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Identification of the payload inertial parameters of industrial manipulators

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***Abstract* — In this paper we present four methods for the identification of the inertial parameters of the load of a manipulator. The knowledge of the values of these parameters can be used to tune the control law parameters in order to improve the dynamic accuracy of the robot. They can also be exploited to verify the load transported by the robot. The methods presented have been validated using Stäubli RX 90 robot. The experimentation has been carried out using data collected from the industrial control system (version CS8) of the manufacturer. This version allows to have access to joint positions, velocities and torques. The methods presented are based on solving linear system of equations using weighted least squares solution.**

***Keywords* — Identification, inertial parameters, dynamic modeling, least squares, payload parameters.**

I. Introduction

Several schemes have been proposed in the literature to identify the dynamic parameters [1]-[16]. Most of the methods use an identification model linear in the parameters, and solve the system using least squares techniques (LS).

The experimental works have been carried out either on prototypes of laboratories or on industrial robots after replacing the industrial controller by an open loop controller specially developed for the application. In this paper, we show that new standard controllers allow now the identification of the dynamic parameters of the robot by providing the joint positions and torques for any trajectory. We show also that the classical trajectories of the manufacturer are sufficiently exciting for the identification. Very small number of papers were devoted for the identification of the payload [1], [8]. In this paper we put the accent on the identification of the inertial parameters of the payload, but the identification of dynamic parameters of the robot will be also presented because they are needed also in some methods.

II. Modeling Of The Robot RX 90

The Stäubli RX-90 robot has a serial structure with six rotational joints. Its nominal payload is equal to 6 Kg.

A. Description of the kinematics

The robot kinematics is defined using Khalil and Kleinfinger notation [17]. In this notation the link j fixed frame is defined such that the $\mathbf{z}_j$ axis is taken along joint j axis and the $\mathbf{x}_j$ axis is along the common normal with $\mathbf{z}_j$ and $\mathbf{z}_{j+1}$. The link frames are shown in Figure 1. The main advantage of using this notation is that the identifiable inertial parameters can be determined symbolically using simple closed-form rules [16], [18], [19].

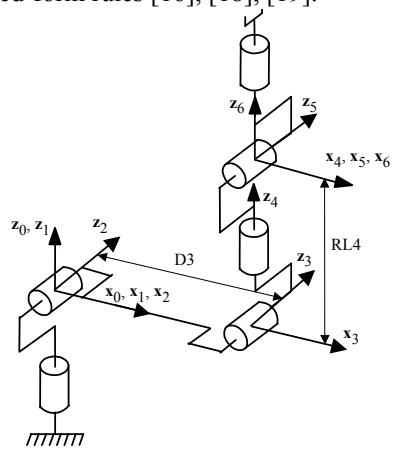

Figure 1. Link frames of Stäubli RX-90 robot.
(D3 = 0,45m and RL4 = 0,45m)

B. Dynamic identification model

Different identification models have been used in robotics [2], [3], [4], [5], [9], [10], [12], [13], [15]. In the following, we use the inverse dynamic model, which was found to be the best one. It is represented for a robot with n joints by:

$$\mathbf{\Gamma} = \mathbf{ID}(\mathbf{q}, \dot{\mathbf{q}}, \ddot{\mathbf{q}}, \chi_s) \qquad (1)$$

$\mathbf{q}$, $\dot{\mathbf{q}}$ and $\ddot{\mathbf{q}}$ are the (nx1) vectors of joint positions, velocities and accelerations.

$\mathbf{\Gamma}$ is the (nx1) vector of motor torques.

χ_s is the (Nsx1) vector of standard dynamic parameters (inertial parameters and friction parameters) of the robot.

A common friction model at non zero velocity is given by:

$$\tau_{f_j} = Fs_j \ \mathrm{sign}(\dot{q}_j) + Fv_j \ \dot{q}_j \qquad (2)$$

where $\dot{q}_j$ is the velocity of joint j,

sign(.) denotes the sign function,

Fv_j , Fs_j , are the viscous and Coulomb friction parameters.

The inertia of the rotors is generally taken in this model as:

$$\tau_{r_j} = IA_j \ \ddot{q}_j \qquad (3)$$

We take into account IA_j , Fv_j and Fs_j in χ_s .

A particular choice of the link inertial parameters allows obtaining the dynamic model linear in relation to the dynamic parameters, such that:

$$\Gamma = \Phi_S(\mathbf{q}, \dot{\mathbf{q}}, \ddot{\mathbf{q}})\, \chi_s = \sum_{i=1,N_s} \Phi_s^i \ \chi_{si} \qquad (4)$$

where:

Φ_S is a (nxNs) matrix, and Φ_s^i is the ith column of Φ_S ,

χ_{si} is the ith element of χ_s ,

χ_s is the vector of standard dynamic parameters given by:

$$\chi_s = [\chi_s^{1T} \ \chi_s^{2T} \ \cdots \ \chi_s^{nT}]^T \qquad (5)$$

with χ_s^j is the dynamic parameters of joint and link j:

$$\chi_s^j = [XXj \ XYj \ XZj \ YYj \ YZj \ ZZj \ MXj \ MYj \ MZj \ M_j \ IAj \ F_{sj} \ F_{vj}]^T \qquad (6)$$

where:

- XX_j, XY_j, XZ_j, YY_j, YZ_j, ZZ_j are the six components of the inertia matrix of link j at the origin of frame j;
- M_j is the mass of link j;
- MX_j, MY_j, MZ_j are the components of the first moments;
- IA_j is the inertia moment for rotor and gears of actuator j.

The columns of the matrix $\Phi_s(\mathbf{q}, \dot{\mathbf{q}}, \ddot{\mathbf{q}})$ can be obtained using the recursive algorithm of Newton-Euler, which calculates Γ in terms of the same set of standard dynamic parameters, such that the ith column of Φ_s is equal to:

$$\Phi_s^i = \mathbf{ID}\,(\mathbf{q}, \dot{\mathbf{q}}, \ddot{\mathbf{q}} \text{ with } \chi_{si} = 1, \chi_{sj} = 0 \text{ for } j \neq i) \qquad (7)$$

To increase the efficiency of this algorithm, we use the customized symbolic technique. Moreover, this technique is convenient for the computation of the observation matrix, which is composed of the concatenation of Φ_s on all the points of a given trajectory, using an array multiply operator (.* of Matlab) without using loop calculations.

C. Particularities of the robot RX 90

The RX 90 robot is characterized by:

1. There is a spring on the joint 2, which compensates the gravity torque due to the robot links. The corresponding torque is added to the torque Γ_2 of joint 2, it is calculated using the manufacturer data in terms of θ_2.

2. There is a coupling among the joints 5 and 6 such that:

$$\begin{bmatrix} \dot{q}r_5 \\ \dot{q}r_6 \end{bmatrix} = \begin{bmatrix} K5 & 0 \\ K6 & K6 \end{bmatrix} \begin{bmatrix} \dot{q}_5 \\ \dot{q}_6 \end{bmatrix} \qquad (8)$$

Thus, the duality relation of torques gives:

$$\begin{bmatrix} \Gamma c_5 \\ \Gamma c_6 \end{bmatrix} = \begin{bmatrix} K5 & K6 \\ 0 & K6 \end{bmatrix} \begin{bmatrix} \Gamma r_5 \\ \Gamma r_6 \end{bmatrix} \qquad (9)$$

where:

$\dot{q}r_j$: is the velocity of the rotor of motor j,

$\dot{q}_j$: is the velocity of joint j,

Γc_j : the motor's torque of joint j, with coupling effect,

Γr_j : electro-magnetic torque of the rotor of motor j,

K5 : the transmission gain ratio of axis 5,

K6 : the transmission gain ratio of axis 6.

The coupling between joints 5 and 6, leads also to add the effect of the inertia of rotor 6 and new viscous and Coulomb friction parameters Fv_{m6} and Fs_{m6} to both Γ_{c5} and Γ_{c6}. Thus, we can write:

$$\Gamma_{c5} = \Gamma_5 + IA_6\, \ddot{q}_6 + Fv_{m6}\, \dot{q}_6 + Fs_{m6}\, \mathrm{sign}(\dot{q}_6) \qquad (10)$$

$$\Gamma_{c6} = \Gamma_6 + IA_6\, \ddot{q}_5 + Fv_{m6}\, \dot{q}_5 + Fs_{m6}\, \mathrm{sign}(\dot{q}_5) \qquad (11)$$

where:

Γ_5 , Γ_6 are obtained from (4), they have already the terms $(IA_j\, \ddot{q}_j + Fvj\, \dot{q}_j + Fs_j\, \mathrm{sign}(\dot{q}_j))$ for j =5 and 6

$IA_5 = K5^{\wedge 2}\, JA_5 + K6^{\wedge 2}\, JA_6$,

$IA_6 = K6^{\wedge 2}\, JA_6$,

JA_j is the moment of inertia of the rotor j,

Fv_{m6} and Fs_{m6} are the friction parameters due to coupling.

D. Calculation of the base dynamic parameters

It has been seen that some inertial parameters cannot be identified because they have no effect on the dynamic model, and some parameters are grouped with some others. The identifiable parameters, called also base inertial parameters [20], can be determined for the serial robots using simple closed-form rules if the Khalil and Kleinfinger notations are used to describe the robot kinematics [16], [18]. For the robot RX 90 the following parameters cannot be identified, they do not belong to the base inertial parameters:

- YYj, MZj and Mj for j = 1, … , 6.
- XX1, XY1, XZ1, YZ1, MX1, MY1, IA1 and IA2.

The grouped parameters are:

ZZ1R=IA1 + D3^2*(M3 + M4 + M5 + M6) + YY2 + YY3 + ZZ1
XX2R= - D3^2*(M3 + M4 + M5 + M6) + XX2 - YY2
XZ2R= - D3*MZ3 + XZ2
ZZ2R=IA2 + d3^2*(M3 + M4 + M5 + M6) + ZZ2
MX2R=D3*(M3 + M4 + M5 + M6) + MX2
XX3R=2*MZ4*RL4+(M4 + M5 + M6)*RL4^2 + XX3 - YY3+YY4
ZZ3R=2*MZ4*RL4 + (M4 + M5 + M6)*RL4^2 + YY4 + ZZ3
MY3R=MY3 - MZ4 - (M4 + M5 + M6)*RL4
XX4R=XX4 - YY4 + YY5 (12)
ZZ4R=YY5 + ZZ4
MY4R=MY4 + MZ5
XX5R=XX5 - YY5 + YY6
ZZ5R=YY6 + ZZ5
MY5R=MY5 - MZ6
XX6R=XX6 - YY6

A numerical method based on the QR decomposition can also be used to determine the base inertial parameters [21].

The dynamic model of the RX90 model is a function of 40 inertial parameters. It is also a function of 14 friction parameters: (Fvj and Fs_j for j=1,…,6) and (Fv_{m6} and Fs_{m6}). The total number of the dynamic base parameters, denoted by N_b ,is equal to 54.

The dynamic model can be written using the base inertial parameters as follows:

$$\Gamma = \Phi(\mathbf{q}, \dot{\mathbf{q}}, \ddot{\mathbf{q}})\, \chi = \sum_{i=1,N_b} \boldsymbol{\Phi}^i \chi_i \qquad (13)$$

where Φ is obtained from Φ_s by eliminating the columns corresponding to the non identifiable parameters.

III. Recall of the Identification Method

We consider off-line identification of the base dynamic parameters $\boldsymbol{\chi}$, given measured or estimated off-line data for $\boldsymbol{\Gamma}, \boldsymbol{q}, \dot{\boldsymbol{q}}, \ddot{\boldsymbol{q}}$, collected while the robot is tracking some planned trajectories.

The principle is to sample the identification model (13) at a sufficient number of samples t_i , for i=1, ..., n_e , with $(nxn_e) >> N_b$, in order to get an over-determined linear system of (nxn_e) equations:

$$\boldsymbol{Y} = \boldsymbol{W}\ \boldsymbol{\chi} + \boldsymbol{\rho} \qquad (14)$$

$\boldsymbol{\rho}$ is the $((nxn_e)x1)$ vector of errors between the data in $\boldsymbol{Y}$ (measurement or estimation of the torques), and the data $\boldsymbol{W}\,\boldsymbol{\chi}$, predicted by the model.

$\boldsymbol{W}(\boldsymbol{q}, \dot{\boldsymbol{q}}, \ddot{\boldsymbol{q}})$ is the ((nxn_e) x N_b) observation matrix.

$\boldsymbol{Y}$ and $\boldsymbol{W}$ are obtained by grouping together the equations of each joint on all the trajectory such that:

$$\mathbf{Y} = \begin{bmatrix} \mathbf{Y}_1 \\ \dots \\ \mathbf{Y}_n \end{bmatrix}, \ \mathbf{W} = \begin{bmatrix} \mathbf{W}_1 \\ \dots \\ \mathbf{W}_n \end{bmatrix} \qquad (15)$$

where $\mathbf{Y}_i$ and $\mathbf{W}_i$ represent all the equations of joint i.

Most of the schemes in robotics solve the system (14) using ordinary (OLS) or weighted (WLS) least squares methods [2], [11], [16]. A maximum likelihood approach proposed by [6], reduces in practice to a WLS method. An approach based on LMI (linear matrix inequality) tools takes into account perturbations in the observation matrix but without improving the estimation given by the WLS. To our knowledge the best experimental results have been obtained with the WLS method, which is presented in the following.

The estimation of $\boldsymbol{\chi}$ is obtained as the OLS solution of the over-determined linear system (14):

$$\hat{\boldsymbol{\chi}} = \underset{\boldsymbol{\chi}}{\text{Arg.min}}\ \|\boldsymbol{\rho}\|^2 = \boldsymbol{W}^+\ \boldsymbol{Y} \qquad (16)$$

where $\boldsymbol{W}^+ = (\boldsymbol{W}^T\ \boldsymbol{W})^{-1}\ \boldsymbol{W}^T$ is the pseudo inverse of $\boldsymbol{W}$.

If $\boldsymbol{W}$ is a full rank matrix the LS solution $\hat{\boldsymbol{\chi}}$ is unique. $\boldsymbol{W}$ numerical rank deficiency can come from two origins:

- structural rank deficiency, which is solved by calculating the base or minimal parameters;
- data rank deficiency due to a bad choice of noisy experimental $\boldsymbol{q}, \dot{\boldsymbol{q}}, \ddot{\boldsymbol{q}}$ samples in $\boldsymbol{W}$, which can be solved by a good planning of exciting trajectories.

In practice, the experimental measurements or estimations of $\boldsymbol{\Gamma}(t_i)$, $\boldsymbol{q}(t_i)$, $\dot{\boldsymbol{q}}(t_i)$, $\ddot{\boldsymbol{q}}(t_i)$ give noisy data. The matrices $\boldsymbol{Y}$ and $\boldsymbol{W}$ are perturbed and the LS solution may lead to a bias estimation if the two random matrices are not independent. Because the coefficients in the observation matrix $\boldsymbol{\Phi}(\boldsymbol{q}, \dot{\boldsymbol{q}}, \ddot{\boldsymbol{q}})$ are non linear functions of $\boldsymbol{q}, \dot{\boldsymbol{q}}, \ddot{\boldsymbol{q}}$, it is not possible to get a theoretical expression of the bias and variance. To overcome this difficulty we adopt a practical strategy which reduces bias and variance of the LS solution with twofold:

- data filtering to decrease noise effect in (14);
- closed loop identification for the robot to track exciting trajectories which ensure persistency excitation.

In order to cancel high frequency torque ripple in Γ, the vector $\mathbf{Y}$ and the columns of the observation matrix $\mathbf{W}$ are both low pass filtered and decimated. This parallel filtering procedure [22] can be carried out with the Matlab *decimate* function [3], [5], [16].

Standard deviations are estimated considering $\mathbf{W}$ to be deterministic, and ρ to be a zero mean additive independent Gaussian noise, with standard deviation σ_ρ such that [3]:

$$\mathbf{C}_\rho = E(\boldsymbol{\rho}\ \boldsymbol{\rho}^T) = \sigma_\rho^2\ \mathbf{I}_r \qquad (17)$$

where E is the expectation operator and $\mathbf{I}_r$ is the (rxr) identity matrix.

An unbiased estimation of σ_ρ can be:

$$\sigma_\rho^2 = \frac{\|\mathbf{Y} - \mathbf{W}\,\hat{\boldsymbol{\chi}}\|^2}{(r - c)} \qquad (18)$$

The covariance matrix of the estimation error is given by:

$$\mathbf{C}_{\hat{\boldsymbol{\chi}}} = E[(\boldsymbol{\chi} - \hat{\boldsymbol{\chi}})\,(\boldsymbol{\chi} - \hat{\boldsymbol{\chi}})^T] = \sigma_\rho^2\,(\mathbf{W}^T\,\mathbf{W})^{-1} \qquad (19)$$

The standard deviation $\sigma_{\hat{\boldsymbol{\chi}}_j}$ and its relative value $\sigma_{\hat{\boldsymbol{\chi}}_{jr}}\%$ by:

$$\sigma_{\hat{\boldsymbol{\chi}}_j} = \sqrt{\mathbf{C}_{\hat{\boldsymbol{\chi}}}(j,j)} \qquad (20)$$

$$\sigma_{\hat{\boldsymbol{\chi}}_{jr}}\% = 100\ \frac{\sigma_{\hat{\boldsymbol{\chi}}_j}}{|\hat{\boldsymbol{\chi}}_j|} \qquad (21)$$

The equations of joint i will be weighted with the inverse of the standard deviation of the error calculated using the equations of joint i [3], [5]. This weighting operation normalises the errors to give the WLS estimation of the parameters.

The WLS solution is obtained by a recursive formulation of the QR decomposition of the weighted matrix **W** [3].

Some small parameters remain poorly identifiable because they have no significant contribution in the torque. These parameters can be cancelled in order to simplify the dynamic model. Parameters such that $\sigma_{\hat{\chi}_{jr}}\%$ is greater than a bound between 5 and 10 are cancelled to keep a set of essential parameters of a simplified dynamic model without loss of accuracy [3]. The essential parameters are calculated using an iterative procedure starting from the base parameters estimation. At each step the base parameter which has the largest relative standard deviation is cancelled. A new parameter estimation of the simplified model is carried out with a new error standard deviation $\sigma_{\rho e}$. The procedure ends when $\sigma_{\rho e} \geq 1.02\ \sigma_{\rho b}$, where $\sigma_{\rho b}$ is the initial error standard deviation obtained with all the parameters.

IV. Identification Of The Dynamic Parameters Of The Robot RX 90

A. Data Acquisition and identification

The identification of the dynamic parameters without load has been carried out using 18 trajectories. The path of each trajectory consists of about 14 intermediate points. The trajectory between the points is carried out using the interpolation function of the controller CS8 of the Stäubli robots. The joint positions and torques are read with a sampling frequency equal to 250 Hz. The condition number of the observation matrix of all the trajectories is equal to 58, which is considered as being sufficiently exciting. The total number of equations is about r = 63000. A supplementary trajectory is used in the validation of the estimated values of the dynamic parameters.

The estimation of $\dot{\mathbf{q}}$ and $\ddot{\mathbf{q}}$ are carried out from **q** by a low pass Butterworth filter and a central derivative algorithm. The Matlab function filtfilt, which is a zero-phase forward and reverse digital filtering, can be used.

After elimination of the parameters with large relative standard deviation (RSD), the robot dynamics is represented by 28 essential parameters. The estimated values of these parameters are not given here. They are close to the first 28 parameters of Table 2.

B. Validation of the identification results

The validation of the identification result is carried out by comparing the measured joint torques $\boldsymbol{Y}_{mes}$ and the estimated torques $\boldsymbol{W}\,\chi_{est}$ on a trajectory which has not been used in the identification (cross validation). Owing to the limited number of pages, the validation curves are not presented in this paper. However, the identification of the payload inertial parameters presented in the following section constitutes another validation procedure.

V. Identification Of The Inertial Parameters Of The Payload

A. Presentation of the different methods

Having estimated the dynamic parameters of the robot without load, we present in this section four methods for the identification of the inertial parameters of a payload fixed on the terminal link of the robot.

1) Making use of the values estimated without payload

When the robot is carrying a payload, the dynamic equations can be written as follows:

$$\mathbf{Y}_T = \mathbf{W}(\mathbf{q}, \dot{\mathbf{q}}, \ddot{\mathbf{q}})\,\chi + \mathbf{W}_L(\mathbf{q}, \dot{\mathbf{q}}, \ddot{\mathbf{q}})\,\chi_L + \rho \qquad (22)$$

where

$\mathbf{Y}_T$: the measured torques when the robot is loaded,

$\mathbf{W}$: the observation matrix without load,

χ : the vector of the dynamic parameters of the robot without load (this is already estimated),

χ_L : the(10x1) vector of the inertial parameters of the load,

$\mathbf{W}_L$: the observation matrix corresponding to the load inertial parameters.

The load inertial parameters are estimated from (22) by:

$$\hat{\chi}_L = (\mathbf{W}_L)^+\,(\mathbf{Y}_T - \mathbf{W}\,\chi) \qquad (23)$$

We note that physically the 10 inertial parameters are identifiable.

In this method we suppose that the friction parameters are invariant with respect to the payload. If this hypothesis is not satisfied these parameters should be taken into account in both $\mathbf{W}_L$ and χ_L.

2) New identification of the robot parameters with the payload

We identify once more all the dynamic parameters while the robot is carrying the payload. The inertial parameters of the load can be computed using the variation on some estimated inertial parameters with and without payload. In this case we make use of the grouping relations (12). Let $\Delta\chi_i$ be the variation of an inertial parameter:

$$\Delta\chi_i = \hat{\chi}_j\,(\text{robot with payload}) - \hat{\chi}_j\,(\text{robot without payload}) \qquad (24)$$

The load inertial parameters XY_L, XZ_L, YZ_L, ZZ_L, MX_L, MY_L can be obtained directly as ΔXY6, ΔXZ6, ΔYZ6, ΔZZ6, ΔMX6, ΔMY6. Using (12) and (24), the parameters XX_L, YY_L, MZ_L and M_L can be obtained by solving the following relations:

$$\begin{aligned} \Delta ZZ1R &= D3\text{^}2 * M_L \\ \Delta XX2R &= -\,D3\text{^}2 * M_L \\ \Delta ZZ2R &= D3\text{^}2 * M_L \\ \Delta MX2R &= D3 * M_L \\ \Delta XX3R &= RL4\text{^}2 * M_L \end{aligned} \qquad (25)$$

$\Delta ZZ3R = RL4^2 * M_L$
$\Delta MY3R = - RL4 * M_L$

$\Delta XX5R = YY_L$
$\Delta ZZ5R = YY_L$ (26)

$\Delta MY5R = - MZ_L$ (27)

$\Delta XX6R = XX_L - YY_L$ (28)

The parameters M_L and YY_L are estimated by the least squares solution of equations (25) and (26) respectively, whereas the parameters MZ_L and XX_L are directly obtained from equations (27) and (28) respectively.

3) Using the difference between the joint torques before and after loading the robot on the same trajectory

In this method we make use that the term $\mathbf{W}\,\chi$ of (22) is equal to the joint torques without load. Consequently the payload parameters could be identified by (23) after replacing $\mathbf{W}\,\chi$ by $\mathbf{Y}_{wL}$ representing the joint torques on the same trajectory without load, which gives:

$$\hat{\chi}_L = (\mathbf{W}_L)^+ (\mathbf{Y}_T - \mathbf{Y}_{wL}) \quad (29)$$

The unknowns of this method are only the 10 inertial parameters of the payload, which lead to the possibility of reducing considerably the number of points needed for the construction of the observation matrix. In our experiment just one trajectory (out of the planned 8) was sufficient.

This method supposes that the control system is efficient such that the difference between the joint positions with and without payload is negligible and that the friction parameters are the same under the two conditions. For the RX 90 robot the maximum error on joint positions due to the load is 10^{-3} rad while carrying a load of 7.025 Kg, which allowed obtaining good results with this simple method.

4) Global identification of the robot parameters and the load parameters

In this method the identification model is constructed by grouping two sets of equations, the first representing a trajectory without load, and the second representing a trajectory with load. These two trajectories could be different:

$$\begin{bmatrix} \boldsymbol{Y}_a \\ \boldsymbol{Y}_b \end{bmatrix} = \begin{bmatrix} \mathrm{W_a} & \mathbf{0} \\ \mathrm{W_b} & \mathrm{W_L} \end{bmatrix} \begin{bmatrix} \chi \\ \chi_L \end{bmatrix} \quad (30)$$

where the first row represents the equations of the trajectory without payload, whereas the second row corresponds to the trajectory with payload.

The link parameters χ and the payload inertial parameters χ_L are estimated by solving (30) using weighted least squares solution. This method has the advantage of using a global identification procedure that can avoid the accumulation of errors, which may occur for sequential identification methods.

B. Experimental results

To test the proposed methods, a calibrated payload is used. The inertial parameters are provided by the software package CATIA. These values, denoted in the following as a priori, are sufficiently accurate due to the simplicity of the shape of the load. The mass of the reference payload is estimated as 7.025 Kg using a weighing machine whose accuracy is ± 0.050 Kg. The four methods have been applied and the results are nearly the same. We give the results of methods 3 and 4. Method 3 is considered as the simplest one, whereas method 4 is considered as the best scientific one.

The results of methods 3 and 4 are given in Tables 1 and 2 respectively. We note that the parameters XX_L, YY_L, MZ_L and M_L are very well identified in both methods in terms of relative standard deviation. The reference values of the other parameters are almost zero. In method 3, they have big relative standard deviations, but the estimated values are almost zero. In method 4, the application of the elimination strategy led to eliminate automatically these parameters because they have negligible effect on the dynamics of the robot.

The robot parameters identified in method 4 are very close to those estimated in section 4.

VI. CONCLUSION

In this paper we dealt with the problem of the identification of the inertial parameters of the payload of industrial robots. In the experimentation we used the Stäubli RX 90 robot with its CS8 controller for the data acquisition and for the trajectory generation. Four methods have been proposed and validated by comparing the inertial parameters of a reference-calibrated payload. We put the accent on two methods, the method 3 makes use of data of a given trajectory executed twice, once without the payload and then with the payload. This method relies on a good control tuning in order that the position error between the two executions will be small enough. The method 4 identifies both robot parameters and payload parameters in one step by a global procedure. This method avoids the accumulation of errors, which may occur in methods 1 and 2, and does not impose any hypothesis as in method 3. The experimental results, for the RX 90 robot, are very close for the four methods, thus any of them can be used for the RX90 robot. This may be not the case for other robots using method 3.

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Parameter	A priori	Identified	$2\,\sigma_\chi$	$\sigma_{\chi r}$ %
XX_L	**0.161**	**0.157**	**0.019**	**5.931**
XY_L	0	0.007	0.009	66.152
XZ_L	0	0.008	0.009	62.705
YY_L	**0.161**	**0.153**	**0.018**	**5.738**
YZ_L	0	-0.005	0.009	91.418
ZZ_L	0.035	0.025	0.012	24.612
MX_L	0	0.034	0.015	21.869
MY_L	0	0.006	0.015	119.190
MZ_L	**1.003**	**0.977**	**0.020**	**1.015**
M_L	**7.025**	**7.216**	**0.045**	**0.313**

Table 1. *Identification of the payload parameters using method 3*

	Parameter	A priori	Identified	$2\,\sigma_\chi$	$\sigma_{\chi r}$ %
Robot parameters	ZZ1R		12.600	0.040	0.158
	FV1		29.300	0.139	0.237
	FS1		21.700	0.228	0.526
	XX2R		-7.770	0.053	0.339
	XZ2R		-0.866	0.039	2.227
	ZZ2R		11.400	0.046	0.204
	MX2R		15.900	0.026	0.081
	FV2		27.300	0.218	0.399
	FS2		21.300	0.286	0.670
	XX3R		1.230	0.042	1.723
	ZZ3R		1.300	0.017	0.655
	MY3R		-3.170	0.012	0.189
	IA3		1.480	0.019	0.636
	FV3		7.090	0.067	0.472
	FS3		12.800	0.102	0.399
	MX4		-0.052	0.004	4.252
	IA4		0.866	0.004	0.231
	FV4		6.000	0.023	0.191
	FS4		5.800	0.048	0.412
	IA5		0.280	0.010	1.847
	FV5		4.730	0.049	0.519
	FS5		2.310	0.063	1.369
	YZ6		-0.020	0.001	3.246
	IA6		0.104	0.002	0.997
	FV6		1.200	0.015	0.612
	FS6		0.820	0.022	1.371
	FVM6		1.050	0.012	0.552
	FSM6		0.700	0.024	1.679
Payload parameters	XX_L	0.161	0.157	0.008	2.572
	YY_L	0.161	0.151	0.008	2.567
	ZZ_L	0.035	0.027	0.002	4.487
	MZ_L	1.003	0.979	0.010	0.495
	M_L	7.025	6.700	0.039	0.294

Table 2. Identification results using method 4

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