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Fault-tolerant robot manipulators based on output-feedback $\mathcal{H}_\infty$ controllers

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Abstract

This paper develops two fault-tolerant control strategies for robot manipulators. The first is based on linear parameter-varying systems and the second on Markovian jump linear systems. Firstly, it is shown that with the LPV approach post-fault stability is guaranteed only if the robot stops completely after a fault detection. Then, with an underactuated configuration, the manipulator can be controlled appropriately. Secondly, it is shown that with the fault-tolerant system based on Markovian jump linear systems, stability is guaranteed after a fault is detected even with the robot still moving. This approach incorporates all manipulator configurations in a unified model. Both strategies have been implemented based on output-feedback $\mathcal{H}_\infty$ controllers, which are the main focus of this paper. Experimental results illustrate the performance of each controller.

Keywords: Fault-tolerant system; $\mathcal{H}_\infty$ control; Markovian jump linear system; Linear parameter-varying system; Robot manipulator

1. Introduction

Parametric uncertainties and exogenous disturbances increase the difficulty of reference tracking control for robot manipulators. $\mathcal{H}_\infty$ control strategies for robot manipulators based on state-feedback control have been used to minimize the disturbance effects in system performance, [1]. However, the velocity signal, considered as state, generally is not available and can be obtained indirectly from a position measurement. This procedure can introduce noises and delays, which decrease tracking control efficiency. An output-feedback controller can be used in order to avoid these problems. Two design techniques for output-feedback gain-scheduling controllers with a guaranteed $\mathcal{H}_\infty$ performance are proposed in [2] for linear parameter-varying (LPV) systems. In this paper, the second design technique, named as *Projected Characterization*, is applied to an actual robot manipulator in its Quasi-LPV representation, which means the parameters matrix of the model depends on the state.

Fault-tolerant systems for robot manipulators have been developed by several authors; see, for instance, [3–5] and references therein. Free torque failures in robot manipulators, where the torque supply in the motor breaks down suddenly, can make these systems uncontrollable. Furthermore, if the robot is working in hazardous or unstructured environments, where repairs are not allowed, the requested movement must be completed according to the fault configuration. When a free torque failure occurs, the fully actuated manipulator changes to an underactuated configuration. However, when the manipulator changes, after a fault occurrence, from a fully actuated to an underactuated configuration, the system stability is not guaranteed with the deterministic output-feedback controllers proposed in [2]. To use these controllers in a fault-tolerant robot system, it is necessary to stop completely the movement of all joints after the fault detection, restarting it from zero velocity.

To avoid the necessity of stopping the robot when a fault occurs, Markov theory is used in this paper to characterize abrupt changes in the operation points of the robotic manipulator. A model is developed based on linear systems subject to abrupt variations, namely, Markovian jump linear systems (MJLS) [6,7]. In order to formulate this model, the manipulator dynamic is linearized around operation points, and a Markovian model is developed to encompass the changes of the operation points and the transition rate between fault configurations [1,8]. With the proposed model, that represents

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all manipulator configurations in a unified way, the output-feedback $\mathcal{H}_\infty$ controller for MJLS proposed in [9] is used to guarantee stability after the occurrence of a sequence of faults.

This paper is organized as follows: in Section 2, the Quasi-LPV representations of fully actuated and underactuated robot manipulators are presented, with experimental results, using a deterministic output-feedback $\mathcal{H}_\infty$ controller; in Section 3, the fault-tolerant manipulator model and the control system based on output-feedback $\mathcal{H}_\infty$ controller for MJLS are presented, and two fault sequences for the UArm II robot are evaluated to demonstrate the effectiveness of this approach.

2. Quasi-LPV representation of the manipulator

2.1. Fully actuated manipulator

The dynamic equations of a robot manipulator can be found by Lagrange theory as

$$\tau = M(q)\ddot{q} + C(q,\dot{q})\dot{q} + F\dot{q} + G(q), \tag{1}$$

where $q \in \Re^n$ is the joint position vector, $M(q) \in \Re^{n\times n}$ is the symmetric positive definite inertia matrix, $C(q,\dot{q}) \in \Re^{n\times n}$ is the Coriolis and centripetal matrix, $F \in \Re^{n\times n}$ is the diagonal matrix of frictional torque coefficients, $G(q) \in \Re^n$ is the gravitational torque vector, and $\tau \in \Re^n$ is the applied torque vector. A parametric uncertainty can be introduced dividing the parameter matrices $M(q)$, $C(q,\dot{q})$, F, and $G(q)$ into a nominal and a perturbed part, where $M_0(q)$, $C_0(q,\dot{q})$, F_0, and $G_0(q)$ are the nominal matrices, and $\Delta M(q)$, $\Delta C(q,\dot{q})$, ΔF, and $\Delta G(q)$ are the parametric uncertainties. A finite energy exogenous disturbance, $\tau_d \in \Re^n$, can also be introduced resulting in

$$\tau + \delta(q,\dot{q},\ddot{q},\tau_d) = M_0(q)\ddot{q} + C_0(q,\dot{q})\dot{q} + F_0\dot{q} + G_0(q), \tag{2}$$

with

$$\begin{aligned}\delta(q,\dot{q},\ddot{q},\tau_d) = &-(\Delta M(q)\ddot{q} + \Delta C(q,\dot{q})\dot{q} \\ &+ \Delta F\dot{q} + \Delta G(q) - \tau_d).\end{aligned}$$

The state is defined as $x = \left[\dot{q}^{\mathrm{T}}\ q^{\mathrm{T}}\right]^{\mathrm{T}}$, where q and $\dot{q}$ are the positions and the velocities of the manipulator joints, respectively. The Quasi-LPV representation of a fully actuated manipulator is given by

$$\dot{x} = A(q,\dot{q})x + B(q)u + B(q)\delta(q,\dot{q},\ddot{q},\tau_d), \tag{3}$$

with,

$$A(q,\dot{q}) = \begin{bmatrix} -M_0^{-1}(q)\,(C_0(q,\dot{q}) + F_0) & 0 \\ I_{n\times n} & 0 \end{bmatrix},$$

$$B(q) = \begin{bmatrix} M_0^{-1}(q) \\ 0 \end{bmatrix},$$

$$u = \tau - G_0(q).$$

2.2. Underactuated manipulator

Underactuated robot manipulators are mechanical systems with fewer actuators than degrees of freedom. For this reason, the control of passive joints is made considering the dynamic coupling between them and the active joints. Here, the manipulator is considered with n joints, in which n_p are passive and n_a are active joints. From [10], no more than n_a joints of the manipulator can be controlled at every instant when breaks are used in the passive joints. Let n_u be the number of passive joints that have not already reached their set point in a given instant. If $n_u \geq n_a$, n_a passive joints are controlled and grouped in the vector $q_u \in \Re^{n_a}$, the remaining passive joints, if any, are kept locked, and the active joints are grouped in the vector $q_a \in \Re^{n_a}$. If $n_u < n_a$, the n_u passive joints are controlled applying torques in n_a active joints. In this case, $q_u \in \Re^{n_u}$ and $q_a \in \Re^{n_a}$. The strategy is to control all passive joints until they reach the desired position, considering the conditions exposed above, and then turn on the brakes. After that, all the active joints are controlled by themselves as a fully actuated manipulator. The dynamic Eq. (2) can be partitioned as

$$\begin{aligned}\begin{bmatrix}\tau_a \\ 0\end{bmatrix} + \begin{bmatrix}\delta_a \\ \delta_u\end{bmatrix} = \begin{bmatrix} M_{aa} & M_{au} \\ M_{ua} & M_{uu}\end{bmatrix}\begin{bmatrix}\ddot{q}_a \\ \ddot{q}_u\end{bmatrix} + \begin{bmatrix} C_{aa} & C_{au} \\ C_{ua} & C_{uu}\end{bmatrix}\begin{bmatrix}\dot{q}_a \\ \dot{q}_u\end{bmatrix} \\ + \begin{bmatrix} F_{aa} & 0 \\ 0 & F_{uu}\end{bmatrix}\begin{bmatrix}\dot{q}_a \\ \dot{q}_u\end{bmatrix} + \begin{bmatrix}G_a \\ G_u\end{bmatrix},\end{aligned} \tag{4}$$

where the indices a and u represent the active and free (breaks not actioned) passive joints, respectively. Factoring out the vector $\ddot{q}_a$ in the second line of (4) and substituting in the first one, results in

$$\begin{aligned}\tau_a + \overline{\delta}(q,\dot{q},\ddot{q},\tau_d) = &\overline{M}_0(q)\ddot{q}_u + \overline{C}_0(q,\dot{q})\dot{q}_u + \overline{F}_0(q)\dot{q}_u \\ &+ \overline{D}_0(q,\dot{q})\dot{q}_a + \overline{G}_0(q),\end{aligned} \tag{5}$$

with

$$\begin{aligned}
\overline{M}_0(q) &= M_{au} - M_{aa}M_{ua}^{-1}M_{uu},\\
\overline{C}_0(q,\dot{q}) &= C_{au} - M_{aa}M_{ua}^{-1}C_{uu},\\
\overline{D}_0(q,\dot{q}) &= C_{aa} - M_{aa}M_{ua}^{-1}C_{ua} + F_{aa},\\
\overline{F}_0(\dot{q}) &= -M_{aa}M_{ua}^{-1}F_{uu},\\
\overline{G}_0(q) &= G_a - M_{aa}M_{ua}^{-1}G_u,\\
\overline{\delta}(q,\dot{q},\ddot{q},\tau_d) &= \delta_a - M_{aa}M_{ua}^{-1}\delta_u,
\end{aligned}$$

where all matrices and vectors have appropriate dimensions, depending on the numbers of active, n_a, and free passive joints, n_u. The state is defined as $x_u = \left[\dot{q}_u^{\mathrm{T}}\ q_u^{\mathrm{T}}\right]^{\mathrm{T}}$. Hence, a Quasi-LPV representation of the underactuated manipulator can be defined as follows

$$\dot{x}_u = A(q,\dot{q})x_u + B(q)u + B(q)\overline{\delta}(q,\dot{q},\ddot{q},\tau_d), \tag{6}$$

with

$$A(q,\dot{q}) = \begin{bmatrix} -\overline{M}_0^{-1}(q)\left(\overline{C}_0(q,\dot{q}) + \overline{F}_0(q)\right) & 0 \\ I & 0 \end{bmatrix},$$

$$B(q) = \begin{bmatrix} \overline{M}_0^{-1}(q) \\ 0 \end{bmatrix},$$

$$u = \tau_a - \overline{D}_0(q,\dot{q})(\dot{q}_a - \overline{G}_0(q)).$$