is that control design requires a consistent dynamic model with a relatively good knowledge of the dynamic parameters of the robot such as the terms of inertia, mass, and even friction at the level of the actuators, which manage the winding of the cables. Several contributions about identification of a robot cable exist. Kraus *et al.* [10] present an identification method for the complete actuator of a cable robot. A second-order system is established with a dead time as an analogous model. An inverse dynamic method (IDM) is used to identify the model parameters of a cable-driven finger joint for surgical robot [18]. But To our best knowledge the identification parameters of the handling platform of a cable robot during a movement in space is not currently investigated.

A CDPR, named *CRAFT* and located at LS2N, Centrale Nantes campus, is equipped with eight actuators and a *MP*. Each motor has an encoder sensor measuring the angular velocity of its output shaft allowing to evaluate the performances of the differentiation solutions. The *MP* has six degrees of freedom. This *MP* is thus over-actuated [14].

The identification of the parameters of a robot is essential to evaluate its behavior in simulation or to synthesize a control based model. The objective of the identification is not to find physical parameters of a mechanism such as a robot, whose value is the most exact possible but to provide a modeling tool that is consistent in order to make simulation, control or other. The identification methodology is usually based on an inverse dynamic model that is linear in the dynamic parameters to be identified [2], [8], or [1]. Any matrix inversion, which is generally a generator of numerical problems, is thus avoided. However the identification of dynamic parameters is not easy when the dynamic model is complex. Among the many challenges is the search for exciting trajectories that identify the largest number of dynamic parameters and overcome noise problems [9]. However the identification of dynamic parameters is not easy when the dynamic model is complex. The dynamic behavior of the *CRAFT* that moves in 3D space with rotation and translation combinations effectively requires a complex modeling with a lot of inertial parameters. In addition, one or more cables may slacken unexpectedly. As a consequence to initiate an identification work, only the model of the platform maneuvered by the cables is considered. Moreover, the defined trajectories generate only translation movements of the platform, *i.e.* without any rotational movement of the platform with respect to itself, in a horizontal plane. The model to describe the dynamic behavior of *CRAFT* becomes simpler with only four dynamic parameters to identify. To manage the noise problems semi-implicit Euler homogeneous differentiators are

proposed (see e.g. [11] for a comparison of the techniques) and [13]. Off-line identification was conducted in order to compare, respectively from the planned trajectories of the platform, the measured filtered signals and their usual Euler discretization, and measured signals processed with an original semi-implicit homogeneous differentiators without extra filter. The main advantage of this differentiator is to offer the perspective of a real-time identification of dynamic parameters of *CRAFT*. The contribution of this work is based on three parts: Elaboration of a protocol in order to work with a dynamic model for translational movements of the platform and to have only four parameters to identify and experimental definition of this movement; Identification of the four parameters starting respectively from the reference trajectory, the tension measurement of the cable tension, the position measurement and the application of the usual Euler discretization to obtain the speed and acceleration signals. Furthermore these speed and acceleration signals are compared with those obtained an original semi-implicit Euler homogeneous differentiator. The long-term idea of this work is to develop a complete framework that brings together numerical identification and derivation tools to identify the dynamic parameters of the on-line *CRAFT* as it performs handling tasks. The remaining of the paper is outlined as follows. Section 3 is devoted to the presentation of *CRAFT* namely, its geometric, kinematic, dynamic model and its adaptation to the presented strategy. The identification methodology, which is based on the least-squares (*LS*) estimator is presented in Sec. 4, with the solving way. A semi-implicit homogeneous differentiator, which is considered in this study to get the velocities and the accelerations from the measured position, is presented Sec. 5. The experimental results are presented in Sec. 6. Conclusions and future work are offered in Sec. 7.

2 Robot *CRAFT*

The cable-driven parallel robot prototype, named *CRAFT* is located at LS2N, France. The base frame of *CRAFT* is 4 m long, 3.5 m wide, and 2.7 m high, see Figure 1). The three-DoF translational and the three-DoF rotational motions of its suspended *MP* are controlled with eight cables being respectively wound around eight actuated reels fixed to the ground. The *MP* is 0.28 m long, 0.28 m wide, and 0.2 m high, its overall mass being equal to 5 kg. For each of the eight electrical motors an encoder sensor measures the angular variable of its shaft. The eight motors are equipped with a gearbox reducer of ratio $n = 8$. The measured value is divided by n in order to obtain the angular position of the output shaft of the gearbox reducer. The robot *CRAFT* has no tachometer.

The main hardware of the prototype consists of a PC (equipped with © MATLAB and © ControlDesk software), eight © PARKER SME60 motors and TPD-M drivers, a © dSPACE DS1007-based real-time controller and eight custom made winches. Each cable can exert a tension up to 150 N to the *MP*. The maximum velocity of each cable is equal to 5.9 m/s. The cable tensions are measured using eight *FUTEK FSH04097* sensors, one for each cable, attached to cable anchor points. Their signal is amplified using eight *FSH03863* voltage amplifiers and sent

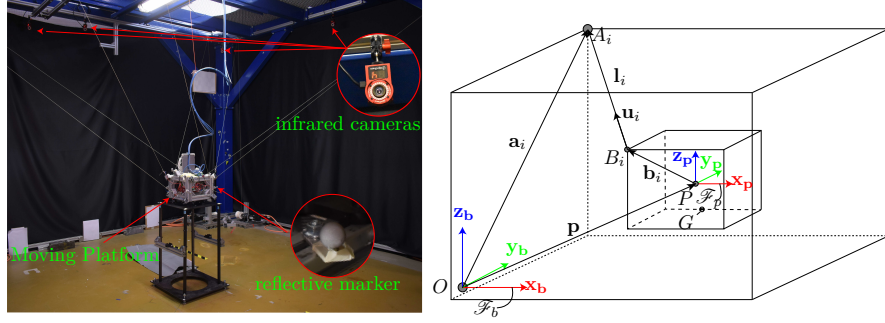


Fig. 1: (left) *CRAFT* prototype located at LS2N, Nantes, France and (right) *CRAFT* Geometric Parametrization.

to the robot controller by a coaxial cable. *CRAFT* is equipped with a motion capture, *OptiTrack* that the sampling period is equal to 0.01 s.

3 Robot Modeling

Figure 1 depicts the main geometric parameters of *CRAFT* and the i^{th} cable where $i \in \{1, \dots, m\}$, m being the number of cables attached to the n Degree-of-freedom (DoF) *MP* (for *CRAFT*, $m = 8$ and $n = 6$). The dynamic equilibrium wrench equation can be expressed as:

$$\mathbf{W}\boldsymbol{\tau} - \mathbb{I}_p\ddot{\mathbf{p}} - \mathbf{C}\dot{\mathbf{p}} + \mathbf{w}_g = \mathbf{0}_m \quad (1)$$

with \mathbf{W} being the robot wrench matrix expressed as:

$$\mathbf{W} = \begin{bmatrix} \mathbf{u}_1 & \dots & \mathbf{u}_i & \dots & \mathbf{u}_m \\ \mathbf{b}_1 \times \mathbf{u}_1 & \dots & \mathbf{b}_i \times \mathbf{u}_i & \dots & \mathbf{b}_m \times \mathbf{u}_m \end{bmatrix} \quad (2)$$

where \mathbf{u}_i is the unit vector of the i^{th} cable vector pointing from cable anchor points B_i to exit points A_i , expressed in the reference frame \mathcal{F}_b . Vector \mathbf{b}_i pointing from point P to point B_i and is expressed in the platform frame \mathcal{F}_p . From Eq. (1), $\boldsymbol{\tau} = [\tau_1, \dots, \tau_i, \dots, \tau_m]$ is the cable tension vector, \mathbb{I}_p is the inertia tensor, \mathbf{C} is the Coriolis matrix and \mathbf{w}_g is the gravity wrench. $\dot{\mathbf{p}} = [\dot{\mathbf{t}}, \boldsymbol{\omega}]^T$ and $\ddot{\mathbf{p}} = [\ddot{\mathbf{t}}, \boldsymbol{\alpha}]^T$ are the vectors of the *MP* velocity and acceleration, where, $\dot{\mathbf{t}} = [\dot{t}_x, \dot{t}_y, \dot{t}_z]^T$ and $\ddot{\mathbf{t}} = [\ddot{t}_x, \ddot{t}_y, \ddot{t}_z]^T$ are the vectors of the *MP* linear velocity and acceleration, while $\boldsymbol{\omega} = [\omega_x, \omega_y, \omega_z]^T$ and $\boldsymbol{\alpha} = [\alpha_x, \alpha_y, \alpha_z]^T$ are the vectors of the *MP* angular velocity and angular acceleration, respectively. The gravity wrench is:

$$\mathbf{w}_g = m \begin{bmatrix} \mathbf{I}_3 \\ {}^b\mathbf{R}_p \hat{\mathbf{S}}_G \end{bmatrix} \mathbf{g} \quad (3)$$

m is the *MP* mass, \mathbf{I}_3 is the 3×3 identity matrix, ${}^b\mathbf{R}_p$ is the rotation matrix of the *MP* \mathcal{F}_p frame w.r.t the base frame \mathcal{F}_b , $\hat{\mathbf{S}}_G$ is the skew-symmetric matrix

associated to $\mathbf{s}_G = [x_G, y_G, z_G]^\top$ which represents the coordinate vector of the center of mass of the *MP* expressed in \mathcal{F}_p as:

$$\hat{\mathbf{S}}_G = \begin{bmatrix} 0 & -z_G & y_G \\ z_G & 0 & -x_G \\ -y_G & x_G & 0 \end{bmatrix} \quad (4)$$

$m {}^b\mathbf{R}_p \hat{\mathbf{S}}_G$ represents the first momentum of the *MP* defined with respect to base frame \mathcal{F}_b . $\mathbf{g} = [0, 0, -g]$ is the gravity acceleration vector where $g = 9.81 \text{ m s}^{-2}$. The matrix \mathbb{I}_p in Eq. (1) can be expressed as:

$$\mathbb{I}_p = \begin{bmatrix} m \mathbf{I}_3 & -m {}^b\mathbf{R}_p \hat{\mathbf{S}}_G \\ m {}^b\mathbf{R}_p \hat{\mathbf{S}}_G & \mathbf{I}_p \end{bmatrix} \quad (5)$$

with \mathbf{I}_p being the *MP* inertia tensor expressed in \mathcal{F}_p . The term \mathbf{C} , which represents the centrifugal and Coriolis effects in Eq. (1) is expressed as:

$$\mathbf{C} = \begin{bmatrix} \mathbf{0}_3 & -m \hat{\boldsymbol{\omega}} \hat{\mathbf{S}}_G \\ \mathbf{0}_3 & \hat{\boldsymbol{\omega}} \mathbf{I}_p \end{bmatrix} \quad (6)$$

Using Eqs. (3), (5), and (6) in Eq. (1), gives:

$$\begin{bmatrix} m \mathbf{I}_3 & -m {}^b\mathbf{R}_p \hat{\mathbf{S}}_G \\ m {}^b\mathbf{R}_p \hat{\mathbf{S}}_G & \mathbf{I}_p \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{t}} \\ \boldsymbol{\alpha} \end{bmatrix} + \begin{bmatrix} \mathbf{0}_3 & -m \hat{\boldsymbol{\omega}} \hat{\mathbf{S}}_G \\ \mathbf{0}_3 & \hat{\boldsymbol{\omega}} \mathbf{I}_p \end{bmatrix} \begin{bmatrix} \dot{\mathbf{t}} \\ \boldsymbol{\omega} \end{bmatrix} - m \begin{bmatrix} \mathbf{I}_3 \\ {}^b\mathbf{R}_p \hat{\mathbf{S}}_G \end{bmatrix} \mathbf{g} = \mathbf{W} \boldsymbol{\tau} \quad (7)$$

As a first step of the identification, in this article, we will only consider platform translations, i.e., the platform does not rotate in relation to itself. Hence, the angular velocities and accelerations of the MP in Eq. (7) vanish and is reduced to:

$$\begin{bmatrix} m \mathbf{I}_3 \\ m {}^b\mathbf{R}_p \hat{\mathbf{S}}_G \end{bmatrix} \ddot{\mathbf{t}} - \begin{bmatrix} m \mathbf{I}_3 \\ m {}^b\mathbf{R}_p \hat{\mathbf{S}}_G \end{bmatrix} \mathbf{g} = \mathbf{W} \boldsymbol{\tau} \quad (8)$$

As the platform orientation is always constant, we can consider ${}^b\mathbf{R}_p = \mathbf{I}_3$. Eq. (8) can be expressed as in the form as:

$$\mathbf{A} \mathbf{x} = \mathbf{b} \quad (9)$$

where,

$$\mathbf{A} = \begin{bmatrix} \ddot{t}_x & 0 & 0 & 0 \\ \ddot{t}_y & 0 & 0 & 0 \\ \ddot{t}_z + g & 0 & 0 & 0 \\ 0 & 0 & \ddot{t}_z + g - \ddot{t}_y & 0 \\ 0 & -\ddot{t}_z - g & 0 & \ddot{t}_x \\ 0 & \ddot{t}_y & -\ddot{t}_x & 0 \end{bmatrix}, \quad \mathbf{x} = \begin{bmatrix} m \\ mx_G \\ my_G \\ mz_G \end{bmatrix}, \quad \mathbf{b} = \mathbf{W} \boldsymbol{\tau} \quad (10)$$

In Eq. (10), we need the linear acceleration of the *MP* $\ddot{\mathbf{t}}$ and the cable tensions $\boldsymbol{\tau}$. As the robot is already equipped with the cable tension sensors so we can directly acquire $\boldsymbol{\tau}$.

4 Identification Methodology

The identification methodology is based on the used of the inverse dynamic model (*ID*) Eq. (9), [2], [3], [1]. This model is linear as function of the four parameters m , mx_G , my_G , and mz_G . An off-line identification of these parameters is then considered, given measured or estimated off-line data for the linear acceleration of the *MP* $\ddot{\mathbf{t}}$ and the cable tensions $\boldsymbol{\tau}$, collected while the robot *CRAFT* is tracking a planned trajectory. The model Eq. (9) is sampled at a sufficient number of time samples t_i , for $i = 1, \dots, n_e$, with $(6n_e) \gg 4$, in order to get an over-determined linear system of $(6n_e)$ equations [1]:

$$\mathcal{Y}_{ID}(\boldsymbol{\tau}) = \mathcal{W}_{ID}\mathbf{x} + \rho \quad (11)$$

where

$$\mathcal{Y}_{ID}(\boldsymbol{\tau}) = \begin{pmatrix} b_1(6 \times 1) \\ \vdots \\ b_{n_e}(6 \times 1) \end{pmatrix}; \quad \mathcal{W}_{ID} = \begin{pmatrix} A_1(6 \times 4) \\ \vdots \\ A_{n_e}(6 \times 4) \end{pmatrix}, \quad (12)$$

ρ is the $(6n_e \times 1)$ vector of errors between the data of the measurement of the torques in $\mathcal{Y}_{ID}(6n_e \times 1)$ and the data $\mathcal{W}_{ID}(6n_e \times 4)$ predicted by the model. These errors are due to noise measurement and modelling error. The identification problem consists in finding \mathbf{x} the norm squared of the error ρ :

$$\|\rho\|^2 = \|\mathcal{Y}_{ID} - \mathcal{W}_{ID}\mathbf{x}\|^2 \quad (13)$$

The *LS* estimator models a process by fitting the parameter vector \mathbf{x} according to the minimisation of Eq. (13). Then model (14) becomes

$$\mathcal{Y}_{ID}(\boldsymbol{\tau}) = \mathcal{W}_{ID}\hat{\mathbf{x}} + \hat{\rho} \quad (14)$$

The estimated parameter $\hat{\mathbf{x}}$ is equal to:

$$\hat{\mathbf{x}} = \mathcal{W}_{ID}^+ \mathcal{Y}_{ID} \quad (15)$$

where \mathcal{W}_{ID}^+ is the pseudo-inverse of \mathcal{W}_{ID} . Since $6n_e > 4$ then $\mathcal{W}_{ID}^+ = (\mathcal{W}_{ID}^\top \mathcal{W}_{ID})^{-1} \mathcal{W}_{ID}^\top$. $\hat{\mathbf{x}}$ is the unique *LS* solution of Eq. (15). The standard deviation $\sigma_{\hat{\mathbf{x}}}$ is estimated assuming that \mathcal{W}_{ID} is a deterministic matrix and ρ is a zero-mean additive independent Gaussian noise, with a covariance matrix $C_{\rho\rho}$

$$C_{\rho\rho} = E(\rho\rho^\top) = \sigma_\rho^2 \mathbf{I} \quad (16)$$

E is the expectation operator and $\mathbf{I}(6n_e \times 6n_e)$ is the identity matrix. By replacing \mathcal{Y}_{ID} in Eq. (15) with its definition Eq. (14) we obtain:

$$\hat{\mathbf{x}} = \mathbf{x} + \mathcal{W}_{ID}^+ \rho \quad (17)$$

Applying the expectation operator at both sides of Eq. (17) ρ being a zero-mean additive independent Gaussian noise we get:

$$E(\hat{\mathbf{x}}) = E(\mathbf{x}) \quad (18)$$

Thus the estimated values are unbiased. An unbiased estimation of the standard deviation σ_ρ is:

$$\hat{\sigma}_\rho^2 = \frac{\|\mathcal{Y}_{ID} - \mathcal{W}_{ID}\hat{\mathbf{x}}\|^2}{(6n_e - 4)} \quad (19)$$

\mathcal{W}_{ID} and being respectively a non-stochastic matrix and a stochastic matrix, the covariance matrix of the *LS* estimation error is then given by:

$$C_{\mathbf{xx}} = E(\mathbf{x} - \hat{\mathbf{x}}^\top) = (\mathcal{W}_{ID}^\top \mathcal{W}_{ID})^{-1} \mathcal{W}_{ID}^\top \sigma_\rho^2 \mathbf{I} \mathcal{W}_{ID} (\mathcal{W}_{ID}^\top \mathcal{W}_{ID})^{-1} = \hat{\sigma}_\rho^2 (\mathcal{W}_{ID}^\top \mathcal{W}_{ID})^{-1} \quad (20)$$

$\hat{\sigma}_{\mathbf{x}_i}^2 = C_{\mathbf{xx}}(i, i)$ is the i^{th} diagonal coefficient of $C_{\mathbf{xx}}$. The relative standard deviation $\% \hat{\sigma}_{\mathbf{x}_i}$ for each identified parameters is given by:

$$\% \hat{\sigma}_{\mathbf{x}_i} = \frac{\hat{\sigma}_{\mathbf{x}_i}}{|\hat{x}_i|} \quad (21)$$

The calculation of Eq. (14) and the condition number of \mathcal{W}_{ID} can be obtained using the singular value decomposition (SVD) of \mathcal{W}_{ID} .

5 Semi-implicit Homogeneous differentiator

The purpose is to estimate the velocity of the angular variable exclusively from the measured position of the output shaft for each of the eight motors. To estimate the velocity let us introduce the continuous-time state:

$$\Sigma : \begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = p(t) \\ y = x_1 \end{cases} \quad (22)$$

where x_1 and x_2 are respectively the angular variable and its velocity; y is the measure of x_1 with additional noise η . Here $p(t)$ is a bounded perturbation, which is unknown and assumed to be a constant parameter or a slowly variable. This implies that for a sufficient small sampling-time $h > 0$, $p \equiv p^+$, with the notation for a discretized variable: $\bullet(t = (k+1)h) = \bullet^+$ and $\bullet(t = kh) = \bullet$. Homogeneity approach is interesting because if a local stability is obtained due to the dilatation, this framework allows extending this local property to global settings, [17]. This differentiator can be written such as [15], [4],

$$\begin{cases} \dot{z}_1 = z_2 + \lambda_1 \mu [\epsilon_1]^\alpha \\ \dot{z}_2 = \lambda_2 \mu^2 [\epsilon_1]^{2\alpha-1} \\ \hat{y} = z_1 \end{cases} \quad (23)$$

where $\alpha \in]0.5 \ 1[$ has to be fixed [6], $\epsilon_1 = y - z_1$, and the notation $[\bullet]^\alpha = |\bullet|^\alpha \text{sgn}(\bullet)$ is adopted along the paper. The degree of homogeneity of the differentiator (23) d is equal to $\alpha - 1$ with respect to dilatation Λ_r with $r = (r_1 = 1, r_2 = 1)$ [15]. Moreover, $\lambda_i > 0$, $i = 1, 2$ are the linear part gains, which are

considered and allow to have the eigenvalues of the differentiation error ϵ_1 sufficiently stables, while the coefficient μ is chosen sufficiently large to cancel the effect of the unknown perturbation $p(t)$.

The discretization of the differentiator (23) is based on the so-called implicit projection that acts as corrective terms and aim to "generalize" the sign function in sliding-based differentiator in order to reduce the chattering and preserve stability properties for high time steps). Two projectors \mathcal{N}_1 and \mathcal{N}_2 are used respectively to design the correction terms with the differentiator SIHD-2. In [12], it has been highlighted that the SIHD-2 algorithm offers better performances than with only one projector since the projectors \mathcal{N}_1 and \mathcal{N}_2 are respectively dedicated to the estimation of z_1 and z_2 . Considering the signal to differentiate y , the error $\epsilon_1 = y - z_1^+$, and the definition of the notation $\lceil \epsilon_1^+ \rceil \equiv |\epsilon_1| \text{sign}(\epsilon_1^+)$, As a result, the semi-implicit homogeneous Euler discretization based on two projectors (SIHD-2) reads as:

$$\begin{cases} z_1^+ = z_1 + h(z_2^+ + \lambda_1 \mu |\epsilon_1|^{\alpha_d} \mathcal{N}_1) \\ z_2^+ = z_2 + E_1^+ h \lambda_2 \mu^2 |\epsilon_1|^{2\alpha_d-1} \mathcal{N}_2. \end{cases} \quad (24)$$

The projector \mathcal{N}_1 , and \mathcal{N}_2 are defined:

$$\mathcal{N}_1(\epsilon_1) := \begin{cases} \epsilon_1 \in SD \rightarrow \mathcal{N}_1 = \frac{\lceil \epsilon_1 \rceil^{1-\alpha_d}}{\lambda_1 \mu h}, & E_1^+ = 1 \\ \epsilon_1 \notin SD \rightarrow \mathcal{N}_1 = \text{sign}(\epsilon_1), & E_1^+ = 0, \end{cases} \quad (25)$$

with the domain of attraction $SD = \{\epsilon_1 / |\epsilon_1| \leq (\lambda_1 \mu h)^{\frac{1}{1-\alpha_d}}\}$.

$$\mathcal{N}_2(\epsilon_1) := \begin{cases} \epsilon_1 \in SD' \rightarrow \mathcal{N}_2 = \frac{\lceil \epsilon_1 \rceil^{2(1-\alpha_d)}}{\lambda_2 h^2 \mu^2} \\ \epsilon_1 \notin SD' \rightarrow \mathcal{N}_2 = \text{sign}(\epsilon_1), \end{cases} \quad (26)$$

where $SD' = \{\epsilon_1 \in SD / |\epsilon_1| \leq (\lambda_1 \mu^2 h^2)^{\frac{1}{2(1-\alpha_d)}} \equiv |\epsilon_2| \leq (\lambda_1 \mu^2)^{\frac{1}{2(1-\alpha_d)}} h^{\frac{\alpha_d}{1-\alpha_d}}\}$. The filtering properties of the differentiator avoid using an extra filter before the differentiation, and the cascade offers the possibility of adjusting the homogeneous parameter α_d with some flexibility. The measured angular positions are noisy such as y becomes $y_m = x_1 + \eta$. The λ_i , $i = 1, 2$ parameters are chosen such as the linear part is stable. The value of homogeneous exponent α_d is chosen to allow better filtering properties of the estimated differentiation. The μ parameter is also chosen by numerical test trial and error in order to determine the best possible action of both projectors \mathcal{N}_1 and \mathcal{N}_2 . The numerical values of these five parameters are tuned as follows:

$$\lambda_1 = 210, \lambda_2 = 210, \lambda_3 = 525, \lambda_4 = 525, \alpha_d = 0.95, \mu = 1. \quad (27)$$

6 Experiments

The platform performs four orbital movements. A video of these movements is available at ³. A sampling period of 10 ms is used to measure the position

³ <https://youtu.be/I-IOcAGha3o>

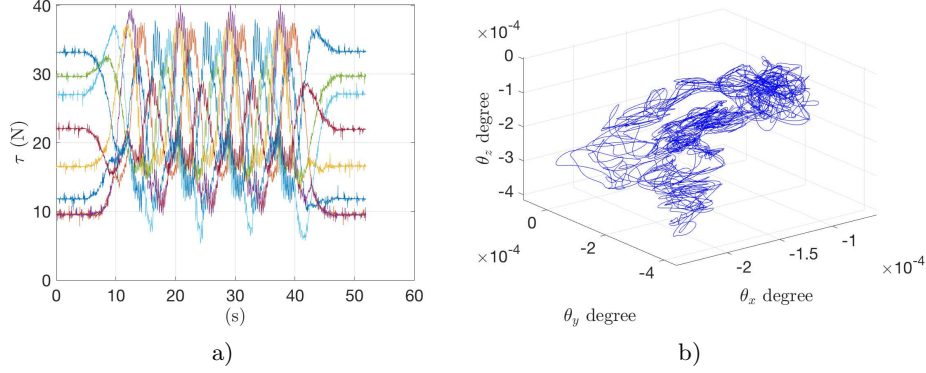


Fig. 2: a) Cable tensions τ as function of time, b) Orientation of the mobile platform.

vector \mathbf{t} and the cable tension τ with the *FUTEK FSH04097* sensors. The eight measured cable tensions are plotted Fig. 2 a). The Euler angles of the platform during its motion are shown in Fig. 2 b). This motion of the platform is indeed translational as it is predicted by the trajectory planning. The identification of the parameters m , mx_G , my_G , and mz_G needs the linear acceleration vector of the *MP* $\ddot{\mathbf{t}}$. For the best knowledge of this acceleration vector a comparison is made from the measured platform position \mathbf{t} between the estimation of the velocity vector $\dot{\mathbf{t}}$ and the acceleration vector $\ddot{\mathbf{t}}$ respectively thanks to the proposed SIHD-2 algorithm and the estimation of these vectors thanks the usual Euler discretization method. With the usual Euler discretization method the numerical tests shows that the estimation of $\dot{\mathbf{t}}$ and $\ddot{\mathbf{t}}$ requires filtering the position vector \mathbf{t} of the platform with a cutoff frequency of 4Hz. The filter applies a zero-phase forward and reverse digital infinite impulse response (*IIR*) filtering. Figure 3 shows the estimated velocity and acceleration vectors in 3D by using the SIHD-2 algorithm and the usual Euler discretization method. The curves are similar between the two algorithms. Table 1 gathers the four identified parameters. The standard deviations are not computed based on the standard deviation from the actual parameter values that are unknown. The numerical values obtained by the two methods for each identified parameter are very close to each other. However, having to filter the position measurement of the platform is a strong constraint in the perspective of doing real time identification of the dynamic parameters of *CRAFT*. That is why the SIHD-2 algorithm, which is iterative, is a relevant solution in the perspective of real time identification.

7 Discussion and Future Work

This research paper presents a novel methodology for identifying the dynamic parameters of Cable-Driven Parallel Robots (CDPRs). Initially, the focus is on

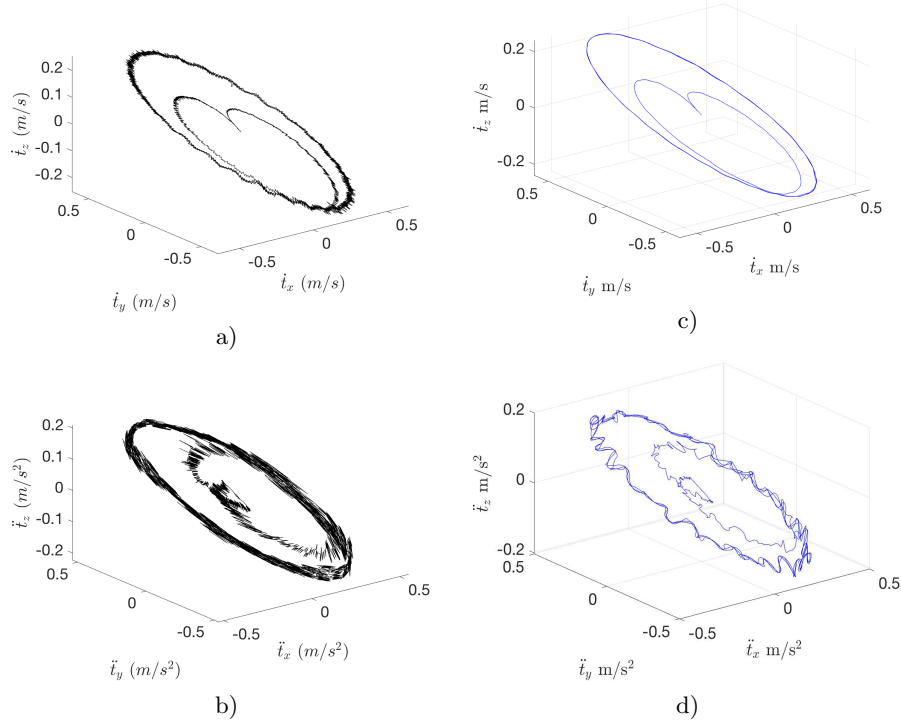


Fig. 3: $\dot{\mathbf{t}}$ and $\ddot{\mathbf{t}}$ along the orbital trajectory of the platform: velocity (a) and acceleration (b) with SIHD-2; velocity (c) and acceleration (d) with Euler discretization.

Table 1: Numerical values of the identified parameters

Identified parameters	differentiation SIHD-2			Euler discretization		
	$\hat{\mathbf{x}}_{\mathbf{i}}$	$\hat{\sigma}_{\mathbf{x}_{\mathbf{i}}}$	$\% \hat{\sigma}_{\mathbf{x}_{\mathbf{i}}}$	$\hat{\mathbf{x}}_{\mathbf{i}}$	$\hat{\sigma}_{\mathbf{x}_{\mathbf{i}}}$	$\% \hat{\sigma}_{\mathbf{x}_{\mathbf{i}}}$
m (kG)	9.88	0.0027	0.027	9.88	0.0027	0.027
$m x_G$ (kGm)	-0.064	0.0027	4.21	-0.064	0.0027	4.16
$m y_G$ (kGm)	0.019	0.0027	13.86	0.019	0.0027	13.65
$m z_G$ (kGm)	-1.059	0.070	6.67	-1.210	0.078	6.41

identifying four parameters, specifically the platform mass and the location of its center of mass, using an orbital trajectory that has been specifically designed to achieve pure platform translation movement in all the three xyz -plane. The trajectory, which occurs within a single plane, allows for the identification of these four dynamic parameters. The values determined by the identification of the inertial parameters are consistent with the actual platform mass (measured)

and the estimated center of mass location from the computer aided Design. The results have also been compared with other types of trajectories, such as point-to-point linear trajectories. The reason for choosing a circular trajectory is the availability of continuous platform accelerations which facilitates the use of the proposed methodology. The results obtained from experimental measurements of the platform position, as well as measurements treated with the application of a homogeneous semi-implicit differentiator, indicates that despite the complexity of the *CRAFT*, these results allow for the real-time identification of all the essential dynamic parameters.

In future work, the proposed approach will be used to identify the remaining six dynamic terms associated with the inertia tensor, specifically three terms associated with the platform moment of inertia and other three are products of inertia. To manage the future identification tasks, an IMU sensor will be used in order to provide acceleration measurements that are synchronized with those of the cable tensions. Additionally, we will also aim to identify the friction that acts throughout the actuators of *CRAFT*.

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