Identification of Robots Inertial Parameters by Means of Spectrum Analysis

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Abstract

A common way to identify the inertial parameters of robots is to use a linear model as function of a minimal set of base parameters and standard least squares techniques. In experimental applications, noise on position and torque measurements, friction modeling error and bad excitation restrict dramatically the identification. This paper presents a methodology to overcome these difficulties. The proposed identification method is based on experiments which are designed by means of physical interpretation and spectrum analysis of the robot dynamic model in order to reduce sensibility to noise. These experiments are planned in order to ensure optimal condition number of the observation matrix. The proposed algorithms have been integrated in a software package called Robot Identification Software Tool (R.I.S.T). The successfull application of this new method to a 3 degrees of freedom robot proves the efficiency of the algorithms.

1 Introduction

Advanced control techniques, such as computed torque control, and robotic simulators require dynamic models of manipulator robots in order to improve the dynamic performances. Identification methods must be used because the inertial parameters of the robot links are difficult to measure directly. Least squares techniques using robot dynamic or energetic models are generally used to estimate the values of these parameters. However, noise on joint position measurements and friction modeling errors may imply bias of the estimated parameters. Previously, specific trajectories have been proposed in order to identify parameters subsets in a sequential way [1]. Unfortunately, these methods may provide low accuracy of the parameters estimates. Exciting trajectories have been used as well for the global identification of overall inertial parameters [2]. The proposed method mixes this two approaches but avoids their drawbacks :

- exciting periodic trajectories and the spectrum analysis technique are used in order to emphasize the contribution of the inertial parameters and to reduce measurement noise and friction effects in the dynamic model.

- optimized experiments are planned in order to obtain a low condition number of the observation matrix and to perform a global identification.

This paper includes 5 sections. The inertial parameters identification model is described in section 2. In section 3, the identification method is presented. Experimental validation of the method using a 3 degrees of freedom robot is provided in section 4. Guidelines for the future are drawn in conclusion.

2 Dynamic identification model

Robots parameters identification requires a preliminary modeling. This task, which can be supported by software tools, aims to produce a robot dynamic model and a set of inertial parameters suitable for the identification algorithms.

IEEE International Conference
on Robotics and Automation
0-7803-1965-6/95 $4.00 ©1995 IEEE

2.1 Dynamic model of robots

It is well known that the dynamic model of a manipulator robot can be written linearly as function of a $(n_s \times 1)$ vector of standard inertial parameters X_I. For example, an open-loop rigid robot composed of n moving links, has 11n standard parameters. For each link j, the parameters are the mass M_j, the 3 components of the first moment (MX_j, MY_j, MZ_j), the 6 components of the inertia tensor $(XX_j, XY_j, XZ_j, YY_j, YZ_j, ZZ_j)$ and the inertia of the motor I_{aj}. The dynamic model of the robot can be expressed as follows :

$$\begin{aligned} \Gamma &= I(q)\ddot{q} + N(q)\underline{\dot{q}\dot{q}} + U(q) \quad \text{or} && (1) \\ \Gamma &= D(q, \dot{q}, \ddot{q}) \cdot X_I && (2) \end{aligned}$$

where : Γ is the $n \times 1$ vector of generalized joint torques. q, $\dot{q}$, $\ddot{q}$ are the $n \times 1$ vectors of generalized positions, velocities and accelerations respectively. $I(q)$ is the $n \times n$ inertia matrix of the robot. $N(q)$ is the $n \times n(n+1)/2$ matrix of centrifugal and Coriolis terms. $\underline{\dot{q}\dot{q}}$ is the $n(n+1)/2 \times 1$ vector of joint velocity products. $U(q)$ is the $n \times 1$ vector of gravity torques. D is the $n \times n_s$ regression matrix of the linear dynamic model, which depends on q, $\dot{q}$, $\ddot{q}$ and on constant geometric parameters.

By sampling equation (2) at e different sample times t_i, and assuming there are neither modeling errors nor perturbations, one obtains a compatible overdetermined linear system of r equations and n_s unknowns.

$$Y(\Gamma) = W(q, \dot{q}, \ddot{q}) \cdot X_I \qquad (3)$$

$$Y = \begin{pmatrix} \Gamma_1(1:e) \\ \vdots \\ \Gamma_n(1:e) \end{pmatrix}, \quad W = \begin{pmatrix} D_1(1:e) \\ \vdots \\ D_n(1:e) \end{pmatrix}$$

where e is the number of equations (2) such as $r = n * e \geq n_s$ and $\Gamma_k(1:e)$ is the $e \times 1$ vector of torque measurements of joint k. $D_k(1:e)$ is the $e \times n_s$ matrix built by sampling the kth row of $D(q(t_i), \dot{q}(t_i), \ddot{q}(t_i))$. In the following, W is called the observation matrix and $F = W^t \cdot W$ the Fischer matrix.

2.2 Minimal set of inertial parameters

Previous works on model reduction have been focused on the determination of the structural rank of W. W is not full structural rank if some of its columns, i.e some columns of D, are linearly dependant for any values of q, $\dot{q}$, $\ddot{q}$. Reducing the matrix W to a full rank column matrix leads to eliminate some standard inertial parameters which do not affect the model (the corresponding columns of W are zero) and to regroup some other parameters in linear relations. At this stage, a set of n_b base parameters is obtained with $n_b \leq n_s$. Analytical or numerical methods have been proposed to get this set of base parameters [4]. In the following, we suppose that this stage has been reached, that is W is a $(r \times n_b)$ full rank matrix and we search the numerical values of $(n_b \times 1)$ identifiable parameters (X vector).

3 Identification method

Perturbations on identification model corrupt dramatically the solution obtained by direct least squares algorithms without data filtering. The proposed identification method allows to decrease this bias. Our identification process can be decomposed in five steps :

1. Choice of exciting trajectories.
2. Planning of experiments.
3. Experimentation.
4. Parameters identification.
5. Validation of results.

The identification of parameters is performed by usual least squares techniques and is not explained in detail here. In this section, only the most significant steps, i.e exciting trajectories and planification, are presented.

3.1 Introduction to the method

Practical problems of identification In practical identification, equation (3) is perturbated :

$$Y(\Gamma) = W(q, \dot{q}, \ddot{q}) \cdot X + \rho \qquad (4)$$

As the perturbation vector ρ and the observation matrix W cannot be considered as being random independent matrices, least squares solution of (4) is biaised leading to bad identification results. In fact, there are four kinds of perturbations :

1. The observation matrix is function of q, $\dot{q}$, $\ddot{q}$. Usually, robot sensors provide measurements of joints positions q only. Joints velocities and accelerations are computed by differentiating q, which introduces noise on the observation matrix. In this case, it is well known that the Least Squares estimator is biaised. However, This noise can be reduced by filtering the torque Γ and the columns of W [5] [6].
2. Joint friction implies modeling errors and an average model of friction must be added to equation (1) [5] [6]. Then, the joint torque Γ_k can

be computed using the measurement of the joint motor torque Γ_{mk} and the friction torque Γ_{fk} :

$$\Gamma_{mk} = \Gamma_k + \Gamma_{fk}$$

where Γ_{fk} can be modelized by this average model :

$$\begin{aligned} \Gamma_{fk} &= Fv1 \cdot \dot{q}_k + Fs1 \text{ if } \dot{q}_k > 0 \\ \Gamma_{fk} &= Fv2 \cdot \dot{q}_k + Fs2 \text{ if } \dot{q}_k < 0 \end{aligned} \quad (5)$$

where $Fv1$ and $Fv2$ represent the asymmetry of the viscous friction, $Fs1$ and $Fs2$ the asymmetry of the Coulomb friction.

3. The motor torque Γ_{mk} is calculated using the following relation :

$$\Gamma_{mk} = G_{tk} * C_k$$

where C_k is the motor current reference of the amplifier current loop, G_{tk} is the drive gain of joint k [3].

4. Generally, all the parameters cannot be identified using usual intuitive trajectories because some of them are not excited, i.e the system of equations (4) becomes ill conditionned. In order to solve this problem, some methods based on exciting trajectories have been proposed [2]. Despite the good results obtained, these methods are difficult to implement in practice because they use high-sophisticated non-linear optimization algorithms and require high computation time.

Advantages of the method The method proposed in this paper simplifies the identification process and provides high robustness as regards the deep problems mentionned hereabove. The main features of this method are the following :

- the design of the exciting trajectories is based on the physical interpretation of the robot dynamic model only (without friction). These trajectories allow to reduce the pertubations on the observation matrix W by means of the frequency analysis of its columns.
- The experiments are optimized in order to obtain a very low condition number of the observation matrix. This step of the method called " planning of experiment " is based on a very simple optimization algorithm.
- General and efficient identification software based on standard least-squares algorithms can be achieved at low cost.

3.2 Choice of exciting trajectories

Four different types of exciting trajectories have been defined to sensitize four different physical phenomena which are : inertial effect, centrifugal coupling, inertial coupling and gravity effect.

During an experiment, only a limited number of joints move while the others are locked by the robot controller at a fixed position. For each joint, the motor position and the torque control signals must be measured. The exciting trajectories are periodic movements (except for gravity) between two points A and B, at a frequency f_P. These trajectories may be provided by classical trajectory generators as bang-bang ones. We call " small velocity " of a given joint, the smallest velocity such as there is no friction stick slip, i.e the average friction model (5) keeps a physical meaning. The equations of movement are written for manipulator robots having an open loop kinematic structure and rotoid joints but can be extented to closed-loop kinematics.

Notation The spectrum of a $e \times n$ matrix M, normalized by a $e \times 1$ vector v is the $1 \times n$ vector given by :

$$\mathrm{Sp}(M, v, f) = (\lambda_1, \ldots, \lambda_n)$$

$$\lambda_k = |M_k(f)| * \cos(\arg(M_k(f)) - \arg(v(f)))/|v(f)|$$

where M_k is the kth column of M. $v(f)$ (resp.$M_k(f)$) is the value of the Discrete Fourier Transform (DFT) of v (resp. M_k) at the frequency f.

Analysis of inertial forces The first type of trajectory requires a periodic movement of a single joint k whose dynamic model of joint k reduces to :

$$I(q_{k+1}, .., q_n)_k * \ddot{q}_k + U(q)_k + \Gamma_{fk}(\dot{q}_k) = \Gamma_{mk} \quad (6)$$

where $\Gamma_{fk}(\dot{q}_k)$ is the average friction torque given by Eq. (5). $I(.)_k$ is a constant inertia momentum.

Points A and B are chosen such as joint k achieves maximum acceleration, in order to increase the inertia torque $I(.)_k\ddot{q}_k$, and low velocity, in order to decrease the effect of the friction torque $\Gamma_{fk}(\dot{q}_k)$.

Furthermore, inertia and friction effects in Γ_{mk} are decoupled in the frequency domain because there is a $\pi/2$ phase shift between fundamental components of velocity and acceleration. Thanks to this property, friction effects can be eliminated.

Equation (6) sampled on the exciting trajectory gives a system similar to (3) for joint k :

$$Y_k(\Gamma_{mk}) = D_k(q, \dot{q}, \ddot{q}) \cdot X_I + \Gamma_{fk}(\dot{q}_k) \quad (7)$$

The DFT of (3) leads to the following linear equation suitable for further least squares identification :

$$\mathrm{Sp}(D_k, \ddot{q}_k, f_P) \cdot X = \mathrm{Sp}(Y_k, \ddot{q}_k, f_P) \qquad (8)$$

The gravity torque, which is of less importance, remains included in the model.

Analysis of centrifugal coupling forces This second type of trajectory requires a periodic movement of two joints k and $l > k$. In this case, the dynamic model of joint l reduces to :

$$\begin{aligned} \Gamma_{ml} &= N(q_l, .., q_n)_{l,k} * \dot{q}_k^2 + I(q_l, .., q_n)_{l,k} * \ddot{q}_k + \\ & I(q_{l+1}, .., q_n)_l * \ddot{q}_l + U(q)_l + \Gamma_{fl}(\dot{q}_l) \end{aligned} \qquad (9)$$

where $N(.)_{l,k}$ represents the centrifugal coupling term and $I(.)_{l,k}$ the inertial coupling term between both links.

Points A and B must be chosen such as joint k achieves maximum velocity in order to increase the centrifugal torque $N(.)_{l,k} * \dot{q}_k^2$. Joint l executes a small movement at " small velocity " in order to decrease the inertial torque $I(.)_l * \ddot{q}_l$, the friction $\Gamma_{fl}(\dot{q}_l)$, as well as the variation of $N(.)_{l,k}$ and $I(.)_l$.

Furthermore, centrifugal effect, inertial and friction effects, can be separated in the frequency domain of Γ_{ml}, because the spectrum of $N(.)_{l,k} * \dot{q}_k^2$ is mainly located in the zero and $2f_P$ frequency components while $I(.)_{l,k} * \ddot{q}_k + I(.)_l * \ddot{q}_l + \Gamma_{fl}(\dot{q}_l)$ has zero component at $2f_P$ frequency. Indeed, the asymmetry of the viscous friction of joint l which might contribute to this frequency can be neglected because the joint speed is small. Gravity torque may have a low contribution but it is included in the model. As before the DFT of the system derived by sampling equation (3) gives the following linear equation :

$$\mathrm{Sp}(D_l, \dot{q}_k^2, 2f_P) \cdot X = \mathrm{Sp}(Y_l, \dot{q}_k^2, 2f_P) \qquad (10)$$

Analysis of inertial coupling forces This third type of trajectory requires a movement of two joints k and $l > k$. The reduced dynamic model of joint l remains that of equation (9).

Points A and B must be chosen such as joint k achieves maximum acceleration, in order to increase the inertial coupling torque $I(.)_{l,k}\ddot{q}_k$ and low velocity in order to decrease the centrifugal torque $N(.)_{l,k} * \dot{q}_k^2$. Joint l must execute a small movement at " small velocity " in order to limit the inertial torque $I(.)_l * \ddot{q}_l$, the friction $\Gamma_{fl}(\dot{q}_l)$ and the variation of $N(.)_{l,k}$ and $I(.)_l$.

Using previous results of this sections, one can demonstrate that centrifugal and friction effects have no influence at the fundamental frequency f_P. The gravity torque is included in the model. The DFT of equation (3) at this frequency provides the following equation suitable for further identification :

$$\mathrm{Sp}(D_l, \ddot{q}_k, f_P) \cdot X = \mathrm{Sp}(Y_l, \ddot{q}_k, f_P) \qquad (11)$$

Analysis of gravity forces This last type of trajectory consists in a movement at constant and weak velocity of a single joint k between two points A and B. In this case, the dynamic model of joint k reduces :

$$U(q)_k + \Gamma_{fk}(\dot{q}_k) = \Gamma_{mk} \qquad (12)$$

where $\Gamma_{fk}(\dot{q}_k$ is constant during the movement. This movement must be large in order to increase the gravity effect and must be executed at " small velocity " in order to decrease the friction $\Gamma_{fk}(\dot{q}_k)$. When sampling equations (12) along the trajectory, the set of equations (3) becomes :

$$Y_k(\Gamma_{mk}) = D_k(q) \cdot X + \Gamma_{Fk}(\dot{q}_k)$$

$$\Gamma_{Fk}(\dot{q}_k) = \begin{pmatrix} \Gamma_{fk}(1) & \ldots & \Gamma_{fk}(e) \end{pmatrix}^t$$

where e is the number of samples.

As only the gravity parameters have a contribution in Y_k, the matrix D_k and the parameters vector X can be reduced in size. The friction is eliminated by centering D_k and Y_k. Let D_k^c (resp. Y^c) be the centered observation matrix (resp. the centered torque vector).

$$Y_k^c = Y_k - \bar{Y}_k = (D_k - \bar{D}_k) \cdot X = D_k^c \cdot X \qquad (13)$$

By multiplying each term of equation (13) by $(D_k^c)^t$, it comes :

$$F^c \cdot X = (D_k^c)^t \cdot Y^c \text{ with } F^c = (D_k^c)^t \cdot D_k^c \qquad (14)$$

This last square system of equation can be used for further identification.

3.3 Planning of experiments

An experiment is composed of one of the exciting trajectories described before in addition to a set of locked position values. Each experiment (except for gravity) provides a scalar equation in order to build the rows of a global observation matrix. Thus, the number n_{exp} of experiments to be carried out must be larger than the number of unknown parameters n_b. The goal is to plan experiments in order to ensure optimal condition number of the observation matrix.

Our algorithm simulates the selected exciting trajectories for each possible locked configuration of the

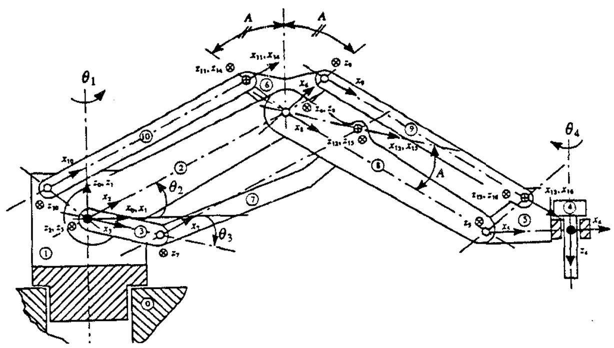


Figure 1: the R.A.C.E robot

robot using a reasonable position increment. The left part of the result equation is computed. Hence, a large set of equation called W^{all}, corresponding to all achievable experiments is built.

Obviously, it is not possible (and not necessary) to carry out all these experiments. The planning algorithm selects a limited number of experiment corresponding to the best rows of W^{all} (in the sense of the optimal condition number for W^{all}). Let W be the reduced observation matrix obtained by this way.

The algorithm which finds W is based on the minimization of the frobenius condition number of W :

$$\mathrm{cond}_{\mathrm{fro}}(W) = \sqrt{\mathrm{trace}(W^t \cdot W) * \mathrm{trace}((W^t \cdot W)^{-1})} \tag{15}$$

This criterion allows to use a simple and well known algorithm based on the maximization of the determinant of the Fischer Matrix [7]. It is close to the euclidian condition number usually used in inertial parameter identification [2].

4 Application

The identification method presented in this paper has been applied successfully to several prototype and industrial manipulator robots. The result reported in this section refers to the first application of the method using a four axes assembly robot.

4.1 Presentation of the R.A.C.E robot

The RACE robot has been developed by the french Atomic Energy Commission (C.E.A) in the 80s as a prototype of high-speed assembly robot. The mechanical structure of the robot is shown on figure 1. Gravity effects are staticaly balanced, independently of the links configurations, by a mechanical system with helical springs. It has four actuated direct drive joints. The first three degrees of freedom have been identified.

The dynamic model of the robot and the base parameters have been automatically generated using the SYMORO software [8]. The robot model includes 18 inertial parameters and 3 drive gain parameters [9]. Two parameters $D8MY9$ and $D2MY10$ can be neglected. The robot controller developed by C.E.A includes SYCLOP, a trajectory generator and provides large facilities for data acquisition at 1 KHz sample rate.

4.2 Presentation of the R.I.S.T software

The identification algorithm presented in section 3 has been integrated in a software package called R.I.S.T (Robot Identification Software Tool) based on MATLAB^{TM}. Two kinds of experiments have been used for the RACE robot :

- experiments of type 1 (inertial effect) for joint 2 and joint 3.
- experiments mixing types 1,2 and 3, i.e inertial effect for joint 1 (J1), centrifugal coupling for J1/J2 as well as J1/J3, inertial coupling for J1/J2 and J1/J3.

In order to identify the overall inertial parameters, R.I.S.T planned 8 experiments only. As the drive gain parameters of the robot was unknown, a Total Least Squares technique has been used for these additional parameters [3].

The values of the inertial parameters of the RACE robot which have been identified are given in figure 2(d). A good coherence of the parameters values with the available construction data of the robot has been obtained. For instance, the low numerical values of some parameters have been explained by the geometry of the links. Moreover, the robot dynamic model fitted with the estimated parameters has been validated using ten different trajectories which were not used for the identification. As shown on figure 2(a),(b) and (c), the predicted torques for each joint match the actual torques closely which validates the identification process.

5 Conclusion

In this paper, a new method to identify robot inertial parameters has been proposed. The robot dynamic model, linear as function of a minimal set of inertial parameters, has been used. The design of exciting trajectories, based on the physical interpretation of robot dynamics, has been proposed. Thanks to these trajectories and to the spectrum analysis of the robot model, the method is robust as regards the measurement noises and the modeling errors. The planning of experiments, by means of a simple algorithm minimizing the frobenius condition number of the observation matrix, provides optimum conditions for parameters identification by means of standard least squares algorithms. The method has been validated from an experimental point of view and applied with success to a 3 degrees of freedom direct drive robot. Application to RD500, a nuclear telemanipulator robot available at CEA, is being in progress and should be reported at short term.

References

[1] H. MAYEDA, K. OSAUKA and A. KANGAWA - A new identification method for serial manipulators arms *Preprint IFAC* 9^{th} *World Congress,4,74-79 (1984).*

[2] PRESSE C. GAUTIER M. - New Criteria of Exciting Trajectories for Robot Identification *Proc. IEEE Conf. on Robotics and Automation 907-912, 1993.*

[3] M. GAUTIER PO. VANDANJON C. PRESSE - Identification of inertial and drive gain parameters of robots *33rd Conf. On Decision and Control (1994)*

[4] GAUTIER M. Numerical Calculation of the base inertial parameters *Journal of Robotics Systems, 8(4) 485-506, 1991.*

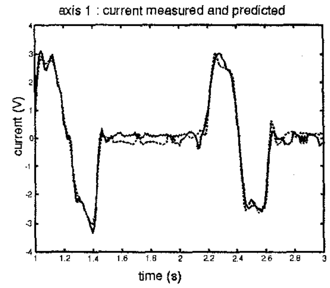
[5] ZIREN LU, KARUNAKAR B. SHIMOGA, and Andrew A. GOLDENBERG - Experimental Determination of Dynamic Parameters of robotic arms *Journal Of Robotic Systems, 10(8), 1009-1029,1993.*

[6] M. GAUTIER, W. KHALIL, P.P RESTREPO Identification of the dynamic parameters of a closed loop robot *Proc. IEEE Conf. on Robotics and Automation Nagoya, 1995.*

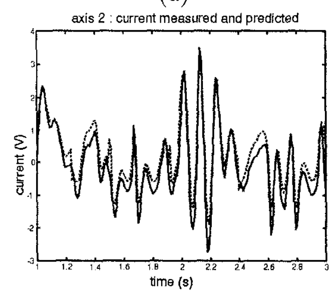
[7] MITCHELL T.J - An algorithm for the construction of 'D-OPTIMAL' experimental Designs *Technometrics,16203-210 (1974)*

[8] W. KHALIL, D. CREUSOT, C. CHEVALLEREAU, F. BENNIS - SYMORO+ Symbolic modeling of robots user guide *Lab. Auto. Nantes (LAN)*

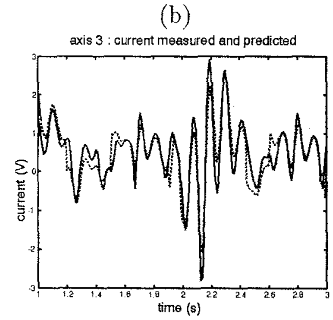
[9] P. DESBATS - A. MICAELLI - Global determination of the minimal set of inertial parameters of robot having open or closed-loop kinematic structures. *2nd international workshop on advances in robot kinematics, 10-12 sept 90, Linz (AUSTRIA)*



(a)



(b)



(c)

param.	value	Confidence	
ZZR1	0.293	0.237	0.349
XXR2	-0.108	-0.1127	-0.0886
XYR2	0	-0.014	0.014
XZR2	-0.011	-0.016	-0.007
YZR2	0	-0.012	0.002
ZZR2	0.098	0.095	0.100
D2MXR3	0	-0.018	0.073
XXR4	-0.068	-0.088	-0.048
XYR4	0.008	0.002	0.014
XZR4	0	-0.011	0.002
YZR4	-0.020	-0.025	0.014
ZZR4	0.065	0.062	0.068
D2MXR4	0.067	0.052	0.083
D2MYR4	0	-0.031	0.025
D2MXR5	0.024	0.005	0.043
D7MY7	0	-0.003	0.017
D8MY9	0	∞	∞
D2MY10	0	∞	∞
kt1	2.393		
kt2	0.870		
kt3	1.0		

(d)

Figure 2: (a) (b) (c) measured (–) and predicted (...) currents axis. (d) identified parameters