

Practical Design of Independent Joint Controllers for Industrial Robot Manipulators

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1. Introduction

Compensation of manipulator nonlinear dynamics, which is typical of model-based control schemes, has been shown to give tracking performance improvements not only for direct-drive robots [1] but also for gear-drive robots [2,3]. Nevertheless, whenever it is difficult to obtain a complete accurate modeling of the system components, e.g. actuators and joint transmissions, or large parameter variations occur, e.g. variable payloads, the adoption of independent joint controllers might still prove to be an engineering solution that deserves consideration. This paper addresses the problem of robust design of linear independent joint feedback controllers in order to contrast imperfect dynamic modeling and disturbance effects. A new scheme that makes use of additional acceleration feedback is proposed and compared with the classical position + velocity feedback scheme, so as to provide robustness to disturbances at very low expense. Further, it is shown how linear feedforward compensation confers enhanced tracking capabilities to the schemes in the case of good model accuracy. Simulation results are provided.

2. Independent Joint Controllers

In an industrial robot manipulator, each joint axis can be regarded as a linear single-input/single-output system with the nonlinear dynamic coupling effects treated as disturbances. In view of this, *independent joint controllers* can be designed with the typical goal of achieving good *disturbance rejection* and *trajectory tracking*.

The most general control scheme for a joint servo is shown in Fig. 1, where the motor is described by the voltage to position transfer function

$$G(s) = \frac{k_m}{s(1 + sT_m)} \quad (1)$$

with k_m and T_m being the gain and time constants. The three blocks $C_P(s)$, $C_V(s)$, $C_A(s)$ represent the transfer functions of the *position*, *velocity*, *acceleration* controllers to be specified; k_{TP} , k_{TV} , k_{TA} are the relative transducer constants. An effective rejection of the disturbance d is ensured by a PI action in the controller, yielding zero error at steady-state for a step disturbance and offering a stabilizing effect. Two solutions that derive from the scheme of Fig. 1 are presented below.

2.1. Position + Velocity Feedback

In this case:

$$C_P(s) = K_P \quad C_V(s) = K_V \frac{1 + sT_V}{s} \quad C_A(s) = 1 \\ k_{TA} = 0.$$

A root locus analysis shows that it is convenient to choose $T_V = T_m$ so as to get a second-order system. In fact, the

closed-loop input/output transfer function is

$$\frac{\Theta(s)}{\Theta_d(s)} = \frac{\frac{1}{k_{TP}}}{1 + \frac{sk_{TV}}{K_P k_{TP}} + \frac{s^2}{k_m K_P k_{TP} K_V}}, \quad (1)$$

which can be compared with the typical transfer function of a second-order system

$$W(s) = \frac{\frac{1}{k_{TP}}}{1 + \frac{2\zeta s}{\omega_n} + \frac{s^2}{\omega_n^2}}. \quad (2)$$

Hence, if the natural frequency ω_n and the damping ratio ζ are given as design requirements, the following relations can be established:

$$K_V k_{TV} = \frac{2\zeta\omega_n}{k_m} \quad (3)$$

$$K_P k_{TP} K_V = \frac{\omega_n^2}{k_m}. \quad (4)$$

The closed-loop disturbance/output transfer function is

$$\frac{\Theta(s)}{D(s)} = \frac{\frac{s}{K_P k_{TP} K_V (1 + sT_V)}}{1 + \frac{sk_{TV}}{K_P k_{TP}} + \frac{s^2}{k_m K_P k_{TP} K_V}}, \quad (5)$$

which shows that the rejection factor affecting the amplitude of the output due to the disturbance is

$$X_R = K_P k_{TP} K_V \quad (6)$$

and is fixed, once K_P and K_V have been chosen via (3,4). Also, an estimate of the disturbance recovery time is given by the time constant

$$T_R = \sup\{T_m, \frac{1}{\zeta\omega_n}\}. \quad (7)$$

The reference input to the control scheme can be modified into

$$\left(k_{TP} + \frac{sk_{TV}}{K_P} + \frac{s^2}{k_m K_P K_V}\right) \Theta_d(s), \quad (8)$$

so that perfect tracking of the desired joint trajectory $\Theta_d(s)$ is ensured.

2.2. Position + Velocity + Acceleration Feedback

In this case:

$$C_P(s) = K_P \quad C_V(s) = K_V \quad C_A(s) = K_A \frac{1 + sT_A}{s}.$$

Like above, an opportune cancellation can be performed by setting $T_A = T_m$, or $k_m K_A k_{TA} T_A \gg T_m$ and $k_m K_A k_{TA} \gg 1$. The two solutions are essentially the same, as far as the dynamic features of the control system are concerned. The closed-loop input/output transfer

function is

$$\frac{\Theta(s)}{\Theta_d(s)} = \frac{\frac{1}{k_{TP}}}{1 + \frac{sk_{TV}}{K_P k_{TP}} + \frac{s^2(1 + k_m K_A k_{TA})}{k_m K_P k_{TP} K_V K_A}} \quad (9)$$

The closed-loop disturbance/output transfer function is

$$\frac{\Theta(s)}{D(s)} = \frac{\frac{s}{K_P k_{TP} K_V K_A (1 + sT_A)}}{1 + \frac{sk_{TV}}{K_P k_{TP}} + \frac{s^2(1 + k_m K_A k_{TA})}{k_m K_P k_{TP} K_V K_A}} \quad (10)$$

The resulting disturbance rejection factor and recovery time are respectively given by

$$X_R = K_P k_{TP} K_V K_A \quad (11)$$

and

$$T_R = \sup\{T_A, \frac{1}{\zeta\omega_n}\} \quad (12)$$

where T_A can be made less than T_m . With reference to the transfer function in (2), the following relations can be established for design purposes:

$$\frac{2K_P k_{TP}}{k_{TV}} = \frac{\omega_n}{\zeta} \quad (13)$$

$$1 + k_m K_A k_{TA} = \frac{k_m X_R}{\omega_n^2} \quad (14)$$

$$K_P k_{TP} K_V K_A = X_R. \quad (15)$$

Remarkably, with respect to the previous case, the acceleration feedback allows not only to achieve any desired dynamic behavior, but also to prescribe the disturbance rejection factor. Notice that acceleration measurements can be reconstructed from position and velocity measurements via a suitable state variable filter, whose bandwidth is to be chosen larger than the joint servo bandwidth. Analogously to the previous scheme, modifying the reference input into

$$\left(k_{TP} + \frac{sk_{TV}}{K_P} + \frac{(1 + k_m K_A k_{TA})s^2}{k_m K_P K_V K_A}\right) \Theta_d(s) \quad (16)$$

ensures perfect tracking of the desired joint trajectory $\Theta_d(s)$.

3. Case study

In order to test the performance of the schemes illustrated in the previous section, a case study was carried out for the first three joints of the industrial robot manipulator MANUTEC R3 [4]. The independent joint controllers were tuned for an ideal, purely inertial system with decoupled joints, absence of gravity, and inertia equal to the maximum value of the total joint inertia. Both the above schemes were simulated with feedforward action, using the software package SIMNON. The dynamic behavior of the closed-loop system was specified by $\omega_n = 34$ rad/sec and $\zeta = 0.7$. The disturbance rejection factor for the third scheme was chosen as $X_R = 2000$. The desired joint motions are of π rad for the first two joints and of $2\pi/3$ rad for the third joint, to be executed in a time of 1 sec. Suitable fifth-order polynomials were used to compute the joint trajectories. These cause the manipulator to almost reach its joint velocity limits, so that a strong interaction between the motion of the joints occurs.

The time history of the errors confirms that, with respect to the classical position + velocity feedback

scheme (Fig. 2a), the scheme that utilizes also acceleration feedback (Fig. 2b) achieves a satisfactory rejection of the disturbance torques generated by nonlinear coupling with other joints, and tracking performance favorably compares with that obtained for the same manipulator with partial model-based compensation [3].

Acknowledgments

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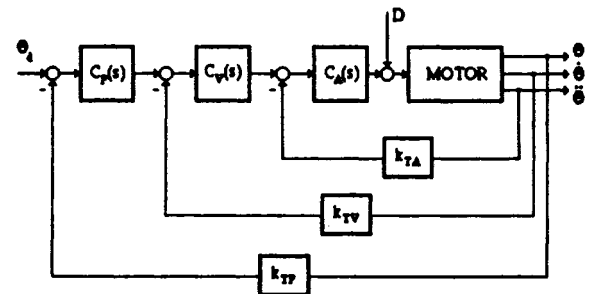


Fig. 1 — Joint servo control scheme.

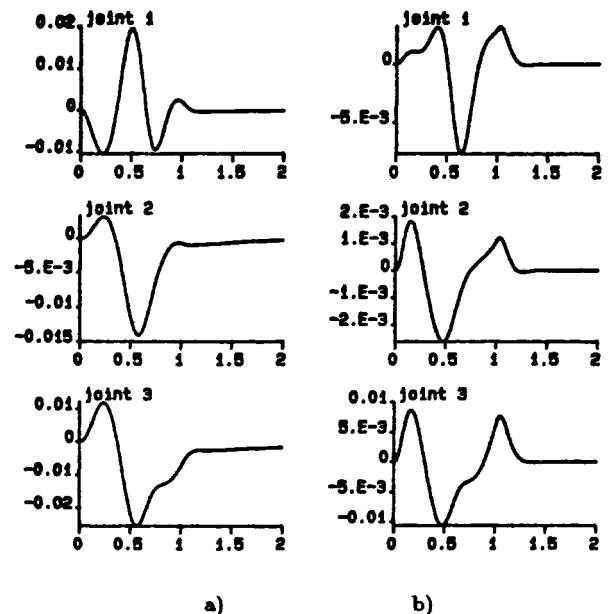


Fig. 2 — Tracking errors.