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DYNAMICAL MODEL PARAMETERS IDENTIFICATION OF A WHEELED MOBILE ROBOT

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Abstract: Even though the commercial wheeled mobile robot Pioneer is very important to the scientific community, there is not much information available about its dynamical model. In this paper this model is deduced, including the effect of the free wheel. The result is a complex equation of motion that depends on several physical parameters. Some of them are provided by the manufacturer; others can be directly measured and the rest of them are identified applying the Least Square Method to the integral of the uncoupled motion equation for each degree of freedom. After few assumptions, the whole model is obtained.

Keywords: Identification, dynamical model, parameter estimation, wheeled mobile robot.

1. INTRODUCTION

A dynamical model relates the motion parameters of the mobile robot to the applied forces and torques. While forward dynamics is used to analyze the response of the robot to a given command, the inverse dynamic model is used in the design of the controller; so a good dynamical model is a key issue towards the appropriate control design and towards the simulation of the behavior of the hardware in the control loop.

The dynamics equations of motion of a mobile robot can be deduced using the Newton-Euler method (Pereira *et al.*, 2000), (Rajagolapan and Barakat, 1996) or the Lagrangian formulation (D'Andréa-Novel *et al.*, 1991), (Campion *et al.*, 1991), (D'Andréa-Novel *et al.*, 1992), (Tounsi *et al.*, 1995*b*), (Tounsi *et al.*, 1995*a*), (Leroquais, 1998), (Thuilot, 1995). In this paper, the Lagrange formalism is used to formulate the dynamics equation of motion of the well-known Pioneer mobile robot manufactured by ActivMedia Robotics. This equation depends on several physical parameters: some of them are provided by the robot specifications, others can be measured in an easy way and the rest of them should be estimated through identification.

Although the complete equation of motion is a complex nonlinear equation, it would be shown that, when uncoupled experiments are carried out (only one degree of freedom is in motion), the equation can be simplified and can be formulated as a linear equation in the vector of unknown parameters. Hence, Least Square (LS) identification method can be applied to the integral of this equation and the unknown parameters can be estimated. This method, that presents a good statistical behavior can be used for off-line (simulation)

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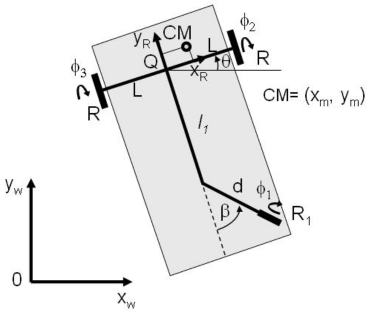

Fig. 1. Mobile Robot

or on-line identification (control) (Tiano, 2002). It has been successfully applied to the parameters identification of an unmanned underwater vehicle (Tiano, 2002) (Carreras, 2003) and of a Sony SCARA robot (Ha *et al.*, 1989), (Chan, 2001).

This paper is organized as follows. In Section 2, the robot dynamic model is deduced. A brief description of the identification method is given in Section 3. The results of the identification are shown in Section 4. And finally, the conclusions are drawn in Section 5.

2. DYNAMICAL MODEL OF A WHEELED MOBILE ROBOT

The dynamical model object of study, is for a three wheeled mobile robot shown in Figure 1. It has two driving wheels fixed in the front, with the same axis of rotation, motorized with DC motors. The third one, a free wheel, is connected to the platform by a rigid structure and can rotate around its vertical axis. The robot moves on the horizontal plane and it is assumed that the wheels - ground contact point satisfies the conditions of pure rolling and non slipping.

Table 1 shows all the parameters involved in the robot model, their significance and their units. Next sections presents the deduced equations for the robot model and the motor model.

2.1 Robot Model

Let consider an earth fixed reference frame $\{0, X_w, Y_w\}$ in the plane of motion and robot fixed reference frame $\{Q, X_r, Y_r\}$ (see Figure 1). The vector of generalized coordinates that completely describes the robot motion is:

$$q(t) = (x, y, \theta, \beta, \phi_1, \phi_2, \phi_3) \tag{1}$$

Since this system has 5 independent constraints, it can be proved that it has 2 degrees of freedom (D'Andréa-Novel *et al.*, 1991). As proposed

Table 1. Parameters

Symbol	Description	Units
x, y	origin of robot fixed frame	[m]
θ	robot heading	[rad]
β	orientation of the free wheel	[rad]
ϕ_1	angular position wheel 1	[rad]
ϕ_2	angular position wheel 2	[rad]
ϕ_3	angular position wheel 3	[rad]
η_1	linear velocity of robot	[m/s]
η_2	angular velocity of robot	[rad/s]
M	mass of the robot	[kg]
m_2	mass of driving wheel 2	[kg]
m_3	mass of driving wheel 3	[kg]
m_1	mass of free wheel	[kg]
R	radius of wheels 2 and 3	[m]
R_1	radius of wheel 1	[m]
L	distance from robot frame to driving wheels	[m]
l_1	distance from robot frame to the moving bar of the free wheel	[m]
d	distance of the moving bar of the free wheel	[m]
V_a	armature voltage	[V]
i_a	armature current	[A]
x_m, y_m	coordinates of the center of mass	[m]
I_0	inertia robot	$[kg.m^2]$
I_{r1}	inertia free wheel	$[kg.m^2]$
I_{r2}	inertia driving wheel 2	$[kg.m^2]$
I_{r3}	inertia driving wheel 3	$[kg.m^2]$
I_{p1}	inertia free wheel	$[kg.m^2]$
C_{s1}	coulomb friction torque	$[N.m]$
C_{v1}	viscous friction coefficient	$[kg.m^2/s]$
C_s	coulomb friction torque	$[N.m]$
C_v	viscous friction coefficient	$[kg.m^2/s]$

by other authors (D'Andréa-Novel *et al.*, 1991), (Tounsi *et al.*, 1995*b*), (Campion *et al.*, 1991), the dynamics equations can be deduced from the Lagrangian formulation:

$$\frac{d}{dt}\left[\frac{\partial[L(q,\dot{q})]}{\partial\dot{q}}\right] - \frac{\partial[L(q,\dot{q})]}{\partial q} = A(q)^T\lambda + B(q)\tau - F_r \tag{2}$$

Where $L(q,\dot{q})$ is the system's Lagrangian function, equal to the kinetic energy minus the potential energy. In this particular case, a wheeled mobile robot, the potential energy is zero, so $L(q,\dot{q}) = Ec$ (kinetic energy). As kinetic energy is:

$$Ec = \frac{1}{2}\dot{q}^T M(q)\dot{q} \tag{3}$$

it can be found (Campion *et al.*, 1991), (Tounsi *et al.*, 1995*b*) that:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} = A(q)^T\lambda + B(q)\tau - F_r \tag{4}$$

Where

- $M(q)$ is a 7x7 positive symmetric inertia matrix,
- $C(q,\dot{q})\dot{q}$ represents the centrifugal and Coriolis forces and torques,
- $A(q)$ is the constraints matrix,

- λ is 5-vector of Lagrangian multipliers associated to the independent kinematic constraints,
- $B(q)$ is the matrix of external torques or forces applied to the robot,
- F_r is the vector of friction forces.

Because of the constraints, there exists a matrix S(q) that satisfies:

$$\dot{q} = S(q)\eta \tag{5}$$

Where $\eta = \left[\, \eta_1, \eta_2 \,\right]^T$.

An important property of S(q) (Campion *et al.*, 1991), is that

$$S(q)^T A(q)^T = 0 \tag{6}$$

This equation allows the elimination of Lagrangian multipliers. Through time differentiation of Equation 5, we get:

$$\ddot{q} = \frac{d[S(q)\eta]}{dt} = \frac{\partial[S(q)\eta]}{\partial q}\dot{q} + S(q)\dot{\eta} \tag{7}$$

Pre-multiplying Equation 4 by $S(q)^T$ and replacing $\ddot{q}$ by Equation 7, we obtain:

$S(q)^T M(q) S(q)\dot{\eta} + S(q)^T M(q)\frac{\partial S(q)}{\partial q} S(q)\eta^2 + S(q)^T C(q,\dot{q}) S(q)\eta = S(q)^T A(q)^T \lambda + S(q)^T B(q)\tau - S(q)^T F_r$

And the dynamical model written in the space state form is (Campion *et al.*, 1991):

$$\left\{ \begin{array}{c} J(q)\dot{\eta} + g(q,\eta) = G(q)\cdot\tau - f_r \\ \dot{q} = S(q)\eta \end{array} \right\} \tag{8}$$

Where:

$$J(q) = S(q)^T M(q) S(q) \tag{9}$$

$g(q, S(q)\eta) = S(q)^T M(q)\frac{\partial S(q)}{\partial q} S(q)\eta^2 + S(q)^T C(q,\dot{q}) S(q)\eta$

$$G(q) = S(q)^T B(q) \tag{10}$$

$$f_r = S(q)^T F_r \tag{11}$$

And:

$$S(q) = \begin{bmatrix} -\sin(\theta) & 0 \\ \cos(\theta) & 0 \\ 0 & 1 \\ -\dfrac{\sin(\beta)}{d} & -\dfrac{d + l_1\cos(\beta)}{d} \\ \dfrac{\cos(\beta)}{R_1} & -\dfrac{l_1\sin(\beta)}{R_1} \\ \dfrac{1}{R} & \dfrac{L}{R} \\ \dfrac{1}{R} & -\dfrac{L}{R} \end{bmatrix} \tag{12}$$

$$M(q) = \begin{bmatrix} R(\theta)^T M(\beta) R(\theta) & R(\theta)^T V(\beta) & 0 \\ V(\beta)^T R(\theta) & I(\beta) & 0 \\ 0 & 0 & I(\phi) \end{bmatrix} \tag{13}$$

$$R(\theta) = \begin{bmatrix} \cos(\theta) & \sin(\theta) & 0 \\ -\sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{14}$$

$$M(\beta) = \begin{bmatrix} M(\beta)_{11} & 0 & M(\beta)_{13} \\ 0 & M(\beta)_{22} & M(\beta)_{23} \\ M(\beta)_{31} & M(\beta)_{32} & M(\beta)_{33} \end{bmatrix} \tag{15}$$

$M(\beta)_{11} = M(\beta)_{22} = M + 2\cdot m + m_1$
$M(\beta)_{13} = M(\beta)_{31} = M\cdot y_m + m_1\cdot l_1 + m_1\cdot d\cdot cos(\beta)$
$M(\beta)_{23} = M(\beta)_{32} = M\cdot x_m + m_1\cdot d\cdot sin(\beta)$
$M(\beta)_{33} = M(x_m^2 + y_m^2) + 2\cdot m\cdot L^2 + m_1\cdot l_1^2 + m_1\cdot d^2$
$+ 2\cdot m_1\cdot l_1\cdot d\cdot cos(\beta) + I_0 + Ip_1$

$$V(\beta) = \begin{bmatrix} m_1\, d\cos(\beta) \\ m_1\, d\sin(\beta) \\ Ip_1 + m1\, d^2 + m_1\, l_1\, d\cos(\beta) \end{bmatrix} \tag{16}$$

$$I_\phi = \begin{bmatrix} I_{r1} & 0 & 0 \\ 0 & I_{r2} & 0 \\ 0 & 0 & I_{r3} \end{bmatrix} \tag{17}$$

$$I_\beta = \left[\, m_1 d^2 + I_{p1} \,\right] \tag{18}$$

$$C(q,\dot{q})\dot{q} = \frac{d[M(q)]}{dt}\dot{q} - \frac{1}{2}\frac{\partial[\dot{q}^T M(q)\dot{q}]}{\partial q} \tag{19}$$

$$B = \begin{bmatrix} 0_{5x2} \\ I_{2x2} \end{bmatrix} \tag{20}$$

$$F_r = \left[\, 0_{3x1}\;\; F_1\;\; 0\;\; F_2\;\; F_3 \,\right]^T \tag{21}$$

$$F_j = C_s sign(\dot{\phi_j}) + C_v\dot{\phi_j}, (j = 2,3) \tag{22}$$

$$F_1 = C_{s1} sign(\dot{\beta}) + C_{v1}\dot{\beta} \tag{23}$$

F_j and F_1 are the friction forces or torques of the wheels (Tounsi *et al.*, 1995*b*). As pure rolling and non-slipping conditions are assumed, these friction torques are due to the shaft friction of the wheels.

2.2 Motor Model

In the case of the Pioneer robot, we can only measure the voltage applied to the motors, so a relation between the voltage and the torque must be found.

The torque generated by each motor is:

$$\tau_m = K_T i_a \tag{24}$$

While the torque applied to the wheels is:

$$\tau = t_r\mu\{\tau_m - \tau_{f_r}\} \tag{25}$$

The applied armature voltage is:

$$V_a = R_a i_a + L_a\frac{di_a}{dt} + K_E t_r\dot{\phi}_i \tag{26}$$

Being $\dot{\phi}_i$ the speed of the wheel.

Neglecting the inductance L_a:

$$i_a = \frac{V_a - K_E t_r \dot{\phi}_i}{R_a} \quad (27)$$

And the torque applied to the wheels is:

$$\tau = t_r \mu \{K_T(\frac{V_a - K_E t_r \dot{\phi}_i}{R_a}) - \tau_{f_r}\} \quad (28)$$

Parameters are referenced in Table 2.

Table 2. Motor parameters provided by the manufacturer.

Symbol	Parameter	Value	Units
K_T	Torque constant	0.023	$[N.m/A]$
K_E	Back-EMF constant	0.023	$[V/rad/s]$
R_a	Resistance	0.71	$[\Omega]$
L_a	Inductance	Negligible	$[Hy]$
t_r	gear ratio	19.7:1	-
μ	gearbox efficiency	73	%
τ_{f_r}	friction torque	$5.6 * 10^{-3}$	$[N.m]$

So in Equation 8 we have to replace τ of each motor by Equation 28.

3. IDENTIFICATION METHOD

3.1 Basic Concepts

If the equation of a model can be expressed as:

$$\dot{\eta} = \Psi(\eta, \tau)\Theta \quad (29)$$

then the parameters vector can be estimated using the Least Square Method, as the system is linear respect to the parameters vector (Tiano, 2002), being $\Psi(\eta, \tau)$ a matrix which values only depends on the state and control vectors and Θ the vector of unknown parameters. The objective of Least Square method is to minimize the cost function of the quadratic error. It can be proven (Tiano, 2002) that integrating both sides of Equation 29 between t_{k-1} and t_k:

$$\eta(t_k) - \eta(t_{k-1}) = \int_{t_{k-1}}^{t_k} [\Psi(\eta(t), \tau(t))dt]\Theta \quad (30)$$

the values of the parameters that minimizes the cost function are obtained as:

$$\Theta(N) = (F(N)^T F(N))^{-1} F(N)^T Y(N) \quad (31)$$

Where:

$$F(N) = \begin{bmatrix} \int_{t_0}^{t_1} [\Psi(\eta(t), \tau(t))dt] \\ \int_{t_1}^{t_2} [\Psi(\eta(t), \tau(t))dt] \\ \dots \\ \int_{t_{N-1}}^{t_N} [\Psi(\eta(t), \tau(t))dt] \end{bmatrix}$$

$$Y(N) = \left[\ (\eta(t_1) - \eta(t_0))\ \dots\ (\eta(t_N) - \eta(t_{N-1}))\ \right]^T$$

Using this algorithm we avoid the noise introduced by the calculation of the acceleration (Chan, 2001).

3.2 Mobile Robot Application

To identify the parameters, Equation 8 can be rewritten as:

$$\dot{\eta} = J(q)^{-1}[G(q) \cdot \tau - g(q, S(q)\eta) - f_r] \quad (32)$$

Or in a compact form:

$$\begin{array}{l} \dot{\eta}_1 = a_{11} \cdot F + a_{12} \cdot \Gamma - a_{13} \cdot \eta_1^2 - a_{14} \cdot \eta_2^2 - a_{15} \cdot \eta_1 - \\ a_{16} \cdot \eta_2 - a_{17} \cdot \eta_1 \cdot \eta_2 - a_{18} \cdot sign(\eta_1) - a_{19} \cdot sign(\eta_2) \\ \dot{\eta}_2 = a_{21} \cdot F + a_{22} \cdot \Gamma - a_{23} \cdot \eta_1^2 - a_{24} \cdot \eta_2^2 - a_{25} \cdot \eta_1 - \\ a_{26} \cdot \eta_2 - a_{27} \cdot \eta_1 \cdot \eta_2 - a_{28} \cdot sign(\eta_1) - a_{29} \cdot sign(\eta_2) \end{array} \quad (33)$$

Where coefficients a_{ij} are a non-linear combination of the physical parameters of the robot.

In order to simplify the identification process, experiments can be carried out for each degree of freedom. For the linear movement ($\eta_2 = 0$ and $\beta = 0$), Equation 33 becomes:

$$\dot{\eta}_1 = a_{11} \cdot F - a_{15} \cdot \eta_1 - a_{18} \cdot sign(\eta_1) \quad (34)$$

And:

$$F = \frac{t_r \cdot \mu \cdot K_T \cdot (V_2 + V_3)}{R \cdot R_a}$$

$$a_{11} = \frac{1}{(M + 2 \cdot m + m_1 + \frac{I_{r1}}{R_1^2} + \frac{2 \cdot I_r}{R^2})}$$

$$a_{15} = \frac{2 \cdot (t_r^2 \cdot \mu \cdot K_T \cdot K_E + R_a \cdot C_v)}{R^2 \cdot Ra} \cdot a_{11}$$

$$a_{18} = \frac{2 \cdot [C_s + t_r \cdot \mu \cdot \tau_r]}{R} \cdot a_{11}$$

For the angular movement ($\eta_1 = 0$ and $\beta = -90^o$), Equation 33 becomes:

$$\dot{\eta}_2 = a_{22} \cdot \Gamma - a_{26} \cdot \eta_2 - a_{29} \cdot sign(\eta_2) \quad (35)$$

Where:

$$\Gamma = \frac{L \cdot t_r \cdot \mu \cdot K_T \cdot (V_2 - V_3)}{R \cdot R_a}$$

$$a_{22} = \frac{1}{[M\cdot(x_M^2+y_M^2)+I_0+2\cdot I_p+2\cdot m\cdot L^2+m_1\cdot l_1^2+\frac{l_1^2\cdot I_{r1}}{R_1^2}+\frac{2\cdot L^2\cdot I_r}{R^2}]}$$

$$a_{26} = \frac{(2\cdot L^2\cdot t_r^2\cdot\mu\cdot K_T\cdot K_E+C_{v1}\cdot R^2\cdot R_a+2\cdot L^2\cdot C_v\cdot R_a)}{R^2\cdot R_a}\cdot a_{22}$$

$$a_{29} = \frac{(2\cdot L\cdot t_r\cdot\mu\cdot\tau_r+C_{s1}\cdot R+2\cdot L\cdot C_s)}{R}\cdot a_{22}$$

Equations 34 and 35 are linear respect to a_{ij}, then the method explained in 3.1 can be applied.

The unknown parameters to be identified are: I_0, I_{r1}, $I_r = I_{r2} = I_{r3}$, I_{p1}, C_{s1}, C_{v1}, C_s and C_v.

4. RESULTS

The method has been applied to the Pioneer robot. Some known characteristics are:

Parameter	Value	Unit
R	0.0825	m
R_1	0.035	m
L	16.89	m
l_1	0.18	m
d	0.03	m
x_m	0	m
y_m	-0.07	m
M	15.5	[kg]
m	0.35	[kg]
m_1	0.35	[kg]

Measured variables: Voltage applied to the motors V_2, V_3 and linear η_1 and angular η_2 speeds. Velocities are provided directly from the software of the robot, while for voltages an external board was used to adapt them to the analog inputs of the micro-controller.

The inputs used, are STEP and PRBS signals. The gathered data is validated in order to eliminate outliers and trends and filtered to reduce the effects of noise.

For each degree of freedom, 3 experiments at different speeds were carried out. In the case of linear movement, results found are shown in Table 3. Last row represent the mean value for each estimated parameter.

Table 3. Translational movement.

Exp.	$1/a_{11}$	C_v	C_s	Input
1	17.83	0.0441	0.3349	PRBS
2	16.49	0.0445	0.3287	PRBS
3	16.89	0.0446	0.2921	STEP
Mean	17.07	0.0444	0.3186	

In order to validate the results, another set of experiments were carried out. Figure 2 depicts the input signal used for one experiment, a step forward and backward. Figure 2 a) shows the input voltage applied to each motor; Figure 2 b) the total force applied to the robot and Figure 2 c) the linear speed of the vehicle. The performance

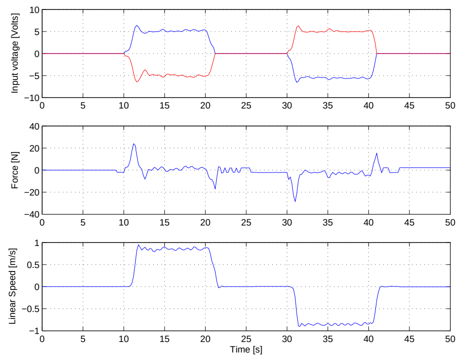

Fig. 2. Input and output signals from the robot.

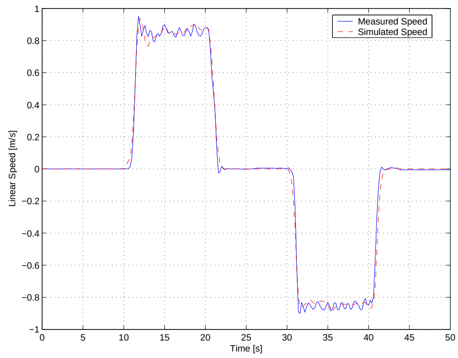

Fig. 3. Speed response of the robot and the model.

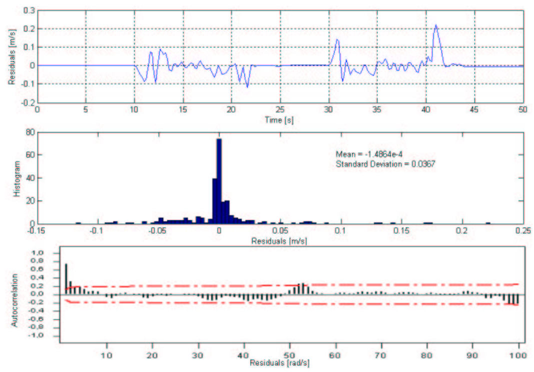

Fig. 4. Residuals, their histogram and their autocorrelation.

of the model is presented in Figure 3; while the statistical validation is shown in Figure 4. Figure 4 a) shows the residuals, Figure 4 b) the histogram of the residuals, that have a mean value of $-1.4864e^{-4}$, a standard deviation of 0.0367 and are approximately gaussian. Figure 4 c) shows the autocorrelation of the residuals.

Applying the same ideas to the rotational movement, we obtain Table 4.

Table 4. Rotational movement.

Exp.	$1/a_{22}$	C_{v1}	C_{s1}	Input
1	0.4301	0.000429	0.004535	STEP
2	0.4127	0.000389	0.004532	PRBS
3	0.4292	0.000469	0.004541	PRBS
Mean	0.424	0.000429	0.004536	

With this method we found values for the combination of the model parameters. As the purpose of this work is to find the model suitable for simulation, the exact value of these parameters have been deduced from the theoretical one. For example:

$$M + 2 \cdot m + m_1 + \frac{I_{r1}}{R_1^2} + \frac{2 \cdot I_r}{R^2}$$
$$= 15.5 + 2 \cdot 0.35 + 0.35 + \frac{2.144 \cdot 10^{-4}}{0.035^2} + \frac{2 \cdot 0.0012}{0.0825^2}$$
$$= 17.0750$$

that is quite similar to the value found empirically.

The estimated parameters for both degree of freedom are shown in Table 5. It is worth to mention that, even though an uncoupled identification of the parameters has been carried out, all the coefficients of the coupled model are found.

Table 5. Estimated parameters

Symbol	Value	Units
I_0	0.3	$[kg.m^2]$
I_{r1}	$2.144 * 10^{-4}$	$[kg.m^2]$
I_{r2-3}	0.0012	$[kg.m^2]$
I_{p1}	$1.072 * 10^{-4}$	$[kg.m^2]$
I_p	$5.95 * 10^{-4}$	$[kg.m^2]$
C_{s1}	0.004536	$[N.m]$
C_{v1}	0.000429	$[N.m.s]$
C_s	0.3184	$[N.m]$
C_v	0.0444	$[N.m.s]$

As it can be seen from Figure 4 that the residuals are gaussian and the mean value is approximately zero. These results can be considered statistically acceptable. The parameters' value shown in Table 5 is the mean of all the different values obtained in each experiment.

5. CONCLUSION

In this paper we have found the mathematical model of a 3 wheeled mobile robot, based on the Lagrangian formulation. We have used an integral algorithm to identify the motion parameters, avoiding, thus, the need of measure the acceleration and reducing the number of inputs to the identification algorithm. Parameters have been estimated by making uncoupled experiments in both degrees of freedom. The results obtained with the integral identification method are statistically good and the model will be used for simulation purposes.

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