Proceedings of the 17th World Congress
The International Federation of Automatic Control
Seoul, Korea, July 6-11, 2008

Friction Compensation in Servo Systems Using a Local Control Design Approach

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Abstract: Nonlinearities degrade considerably performances in motion control systems. Nonlinear friction is a major source of many serious problems such as wear, tracking errors and limit cycles. There has been an extensive research activity dealing with the design of compensating techniques. The approaches cited in the litterature can be divided into: free model compensation or model based compensation strategy. In the present work, a dynamic fuzzy modeling approach of a servo system with friction is developed. The main idea is to take advantage of the linear form of the resulting dynamics to design: 1- a friction observer used as a compensating term of friction effects, 2- a stable tracking controller that allows the system to achieve a trajectory involving slow motions and velocity reversal. The proposed control method is relatively simple to design and efficient for the compensation of friction induced errors. The experimental tests on a robot joint control have demonstrated precise motion control and smoother velocity reversal in the presence of significant level of friction.

1. INTRODUCTION

In general, mechanical nonlinearities have a negative impact on performances of servo systems; for this reason, modelling and compensating nonlinearities have been a topic of special interest in motion control systems. Friction is one of these hard nonlinearities that are unavoidable, undesirable and challenging for control engineers (Armstrong-Helouvry *et al*., 2004). Special care has been made for modelling, and several approaches have been adopted to deal with their effects such as: variable structure and high stiff gains control techniques (Li *et al*., 2004) and other depending on models and their ability to reproduce the nonlinearity. Adaptive control techniques were also used to cope with the varying nature of these nonlinearities due to various effects such as: temperature, load and even wear (Lischinsky *et al*., 1999).

Friction is usually modelled as a discontinuous static map of velocity. Static models are often restricted to Coulomb and viscous friction components or described by the Stribeck curve (Stribeck *et al*., 1902). Many other models have been developed to describe better friction phenomenon (Swevers *et al*., 2000). Mainly based on experimental observations, there are several dynamic models that provide a reliable description of the phenomenon (Canudas de Wit *et al*., 1995); they include many interesting characteristics such as: frictional lag, Dahl effect (Dahl *et al*., 1968). However, their good capability to describe friction makes them at the same time very complicated, and even showing a hybrid nature that have been treated in (Choi *et al*., 2006), this results in a more complex model of the system and has negative impact on the identification effort, parameters estimation and the control design itself. One can also note that other models giving less precise description of friction can have serious problems in compensating friction induced errors especially at low velocities.

In the following work, we first start by adopting a local approach a dynamic fuzzy model of the robot joint with friction is developed (Mostefai *et al*., 2007). After that, conventional experiments to identify the parameters of local models are conducted on a robot joint. The proposed control strategy is basically divided into two actions based on: first, a linear tracking controller; then, a nonlinear friction estimator-compensator based on local modelling approach in section 2. Local stability of the overall system is verified for the designed controller. Finally, experimental results allowed us to verify the efficiency of the proposed control method.

2. SYSTEM DESCRIPTION: LOCAL MODELING

Since this work focuses on friction compensation, all other nonlinearities acting on the robot joint are assumed to have no effects on the dynamics. We consider a single joint robot with the mathematical model given by:

$$J\ddot{q} + F = \tau \tag{1}$$

where J denotes a constant inertia, F the nonlinear dynamic friction. q, $\dot{q}$ and $\ddot{q}$ are the acceleration, velocity and position, respectively.

Friction is locally modelled as dynamical linear state space system changing with velocity of the joint; it has two main actions: a part related to velocity characterized by a damping nature, and a second part related to the displacement characterized by a stiff nature.

IF $\dot{q} = \dot{q}_i$
THEN

$$\begin{aligned} \dot{z} &= \alpha_i z + q \\ F &= \sigma_i z + d_i q \end{aligned} \tag{2}$$

i indicates the local velocity range. σ_i : is a local stiff coefficient of friction torque. d_i : local damping coefficient. σ_i and d_i are kept constant for low velocity for simplifying the design of the proposed control. $\alpha_i \in \left[-\sigma_i \frac{|\dot{q}_i|}{F_{\min}}, 0 \right]$ is a very important parameter that characterizes the model dynamics and stability.

$F_{\min}$: is a positive value of the lower identified level of friction for $|\dot{q}| > 0$, we will use a symmetric values of friction.

The influence of this parameter on the overall controlled system will be evaluated later in section 3. The linear time invariant resulting model allows local analysis and design of the compensator of friction and its effects. We should note that the introduced internal state z is a non-measurable quantity, though it has an important role in the system description and the overall compensator design. The equivalent model of friction can be formulated using fuzzy inferences (Takagi *et al.*, 1995)

$$\dot{z} = \sum_{i=1}^{n} \mu_i(\dot{q}) \alpha_i z + \dot{q} \tag{3}$$

And since the stiffness and the damping coefficient will be fixed, then we have:

$$F = \sigma_0 z + d_0 q \tag{4}$$

Assuming that only friction parameters are varying with velocity, the state space local model of the robot joint with friction

IF $\dot{q} = \dot{q}_i$
THEN

$$\frac{d}{dt}\begin{bmatrix} z \\ q \\ \dot{q} \end{bmatrix} = \begin{bmatrix} \alpha_i & 0 & 1 \\ 0 & 0 & 1 \\ \sigma_0 & 0 & d_0 \end{bmatrix} \begin{bmatrix} z \\ q \\ \dot{q} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \tau \tag{5}$$

One of the most sensitive steps is the identification of local parameters. Common experiments are conducted to determine each parameter (Lantos *et al.*, 2007); the process can be summarized in the following steps:

1- For the presliding regime, where the input torque level is lower than the break-away torque, the Dahl curve can be plotted and the parameter σ_0 is then deduced (Fig. 1).

2- For slow motions regime, and specially at low velocities where friction is characterized by the Stribeck effect and the torque has neither a pure stiff nature nor a pure damping nature but a mix of both effects, the position of the robot joint is controlled by low gains PD compensator under constant velocities (Fig. 2).

3- For higher velocities, friction has a linear damping nature: the viscous friction.

In this work, we are more concerned with the first two cases, where friction is highly nonlinear, and can be source of stick-slip motions and performance degradation. The parameters identified on the robot joint are given in appendix A.

By applying a standard fuzzy inference method to the identified local parameters, i.e. using a singleton fuzzifier, product fuzzy inference and center average defuzzifier, the robot joint model with friction can be written across the overall operating domain

$$\frac{d}{dt}\begin{bmatrix} z \\ q \\ \dot{q} \end{bmatrix} = \sum_{i=1}^{n} \mu_i(\dot{q}) \begin{bmatrix} \alpha_i & 0 & 1 \\ 0 & 0 & 1 \\ \sigma_0 & 0 & d_0 \end{bmatrix} \begin{bmatrix} z \\ q \\ \dot{q} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \tau \tag{6}$$

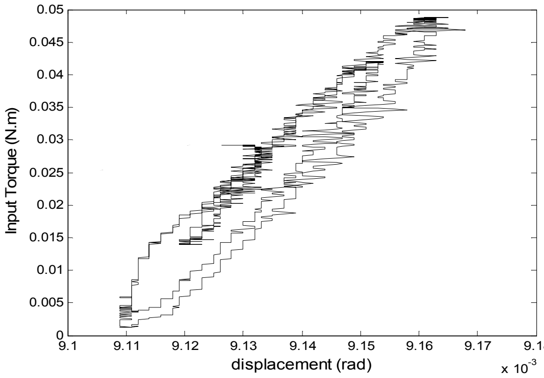

Fig. 1. Micro-displacement regime identified in the robot joint in the sticking mode

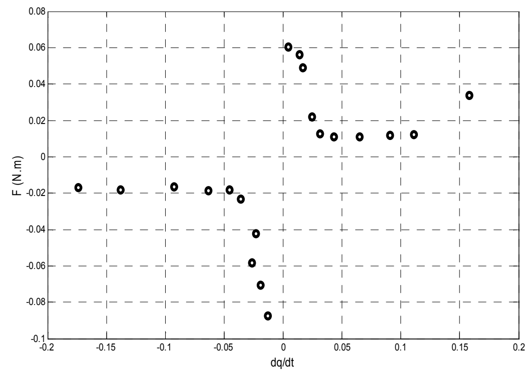

Fig. 2. Friction levels in the velocity reversal area, showing a high nonlinearity and asymmetry.

The number of the local models used in the proposed structure has to increase to give a precise description (Wang *et al*., 1992). In that case, we should note that all parameters in (4) would vary for different velocities. This model will be used in the design of a stable friction compensator

3. COMBINED COMPENSATOR-CONTROLLER DESIGN

First, let us define the filtered tracking error as

$$r = Q(e) = \dot{e} + \lambda e \tag{7}$$

where $e = q_r - q$ is the position error, $\dot{e} = \dot{q}_r - \dot{q}$ the position error variation, $\lambda > 0$ is a positive gain characterizing the controller dynamics.

The structure of the servo system model in (4) and (5) allows us to propose a control algorithm based on two actions: first a compensating input based on local estimated friction

$$\dot{\hat{z}} = \alpha_i \hat{z} + \dot{q} - l_i . r \tag{8}$$

and second a Proportional Derivative action for achieving tracking control of the overall system, giving the following local control input,

IF $\dot{q} = \dot{q}_i$

THEN

$$\tau = J\ddot{q}_r + Kr + \sigma_0 \hat{z} + d_0 \dot{q} \tag{9}$$

The tracking performance can be verified by substituting the control signal (8) and (9) into the robot joint model (5).

The error model is then obtained

$$\dot{E} = A_i E \tag{10}$$

with $E = [\tilde{z} \quad e \quad \dot{e}]^T$ as the error vector and,

and the matrix characterizing its stability

$$A_i = \begin{bmatrix} \alpha_i & \lambda . l_i & l_i \\ 0 & 0 & 1 \\ \frac{\sigma_0}{m} & -\frac{K.\lambda}{m} & -\frac{K}{m} \end{bmatrix} \quad \text{for} \quad q \approx q_i \tag{11}$$

In case of perfect friction compensation, the model is linearied and the tracking control problem can be converted to a classical PID tracking of a linear servo system. Since it is not true for real plants, we have to consider error dynamics by introducing the compensation term plus the tracking controller, and choose the gains K and l_i of the controller that make the error dynamics stable and ensure its convergence to zero. That means gains that yield eigen values of A_i with negative damping.

The analysis of the effect of the controller on local stability starts from the model at very low velocities where $\alpha_i \approx 0$ (fig. 4), once the gain of the controller K is fixed first to a certain value that stabilize the system with l_i= 0 for the entire operating domain. The observer gains l_i can be then chosen in the stable regions according to the equivalent velocity of the model of friction, the goal is to ensure good performances without compromising the stability of the system. The observer gains will be tuned during experiments in order to improve the tracking performances.

The local stability is guaranteed by the design method. In the region of mixed dynamics, where two different models are interacting, we can see the problem as two weighted stable systems interconnected to each other.

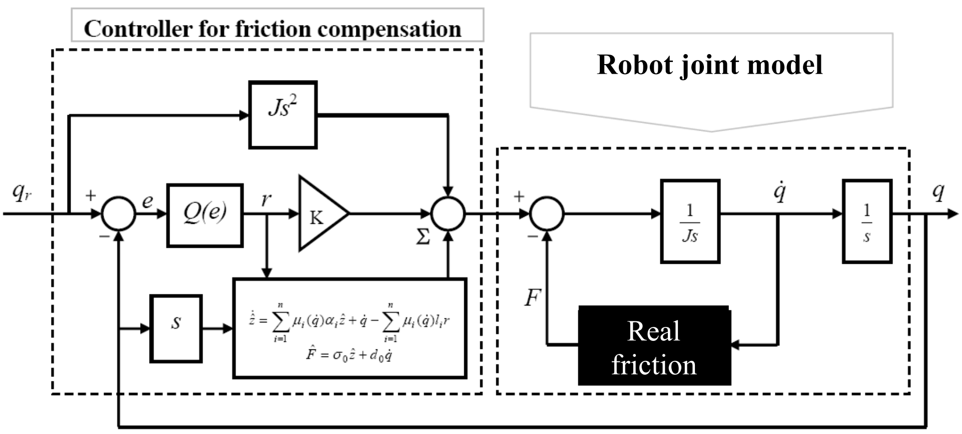

Fig. 3. Proposed control scheme for tracking enhancement for servo system using local modelling approach of friction.

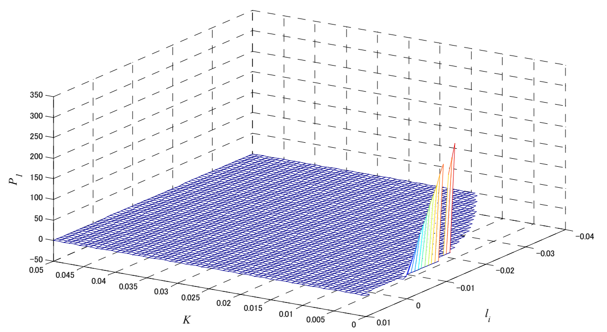

Fig. 4.a Map of damping values variations of one real pole in (10), at very low velocities, the darkest region in blue has value of -0.04 using the parameter identified in the robot joint.

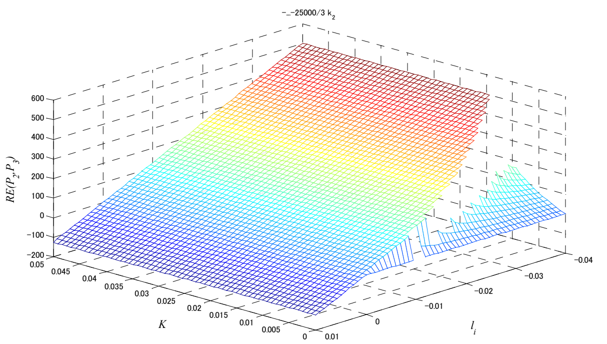

Fig. 4.b Map for damping values of the 2 complex poles in (10), at low velocities. The dark blue is equivalent to negative damping.

The interpolation process is linear, thus the dynamics of the state matrix characterizing the stability inside the mixed region can be written by

$$A_{i/i+1} = \begin{bmatrix} \alpha_i & \lambda.(\mu_i l_i + \mu_{i+1} l_{i+1}) & \mu_i l_i + \mu_{i+1} l_{i+1} \\ 0 & 0 & 1 \\ \dfrac{\sigma_0}{m} & -\dfrac{K.\lambda}{m} & -\dfrac{K}{m} \end{bmatrix} \qquad (12)$$

Using the properties of the weighting functions and the design parameters to ensure local stability, the eigen values of (12) can be calculated and local stability between two successive regions can be checked. Compared to some methods using one fixed gain for all the operating range of the system with friction (Canudas de Wit *et al.*, 1995), the gain scheduling used in the compensator (9) combined with the estimation mechanism (8), allow flexibility in the design, enhanced tracking performances, and avoiding a high control input specially at very low velocities.

The parameters used in the compensator design were identified in robot joint. The model used for the friction compensation is tuned during experiments. We should note that the reference trajectory make the system going into a severe regime of slow motions and reversal velocities.

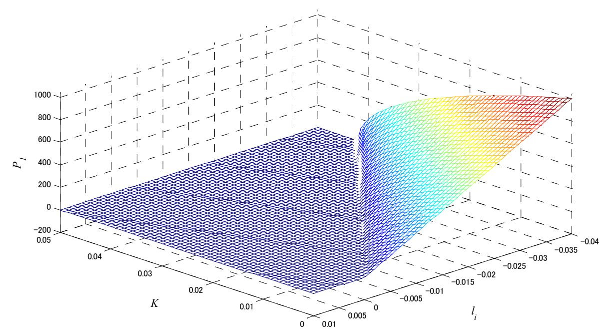

Fig. 5.a Map of damping of one real pole in (10) at higher velocities. The darkest region in blue has the same value as in the model for very low velocities.

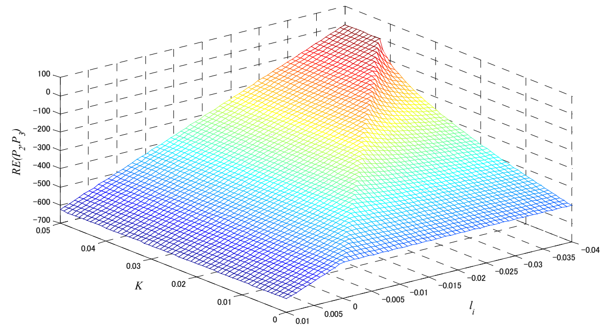

Fig. 5.b Map for damping of the 2 complex poles of (10) at very low velocities. The regions in dark blue give negative damping.

4. EXPERIMENTAL RESULTS AND EVALUATION

Experiments were performed on a joint of FANUC robot in order to evaluate the proposed control strategy. The experimental setup as shown in (fig. 6) consisted of: a PC 700 MHz operating system RT-LINUX. The PC connected by an optical cable to a digital servo adapter that ensures signals interfacing between the PC and a servo amplifier module. The control algorithm is implemented in C language.
The reference trajectory makes the robot joint go through the low velocities region and velocity reversal.

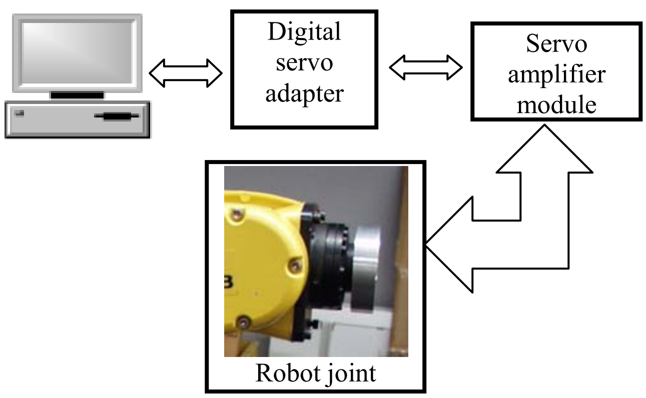

Fig. 6 Experimental setup for the robot joint control.

$$x_d(t) = \sin(2\pi f t)\sin\left(\frac{2\pi f t}{10}\right) \qquad (13)$$

The robot joint will be operating at low velocities region and performing reversal many reversal velocities during the experiments (f = 0.1Hz).
The results in (fig. 7), (fig. 8) and (fig. 9) shows the tracking error and the joint position with reference (13). After compensation, it is clear that, the RMS tracking error is reduced more than 10 times. This confirms the effectiveness of the use of the combined action of the observer -controller.

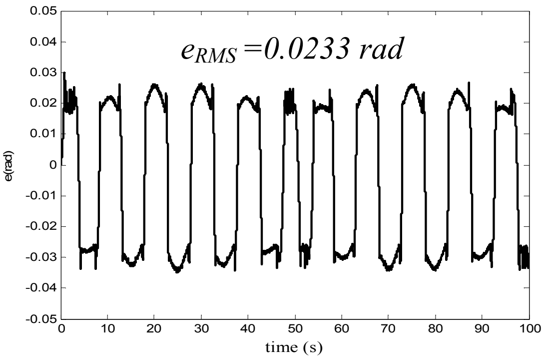

Fig. 7.a tracking error without friction compensation.

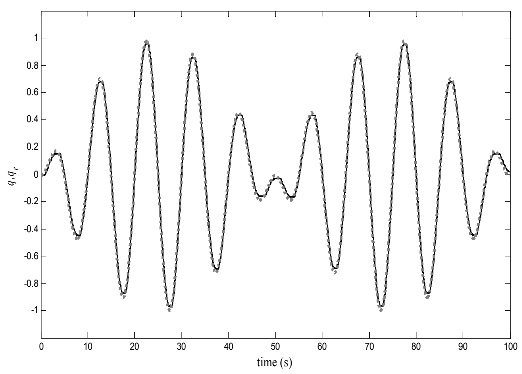

Fig. 7.b without friction compensation: position of the robot (in black) joint tracking a reference trajectory (12) (in dotted grey).

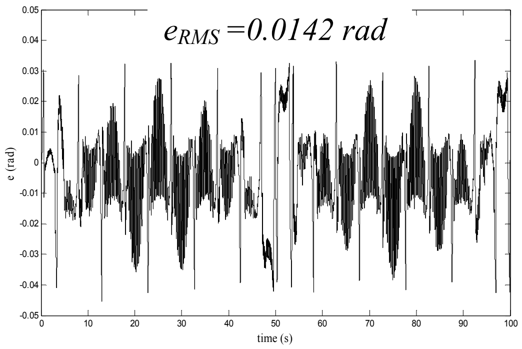

Fig. 8.a tracking error under proposed friction compensation scheme without compensating gains

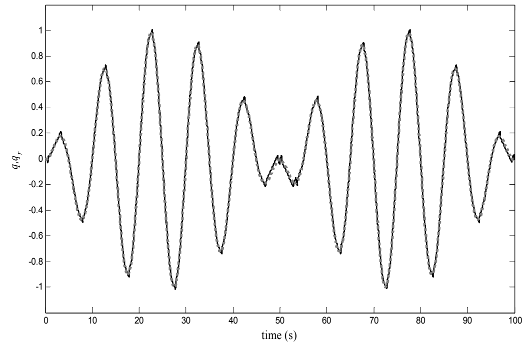

Fig. 8.b with fuzzy model as compensor: position of the robot joint (in black) tracking a reference trajectory (12) (in dotted grey).

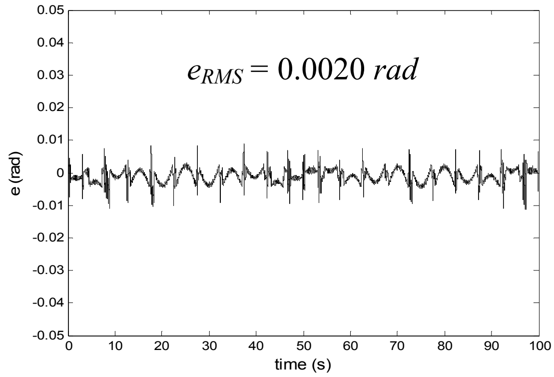

Fig. 9.a tracking error under proposed friction compensation scheme with compensating gains

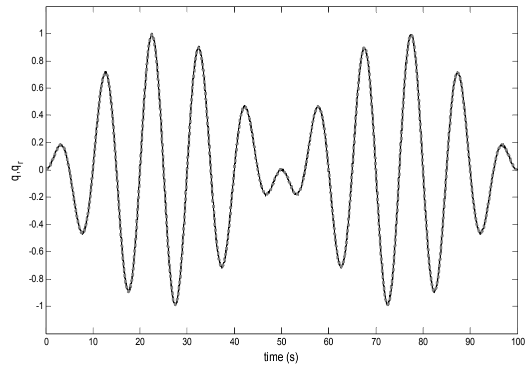

Fig. 9.b position of the robot joint (in black) tracking a reference trajectory (12) (in dotted grey).

In case only the fuzzy model is used (fig.8), better results can be reached by using more local models, this require more parameters to identify which give the advantage to the use of compensating gains for the observer to reduce the estimation error between two known local models.

5. CONCLUSIONS

This paper proposes a local design approach applied to a robot joint tracking control for friction compensation. The control is based on a fuzzy model of nonlinear friction.

Stability analysis of the overall controlled system was used for choosing local observer gains. Experiments on robot joint show the effectiveness of the proposed method. Further developments are to be done in the parameters modelling and a design of a robust compensation scheme, and the extension to other applications such us disk drive control and traction control systems.

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Appendix A. Identified and designed parameters

F_i (N.m)	-0.02,-0.08,0,0.06,0.015
σ_0	980
d_0	0.05
J (kg.m^2)	0.001
K	0.1
λ	25.0
$\dot{q}_i$ (rad/s)	-1,-0.2,-0.002,0,0.002,0.2,1
K_i	0,0.1,0.05,0.01,0.05,0.1,0