13th Triennial World Congress, San Francisco, USA

EXPERIMENTAL IDENTIFICATION OF ROBOT AND LOAD DYNAMICS

Krzysztof R. Kozlowski *,[1] **Piotr Dutkiewicz** **

* *Poznan Technical University, Department of Control, Robotics and Computer Science, ul. Piotrowo 3a, 60-965 Poznan (Poland), kk@ar.kari.poz.edu.pl*
** *Poznan Technical University, Department of Control, Robotics and Computer Science, ul. Piotrowo 3a, 60-965 Poznan (Poland), pdut@ar.kari.poz.edu.pl*

Abstract. The main objective of this paper is presentation of an experimental identification of a non-direct drive robot and load dynamic parameters, which appear in the differential and integral models. In the robotics literature there are not many experimental results known to the authors, concerning the identification of the dynamic parameters of different models. In order to satisfy this, the experimental system has been built around ASEA IRp-6 robot. In the paper we propose to precompute the friction characteristics which are seperated in the integral model. Various aspects of the exciting trajectories are considered. The experimental results are presented. The identified models are verified by computing the predicted torques and trajectories.

Keywords. Robot and load dynamics models, Friction, Parameter identification, Exciting trajectories.

1. INTRODUCTION

Recently, robot control based on a mathematical model of the nonlinear and coupled arm and the gripped load dynamics reaches great importance. Therefore, many attempts have been carried out in identification of these parameters. Very useful are methods, where links of the robot are made to follow the predefined test trajectory (Gautier and Khalil, 1988; Kozlowski and Prüfer 1992). The movement parameters (positions, velocities, etc.) are measured simultaneously, and from them the robot and load dynamic parameters can be calculated.

Generally we can consider differential or integral dynamics models. The first one is the same as the standard equations of motion for robot dynamics. It is assumed that the robot model is canonical (Lu et al, 1993; Seeger, 1991), which means that the vector, X, of the parameters consists of the minimum number of parameters which are the combinations of the link inertial parameters (namely mass, and first and second moments of the individual links).

Integral models are derived based on the energy theorem (Gautier and Khalil, 1988). Both differential and integral models have the same set of the minimum number of the inertial parameters (Lu et al., 1993). In both representations it is assumed that the friction torques, τ_f, are represented by appropriate curves (Prüfer and Wahl, 1994), and we do not look for the friction coefficients which appear in approximation of the friction model. It is usually difficult to measure the friction torques for both differential and integral models. Seeger (1991) proposed to measure the friction torques for a class of

[1] This paper presents research performed under grant KBN 8 S505 009 06 (Polish Committee on Scientific Research)

geared robots, taking Manutec r3 robot as an example. For the same class of robots but described by an integral model Kozlowski and Dutkiewicz (1995a) proposed a method to measure the friction torques.

So for only a few experimental studies on off-line robot dynamics estimation were analyzed in the robotics literature (An et al., 1988; Prüfer and et al., 1994). Not many papers are devoted to the identification of load parameters (namely mass, center of mass and six parameters of the inertia tensor). Some results can be found in An et al. (1988). In order to do these experiments the robot has to be equipped with force and torque sensor.

Some remarks concerning comparison of the differential and integral models can be found in the work done by Prüfer et al. (1994). In this paper we extend these results by considering design of an optimal trajectory for both types of models. Generally one can notice that the differential model is more reach in information since all equations for the generalized torques are present. In case of the integral model (energy model) we deal only with one scalar equation. Because of that the optimal trajectory design for the integral model is more crucial and diffficult. It has been noticed that the identification results in case of the integral model appears to be not very sensitive to filtering measurements because of its natural lowpass filter behaviour. Comparing both models from the measurement point of view one can notice that in case of the integral model the acceleration signals are not required. In order to avoid the acceleration signals in the differential model one can integrate the differential model but it is not preferred because an integrator is an infinite-gain filter at zero frequency (Lu et al., 1993). This means that large errors can result from small low-frequency errors such as offsets. To overcome this shortcoming, a low-pass filter with unit gain at zero frequency can be applied to the differential model (Lu et al., 1993; Gautier et al., 1995). In this paper we rather focus our attention on optimal trajectory design for both discussed models.

Originally first considerations on finding exciting trajectories for the identification of the dynamic parameters of robot were carried out by Armstrong (1989). He suggested to minimize the condition number or one over the minimum singular value (Golub and Van Lean, 1989) of the information matrix. Vandanjon, et al. (1995) proposed the minimization of the frobenius condition number of the information matrix. A comparison of different criteria of exciting trajectories for robot identification were considered by Presse and Gautier (1993). We have decided to use as a criterion the condition number. We have implemented this criterion for both integral and differential models for robot and load. The optimization scheme follows one presented by Armstrong (1989) with the extension to the integral model. Some results obtained by the authors are presented in Kozlowski and Dutkiewicz (1995b).

Paper is organized as follows. In Section II, the differential and integral (for robot and load) dynamic models have been presented, including friction effects. In Section III, the identification algorithm has been outlined. In Section IV, different friction characteristics have been depicted. In Section V, the experimental results of the differential and integral robot model parameters identification have been presented. Friction characteristics, load identification, and optimal trajectories are presented too. In Section VI, verification of the models is discussed, and finally concluding remarks end the paper.

2. ROBOT AND LOAD DYNAMICS MODEL

The dynamic properties of the i-th link of the manipulator are characterized by the inertia tensor ${}^iI_i$, the first moment $m_i{}^ic_i$, and the mass m_i. The friction generalized force acting at the i-th joint is assumed to be of the form (which is a simplified form)

$$\tau_{if}(\dot{q}_i) = F_{iv}\dot{q}_i + F_{ic}\mathrm{sign}(\dot{q}_i) \; , \tag{1}$$

where F_{iv} is the viscous friction coefficient of the i-th link, F_{ic} is the coefficient of the Coulomb friction (independent of the magnitude of the velocity).

Since the total energy of the robot is linear with respect to inertial parameters, formal differentiating of the lagrangian leads to the following vector equation

$$\tau = D(q, \dot{q}, \ddot{q}) \; X \; , \tag{2}$$

where $q = [q_1, q_2, \cdots, q_n]^T$ is the vector of generalized coordinates q_i (angular or linear displacements), $\dot{q} = [\dot{q}_1, \dot{q}_2, \cdots, \dot{q}_n]^T$, $\ddot{q} = [\ddot{q}_1, \ddot{q}_2, \cdots, \ddot{q}_n]^T$, $\tau = [\tau_1, \tau_2, \cdots, \tau_n]^T$ is the vector of generalized forces τ_i (force or torque, depending on the type of the joint), and D is a $(n \times 12n)$ matrix, whose elements depend on q, $\dot{q}$, $\ddot{q}$, and X is a vector of robot dynamic parameters. So described robot dynamics model is called a differential model.

Application of the energy theorem leads to the following equation

$$y = \int_{t_1}^{t_2} \tau^T \dot{q} dt = d^T(q, \dot{q}) X \; , \tag{3}$$

which is linear in the inertial and friction parameters, and vector d depends on q and $\dot{q}$. It does not require the knowledge of the joint acceleration, and is often called the integral model (Gautier and Khalil, 1988) as opposite to the differential model (2). Here we make one comment. For the purpose of identification a sufficient number of equations has to be calculated based on equation (3) between different time intervals. One possibility is to calculate the k-*th* equation in the time interval $(t_1, t_2)_k$. Another one is to calculate equation (3) in time interval which start from $t_0 = 0$ and end t_f where t_f denotes a final time of calculations (Kozlowski and Prüfer, 1992; Prüfer and Wahl, 1994). In the first situation we are dealing with a short-time integral, in the second case we have long time integral.

Now we recall the results for the load dynamic parameters models (An et al., 1988). The differential model for the load parameters holding at the gripper can be written as follows

$$W = K\,\Phi\,, \tag{4}$$

where $W = [F_x, F_y, F_z, N_x, N_y, N_z]^T$ is a (6×1) vector consisting of force and torque coordinates, expressed in the local coordinate frame of the force/torque sensor. K is a (6×10) matrix which depends on angular and linear velocities and accelerations of the frame in which the forces and torques are measured, and Φ is a vector (10×1) of the load dynamic parameters. The acceleration signals are difficult to measure. To avoid this, (4) can be integrated (An et al., 1988) in the time interval $(t, t+T)$, where $(t, t+T) = (t_1, t_2)_k$, or $(t, t+T) = (t_0, t_f)$ in the local coordinate frame with the origin at the point affixed to the force/torque sensor.

3. IDENTIFICATION SCHEME

The identification scheme for both robot and load dynamic models is the same. Therefore, only the robot dynamic parameters identification algorithm for the integral robot dynamics (short integral) model will be shortly outlined. Moreover, it will be assumed that the model described by equation (3) is canonical. In order to identify X, a sufficient number of equations, obtained by calculating the equation (3) in different time intervals, should be used. For the k-th interval $(t_1, t_2)_k$, such an equation has the form

$$y_k = d_k^T\,X\,. \tag{5}$$

Recall that y_k in equation (5) is the integral value of the dot product of generalized forces vector τ and generalized velocities vector $\dot{q}$ in time interval $(t_1, t_2)_k$. Assuming that k varies from 1 to r and taking into account equation (5), the following equation can be written:

$$y_r = h_r\,X + w\,, \tag{6}$$

where w is the observation error vector, $h_r = [d_1, \cdots, d_r]^T$, and $y_r = [y_1, \cdots, y_r]^T$. Assuming that $r > M_c$ (M_c is the number of inertial parameters of the canonical model), the least squares method leads to the formula

$$X = \left(h_r^T h_r\right)^{-1} h_r^T y_r\,. \tag{7}$$

The condition for the solution of this equation to exist is that matrix h_r be positive definite. As it was mentioned before for the k-th equation (3) different lengths of the time interval $(t_1, t_2)_k$ may be assumed. In case when $t_1 = t_0$ and $t_2 = t_k$, the observation of equation (3) is performed from the start with growing time interval.

4. FRICTION CHARACTERISTICS

In Section 2 we have introduced a very simple friction model given by equation (1). Armstrong-Hélouvry (1991) studied different friction models. Usually researches assume the existence of dry and velocity dependent parts in the friction phenomena An et al., 1988; Lu et al., 1993). Very seldom authors analyze the friction coefficients as a function of temperature changes (Prüfer and Wahl, 1994), which is particularly important for geared robots.

In this section we propose a simple experimental method, which allows to model the exponential friction characterization at a wide range of velocities for a geared robot. First we rearange (3) as follows

$$\int_{t_1}^{t_2} \tau^T \dot{q}\,dt = H(t_2) - H(t_1) + \int_{t_1}^{t_2} \tau_f^T \dot{q}\,dt \tag{8}$$

where τ_f represents the vector of joint friction torques, and $H(t_1)$ is the total energy of the system at time t_i. Notice that the vector τ_f incorporates Coulomb and viscous friction coefficients (compare equation (1)) and all the other friction phenomena. In order to measure the friction torque we propose the following method:

- i-th link is moved alone with constant velocity (possible the smallest). During the movement, corresponding current is measured, as well as the desired constant velocity and position.
- The velocity is incremented by $\Delta\dot{q}$ and the procedure described in the first point is repeated.
- The procedure is terminated when the maximum velocity for the i-th link is achieved.

The assumption of the constant velocity leads to the situation in which the difference between the kinetic energy in equation (8) vanishes. For the column of the robot there is no gravitation, and the difference of the potential energy vanishes. For other joints in order to make the difference of the potential energy equal to zero one can move a joint with constant velocity in a small vicinity around a given position (we recognize the direction of the movement, which is consistent with the assumption that the friction depends on the direction of the rotation). Making use of the above assumptions we can rearrange equation (8) as follows

$$\tau_{f_i}|_{q=const} = \frac{\int_{t_1}^{t_2} \tau_i dt}{t_2 - t_1}. \tag{9}$$

If it is not possible to keep the constant velocity during the movement, one can average the measured velocity signal during its movement. A similar approach has been implemented for the differential model of the Manutec robot by Seeger (1991).

5. EXPERIMENTAL RESULTS

The main part of an experimental set-up consists of the IRp-6 robot. The IRp-6 robot has gear mechanism in which harmonic drives are used. Each motor's position, velocity, and current can be measured by means of a resolver, a tachometer, and the external measurement unit, enabling monitoring (with a sampling rate of 0.5 ms) of axis positions q_i, velocities $\dot{q}_i$, and currents of the DC motors of the robot, which are proportional to the driving torques τ_i. A strain gauge force/torque sensor is used to measure, in the local coordinate frame, coordinates of force and torque exerted at the load gripped by the robot.

The experimental identification of the IRp-6 robot inertial and friction parameters has been carried out for the first three links. The parameterization of the IRp-6 robot dynamics integral model leads to 13 aggregated parameters $X_1, \cdots, X_{13}$ (aggregated parameters are linear combinations of parameters of individual links given by equation (2) which lead to canonical differential or integral model) and accompanying expressions d_i which are omitted due to lack of space.

Identification of all 13 parameters during simultaneous movement of the three links, using both short and long integral, did not complete successfully. Because of this only movements of single joints as well as simultaneous movement of two joints were executed. For example, the data measured during the movement of the 2-nd link allow to obtain the following aggregated parameters X_i and the d_i expressions:

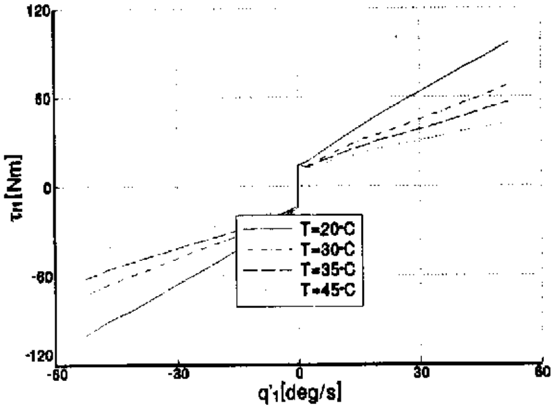

Fig. 1. Friction torques versus velocity for the first joint

$$\begin{aligned} X_1 &= m_2 c_{2x} + m_3 l_2 & d_1 &= g \cos q_2 \\ X_2 &= I_{2zz} + \left(\frac{dF_2}{d\phi_2}\right)^2 I_{a2} + m_3 l_2^2 & d_2 &= \tfrac{1}{2}\dot{q}_2^2 \\ X_3 &= F_{2v} & d_3 &= \int \dot{q}_2^2 dt \\ X_4 &= F_{2c} & d_4 &= \int |\dot{q}_2| dt \end{aligned}$$

The test trajectory consists of splined polynomials of the 5-th order. The estimates $\hat{X}_1$, $\hat{X}_2$, $\hat{X}_3$, and $\hat{X}_4$ of the aggregated parameters are equal to $\hat{X}_1 = 8.125$ kgm, $\hat{X}_2 = 5.5$ kgm^2, and the friction parameters $\hat{X}_3 = 26$ Nms, and $\hat{X}_4 = 28.75$ Nm. The estimates, settle in the time of $1 \div 1.5$ s and 8000 samples have been measured for one movement. The results of three separate movements of different single joints allow to identify all of 13 aggregated parameters mentioned above. The presented results were calculated using short integral (with the step of 5 ms). The results of long integral were significantly worse, as in this case the errors of the measurements of $\dot{q}$ and τ were accumulated.

General procedure to measure the friction characteristics has been described in previous section. Nevertheless, a different scenario has been proposed for the link at the base of the manipulator. It has been observed, that due to the presence of oil in the harmonic drive, the friction characteristic depends on the temperature. The temperature has been changed from 20°C to 45°C. For the arm and forearm of the IRp-6 robot this phenomenon has not been observed. For each joint the sticktion friction in both directions has been measured. In order to observe this phenomenon for each increment, motor positions were inputted to the controller, and at the same time a torque was measured by the force/torque sensor in contact with rigid environment. When tested joint started to move the measured torque was recorded as a sticktion friction. For the first joint in both directions the sticktion torque is 14.1Nm. For the second joint the sticktion torque in positive velocity direction is 16.8Nm and in negative direction is 10.6Nm. For the third joint these numbers are 18.0Nm and 14.1Nm, respectively. In

Table 1. Dynamic Parameters of the Load

Parameter	Computed Values	Estimated Values	Standard Deviation	Confidence Interval
m $[kg]$	1.910	1.916	0.024	0.011
mc_x $[kgm]$	0.0573	0.0568	0.0028	0.0013
mc_y $[kgm]$	−0.0210	−0.0207	0.0088	0.0042
mc_z $[kgm]$	0.1394	0.1396	0.0091	0.0044
I_{xx} $[kgm^2]$	0.01050	0.01186	0.0051	0.0024
I_{xy} $[kgm^2]$	0.00094	−0.00083	0.0014	0.00067
I_{xz} $[kgm^2]$	−0.00450	−0.00751	0.0017	0.00084
I_{yy} $[kgm^2]$	0.01635	0.01567	0.0071	0.0034
I_{yz} $[kgm^2]$	0.00169	0.00001	0.00060	0.00029
I_{zz} $[kgm^2]$	0.00520	0.00449	0.00037	0.00018

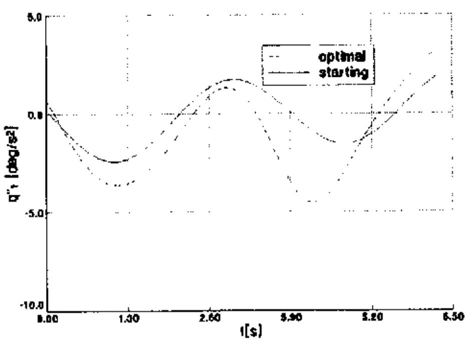

Fig. 2. Starting and optimal trajectories for the first joint; load identification

Fig.1 the friction torques versus velocity for the first joint are presented.

In load identification the differential model with dynamic parameters, described by equation (4), has been used. As an example, the identification results of a steel cuboidal load are presented. Its dynamic parameters are easy to calculate using its measured mass and geometric parameters. Dynamic parameters, presented in Table I, were determined in the local coordinate frame, assigned to the force/torque sensor. It was assumed that the movement of each joint was described by a polynomial of the 5-th order in the joint coordinate. The time of the movement was equal 1.83 s for each joint. Comparing the estimates to the computed values (see Table I), it can be noticed that the mass and the static moment were estimated exactly. The estimates of the inertia products, smaller than the inertia moments, are worse. By repeating the measurement 20 times, the standard deviation was obtained. This means that should the model be correct the true values of the dynamic parameters can be precisely identified with high confidence level (in our case of 99 %).

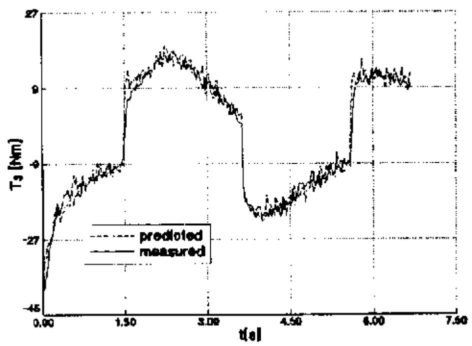

Fig. 3. Measured and predicted torques for the third joint

To improve the accuracy of the identified parameters we have run program which calculates optimal trajectories according to the scheme presented by Armstrong (1989) and then we extended these results to the integral model. We have run numerical calculations for the integral model moving only one joint and having other joints idle. For numerical experiments we have used equation (8). Moving second joint only and not actuating first and second joints, and assuming cosine input trajectory for the second joint we have got the initial value of the condition number about 3000. After about 23 iterations this value changed to 500. We did not neglect the friction coefficients in equation (8).

Finally we have run numerical calculations for optimal trajectories for load identification. It was more difficult to find a good trajectory due to the fact that for load identification we have to choose five joint positions q_i. The problem is bigger in size and takes more computation time. The best result were obtained by using trajectories being linear combination of sine and cosine functions. The initial value for this set of trajectories was 90830 and after 40 iterations went down to about 3000. Starting from this point it was not possible to improve the condition number. For each trajectory we have calculated 200 points with sampling instant $\Delta t = 32ms$. As an example we show the numerical results for the first joint in Figure 2.

6. VERIFICATION OF THE MODEL

The accuracy of the estimation is also verified by comparing the measured joint torques with the predicted torques using the identified parameters with optimal trajectories. As shown in Figure 3, for the third joint, the predicted torques match the measured (actual) torques closely. This means that the model we have determined accurately reflects the dynamic relationship of the robot.

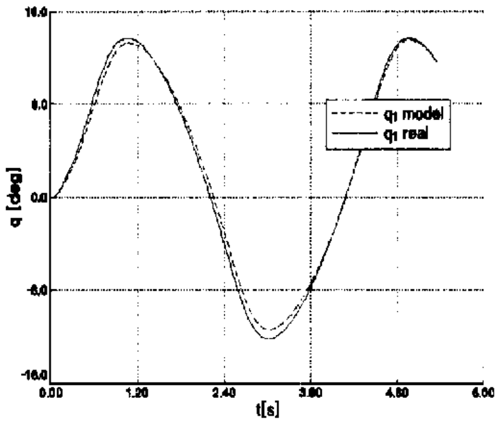

Fig. 4. Measured and simulated positions for the first joint

We have also compared the measured – real and simulated – modelled (calculated by solving a set of differential equations describing the robot model with estimated dynamic parameters) joint positions. As an example positions for the first joint are presented in Figure 4. The results in that case show good agreement of the simulation with the measured behaviour. In both cases the results for other joints are of similar nature. Here we make one comment. Authors seldom compare the measured and simulated trajectories, except Pfeiffer and Hölzl (1995).

7. CONCLUDING REMARKS

Exciting trajectories are very important for the integral model due to loss of information in this model in comparison with the differential model. Therefore we have run several numerical experiments particularly for this model for both robot and load dynamic parameters identification. We argue that a trial and error method in choosing an exciting trajectory does not necessary always give good results. This phenomenon was observed in the process of load identification. Some initial trajectory were chosen close to optimal, for example we have chosen some trajectories with initial condition number as low as 181 which next was not improved by the optimization procedure. The numerical results were successfully verified by the experimental results with the IRp-6 industrial robot.

8. REFERENCES

An C.H., Atkeson C.G., & Hollerbach J.M. (1988). Model-based control of a robot manipulator. *The MIT Press.*

Armstrong-Hélouvry (1991). Control of machines with friction. *Kluwer Academic Publishers.*

Armstrong B., (1989). On finding exciting trajectories for identification experiments involving systems with nonlinear dynamics. *The International Journal of Robotics Research* **8**, 28–48.

Dutkiewicz P., Kozlowski K., & Wroblewski W. (1993). Experimental identification of robot and load dynamics parameters. *Proc. of the 2-nd IEEE Conference on Control Aplication* pp. 767–776.

Gautier M., Khalil W. (1988). On the identification of the inertial parameters of robots. *Proc. of the 27th CDC* pp. 2264–2269.

Gautier M., Khalil W., & Rastrepo P.P. (1995). Identification of the dynamic parameters of a closed loop robot. *Proc. of the 1995 IEEE International Conference on Robotics and Automation* pp. 3045–3050.

Golub G.H., Van Loan C.F. (1989). Matrix computation. *John Hopkins University Press.*

Kozlowski K., Dutkiewicz P. (1995a). Identification of friction and robot dynamics for a class of geared robots. *Proc. of the Fourth Int. Symposium on Measurement and Control in Robotics* pp. 301–306.

Kozlowski K., Dutkiewicz P. (1995b). Optimal trajectory design for the identification of robot and load dynamics. *Appl. Math. and Comp. Sci.* **5**, 671–687.

Kozlowski K., Prüfer M. (1992). Parameter identification of an experiment 2-link direct drive arm. *Proc. of the IASTED Int. Conf., C&R* pp. 313–316.

Lu Z., Shimoga K.B. & Goldenberg A.A. (1993). Experimental determination of dynamics parameters of robotic arms. *Journal of Robotics Systems* **10**, 1009–1029.

Pfeiffer F., Hölzl (1995). Parameter identification for industrial robots. *Proc. of the 1995 IEEE Int. Conf. on Robotics and Automation* pp. 1468–1475.

Presse C., Gautier M. (1993). New criteria of exciting trajectories for robot identification. *Proc. of the IEEE Int. Conf. on R&A* pp. 907–912.

Prüfer M., Schmidt C., & Wahl I. (1994*a*). Identification of robot dynamics with differential and integral models: A comparison. *Proc. of the 1994 IEEE Int. Conf. on Robotics and Automation* pp. 340–345.

Prüfer M., Wahl F. (1994*b*). Friction analysis and modelling for geared robots. *Preprints of the Fourth Symposium on Robot Control* pp. 551–556.

Seeger S., (1991). Self-tuning control of a commercial manipulator based on an inverse dynamic model. *Proc. of SYROCO'91* pp. 453–458.

Vandanjon P.O., Gautier M., & Desbats P. (1995). Identification of robot inertial parameters by means of spectrum analysis. *Proc. of the 1995 Int. Conf. on Robotics and Automation* pp. 3033–3038.