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► **To cite this version:**

Sébastien Briot, Maxime Gautier. Global Identification of Drive Gains and Dynamic Parameters of Parallel Robots - Part 2: Case Study. 19th CISM-IFToMM Symposium on Robot Design, Dynamics, and Control (ROMANSY 2012), Jun 2012, Paris, France. hal-00687697

**HAL Id: hal-00687697**

**<https://hal.science/hal-00687697v1>**

Submitted on 25 Jun 2019

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# Global Identification of Drive Gains and Dynamic Parameters of Parallel Robots - Part 2: Case Study

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**Abstract** Usually, identification models of parallel robots are simplified and take only the dynamics of the moving platform into account. Moreover the input efforts are estimated through the use of the manufacturer's actuator drive gains that are not calibrated thus leading to identification errors. In this paper a systematic way to derive the full dynamic identification model of the Orthoglide parallel robot in combination with a method that allows the identification of both robot inertial parameters and drive gains.

## 1 Introduction

Many modern robotic applications require high-performances (in terms of speed, accuracy, payload capability, etc.) that cannot be obtained without a good controller (Amiral et al., 1996; Vivas and Poignet, 2005). It appears that, for high-speed robots or when varying loads have to be compensated (e.g. in pick-and-place operations or machining), computed torque control is generally used (Khalil and Dombre, 2002). This approach needs a correct identification of the dynamic model of the robot with the load (Khalil et al., 2007).

Several papers deal with the identification of parallel robots (Honegger et al., 2000, 1997). These publications are restricted to very simple models, which take only the dynamics of the moving platform into account. Only few of them deal with the systematic computation of the full Inverse Dynamic Identification Model (IDIM). In (Guegan et al., 2003), the authors propose an attempt to create a systematic IDIM based on a Newton-Euler approach. The closed loops are first virtually opened to compute the dynamic model of

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\*This work has been partially funded by the French ANR project ARROW (ANR 2011 BS3 006 01).

the tree structure and then, the closure constraints are imposed. However, the way to open the loop is not straightforward. In (Grotjahn et al., 2004; Diaz-Rodriguez et al., 2010), the authors propose methods for computing the IDIM based on the Jourdain’s principle or Lagrange multipliers. But the way to identify the drive gains is not treated. Moreover, some jacobian matrices, whose computation is not straightforward, are not clearly derived.

This paper presents the application of a Total Least Square procedure for the identification of the inertial parameters (IDIM-TLS) of the Orthoglide (Chablat et al., 2004). It is the second part of our work on the identification of the parallel robots dynamic parameters and it uses the theoretical approach developed in (Briot and Gautier, 2012).

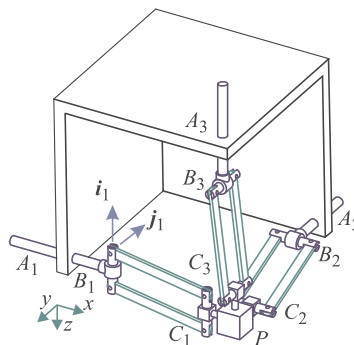
## 2 Modeling of the Orthoglide

### 2.1 Description of the architecture

The Orthoglide is a parallel robot with three translational degrees of freedom (dof) composed of three identical legs (Fig. 1). Each leg is achieved via one linearly actuated foot linked at its extremity to a spatial parallelogram (Fig. 2a). The parallelogram is also attached to the mobile platform.



(a) Prototype



(b) Kinematic chain

Figure 1: The Orthoglide robot.

The direction of the three linear actuators of the Orthoglide are orthogonal (Fig. 1b). This aims at creating a mechanism with a workspace shape close from a cube and whose behavior is close from the isotropy wherever it is located in its workspace.

For the remainder of the paper, it should be mentioned that the gravity field  $g$  is directed along the vector  $\mathbf{y}_0$  of Fig. 2c.

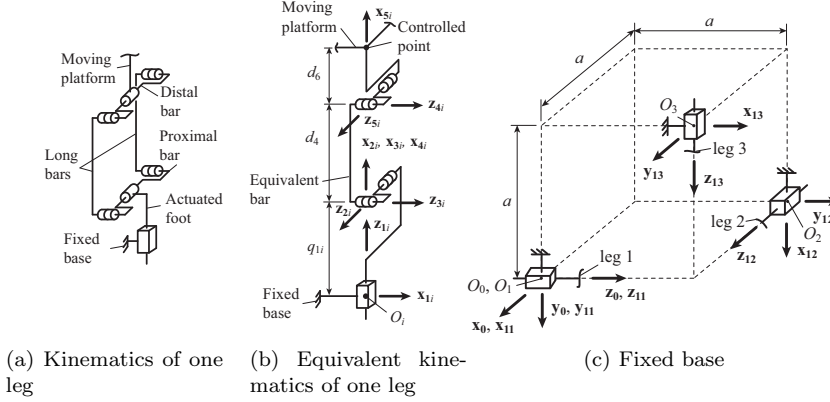


Figure 2: Kinematic chain description.

## 2.2 Dynamic modeling

For the dynamic modeling of the Orthoglide, as the bars of the parallelograms are parallel and as the prototype has been design so that they are identical, it is possible to replace the long bars by only one equivalent bar linked at each extremity by two orthogonal pivots (Fig. 2b) without loss of generality. Let us recall that the computation of the dynamic model is decomposed into two steps (Briot and Gautier, 2012):

1. All closed loops are virtually opened and the robot platform is virtually disassembled from the rest of the structure so that an open-loop tree structure is created;
2. The loops are then closed using the loop-closure equations and the Lagrange multipliers.

**Dynamic modeling of the virtual tree structure** Using the previous assumption, the Orthoglide kinematics necessary for computing the dynamic model are defined using the modified Denavit and Hartenberg notation (MDH) (Khalil and Dombre, 2002). The geometric parameters of the virtual open-loop tree structure are given in Tables 1 and 2. The MDH notation is well known, therefore the parameters of Tables 1 and 2 will not be defined here. For more information concerning the MDH parameters, the reader should refer to (Khalil and Dombre, 2002).

Using these MDH parameters, the dynamic model of the virtual tree structure that expresses the virtual input efforts  $\tau_{idm_t}$  of all joints as a linear function of the inertial parameters  $\chi_{st_t}$  can be automatically computed with

an algorithm based on the Newton-Euler approach (Khalil and Dombre, 2002; Khalil and Creusot, 1997):

$$\tau_{idm_t}(\mathbf{q}_t, \dot{\mathbf{q}}_t, \ddot{\mathbf{q}}_t) = \phi_{st_t}(\mathbf{q}_t, \dot{\mathbf{q}}_t, \ddot{\mathbf{q}}_t) \chi_{st_t} \quad (1)$$

where  $\mathbf{q}_t = [q_{11}, q_{21}, \dots, q_{53}]^T$  is the  $(15 \times 1)$  vector regrouping all joint variables.

Table 1: MDH parameters for the frames corresponding to the first body of each leg.

$j_i$	$a(j_i)$	$\mu_{j_i}$	$\sigma_{j_i}$	$\gamma_{j_i}$	$b_{j_i}$	$\alpha_{j_i}$	$d_{j_i}$	$\theta_{j_i}$	$r_{j_i}$
1 <sub>1</sub>	0	1	1	0	0	0	0	0	$q_{11}$
1 <sub>2</sub>	0	1	1	$\pi/2$	$a$	$\pi/2$	0	0	$q_{12} - a$
1 <sub>3</sub>	0	1	1	0	$a$	$-\pi/2$	0	$-\pi/2$	$q_{13} + a$

Table 2: MDH parameters for the frames corresponding to the leg  $i$ .

$j_i$	$a(j_i)$	$\mu_{j_i}$	$\sigma_{j_i}$	$\gamma_{j_i}$	$b_{j_i}$	$\alpha_{j_i}$	$d_{j_i}$	$\theta_{j_i}$	$r_{j_i}$
2 <sub><math>i</math></sub>	1 <sub><math>i</math></sub>	1	0	0	0	$-\pi/2$	0	$q_{2i}$	0
3 <sub><math>i</math></sub>	2 <sub><math>i</math></sub>	1	0	0	0	$-\pi/2$	0	$q_{3i}$	0
4 <sub><math>i</math></sub>	3 <sub><math>i</math></sub>	1	0	0	0	0	$d_4$	$q_{4i}$	0
5 <sub><math>i</math></sub>	4 <sub><math>i</math></sub>	1	0	0	0	$\pi/2$	0	$q_{5i}$	0

**Dynamic modeling of the actual robot** As proposed in (Briot and Gautier, 2012), the loop constraints can be taken into account by using the robot loop-closure equations (Merlet, 2006) and the Lagrange multipliers (Moon, 2007). The loop closure-equations of the Orthoglide can be expressed as

$$\mathbf{f}_t = [\mathbf{f}_{t_{11}}^T, \mathbf{f}_{t_{21}}^T, \mathbf{f}_{t_{12}}^T, \mathbf{f}_{t_{22}}^T, \mathbf{f}_{t_{13}}^T, \mathbf{f}_{t_{23}}^T]^T = \mathbf{0} \text{ with} \quad (2)$$

$$\mathbf{f}_{t_{1i}} = \begin{bmatrix} x \\ y \\ z \end{bmatrix} - \mathbf{R}_0^i \begin{bmatrix} d_4 \cos q_{2i} \cos q_{3i} + a\delta_i \\ -d_4 \sin q_{3i} + a\delta_{i+1} \\ q_{1i} - a\bar{\delta}_{i+2} - d_4 \sin q_{2i} \cos q_{3i} + d_6 \end{bmatrix}, \mathbf{f}_{t_{2i}} = \begin{bmatrix} q_{2i} \\ q_{3i} \end{bmatrix} + \begin{bmatrix} q_{5i} \\ q_{4i} \end{bmatrix},$$

$$\mathbf{f}_p = \begin{bmatrix} x^2 + y^2 + (z - q_{11} - d_6)^2 - d_4^2 \\ (x - q_{12} - d_6 + a)^2 + y^2 + (z - a)^2 - d_4^2 \\ x^2 + (y - q_{13} - d_6 + a)^2 + (z - a)^2 - d_4^2 \end{bmatrix} = \mathbf{0}, \quad (3)$$

where  $\mathbf{R}_0^i$  is the rotation matrix between the leg frame ( $O_i, \mathbf{x}_{1i}, \mathbf{y}_{1i}, \mathbf{z}_{1i}$ ) and the base frame ( $O_0, \mathbf{x}_0, \mathbf{y}_0, \mathbf{z}_0$ ) (Fig. 2c),  $d_6$  is a length defined at Fig. 2b,

$\delta_i$  is a scalar of which value is equal to 1 if  $i = 3$ , 0 if not and  $\bar{\delta}_i = 1$  ( $\bar{\delta}_i = 0$ , resp.) if  $\delta_i = 0$  ( $\delta_i = 1$ , resp.).

As shown in (Briot and Gautier, 2012), the dynamic model of the real robot can be computed as:

$$\begin{aligned}\tau_{idm} &= \mathbf{J}_t^T \tau_{idm_t} + \mathbf{J}_p^T \mathbf{f}_p = \mathbf{J}_t^T \phi_{st_t}(\mathbf{q}_t, \dot{\mathbf{q}}_t, \ddot{\mathbf{q}}_t) \chi_{st_t} + \mathbf{J}_p^T \phi_p(\gamma) \chi_p \\ &= [\mathbf{J}_t^T \phi_{st_t} \quad \mathbf{J}_p^T \phi_p] [\chi_{st_t}^T \quad \chi_p^T]^T = \phi_{st}(\mathbf{q}, \dot{\mathbf{q}}, \ddot{\mathbf{q}}) \chi_{st}\end{aligned}\quad (4)$$

where  $\chi_p$  represents the standard parameters of the platform (as the Orthoglide is a translational robot, the platform mass  $m_6$  is the only identifiable parameter, i.e.  $\chi_p = m_6$ ),  $\gamma = [\ddot{x}, \ddot{y}, \ddot{z}]^T$  is the platform acceleration and  $\phi_p = \text{diag}(\ddot{x}, \ddot{y} - g, \ddot{z})$ . The same expressions can be used for adding in the model the contribution of the payload 7.

The matrices  $\mathbf{J}_t$  and  $\mathbf{J}_p$  and all positions, velocities and accelerations that are necessary for computing the dynamic model of the real robot can be straightforwardly calculated from (2) and (3) using expressions of (Briot and Gautier, 2012).

### 3 Total Least Square Identification (IDIM-TLS)

In this part, experimentations are performed and the dynamic model identification is carried out on the Orthoglide. The actuation of its feet is achieved by a rotary DC motor Sanyo Denki linked to a ball-screw. The actuators are powered by current source amplifiers Sanyo Denki. The global drive gains given by the manufacturer are equal to  $637\pi \approx 2001$ .

The approach presented in (Briot and Gautier, 2012) requires that the robot moves on two types of exciting trajectories: (i) a first type of trajectory without any payload and (ii) a second type of trajectory with a payload. The way to compute exciting trajectories for identification presented in (Gautier and Khalil, 1992) and is not detailed here. In our experiments, the payload mass has been measured with an accurate weighing machine ( $M_7 = 1.983\text{kg} \pm 0.001\text{kg}$ ).

Table 3 presents the identification results. In this table,  $2\sigma_{\hat{\chi}_i}$  represents the standard deviation of the parameters and  $\% \sigma_{\hat{\chi}_{ri}}$  the percentage of estimation error.

Only the essential parameters are shown (Gautier, 1997), i.e. the parameters that have a real influence on the model. Let us recall that parameter  $g_{\tau_j}$  represents the drive gain of actuator  $j$ ,  $XX_j, XY_j, XZ_j, YY_j, YZ_j, ZZ_j$  are the 6 components of the inertia matrix of link  $j$  at the origin of frame  $j$ ,  $MX_j, MY_j, MZ_j$  are the 3 components of the first moment of link  $j$ ,  $M_j$  is its mass,  $Ia_j$  is the total inertia moment for rotor and gears,  $Fv_j, Fc_j$

are the visquous and Coulomb friction coefficients in the joint. Moreover, subscript 'R' stands for the parameters that have been regrouped (Gautier, 1991)<sup>1</sup>. It should also be noticed that the given value of standard deviation and percentage of error for the payload mass  $M_7$  are those estimated by the use of the weighing machine.

The results show that the identified drive gains are about 5% far from those given by the manufacturer. With these identified parameters, the actuator efforts are reconstructed and compared with the measured ones (Fig 3). It can be seen that the efforts are well simulated.

In order to definitely validate our method, a second payload of 1.136 kg is mounted on the platform and a classical weighted least square identification is performed (Gautier, 1997). Two cases are considered: (Case 1) the drive gains used are those of the manufacturer and (Case 2) the drive gains are those identified in Table 3. The following results are found: (Case 1)  $M_7 = 1.09$  kg with  $2\sigma_{\hat{\chi}_i} = 0.02$  kg, (Case 2)  $M_7 = 1.14$  kg with  $2\sigma_{\hat{\chi}_i} = 0.02$  kg. It is thus possible to conclude that the identification of the drive gain using IDIM-TLS leads to better payload reconstruction.

## 4 Conclusions

This paper has presented a global approach for both the identification of parallel robots dynamic parameters and drive gains. It is based on a IDIM-TLS technique using current reference and position sampled data while the

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1

$$\begin{aligned}
M_{11R} &= M_{11} + I a_{11} + M_{21} + M_{31} + M_{41} + M_{51} + 3.23MX_{32} + M_{42} + M_{52} \\
&\quad + 3.23MX_{33} + M_{43} + M_{53} + M_6 \\
M_{12R} &= M_{21} + I a_{21} + M_{22} - 3.23MX_{32} + M_{32} \\
M_{13R} &= M_{31} + M_{23} - 3.2258MX_{33} + M_{33} \\
ZZ_{21R} &= ZZ_{21} + I a_{21} + YY_{31} + YY_{41} + 0.1M_{41} + 0.1M_{51} + 0.31MX_{32} + 0.1M_{42} \\
&\quad + 0.1M_{52} + 0.31MX_{33} + 0.1M_{43} + 0.1M_{53} + 0.1M_6 \\
Fv_{21R} &= Fv_{21} + Fv_{51} \\
ZZ_{31R} &= ZZ_{31} + I a_{31} + 0.1M_{41} + 0.1M_{51} + 0.31MX_{32} + 0.1M_{42} + 0.1M_{52} \\
&\quad + 0.31MX_{33} + 0.1M_{43} + 0.1M_{53} + 0.1M_6 \\
MX_{31R} &= MX_{31} + 0.31M_{41} + 0.31M_{51} + MX_{32} + 0.31M_{42} + 0.31M_{52} + MX_{33} \\
&\quad + 0.31M_{43} + 0.31M_{53} + 0.31M_6 \\
Fs_{31R} &= Fs_{31} + Fs_{41} \\
Fs_{32R} &= Fs_{32} + Fs_{42} \\
Fv_{33R} &= Fv_{33} + Fv_{43} \\
Fs_{33R} &= Fs_{33} + Fs_{43}
\end{aligned}$$

Table 3: Essential parameters of the Orthoglide.

Par.	Val.	$2\sigma_{\hat{\chi}_i}$	$\% \sigma_{\hat{\chi}_{ri}}$	Par.	Val.	$2\sigma_{\hat{\chi}_i}$	$\% \sigma_{\hat{\chi}_{ri}}$
$g_{\tau_1}$	2110	8.93	0.42	$Fs_{13}$	24.4	0.0813	0.33
$g_{\tau_2}$	2130	8.83	0.41	$ZZ_{21R}$	0.0970	$1.13 \cdot 10^{-3}$	1.17
$g_{\tau_3}$	2070	5.16	0.25	$MX_{21}$	-0.123	$4.87 \cdot 10^{-3}$	3.95
$M_{11R}$	9.93	0.0468	0.47	$Fv_{21R}$	5.50	0.0796	1.45
$Fv_{11}$	83.0	0.377	0.45	$ZZ_{31R}$	0.0739	$1.04 \cdot 10^{-3}$	1.41
$Fs_{11}$	34.5	0.160	0.46	$MX_{31R}$	0.202	$3.43 \cdot 10^{-3}$	1.70
$M_{12R}$	8.86	0.0417	0.47	$Fs_{31R}$	1.60	0.0245	1.54
$Fv_{12}$	87.5	0.463	0.53	$MX_{41}$	0.0377	$7.73 \cdot 10^{-4}$	2.05
$Fs_{12}$	43.0	0.192	0.45	$Fs_{32R}$	1.57	0.0245	1.56
$M_{13R}$	1.10	0.0131	1.19	$Fv_{33R}$	-5.51	0.0851	1.54
$Ia_{13}$	7.93	0.0242	0.31	$Fs_{33R}$	1.37	0.0273	2.00
$Fv_{13}$	84.1	0.238	0.28	$M_7$	1.983	0.001	0.05

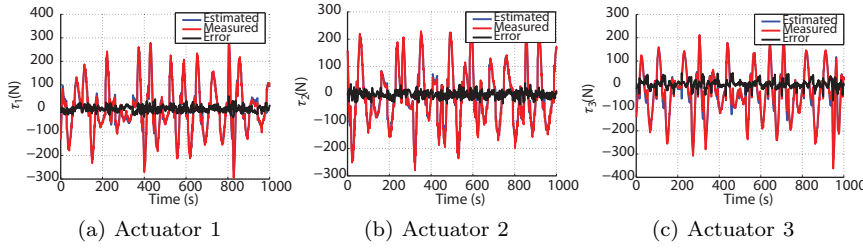


Figure 3: Measured and computed torques of the Orthoglide with the payload of 1.983 kg.

robot is tracking one reference trajectory without load fixed on the robot and one trajectory with a known payload fixed on the robot, whose inertial parameters are measured or calculated with a CAD software. Experiments show that the technique increase the identification quality and that with the new identified gains, the payload reconstruction is improved.

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