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Slow-motion control of an unloaded hydraulic robot arm

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ABSTRACT

The slow-motion control of an experimental hydraulically actuated robot with unknown friction forces and stick-slip oscillations is considered. A solution based on a design well-suited for engineering implementation is proposed. This consists of a double integral action controller with adequate stability margins. With such a configuration, harmful jerky motion is eliminated. Limited resolution of the sensors, friction forces and the integral actions of the controller give rise to stick-slip oscillations. The consideration of a switching control based on a linear observer designed for the closed-loop system makes the mechanism be free of these oscillations. Experimental results show the effectivity of the control scheme. The relevance of the solution here proposed is threefold: (a) well-known control engineering techniques are applied, (b) modelling and identification of elaborated friction force models usually required for more sophisticated controllers are not needed for the solution here proposed, and (c) the control system stability margin specifications considered are adequate.

1. Introduction

In the control of electromechanical systems subject to friction and other unmodelled nonlinear dynamics, the combination of control that does not need the friction model, observer design for system states, and switching control for the elimination of oscillatory behaviour is not usual in the literature. This paper brings together these three aspects, which are relevant separately, for the positioning and trajectory-tracking control of a 3-joint hydraulically actuated robot exhibiting non-smooth motion at low velocities and stick-slip oscillations.

Great progress has been made in the control of hydraulically actuated systems. Some examples are presented in [1–6] and references therein. In most of these works, the control design is based on state-space models. In some of them, the control goal is defined as the elimination of self-excited stick-slip oscillations [2,3]. The analysis and elimination of friction-induced stick-slip periodic motion have been extensively treated in the literature from different viewpoints [7–14]. Typically, the control design is based on the modelling of the friction. An integral characteristic of this paper, is that, alternatively, the control system is designed by considering the friction model unknown.

In the mechanism under study, the control goal is fourfold. Firstly, to achieve smooth motion, that is, jerking motion should be avoided in order to eliminate additional mechanical stress. Secondly, to achieve acceptable control performance, that is, zero-steady error in position and good tracking of trajectories. Thirdly, to achieve robustness of the closed-loop joints under uncertainties and unknown parameters. Finally, to eliminate stick-slip oscillations. The former three goals are achieved by means of a linear controller which includes a double-integral term. A successful application of such a strategy has been already reported in [15]. In this case, the same controller is applied to all the joints and does not require the velocity signal, unlike most of the available control schemes for systems with friction [7,16–19].

Another key characteristic of the control strategy here presented is the proposal of the most simple controller which satisfies the design specifications. That is, a well-suited solution for engineering applications avoiding un-necessary sophisticated solutions and overdesign.

Several types of linear controllers were experimentally tested in order to find the most appropriate control for satisfying the specifications set above. Experiments show that proportional controllers lead to damaging shaking motion. Moreover, with this

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Nomenclature

A	area of the base of chamber A of the hydraulic actuator
b	viscous friction coefficient
$C_{PIi}(s)$	controller with single integral action
$C_{IIi}(s)$	controller with double integral action
αA_p	area of the base of chamber B of the hydraulic actuator
d	derivative of flow with respect to voltage
$e(t)$	actuator position error
$\hat{e}(t)$	estimation of the position error
$f(t, x_p, \ddot{x}_p)$	friction force function
F_{ext}	force exerted by the actuator
F_f	external force exerted on the actuator
$F_i(s)$	out-loop conditioning filter
$J_i(s)$	joint i transfer function
L_{IIi}	direct transmittance with the double integral action controller
K	actuator transfer function gain
K_{ef}	observer gain
m_p	mass displaced by the actuator
P_A	pressure in chamber A of the actuator
P_B	pressure in chamber B of the actuator
ΔP	differential pressure of the actuator cameras $\Delta P = \alpha P_B - P_A$
Q_A	fluid flow through port A of the hydraulic actuator
Q_B	fluid flow through port B of the hydraulic actuator
Q_{Li}	net fluid flow into the actuator $Q_{Li} = \lvert Q_A - Q_B \rvert$
$r(t)$	reference of the control system
$T(s)$	closed-loop system of the joint controller
u	derivative of flow with respect to pressure
$U(s)$	Laplace transform of input (valve feeding voltage) u
$x_p, \dot{x}_p, \ddot{x}_p$	reference position, velocity and acceleration of the actuator piston
$X_p(s)$	Laplace transform of x_p
$x_c(t)$	state of the controller realization
$x_s(t)$	state of the joint dynamics realization
$x_T(t)$	state of the closed-loop system realization
$\hat{x}(t)$	observer state
$\dot{\hat{x}}(t)$	estimation of the joint-actuator velocity
$y_T(t)$	closed-loop system output
(A_s, B_s, C_s, D_s)	canonical realization matrices of the joint dynamics
(A_c, B_c, C_c, D_c)	canonical realization matrices of the controller
(A_T, B_T, C_T, D_T)	canonical realization matrices of the closed-loop system
$\epsilon_{position}(t)$	position threshold measurement
$\epsilon_{velocity}(t)$	velocity threshold measurement
τ	actuator transfer function time constant

type of controllers, very poor positioning and tracking performance are obtained. Nevertheless, no stick-slip motion occurs. Controllers with integral action were also tested. They reduce the jerking-shaking motion substantially. Moreover, good positioning control is achieved. However, adequate tracking properties cannot be obtained. Derivative-based action controllers are not an option either. In this system, measurement noise causes high activity and saturation of the control signal, causing severe damaging shaking of the mechanism.

Better results are obtained with controllers which include double integral action. For the mechanism here considered with this type of controllers it is possible to achieve the first three goals mentioned above. The results here presented show that with double integral action controllers, a friction-model-based control scheme is not always necessary in order to achieve good performance for electromechanical systems with dry friction, as it is commonly presented in the literature [7,16,17,19].

The controller has been designed considering an *average model* for the three joints. The result can be referred to as a *generalised joint model*. The tasks of modelling and identification of parameters in industrial robots encounter different problems, as [20] addresses. These aspects are here avoided.

Two important aspects of the solution here presented may need some clarification. Namely, the model and control design specifications (stability margins). It is well-known that there are not concrete rules that dictate on how to select a model. Such an exercise is, as a matter of fact, an iterative process. On the other hand, it is not clear how to establish *a priori* adequate stability margins for any particular system. Even in the so-called robust methods, the selection of adequate disturbances and weighting functions is in general an iterative exercise. In practice, designers resort to rules of thumb.

Following the spirit of intuitive engineering solutions, an observer-based switching controller is introduced in oder to eliminate stick-slip oscillations, which are caused by friction forces, the integral actions of the controller and the limited resolution of the position sensor. The controller design is obtained by applying fundamental frequency-domain methods [21]. Furthermore, the frequency-domain properties of the closed-loop system are crucial for the effectivity of the state observer.

Due to the characteristics of the robot, modelling the friction is unfeasible. Stick-slip behaviour arises in the three joints when the reference position is maintained constant after a manoeuvre has been performed. If the reference position changes relatively quick, the stick-slip phenomenon does not appear.

A switched-type control scheme seems to be the most appropriate control structure for this kind of discontinuous behaviour [22,23]. The controller switching-logic is based on a **linear** full-state observer for the closed-loop system. The double-integral controller is used for the positioning and reference-tracking mode, and is switched off when the position error is *almost zero* and the estimated velocity is close to zero. The zero-error-crossing of the position value cannot be detected accurately due to the sensor resolution. If the reference is changed, the control is again switched on. An integral characteristic of the linear full-order observer proposed is that its performance is maintained during transient responses, equilibrium and limit cycles.

Typically, the compensation of friction effects is not based on the estimation of system states, it is indeed usually based on the estimation of friction [2,3,11]. The problem of friction compensation based on the estimated velocity has been proposed in [5,13,24–26]. In hydraulically actuated systems, very few works propose state-observer-based friction compensation [4,5]. Exceptionally, the control design is based on a cylinder-pressure observer [27]. As it is pointed out in [25,26], very few works are dedicated to the analysis of state-observer-based controlled systems with friction and the elimination of limit cycling problems. This is done in the present paper. Furthermore, the observer design proposed is not based on either the friction model or the friction estimation, unlike other works proposing observer designs in systems with dry friction [13,25,26]. The effectivity of the observer proposed relies on the well-defined frequency-domain characteristics of the closed-loop system.

The experiments results here presented were carried out without pay load for the sake of clarity and in order to facilitated the design and tunning process.