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Research article

Real-time discrete suboptimal control for systems with input and state delays: Experimental tests on a dehydration process

Liliam Rodríguez-Guerrero [a], Omar-Jacobo Santos-Sánchez [a,*], Nicolás Cervantes-Escorcia [b], Hugo Romero [a]

[a] Research Center on Technology of Information and Systems (CITIS) of the Autonomous University of Hidalgo State (UAEH), Mexico
[b] Master in Science student of Research Center on Technology of Information and Systems (CITIS) of the Autonomous University of Hidalgo State (UAEH), Mexico

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ABSTRACT

This article presents a suboptimal control strategy with finite horizon for affine nonlinear discrete systems with both state and input delays. The Dynamic Programming Approach is used to obtain the suboptimal control sequence, but in order to avoid the computation of the Bellman functional, a numerical approximation of this function is proposed in every step. The feasibility of our proposal is demonstrated via an experimental test on a dehydration process and the obtained results show a good performance and behavior of this process. Then in order to demonstrate the benefits of using this kind of control strategy, the results are compared with a non optimal control strategy, particularly with respect to results produced by an industrial Proportional Integral Derivative (PID) Honeywell controller, which is tuned using the Ziegler-Nichols method.

1. Introduction

The dehydration industry segment has one of the highest energy consumption rates. In fact, according to [1] the dehydration process mainly used in industries such as biotechnology, agroindustry, food, textiles, minerals, pulp and paper, polymers, wood and others, consumes about 10% to 25% of the total energy used by these industries [2]. The initial investment in dehydration plants does not represent the highest cost; the highest cost comes from daily operational expenses. Therefore, selecting the proper control strategy is essential to obtain energy savings and proper performance, preserving the quality of the final product [2,3]. With respect to the last point, the drying conditions have to be adjusted to reach the desired performance with respect to color, nutrient retention or energy optimization [3–5]. Then, an important objective is to decrease the production cost related to energy consumption for the process and dehydration time [2].

In these types of processes, time delays appear in the plant dynamics (in the state, in the input or both). The presence of these delays is associated with energy transport or recycling loops. Sometimes, these delays can be ignored, however often they have to be considered in the controller design [6,7] to avoid poor or undesirable performance. In this paper, an atmospheric dehydration plant is considered to carry out the drying process. Hot air (with regulated temperature) flows over the product, and the entire control process is modeled as a scalar nonlinear affine system with delays in the input and state. The input delay is due to the distance between the heat source and the product, while the state delay is induced by a recycling pipe. Due to the high energy consumption of the process, the best approach for regulating the temperature of the drying air could be optimal control [8]. However it could require the inclusion of additional hardware in the control loop and some troubles to consider the delays in the state and input, which hinders its implementation of the advanced control in the industry. So, it is a fundamental issue to demonstrate the advanced control (non linear optimal control) advantages versus classical controllers (industrial PID). Some of these advantages were reported in **[3]**, those results show important energy savings and a greater level of nutrients concentration in the dried product, when the linear continuous optimal control is compared with an industrial PID controller. The synthesis of the optimal controllers with finite horizon which regulate nonlinear plants with both input and state delays is a very complex problem and remains open [9,10]. Nevertheless, due to the practical motivation already exposed, in this article it is found a suboptimal solution for nonlinear discrete delayed systems involving explicit formulas, which represents our main theoretical contribution.

The strategies for solving the finite and infinite horizon optimal control problems (continuous and discrete cases) for free delays

* Corresponding author.
E-mail address: omarj@uaeh.edu.mx (O.-J. Santos-Sánchez).

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and delayed nonlinear systems have been considered by the control community in recent decades [9,11–15]. The main challenge is to find the exact solution for the Hamilton Jacobi Bellman Equation (HJB), which implies finding a Bellman function or functional for free delay and delayed cases respectively, [9,16–19]. In the last case, the solution of the optimal control problem falls on an infinite dimensional space which increases the difficulty [20]. To overcome these obstacles, some recursive numerical methods have been proposed as partial solutions [9,16,17]. For discrete systems, Adaptive or Heuristic Dynamic Programming (ADP, HDP) [12,16,21] are used to find a control sequence which minimizes a given performance index and provides iterative algorithms to obtain an approximate solution to the HJB Equation. The convergence algorithm also has been presented.

In [9] by algorithms based on ADP, an optimal control scheme was proposed for affine nonlinear discrete time delay systems with a quadratic performance index. In [16] an iterative ADP algorithm was proposed to obtain the optimal control law which makes the performance index function closest to the lowest boundary of all performance indices within an ε-error boundary. To facilitate the implementation of the iterative ADP algorithms, neural networks were used to approximate the performance index function, computing the optimal control law, and modeling the nonlinear system; simulation results are presented. In [17] an ADP algorithm for nonlinear discrete systems with state and input delays and simulation results was developed. In [13], the problem of generating an optimal trajectory for a class of nonlinear discrete systems with state delays, was solved by using an iterative algorithm based on HDP, and in [14] the same technique was applied for saturated actuators.

Some interesting results based on ADP for the case of nonlinear discrete systems with delays in the state and input has been proposed, for example in [16] a similar expression (with respect to our proposal) for the suboptimal control was found, but the Bellman function $V(k+1)$ is unknown, and it was found by the proposed numerical method in that article. Then, in [16] not explicit formulas was given, in this article, explicit formulas are provided for the controller, unlike to the problem exposed in [16] (infinite horizon optimal control problem), we address the finite horizon optimal control for nonlinear discrete systems with delays in the state and the input problem, to best knowledge of the authors, any solution involving explicit formulas to this problem has not been reported yet in the specialized literature.

Although optimal control techniques could represent some advantages related with energy savings and nutrients retention for drying process, this type of process could be disturbed by the environmental temperature changes, unmodeled dynamics and uncertain parameters, so other interesting modern robust control techniques can be applied (or a combination of optimal control and robust control). One can cite the sliding mode control (SMC) reported in [22], where dissipativity analysis and dissipativity-based SMC of continuous-time switched stochastic systems was presented. In [23] is exposed the design of a nonlinear observer-based fault diagnosis approach for polymer electrolyte membrane fuel cell air-feed systems, taking into account a fault scenario of sudden air leak in the air supply manifold. By using a simplified nonlinear model, a modified supertwisting (ST) sliding mode algorithm was used. Additionally, in [24] an extended state observer based second-order sliding-mode control for three-phase two-level grid-connected power converters was addressed.

In most of the reported works about discrete nonlinear systems, only simulation results were presented. Thus, the experimental validation of these approaches emerges as an interesting research issue, together with their comparison with non-optimized classical control strategies, such as PID control. Experimental validation can provide evidence about the energy relevance and robustness of the proposed algorithms, required hardware for its implementation, comparison with a classical non-optimized controller, real-time performance of the algorithm, impact on the quality of the final product, etc. A practical motivation is the energy savings in a dehydration process involving sliced tomatoes. Although [15] and [25] considered the same process, only a class of continuous nonlinear systems with delayed state and the Lyapunov Krasovskii Control Function approach were addressed. Here a more general class of nonlinear discrete delayed systems is analyzed.

In this article, the synthesis of the nonlinear discrete suboptimal control is demonstrated using a backward procedure with the Dynamic Programming approach with a finite horizon discrete quadratic performance index. The obtained control sequence is given by explicit formulas, and its implementation does not require additional calculations. As has been shown in other works [2,3,26–28], the use of advanced control techniques implies energy savings and beneficial effects on product quality. However, to the best knowledge of the authors of this paper, the inherent delays in the state and input of the dehydration process are not yet considered in the control strategies dealt with in the specialized literature. This point is our main motivation for proposing the suboptimal control sequence to control a drying process, which considers delays in both state and input, and represents the main contribution of this paper.

The paper is organized as follows: In Section 2 the problem formulation is described, while Section 3 presents the main result. Section 4 is devoted to describing and modelling the dehydration process. The experimental results are reported in Section 5, and finally Section 6 offers a summary of our conclusions.

2. Problem formulation

In this section, the using of the Dynamic Programming approach to design a suboptimal control sequence is proposed, which ensures that a minimum local value for the finite horizon quadratic performance index is achieved.

Let the nonlinear discrete time delay system be

$$x_{k+1} = f_0(x_k, x_{k-M_1}) + f_1(x_k, x_{k-M_1})u_{k-M_2}, \tag{1}$$

where the state variable is $x_k \in \mathbb{R}^n$, $x_{k-M_1} \in \mathbb{R}^n$ corresponds to the delayed state vector, the nonlinear maps $f_0(\cdot,\cdot)$ and $f_1(\cdot,\cdot)$ are well defined, $f_0: \mathbb{R}^n \times \mathbb{R}^n \to \mathbb{R}^n$ is continuous and it is assumed that the origin is a fixed point of the system, it means $f_0(0,0) = 0$ when $u_{k-M_2} \equiv 0$, and $f_1: \mathbb{R}^n \times \mathbb{R}^n \to \mathbb{R}^{n\times m}$, the control vector is $u_k \in \mathbb{R}^m$, the delays satisfy $M_2 \le M_1$, and the index is $k = 0, 1, \ldots, N$. The following assumptions are considered in this paper:

Assumption 1. The state values at the initial instants are arbitrarily given by $x_{-M_1}, x_{-M_1+1}, \ldots, x_0$ and the initial control values $u_{-M_2}, u_{-M_2+1}, \ldots, u_{-1}$ are equal to the zero vector.

Assumption 2. System (1) is controllable on the set Ω, in the sense of the existence of a bounded control sequence such that given an arbitrary initial point x_0, the control sequence transfers x_0 to the trivial solution in $\bar{N}$ steps.

Assumption 2 is required in the most of the reported works such as: [11,29,30] and [31]. The problem is to find the suboptimal control sequence u_{k-M_2}, $\forall\, k \in [M_2, N-1]$ with $N = \bar{N} + M_2 + 1$, which minimizes to the following quadratic cost function

$$J = \frac{1}{2}x_N^T H x_N + \frac{1}{2}\sum_{k=0}^{N-1}\left(x_k^T Q x_k + u_{k-M_2}^T R u_{k-M_2}\right)$$