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AN EXPERIMENTAL VALIDATION OF A NONLINEAR VELOCITIES OBSERVER

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résumé : La mesure des positions angulaires pour la commande des robots est disponible avec précision, cependant la mesure de vitesse est souvent bruitée ou non disponible. Pour remédier à ce problème des observateurs de vitesse sont utilisés. Dans cet article on présente une validation expérimentale d'un observateur de vitesse. Les vitesses estimées sont comparées aux vitesses déduites par dérivation numérique des positions filtrées à l'aide d'un filtre de type F.I.R. L'observateur utilisé est un observateur non linéaire à grands gains, la loi de commande est de type couple calculé. Les manipulations sont réalisées sur un robot SCARA construit au laboratoire.

Abstract : High precision measurements of the joint displacement are available to control the robot manipulators. However the signal delivered by sensors velocities are often contaminated by noise and not so useful in control laws. To overcome this problem velocities observers are used. In this paper we demonstrate experimentally the applicability of the method. The estimated velocities by the observer are compared with the estimated velocities obtained by numerical derivation of the filtered positions with a F.I.R. The observer used is a nonlinear high gain one based on the notion of uniform observability. As control law we use the linearizing and decoupling computed torque law. The experiences are conducted on a SCARA robot manipulator built at the laboratory.

Key words : nonlinear velocity, high gain observer, computed torque, finite impulse response filter, trajectory tracking.

1. INTRODUCTION

The theory of nonlinear observability and the nonlinear observer problem design attracted the attention of many researchers. One of the first important work in this field was done by Hermann and Krener, (1977) who gave the very known rank condition to test the observability of a system. More recently Diop and Fliess, (1991) have given an important contribution to the nonlinear observability.

Krener and Isidori, (1983) proposed a nonlinear observer for systems without input. This work was extended by Krener and Respondek, (1985), Xia-Hua-Xia and Wei-Bing-Gao, (1989) to systems with inputs. The technique used to build the observer is based on the linearization of a nonlinear system, via a state diffeomorphism and output injection. An application on flexible joint robots has been proposed by Plestan and Cherki, (1993). The observer proposed is based on the concept of uniform

observability for any input introduced earlier by Gauthier and Bornard (1991). Different other observers were proposed in the literature for different classes of nonlinear systems Ciccarella *et al*, (1993), Jankovic, (1993), and Lewis, (1992). They rely on change of coordinates or approximation or extended Kalman filter. Recently an observer based on a minimization technique was proposed by Zimmer, (1993). More specialized observers to robotics were proposed to estimate velocities for rigid robots or the velocities and the unmeasured link position for elastic joint robots. These observers are high gain, Tornambe, (1992), or sliding modes Canudas De Wit and Slotine, (1991) or based on the dynamic model of the robot Tomei, (1990), or passivity approach Berghuis H., Nijmeijer H. (1993). We use a MIMO nonlinear observer developed by Bornard et al (1991) to estimate the velocities of a rigid robot, and a computed torque as control law. The applicability of this method on a two rigid arms robot model has been demonstrated in simulation, Aoustin and Cherki (1993). We have implemented this observer on a SCARA robot built at the laboratory. One of the

main advantages with this control in our case, is that the velocity observer equations become linear. They can be discretized with classical linear techniques to minimize the computing time on line. We show that the experimental observer results are good compared to the classical numerical differentiation of the filtered signal joint positions.

2. THEORETICAL PRELIMINARIES

The observer we will use has been proposed in the general context of non linear systems by Bornard *et al* (1991). It is based on high gain output injection and the notion of uniform observability introduced earlier by Gauthier *et al* (1981). we recall here some important features related to this observer. The robot model is given by :

$$A(q)\ddot{q}+H(q,\dot{q})=\Gamma \quad (1)$$

$A(q)$ is the $n \times n$ positive definite inertial matrix.

$H(q,\dot{q})$ is the vector of centrifugal, Coriolis, gravity and friction forces.

Γ : the vector of torques applied to the robot.

In a state representation the model reads as:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = \phi(x, \Gamma) \end{cases} \quad (2)$$

with $x=(x_1, x_2)^T = (q, \dot{q})^T$

$$\phi(x, \Gamma) = A^{-1}(x_1) [\Gamma - H(x_1, x_2)]$$

The nonlinear function $\phi(x, \Gamma)$ contains square terms which are only locally lipschitz, but the saturation of the velocities make them globally lipschitz.

This form meets the requirement of the uniform observability as reported in Bornard *et al* (theorem 1), to work the observer proposed necessite a global Lipschitz assumption for the non linear function $\phi(x, \Gamma)$, this assumption is metted as soon as we suppose the velocities of the robot bounded. The velocities observer is given by:

$$\begin{cases} \dot{\hat{x}}_1 = \hat{x}_2 + \frac{K_1}{T}(x_1 - \hat{x}_1) \\ \dot{\hat{x}}_2 = \phi(\hat{x}, \Gamma) + \frac{K_2}{T^2}(x_1 - \hat{x}_1) \end{cases} \quad (3)$$

$$\text{where } \phi(x, \Gamma) = \begin{cases} \phi(x, \Gamma) & x_2 \in \Omega \\ \phi_1(x_1, \Gamma) & \text{otherwise} \end{cases}$$

$$\hat{\hat{x}} = [x_1, \hat{x}_2]$$

$\phi_1(x_1, \Gamma)$ is obtained from $\phi(x, \Gamma)$ by replacing x_2 by its maximum value on Ω .

It was proved that this observer work well, the states are estimated very fast if the gains K_1 , K_2 , and the parameter T are adequately chosen. The gains K_1 , K_2 are determinated such as the eigenvalues of the linear part of the states equation of the observer lie in the left half plane, see Bornard *et al* (1991).

3. COMPUTED TORQUE WITH ESTIMATED VELOCITIES

The control law we will use is the decoupling and linearizing one

$$\Gamma = A(x_1)[\ddot{x}_{2d} - K_v(x_2 - x_{2d}) - K_p(x_1 - x_{1d})] + H(x_1, x_2)$$

where we replace x_2 by \hat{x}_2 since x_2 is not measurable. This control leads to a linear observer

$$\begin{cases} \dot{\hat{x}}_1 = \hat{x}_2 + \frac{k_1}{T}(x_1 - \hat{x}_1) \\ \dot{\hat{x}}_2 = w + \frac{k_2}{T^2}(x_1 - \hat{x}_1) \end{cases} \quad (4)$$

$$\text{-where } w = \ddot{x}_{2d} - K_v(\hat{x}_2 - x_{2d}) - K_p(x_1 - x_{1d})$$

The equations of the robot in closed loop are:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = w + A^{-1}(x_1)[H(x_1, \hat{x}_2) - H(x_1, x_2)] \end{cases} \quad (5)$$

To assert the convergence of the closed loop we will use a theorem of Teel and Praly (1992). We must precise some importants facts:

- In the case of initial errors on the positions, the observer begins by giving estimates which can be far from the true values, it is the well known peaking phenomenon.

- To avoid the peaking we use an idea of and F. Esfandiari *et al* (1992) reported also in A. Teel *et al* (1992, 1994) which consists of saturating the estimated variables to the maximum known values of the true variables. It is equivalent to say that we disregard the estimated values which are unrealistic.

Let $\tilde{x} = x - x_d$, $e_1 = \frac{1}{T}(x_1 - \hat{x}_1)$, and $e_2 = x_2 - \hat{x}_2$ the equations of the tracking and estimation errors are then:

$$\begin{cases} \dot{\tilde{x}}_1 = \tilde{x}_2 \\ \dot{\tilde{x}}_2 = -K_p \tilde{x}_1 - K_v \tilde{x}_2 + K_v e_2 \\ \quad \quad \quad + A^{-1}(x_1)[H(x_1, \hat{x}_2) - H(x_1, x_2)] \end{cases} \quad (6)$$

$$\begin{cases} \dot{e}_1 = \frac{-K_1}{T} e_1 + \frac{1}{T} e_2 \\ \dot{e}_2 = \frac{-K_2}{T} e_1 + A^{-1}(x_1)[H(x_1, \hat{x}_2) - H(x_1, x_2)] \end{cases} \quad (7)$$

(6) and (7) are of the form :

$$\begin{cases} \dot{\tilde{x}} = h(\tilde{x}, e, t) \\ \dot{e} = LAe + g(\tilde{x}, e, t) \end{cases} \quad (8)$$

$$\text{with } L = \frac{1}{T} \text{ and } A = \begin{pmatrix} -k_1 & 1 \\ -k_2 & 0 \end{pmatrix}$$

Now we recall the theorem of Teel and Praly for the convenience of the reader. One hypothesis is made H: The system $\dot{z} = h(z, 0, d(t))$ is globally asymptotically stabilizable, and a Lyapunov function $v(z)$ proving the result is known. This hypothesis is true for the robot since the

computed torque control law is a globally asymptotically stabilizing one. Since x_1 is measurable, it is reasonable to initialize the system such that $x_1(0)=\hat{x}_1(0)$, so the initial conditions can be bounded independently of T.

Theorem Teel *et al.*, (1992, 1994)

Consider the non linear system

$$\begin{cases} \dot{z}=h(z,e,t) \\ \dot{e}=LAe+g(z,e,t) \end{cases}$$

h and g are C^1 vectors fields. We suppose the hypothesis H verified and the matrix A Hurwitz, we define $\Gamma=\{z: v(z)\leq c+1\}$, $c\geq 1$, let the function:

$$W(z,e)=c\frac{v(z)}{c+1-v(z)} + \mu\frac{e^T P e}{\mu+1-e^T P e}, \mu \geq 1 \text{ and } P \text{ is}$$

solution of the matrix equation $A^T P + P A = -I$.

Let $\Lambda 1=\{z: v(z)<c+1\} \times \{e: e^T P e < \mu+1\}$ then for each $L>0$ $W(z,e): \Lambda 1 \rightarrow \mathbb{R}^+$ is definite positive on $\Lambda 1 \setminus \{0\}$ and proper on $\Lambda 1$. Moreover for each $\rho>0$ there exists $L_*>0$ such that for each $L>L_*$ $\dot{W} \leq -\Phi(z,e)$, where $\Phi(z,e)$ is definite positive on $\{(z,e): \rho \leq W \leq c^2 + \mu^2 + 1\}$.

The theorem proves that the trajectories of the system (8) will enter in a small compact around the origin. To prove the semiglobal asymptotic stability, we must prove that (8) is locally exponentially stable.

Due to the form of $h(\tilde{x},e,d(t))$ and $g(\tilde{x},e,d(t))$ the linearized system around the origin will be of the form $\dot{X}=B(t)X(t)$ with $X=[\tilde{x},e]$,

$$B(t)=\begin{bmatrix} 0 & 1 & 0 & 0 \\ -k_p & -k_v & 0 & f(t) \\ 0 & 0 & \frac{-k_1}{T} & \frac{1}{T} \\ 0 & 0 & \frac{-k_2}{T} & f(t) \end{bmatrix} = \begin{bmatrix} B_1 & B_3 \\ 0 & B_2 \end{bmatrix}$$

$$f(t)=-A^{-1}(x_1)\frac{\partial H(x_1,x_2)}{\partial x_2} \Big|_{x=x_d}$$

$\sigma(B(t))=\sigma(B_1) \cup \sigma(B_2)$, $\sigma(B)$ is the spectrum of B. $f(t)$ is bounded because $x_d(t)$ is bounded, so the

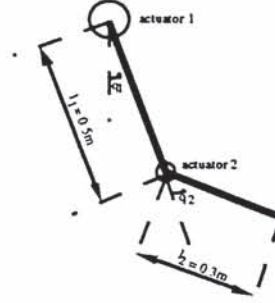
eigenvalues of $A(t)$ and $A^T(t)$ can always be made negative with the gains K_p, K_v, K_1, K_2 and T.

This proves that the closed loop is semi globally asymptotically stable.

4. EXPERIMENTAL CASE STUDY

The experimental study was conducted on a two degrees of freedom robot manipulator (SCARA) moving in the horizontal plane, see figure 1. This robot was manufactured at the laboratory, There is an

encoder to measure each link position, but no tachymetric dynamo for the velocities.



The two degrees of freedom scara robot.

The maximum allowed torques are : $\Gamma_{1max} = 17$ N.m, $\Gamma_{2max} = 8$ N.m. The minimal inertial parameters of the dynamic model robot are, $z_{r1}=3.7$ Kg.m², $z_{r2}=0.08$ Kg.m², $m_{x2}=0.272$ Kg.m. For each link the Coulomb and viscous terms are identified respectively to: $F_{s1}=0.62$ N.m, $F_{s2}=0.17$ N.m and $F_{v1}=0.07$ N.m/rd/s, $F_{v2}=0.013$ N.m/rd/s.

Then the components of the dynamic robot model are:

$$a_{11}(q)=z_{r1}+z_{r2}+2m_{x2}L_1\cos(q_2),$$

$$a_{12}(q)=z_{r2}+m_{x2}L_1\cos(q_2),$$

$$a_{21}(q)=z_{r2}+m_{x2}L_1\cos(q_2), a_{22}(q)=z_{r2}.$$

$$h_1(q,\dot{q})=-m_{x2}L_1[2\sin(q_2)\dot{q}_1\dot{q}_2+\sin(q_2)\dot{q}_2^2]+F_{v1}\dot{q}_1+$$

$$F_{s1}\text{sign}(\dot{q}_1)$$

$$h_2(q,\dot{q})=m_{x2}L_1\sin(q_2)\dot{q}_1^2+F_{v2}\dot{q}_2 + F_{s2}\text{sign}(\dot{q}_2).$$

The actual sampling frequency was set at 100hz for the controller and 4kHz for the joint position measurements. The implementation has been done with a fast digital signal processor from the DSPACE society and a 486PC.

The linear equation of the observer (4) is discretized by using the zoh method under the MATLAB logiciel to minimise the calculation time. The gains are chosen as $K_{p1}=25$, $K_{v1}=10$, for the first arm $K_{p2}=625$, $K_{v2}=50$, for the second arm, $K_1=2$, $K_2=1$ and $T=0.01$ for the two arms, these values seems to be very adequate. We obtain finally for each link,

$\hat{x}_{k+1}=B\hat{x}_k+Du_k$ with $u_k=[x_{1k},w_k]$, B and D are obtained from the discretization of (4). The equations of the observer are linear and decoupled.

$$w_k=\ddot{q}_dk-K_v(\hat{q}_k-\dot{q}_dk)-K_p(q_k-\hat{q}_dk)$$

and $x_{1k}=[q_{1k},q_{2k}]$. The indices d and k mean desired and value of the variable at $t=t_k$.

The finite impulse response filters have been computed with the help of the Matlab logiciel on

forty points of joint link measurement, $y_k =$

40

$\sum_{i=1} b_i q_{ki}$. The cut-off frequency of filters is chosen

equal to 10Hz. Then it is easier to compute the

numerical derivative: $\frac{y_k-y_{k-1}}{\delta}$, δ is the sampling

period of the controller.

5. EXPERIMENTAL RESULTS

The experiments are always done with initial errors equal to zero which is quite natural since the robot start from position zero with a null velocity. So no peaking is expected and we need not to saturate the estimated variables.

The trials are done with a desired trajectory of a trapezoidal velocity profile, the desired joint positions are represented on figures 1 and 5.

In a first trial the loop is closed with the F.I.R and secondly the loop is closed with the observer, the control sampling period is 10 ms and the measurement sampling period is 250 μ s in the two cases. We see that the error position on joint one is slightly smaller when the observer is in the closed loop, but it is bigger on joint two (fig 3, 7) than the case where the filter is in the closed loop (fig 2, 6). We think the reason of the value of the error position on joint two is error modeling in particular error in friction coefficient. The third trial is done with a sampling period equal to 1 ms (fig 4, 8) the errors on the two joints are less than the errors when the F.I.R is used in the closed loop despite the errors modeling which are necessary present.

The F.I.R on forty points can not be used with a sampling period equal to 1 ms because we need a period of 25 μ s for joint measurement which is less than the necessary time to compute the control.

6. CONCLUSION

We have proved the experimental applicability of a nonlinear high gain observer to obtain the joint velocities of a two degrees of freedom SCARA robot. The calculation of the estimated state variables is easy due to the linearity of the equations. The time calculation is very short so we can use short sampling period if needed. The estimation is as good as the one obtained by the numerical differentiation of the filtered positions which need more time calculation.

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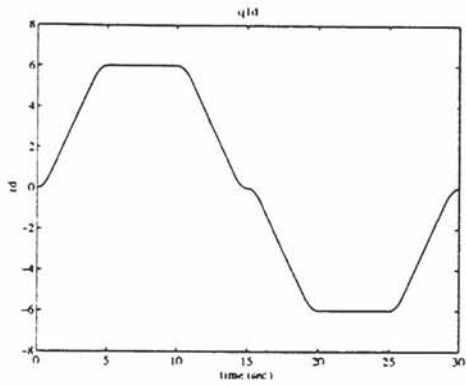


fig 1

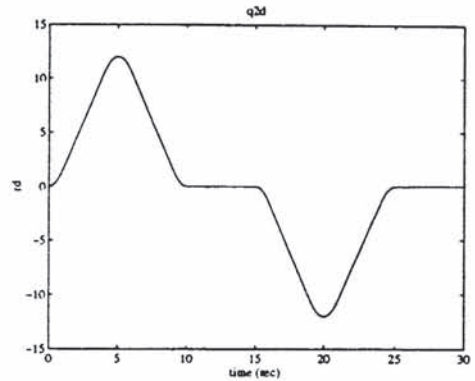


fig 5

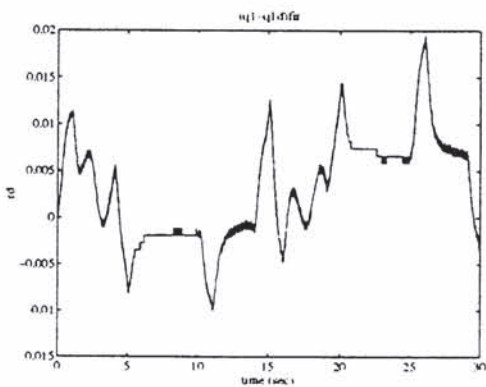


fig 2

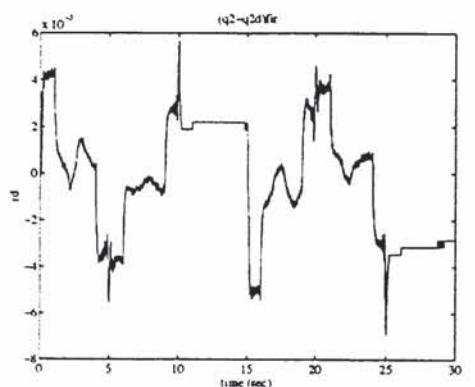


fig 6

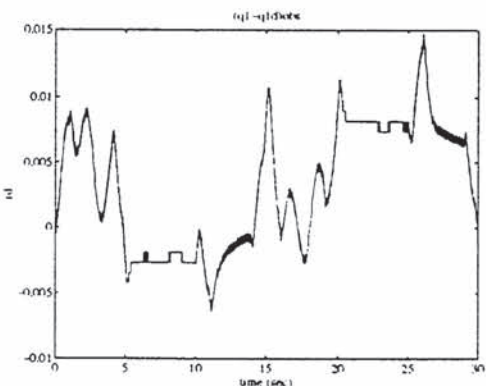


fig 3

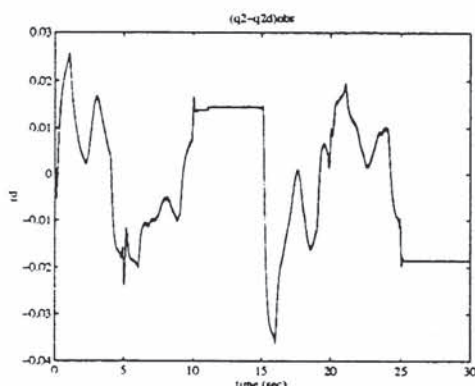


fig 7

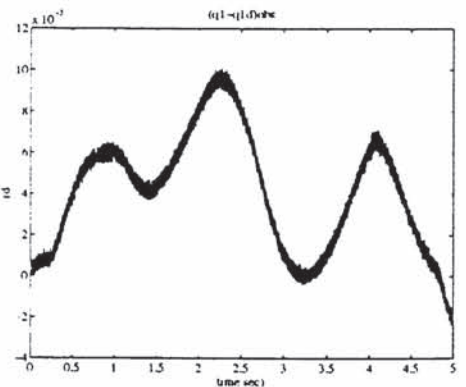


fig 4

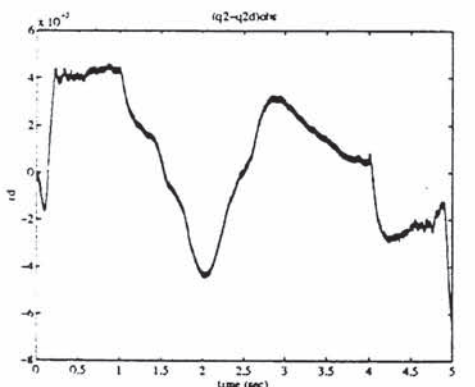


fig 8