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A SDRE-based tracking control for a hydraulic actuation system

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ABSTRACT

This paper presents the design and the experimental evaluation of a tracking control for a hydraulic actuation system in the presence of significant nonlinearities. The adopted control approach consists of a feedforward and a feedback term. The feedforward action is obtained from the known system dynamics and the feedback one is developed starting from the state-dependent Riccati equation (SDRE).

The tracking performance of the presented control is demonstrated by means of both simulations and real-time experiments, solving the algebraic Riccati equation at each time step.

1. Introduction

Hydraulic actuation systems are widely used in industrial applications due to their small size-to-power ratios and their ability for generating large actuation forces and torques at fast motion.

Examples of hydraulic positioning systems can be found in transportations, industrial machineries, seismic applications [1–4], and earth moving equipments. However, the dynamics of hydraulic systems are highly nonlinear [5] due to the pressure–flow rate relationship, the dead band of the control valve and the frictions. In order to take the nonlinearities into account and, at the same time, to meet increasing performance specifications, high efficiency controllers are required. In the past, much of the work in the control of hydraulic systems has used linear model [6–8] or local linearization of the nonlinear dynamics about the nominal operating point [9]. In [10], the nonlinear system model has been linearized about the reference trajectory and the resulting non-autonomous system has been used to develop time-varying feedback gains. Suitable adaptive approaches are employed when there is no knowledge of the parameter values [11,12]. In order to take system uncertainties into account, robust approaches can be adopted [12,13]. In [14], a sliding mode control applied to an asymmetric single-rod cylinder has been presented.

Another interesting approach for the design of high performance controllers is the optimal one. However, for nonlinear systems the optimal control is a very challenging topic. It is well known that the classical optimal control is based on the Hamilton–Jacobi–Bellmann equation that is difficult, if not impossible, to solve for most practical applications [15]. As a consequence, designers of control algorithms have been focused on approximately optimal (suboptimal) control algorithms that sacrifice some performance by introducing approximations that facilitate the implementation. Such suboptimal control

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laws are considered a tradeoff between achieving true optimality, which is expensive and complicated to implement, and achieving an acceptable controller performance. One of these methods is based on the state-dependent Riccati equation (SDRE).

The SDRE method possesses many of the capabilities of other nonlinear design methods, such as stability, optimality, real-time implementability, and inherent robustness with respect to parametric uncertainties and unmodeled dynamics, as well as disturbance rejection. The basic idea of the SDRE algorithm is to fully capture the nonlinearities of the system by bringing the nonlinear system to a (nonunique) linear structure having state-dependent coefficient (SDC) matrices, and minimizing a nonlinear performance index having a quadratic-like structure. An algebraic Riccati equation (ARE) is then solved at each time step to give the suboptimal control law. SDRE technique has been first proposed by Pearson [16] and independently studied by Mracek and Cloutier [17]. Çimen [15] has been presented a good overview of the state of the art concerning SDRE control.

Examples of application of the SDRE technique can be found for aircrafts [18], aerial vehicles [19], spacecraft [20], ships [21], automotive systems [22], magnetorheological devices [23].

In this paper, an SDRE-based tracking control (SDRETC) is designed for a hydraulic actuator and experimentally tested.

According to the authors' best knowledge, this is the first work in which an SDRETC is applied to a hydraulic actuation system and is implemented in real-time.

In general, the optimal linear quadratic tracking control law consists of the sum of two components: the first term is a constant feedback gain obtained by solving an algebraic Riccati equation; the second term involves a steady-state function that solves an auxiliary differential equation with unknown initial condition [24] that can be computed offline. For the nonlinear case, the solution of the optimal tracking control problem is more difficult because the auxiliary function must be also computed offline, but now the computation must include the dependence of the system state [25]. The mentioned problems about the auxiliary function calculation for the nonlinear case motivate the researcher to develop other methods for the nonlinear optimal tracking problem. Cloutier et al. [26] proposed an SDRE controller for a tracking problem as an integral servomechanism by augmenting the system with the integral states.

The SDRETC proposed in this paper is constituted by a feedback term, based on the SDRE technique, and a feedforward term obtained by the system dynamics inversion [27]. The feedforward part provides the necessary input for following the specified motion trajectory, the feedback part then stabilizes the tracking error dynamics.

This paper continues the work done in [28,29], performing the nonlinear optimal tracking which performances are illustrated by means of experimental results.

The paper is organized as follows: a description of the proposed control formulation is given in Section 2 and its application to a hydraulic actuation system is derived in Section 3. Simulation results are reported in Section 4. The real-time implementation of the control is discussed in Section 5, where the main results are also presented. In the last Section, some comments and statements are drawn.

2. SDRETC formulation

Given the desired motion trajectory, the tracking control objective is to synthesize a control input u such that the system output (or the system state) tracks the desired trajectory as closely as possible.

Consider a system which is autonomous, full-state observable, nonlinear in state, and affine (linear) in the input

$$\dot{x} = f(x) + B(x)u, \quad x(0) = x_0 \tag{1}$$

where $x \in \mathbb{R}^n$ is the state vector, $u \in \mathbb{R}^m$ is the input vector, and with the $C^1(\mathbb{R}^n)$ functions $f: \mathbb{R}^n \to \mathbb{R}^n$ and $B: \mathbb{R}^n \to \mathbb{R}^{n \times m}$.

Under the assumption $f(0) = 0$, a continuous nonlinear matrix-valued function $A(x)$ always exists such that $f(x) = A(x)x$, where $A: \mathbb{R}^n \to \mathbb{R}^{n \times n}$ is found by mathematical factorization. So, the extended linearization of the input-affine nonlinear system (1) becomes

$$\dot{x} = A(x)x + B(x)u \tag{2}$$

which has a linear structure with SDC matrices $A(x)$ and $B(x)$.

In order to make the system following the desired state trajectory $x_d(t)$, the performance index to be minimized can be defined as [30]

$$J = \frac{1}{2}\int_0^\infty \left\{ (x - x_d)^T Q (x - x_d) + (u - u_d)^T R (u - u_d) \right\} dt \tag{3}$$

where $Q \in \mathbb{R}^{n \times n} \geq 0$ and $R \in \mathbb{R}^{m \times m} > 0$ are symmetric weighting matrices that penalize deviations between the state and the desired state trajectory and between the control and the desired control, respectively. The term u_d is the desired control signal, computed from the known system dynamics as

$$\dot{x}_d = A(x_d)x_d + B(x_d)u_d. \tag{4}$$

The desired trajectory can be any non-zero, time-varying signal from which the desired control can be computed.