Automatica, Vol. 28, No. 5, pp. 1011–1016, 1992
Printed in Great Britain.

0005-1098/92 $5.00 + 0.00
Pergamon Press Ltd

Brief Paper

Identification of the Barycentric Parameters of Robot Manipulators from External Measurements*

B. RAUCENT,†|| G. CAMPION,‡§ G. BASTIN,‡ J. C. SAMIN† and P. Y. WILLEMS‡

Key Words—Robot modelling; parameter estimation.

Abstract—An original procedure for the estimation of the barycentric parameters of a robot is presented. This procedure requires only the processing of measurements provided by an external experimental set-up. The procedure is based on the property that the relations between the robot motion and its reactions on the bedplate are completely independent of the internal joints forces. A convincing validation experiment on a PUMA 562 is reported.

1. *Introduction*

THE CONTROL ALGORITHMS which are commonly implemented on industrial robots do not account for the inherent nonlinearities of the dynamical robot motion. For this reason these control laws break down for high speed operation when the nonlinear effects become important. High speed and high-precision control can however be achieved using advanced control algorithms, such as "the computed torque" control. Such control laws require an accurate and in-depth knowledge of the robot dynamical model. Under the assumption of n rigid links, the dynamical equations, derived for instance using Lagrange's formalism, take the form of a set of n nonlinear coupled differential equations. The structure of these equations is well known but they involve characteristic parameters which have to be estimated with a good precision. These parameters can be classified in four sets.

(1) The geometrical parameters (lengths of the links, positions of the joints, . . .), which are constant and can be assumed to be known with a good accuracy, because they result directly from the design and the construction of the manipulator.
(2) The inertial parameters of the links, characterizing the mass distribution for each link. The numerical values of these parameters are constant during the lifetime of the manipulator and can therefore be identified once and for all in the course of the acceptance tests.
(3) The terminal mass parameters which are constant for a given operation but can, of course, vary from operation to operation.
(4) The joint parameters (friction in the joints, . . .) undergo a slow variation over the manipulator lifetime. Moreover the modeling of the friction effects (viscous and/or Coulomb friction) is rather complicated.

For most commercial robots the values of these parameters are unknown and parameter estimation is therefore necessary for advanced control algorithm implementation. This paper concentrates on the estimation of the inertial parameters independently of the friction effects and under the assumption that the geometric parameters are known.

In the classical identification approach (see e.g. Mayeda *et al.*, 1984; Ferreira, 1984; Olsen and Bekey, 1985; Gautier, 1986; Armstrong *et al.*, 1986) the values of the parameters are estimated from input (torques applied to the links) and output (positions, velocities and accelerations of the links) data provided by "internal" measurement devices located inside the arms. The dynamical model relating these inputs and outputs is described by a set of differential equations which are linear in a set of so-called barycentric parameters which are themselves nonlinear functions of the inertial and terminal mass parameters (see Raucent, 1990). This implies that the estimation of these barycentric parameters can be performed in principle by linear regression. The practical implementation however presents an important drawback: the torques applied to the links are not directly available but have to be evaluated as sums of the torques provided by the actuators and of the friction torques which may be important. Two problems then occur.

(a) For most commercial robots the torques provided by the actuators can be obtained from internal measurements, but with a poor accuracy. For instance, when the actuator is a DC motor, the torque is measured via the input current through a torque constant which is given from the manufacturer's technical data, albeit with a low precision. Furthermore it can vary over the robot's lifetime.
(b) The implementation of the parameter estimation requires an accurate model of the friction effects. The parameters involved in the friction model have to be estimated together with the barycentric parameters. This coupling can substantially degrade the accuracy of the estimation of the barycentric parameters.

In this paper, we present an alternative approach for the estimation of the barycentric parameters which avoids the two above-mentioned drawbacks (see also Raucent *et al.*, 1988 and Raucent, 1990).

(1) The estimation is based on a reformulation of the dynamics of the system which relates the motion of the robot to the reaction forces and torques on the bedplate and is, therefore, totally independent from the internal torques (i.e. actuator torques and friction torques).

* Received 29 October 1990; revised 9 August 1991; received in final form 15 February 1992. The original version of this paper was presented at the 8th IFAC Symposium on Identification and System Parameter Estimation which was held in Beijing, People's Republic of China during August 1988. The Published Proceedings of this IFAC Meeting may be ordered from: Pergamon Press Ltd, Headington Hill Hall, Oxford, OX3 OBW, U.K. This paper was recommended for publication in revised form by Associate Editor B. Wahlberg under the direction of Editor P. C. Parks.

† Université Catholique de Louvain: Unité de Production Mécanique et Machine (PRM); 2 Place du Levant, B 1348 Louvain la Neuve, Belgium.
‡ Université Catholique de Louvain: Center for Systems Engineering and Applied Mechanics (CESAME); 2 Place du Levant, B 1348 Louvain la Neuve, Belgium.
§ Chercheur qualifié FNRS.
|| To whom correspondence should be addressed.

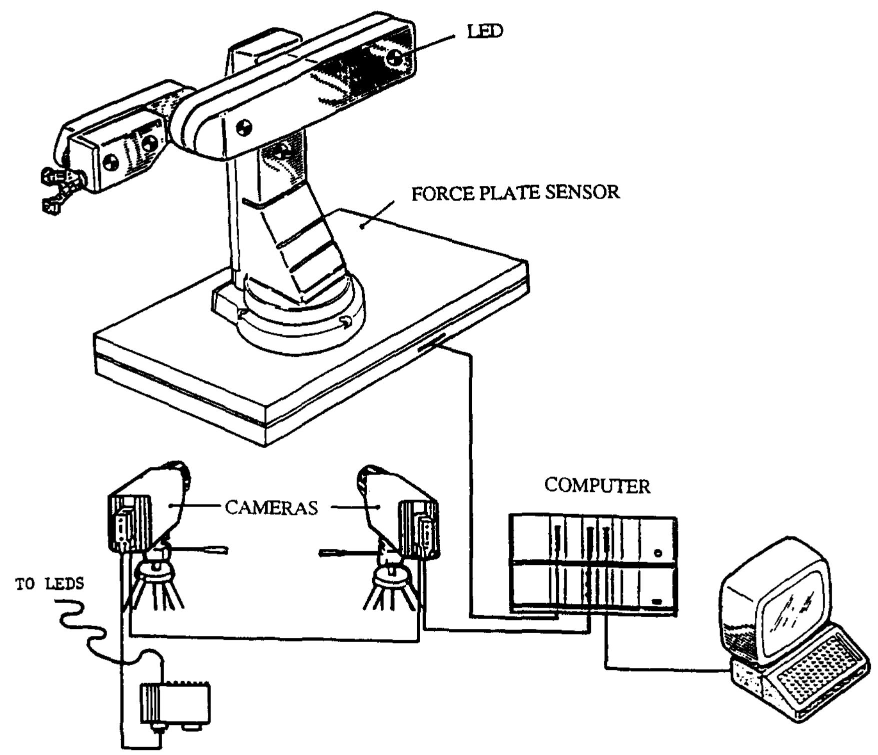

FIG. 1. The experimental set-up.

(2) The estimation method makes use of external measurement only, obtained with a specific experimental set-up.

The paper is organized as follows. The experimental set-up is described in Section 2. The auxiliary reaction model which relates the motion of the robot to the reaction forces and torques on the bedplate is presented in Section 3 while its parametrization is discussed in Section 4. Finally two validation experiments are reported in Section 5.

2. *Sensors and instrumentation*

The experimental set-up we have developed for this study is as follows (see Fig. 1).

(a) The robot is placed on a sensing platform (Kistler Instrumente AG) which is provided with sensors able to measure the three components of the forces and the three components of torques between the bedplate and the first link of the robot. The relative accuracy of this measurement is about 1%. The advantage of this experimental set-up is to provide data (which are processed by the estimation algorithm) with a much better accuracy than those obtained from the actuators.

(b) The measurement of the position of each link is performed by a high-precision visual position sensor (SELCOM AB). Several Light Emitting Diodes are attached to each link of the robot. The light emitted from each diode is captured by two special cameras and, after analogic to digital conversion, a computer programme converts the two images into a three-dimensional result. Positions of the joint are then computed. Finally, the velocity and acceleration are evaluated by numerical differentiation (with appropriate noise digital filtering). The resolution of the system is 1/4096 of the measuring range and the accuracy is about 1/500 of the full scale which depends on the location of the cameras.

By this experimental set-up, all the data which are necessary for the estimation are obtained externally and independently of the hardware of the robot control unit.

3. *Robot models*

In this section we derive the equations describing the *dynamical model* of the robot (relating the motion of the robot to the generalized forces applied to the links) and the *reaction model* (relating the motion of the robot to the forces and torques applied to the bedplate).

Consider a robot manipulator with n rigid links. The n joint coordinates are denoted q_d. Consider in addition a virtual motion of the robot with respect to its bedplate, characterized by six extra coordinates, q_r (three for the virtual translation motion, and three for the virtual rotation motion). In this way we define a generalized system with $(n+6)$-degrees-of-freedom. Of course, any actual motion of the robot is such that q_r remains identically equal to zero: $q_r(t) \equiv 0$ for all t. Due to this constraint, the robot equations are derived using Lagrange multipliers.

Defining the kinetic energy by:

$$T(q_d, q_r, \dot{q}_d, \dot{q}_r) = \tfrac{1}{2}(\dot{q}_d \dot{q}_r) M \begin{pmatrix} \dot{q}_d \\ \dot{q}_r \end{pmatrix}, \tag{1}$$

where

$$M = \begin{pmatrix} M_{dd}(q_d, q_r) & M_{dr}(q_d, q_r) \\ M_{rd}(q_d, q_r) & M_{rr}(q_d, q_r) \end{pmatrix},$$

is the $(n+6) \times (n+6)$ symmetric definite positive inertia matrix of the generalized system; and denoting $U(q_d, q_r)$ the potential energy associated with gravity, the robot motion satisfies the following Lagrange equations:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_d}\right) - \frac{\partial T}{\partial q_d} + \frac{\partial U}{\partial q_d} = Q_d, \tag{2a}$$

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_r}\right) - \frac{\partial T}{\partial q_r} + \frac{\partial U}{\partial q_r} = Q_r, \tag{2b}$$

together with the constraints:

$$q_r = 0. \tag{3}$$

In these equations:

- Q_d is the n-vector of generalized forces associated with q_d, i.e. the vector of the forces and torques applied to the links, including the torques provided by the actuators and the friction effects,
- Q_r is the six-vector of generalized reaction forces and torques applied to the robot by the bedplate. This vector

coincides with the Lagrange multipliers associated with the constraints (3).

Using (1) and (3), the Lagrange equations (2) reduce to:

$$\text{D-model:}\quad M_{dd}(q_d, 0)\ddot{q}_d + f_d(q_d, \dot{q}_d, 0, 0) = Q_d, \qquad (4a)$$

$$\text{R-model:}\quad M_{rd}(q_d, 0)\ddot{q}_d + f_r(q_d, \dot{q}_d, 0, 0) = Q_r. \qquad (4b)$$

Equations (4a) and (4b) are, respectively, the equations of the classical dynamical model of the robot, denoted D-model, and of the reaction model, denoted R-model. The crucial point for the R-model is that Q_r represents only the reactions applied to the first link (which are measured, see Section 2) and is completely independent from the unknown internal forces and torques at the joints (that is the torques produced by the actuators and the friction torques).

4. *Barycentric parametrization*

The dynamical model of any mechanical system made up of rigid bodies is characterized by a set of "inertial" parameters which describe the mass distribution in each link. For each rigid body in the robot there are 10 such basic parameters (one for the mass, three for the position of the center of mass and six for the inertia matrix of the body) but it is well known that there exists a reparametrization, called the barycentric parametrization (Fisher, 1906) which enters the model linearly. Actually, the D- and R-models involve only a few independent linear combinations of the basic set of barycentric parameters. Recursive methods (Raucent, 1990; Gautier, 1990) are used to calculate these linear combinations and lead to the definition of an identifiable linear parametrization, denoted θ_d, for the D-model and another one, denoted θ_r, for the R-model:

$$\theta_d = S_d\theta, \quad \theta_r = S_r\theta,$$

where θ is the full set of N barycentric parameters and S_d and S_r are two full rank constant matrices, respectively of dimension $(N_d \times N)$ and $(N_r \times N)$. It is easily shown in addition that:

(i) $N_d \leq N_r$,

(ii) there exists a full rank $(N_d \times N_r)$ matrix S such that:

$$\theta_d = S\theta_r. \qquad (5)$$

This means that the values of the parameters of the D-model (i.e. θ_d) can be deduced from the values of the parameters of the R-model (i.e. θ_r). It must be kept in mind that we are interested mainly in the numerical values of θ_d, because control design is based on the D-model only.

The linearity of the D- and R-models with respect to the parametrizations θ_d and θ_r implies that M_{rd}, M_{dd}, f_d and f_r can be expressed linearly in the components of θ_d and θ_r as follows:

$$M_{rd}(q_d, 0) = M_{rd0}(q_d, 0) + \sum_{i=1}^{N_r} M_{rdi}(q_d, 0)\theta_{ri}, \qquad (6a)$$

$$M_{dd}(q_d, 0) = M_{dd0}(q_d, 0) + \sum_{i=1}^{N_d} m_{ddi}(q_d, 0)\theta_{di}, \qquad (6b)$$

$$f_d(q_d, \dot{q}_d, 0, 0) = f_{d0}(q_d, \dot{q}_d, 0, 0) + \sum_{i=1}^{N_d} f_{di}(q_d, \dot{q}_d, 0, 0)\theta_{di}, \qquad (6c)$$

$$f_r(q_d, \dot{q}_d, 0, 0) = f_{r0}(q_d, \dot{q}_d, 0, 0) + \sum_{i=1}^{N_r} f_{ri}(q_d, \dot{q}_d, 0, 0)\theta_{ri}, \qquad (6d)$$

where the M_{rd0}, M_{rdi}, M_{dd0}, M_{ddi}, f_{r0}, f_{ri}, f_{d0}, f_{di} are known functions of q_d and $\dot{q}_d$. The R-model can therefore be rewritten as:

$$Q_r - M_{rd0}(q_d, 0)\ddot{q}_d - f_{r0}(q_d, \dot{q}_d, 0, 0) = \varphi(q_d, \dot{q}_d, \ddot{q}_d)\theta_r, \qquad (7)$$

where φ is a $N_r \times 6$ matrix whose ith column is given by:

$$M_{rdi}(q_d, 0)\ddot{q}_d + f_{ri}(q_d, \dot{q}_d, 0, 0). \qquad (8)$$

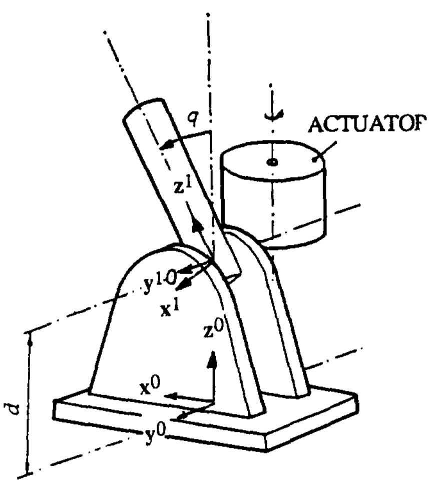

FIG. 2. A one link manipulator.

The left hand side of (7) and the matrix φ can be calculated directly from the measurements provided by the experimental set-up.

We illustrate the notions of the D- and R-models and their parametrizations with an example.

Example. A one link manipulator.

We consider the one-link-manipulator depicted in Fig. 2. In order to describe the geometry and the mass distribution of this manipulator, we introduce two reference frames. The first one is an inertial basis $(\mathbf{x}^0, \mathbf{y}^0, \mathbf{z}^0)$ attached to the base of the robot. $(\mathbf{x}^0, \mathbf{y}^0)$ define the horizontal plane of the bedplate and $\mathbf{z}^0$ is the vertical axis. The second frame $(\mathbf{z}^1, \mathbf{y}^1, \mathbf{z}^1)$ is attached to the link, and $\mathbf{y}^1 = \mathbf{y}^0$ is the axis of rotation (rotation angle q).

The joint is characterized by its position vector $\mathbf{D} = d\mathbf{z}^0$ where d is a known geometric length. The basic inertial parametrization of the link is as follows:

- the mass of the link, denoted m,
- the position of the center of mass given by: $\mathbf{R} = l_y\mathbf{y}^1 + l_z\mathbf{z}^1$
- the central inertia matrix of the link, expressed in the frame $(\mathbf{x}^1, \mathbf{y}^1, \mathbf{z}^1)$ as:

$$J = \begin{pmatrix} J_{xx} & 0 & 0 \\ 0 & J_{yy} & 0 \\ 0 & 0 & J_{zz} \end{pmatrix}.$$

We note that some of the 10 inertial parameters are identically zero. The actuator is assumed to be an electric motor, whose rotation axis is parallel to $\mathbf{z}^0$, with a known inertia moment J^m and a gear down ratio n. These two values are assumed to be given by the manufacturer, and therefore need not to be estimated.

The basic set of barycentric parameters is defined as:

$$\theta = \begin{pmatrix} m \\ mb_y \\ mb_z \\ K_{xx} \\ K_{yy} \\ K_{yz} \\ K_{zz} \end{pmatrix} = \begin{pmatrix} m \\ l_y m \\ l_z m \\ J_{xx} + ((l_y)^2 + (l_z)^2)m \\ J_{yy} + (l_z)^2 m \\ -l_y l_z m \\ J_{zz} + (l_y)^2 m \end{pmatrix}.$$

The equation of the D-model is:

$$\left(-\frac{1}{n} g \sin(q) \quad \frac{1}{n}\ddot{q}\right)\theta_d + F_f = Q_m - n\ddot{q}J^m$$

where F_f is the friction torque (unknown), Q_m is the motor torque and $\theta_d = (mb_z, K_{yy})^T$ is the vector of the model parametrization.

The equations of the R-model are:

$$\begin{pmatrix} 0 & g & 0 & 0 & \sin(q)\ddot{q} + \cos(q)\dot{q}^2 \\ 0 & 0 & \ddot{q} - \sin(q)\dot{q}^2 & 0 & 0 \\ 0 & 0 & d(\cos(q)\ddot{q} - \sin(q)\dot{q}^2) - g\sin(q) & \ddot{q} & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \cos(q)\ddot{q} - \sin(q)\dot{q}^2 \\ g & 0 & -\sin(q)\ddot{q} - \cos(q)\dot{q}^2 & 0 & 0 \end{pmatrix}\theta_r = Q_r - \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ n\ddot{q} \\ 0 \end{pmatrix} J^m,$$

with

$$Q_r = (C_x, F_x, C_y, F_y, C_z, F_z)^T,$$

and

$$\theta_r = (m, mb_y, mb_z, K_{yy}, K_{yz})^T.$$

It appears that five barycentric parameters are involved in the model and that the terms containing m and mb_y are constant. The components of θ_d are a subset of the components of θ_r so that the value of θ_d can be deduced from that of θ_r just by substituting $S = \begin{pmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{pmatrix}$ in equation (5).

5. *Experimental results*

Two experimental applications on an industrial PUMA robot are reported in this section. The first one is presented to illustrate the identification method. The second one is a validation test where the parameter estimates are compared with their true values.

5.1. *Description of the PUMA.* The PUMA 562 (Unimation) is a serial six-degrees-of-freedom manipulator with six revolute joints (Fig. 3). We limit our attention to the first three joints. The other joints which rely on the wrist are assumed to be fixed. We introduce four reference frames:

(a) An inertial basis $(\mathbf{x}^0, \mathbf{y}^0, \mathbf{z}^0)$ attached to the base of the robot, where $(\mathbf{x}^0, \mathbf{y}^0)$ define the horizontal plane of the bedplate and $\mathbf{z}_0$ is the vertical axis.
(b) A basis $(\mathbf{x}^1, \mathbf{y}^1, \mathbf{z}^1)$ attached to the first link with $\mathbf{z}^1 = \mathbf{z}^0$ the axis of rotation (angle q^1) and positioned by the vector: $\mathbf{D}^1 = d^1\mathbf{z}^0$.
(c) A basis $(\mathbf{x}^2, \mathbf{y}^2, \mathbf{z}^2)$ attached to the second link with $\mathbf{y}^2 = \mathbf{y}^1$ the axis of rotation (angle q^2).
(d) A basis $(\mathbf{x}^3, \mathbf{y}^3, \mathbf{z}^3)$ attached to the third link with $\mathbf{y}^3 = \mathbf{y}^2$ the axis of rotation (angle q^3) and positioned by the vector: $\mathbf{D}^3 = d^1\mathbf{z}^0 + d^3\mathbf{z}^2$.

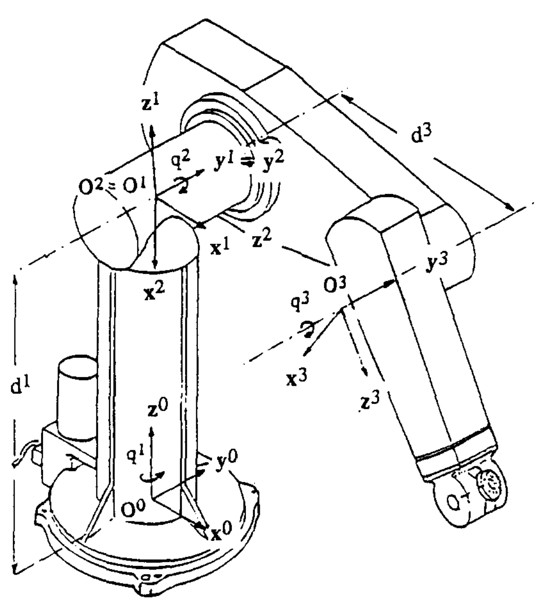

FIG. 3. The PUMA 562 (Unimation).

The mass distribution is described as follows:

- the masses of the three links are denoted m^1, m^2 and m^3,
- the position of the centers of mass are expressed by:

$$\mathbf{R}^1 = d^1\mathbf{z}^0 + l_y^1\mathbf{y}^1,$$
$$\mathbf{R}^2 = d^1\mathbf{z}^0 + l_y^2\mathbf{y}^2 + l_z^2\mathbf{z}^2,$$
$$\mathbf{R}^3 = d^1\mathbf{z}^0 + d^3\mathbf{z}^2 + l_y^3\mathbf{y}^3 + l_z^3\mathbf{z}^3,$$

- the central inertia matrices of the three links are expressed in the bases $(\mathbf{x}^i, \mathbf{y}^i, \mathbf{z}^i)$ with $i = 1$, 2 or 3, by:

$$\mathbf{J}^i = \begin{pmatrix} J_{xx}^i & 0 & 0 \\ 0 & J_{yy}^i & 0 \\ 0 & 0 & J_{zz}^i \end{pmatrix}.$$

As in the example of Section 4, we note that some of these inertial parameters are known *a priori* to be zero. In particular, the inertia matrices of the links are diagonal because the chosen reference frames are supposed to be aligned with the principal axes of inertia. Moreover, it must be pointed out that the motor characteristics are given by the manufacturer and are therefore not to be estimated.

In order to satisfy the identifiability conditions presented in Section 5, the parametrizations θ_d and θ_r must be defined as follows (see Raucent, 1990):

$$\theta_d = \begin{pmatrix} J_{zz}^1 + m^1(l_y^1)^2 + J_{zz}^2 + m^2(l_y^2)^2 + J_{zz}^3 + m^3(l_y^3)^2 \\ J_{xx}^2 - J_{zz}^2 + m^3(d^3)^2 + m^2(l_z^2)^2 \\ J_{yy}^2 + m^3(d^3)^2 + m^2(l_z^2)^2 \\ -m^2 l_y^2 l_z^2 - m^3 d^3 l_y^3 \\ J_{xx}^3 - J_{zz}^3 + m^3(l_z^3)^2 \\ J_{yy}^3 + m^3(l_z^3)^2 \\ -m^3 l_y^3 l_z^3 \\ m^3 d^3 + m^2 l_z^2 \\ m^3 l_z^3 \end{pmatrix},$$

$$\theta_r = \begin{pmatrix} \theta_d \\ m^1 l_y^1 + m^2 l_y^2 + m^3 l_y^3 \end{pmatrix}.$$

It appears that θ_d is included in θ_r. The corresponding D and R-models equations have been automatically generated by the software ROBOTRAN developed by Maes (1990).

5.2. *Identification of the link parameters.* The identification of the PUMA 562 parameters has been performed from data obtained with the external experimental set-up described in Section 2. The results are compared in Table 1 with parameter values calculated on the basis of the data obtained with internal measurements given respectively by Tarn *et al.* (1985) and Armstrong *et al.* (1986).

Table 1 clearly shows that the values obtained with our approach are of the same order of magnitude as the values obtained with other methods. A more precise validation of the results is not possible in this case since the exact values of the parameters of the PUMA 562 are not available. In the next section we present a genuine validation experiment where the estimates can be compared to true values.

TABLE 1. ESTIMATION OF THE PARAMETERS OF THE PUMA 562

Parameters	External identification	Tarn (1985)	Armstrong (1986)
$\theta_d(1)$ (kg m^2)	1.665	1.920	1.357
$\theta_d(2)$ (kg m^2)	2.888	2.384	2.829
$\theta_d(3)$ (kg m^2)	2.234	2.786	2.174
$\theta_d(4)$ (kg m^2)	−0.598	−0.558	−0.605
$\theta_d(5)$ (kg m^2)	0.567	0.533	0.300
$\theta_d(6)$ (kg m^2)	0.545	0.547	0.336
$\theta_d(7)$ (kg m^2)	−0.103	−0.150	−0.142
$\theta_d(8)$ (kg m)	3.212	3.702	3.790
$\theta_d(9)$ (kg m)	0.802	1.061	0.864

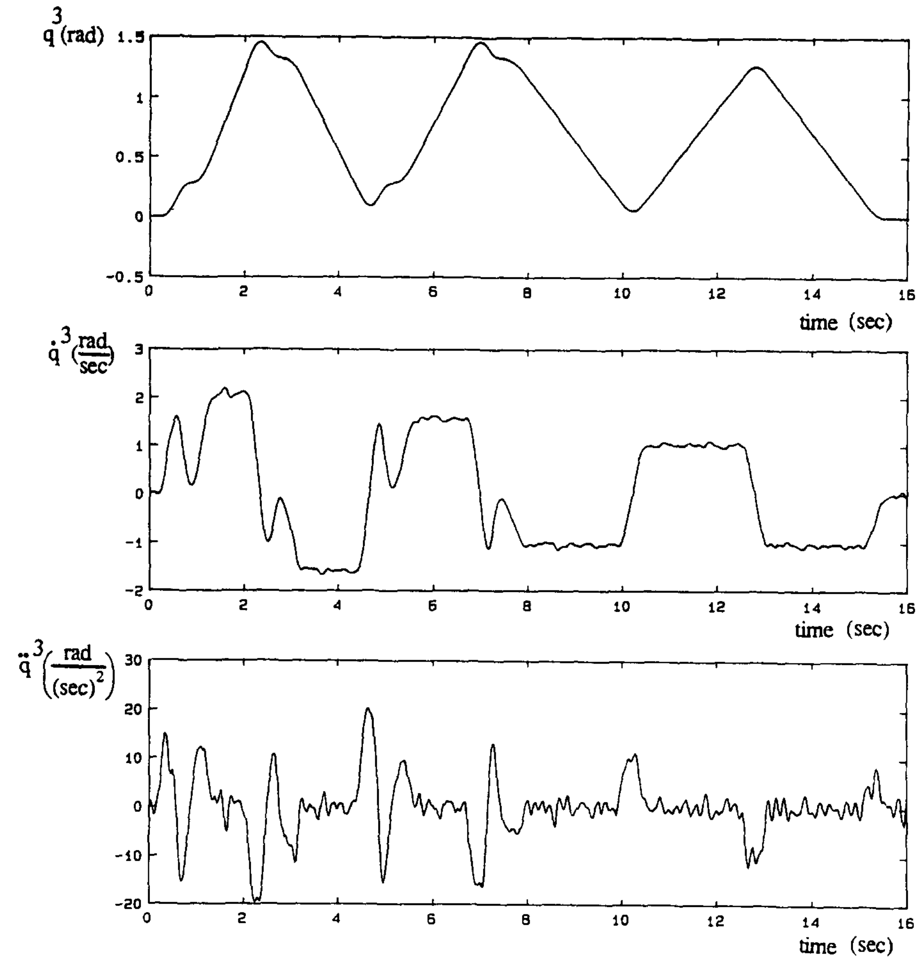

FIG. 4. Example of a test trajectory (motion only on the third axis).

5.3. *Validation test: identification of known load parameters.* We reduce the PUMA to a one-degree-of-freedom robot by only moving the third link (Fig. 4). As shown in Section 4 the parameters of the D-model reduce, in this case, to:

$$\bar{\theta}_d = \begin{pmatrix} mb_z \\ K_{yy} \end{pmatrix}.$$

We now modify the system by adding a known load mass ($M = 3.87$ kg) attached to the third link. The position of the center of mass of the load is given by the vector $\mathbf{R} = l\mathbf{z}^3$ (with $l = 0.514$ m). The parameters of the modified system differ from the previous ones as follows:

$$\bar{\theta}_d^* = \begin{pmatrix} mb_z \\ K_{yy} \end{pmatrix} + \begin{pmatrix} Ml \\ Ml^2 \end{pmatrix}.$$

We estimate $\bar{\theta}_d^*$ with the same test trajectory as before. Then, by the comparison of the estimates of $\bar{\theta}_d^*$ and $\bar{\theta}_d$, we can deduce estimates of Ml and Ml^2 which can in turn be compared to their exact values. This is done in Table 2. The results in this Table show an extremely good agreement between the exact and estimated values, and hence lends the credibility of this identification approach.

TABLE 2. IDENTIFICATION OF THE LOAD

	Estimated	Exact
Ml (kg m)	1.949	1.989
Ml^2 (kg m^2)	1.052	1.025

6. *Conclusions*

We have shown that the estimation of the barycentric parameters involved in the dynamic model of a robot can be achieved by processing external measurements only (reactions at the bedplate; positions, velocities and accelerations provided by a vision device).

The originality of this method lies in the use of the auxiliary reaction model (R-model) which is completely independent of the internal forces and torques at the joints while the usual parameter estimation algorithms are based on internal measurements (torques applied by the actuators) which are noisy and inaccurate, due mainly to the friction effects. In contrast, the use of external measurements of positions, velocities and accelerations is clearly not an imperative requirement. The interest is to devise "acceptance tests" that can be carried out independently of the hardware of the robot control unit. But, obviously if the robot is provided with high accuracy position and velocity sensors, internal measurement can be used as well in our identification method.

Finally, we must mention that even if the barycentric parameters have been identified with a great accuracy, the dynamical model of the robot will still contain some uncertain time varying parameters, namely the friction coefficients, actuator parameters (torque constant) and the barycentric parameters that are affected by the transported load. As usual these remaining uncertain parameters can be compensated by using adaptive techniques for the design of advanced control systems (see Canudas *et al.*, 1987 and Craig, 1988).

Acknowledgements—The results presented in this paper have been obtained within the framework of the Belgian Programme on Concerted Research Actions and on

Interuniversity Attraction Poles initiated by the Belgian State, Prime Minister's Office, Science Policy Programming. The scientific responsibility rests with its authors.

References

Armstrong, B., O. Khatib and J. Burdick (1986). The explicit dynamic model and inertial parameters of the PUMA 560 arm. *Proc. IEEE Int. Cong. Robotics and Automation*, pp. 510–518.

Canudas, de Wit C., K. J. Aström and K. Braun (1987). Adaptive friction compensation in DC motor drives. *IEEE J. of Robotic and Automation*, **3**, 681–685.

Craig, J. J. (1988). *Adaptive Control of Mechanical Manipulators*. Addison-Wesley, Reading, MA.

Ferreira, E. P. (1984). Contribution à l'identification de paramètres et à la commande dynamique adaptive des robots manipulateurs. Thèse, Université Paul Sabatier, Toulouse.

Fisher, O. (1906). *Einführung in die Mechanik Lebender Mechanismen*. Leipzig, Germany.

Gautier, M. (1986). Identification of robot dynamics. *Proc. IFAC Symposium on Theory of Robots*, Vienna p. 351.

Gautier, M. (1990). Contribution à la modélisation et à l'identification des robots. Thèse de doctorat d'état, Université de Nantes, France.

Maes, P., J. C. Samin and P. Y. Willems (1990). AUTODYN and ROBOTRAN Computer Programmes. In W. Schiehlen (Ed.), *Multibody Systems Handbook*, pp. 225–264, Springer-Verlag, Berlin.

Mayeda, H., K. Osuka and A. Kangawa (1984). A new identification method for serial manipulator arms. *Preprints 9th IFAC World Congress*, 2–6 July, Budapest, **4**, 74–79.

Olsen, H. B. and G. A. Bekey (1985). Identification of parameters in models robots with rotary joints. *Proc. IEEE Conf. Robotics and Automation*, 25–28 Mars, St Louis, 1045–1050.

Raucent, B., G. Campion, G. Bastin and J. C. Samin (1988). Identification of barycentric parameters of robotic manipulators from external measurement. *Proc. of 8th IFAC Symposium on Identification and System Parameters Estimation*, Beijing, pp. 1292–1297.

Raucent, B. (1990). Identification des paramètres dynamics des robots manipulateurs. Thèse Université Catholique de Louvain, Louvain-La-Neuve, Belgium.

Tarn, T. J., A. K. Bejczy, Shuotiao Han and Xiaoping Yun (1985). Inertia Parameters of PUMA 560 Robot Arm, Robotics laboratory report.