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TRAJECTORY TRACKING CONTROL FOR NONLINEAR TIME-DELAY SYSTEMS[1]

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The reference trajectory tracking problem is considered in this paper and (constructive) sufficient conditions are given for the existence of a causal state feedback solution. The main result is introduced as a byproduct of input-output feedback linearization.

1. INTRODUCTION

Dynamical control systems involve often nonlinear terms which can not be neglected in case of fast dynamics and/or large transients. Besides, such large industrial plants which go with transportation phenomena are modeled by differential equations which also involve time delayed values of some of the system variables. The situation is standard with rolling mills, chemical reactors, conveying belts and so on. In fact, time delay cases occur in many different areas (see, e.g., [6]).

Standard control schemes, developed for systems without delays, generally yield non causal solutions in the case of time delay systems, that is, solutions which do depend on future values of the system variables in the feedback loop. Such situations require the design of a so-called state estimator. In this paper, one is interested in the search of causal solutions, whenever they exist. This is an important challenge in the solution of control problems for time-delay systems since one avoids approximations and uses as much as possible the structure and intrinsic properties of the system. From a theoretical point of view the main pioneering result on the past 50 years in that area is certainly the celebrated Smith predictor which estimates such future values for control purposes. An intensive research activity on the analysis and control of linear time-delay systems has been done, and general results are now available. However, in the case of nonlinear time-delay systems, the activity on theoretical issues was mainly devoted to the study of stability and stabilization [5], and, as far as other control issues are concerned, they remained practically unexplored for some decades despite the requirements for practical applications. Only recently, such

[1]This work was performed while the first author was at the IRCCyN, in Nantes, France.

problems as feedback linearization [7], noninteracting control [3], or disturbance rejection [8], have started to be investigated.

The problem of trajectory tracking is considered now. Again only causal state feedback solutions are sought. The few contributions which can be found in the current literature are recalled in Section 4 as special cases of the main result in this paper. Trajectory tracking is introduced as a byproduct of input-output linearization of the error between the system output and the reference trajectory.

2. PRELIMINARY DEFINITIONS

2.1. Systems under consideration

The systems under consideration are nonlinear systems with constant, commensurable delays. Without loss of generality, it will be assumed that the time axis has been scaled to have integer delays. Under these conditions, the class of considered systems is described by:

$$\Sigma : \begin{cases} \dot{x}(t) &= f(x(t), x(t-1), \ldots, x(t-s)) \\ & \quad + \sum_{i=0}^{s} g_i(x(t), x(t-1), \ldots, x(t-s))\, u(t-i) \\ y(t) &= h((x(t), x(t-1), \ldots, x(t-s)) \\ x(t) &= \varphi, \;\; u(t) = u_0, \;\; \forall\, t \in [t_0 - s, t_0] \end{cases}$$

where only a finite number of constant time delays occur. The state $x \in I\!R^n$, the input u and the output $y \in I\!R$. The entries of f and g_i are meromorphic functions of their arguments. φ is a piecewise continuous function of initial conditions.

2.2. Mathematical setting

Let $\mathcal{K}$ be the field of meromorphic functions of a finite number of independent variables in

$$\{x(t-\tau), u^{(k)}(t-\tau), \;\; \tau, k \in \mathbb{N}\}.$$

Let also $\mathcal{E}$ be the formal vector space over $\mathcal{K}$ given by

$$\mathcal{E} = \mathrm{span}_{\mathcal{K}}\{\mathrm{d}\xi \mid \xi \in \mathcal{K}\}.$$

Denote the shift operator ∇ defined by

$$\nabla(\xi(t)) = \xi(t-1).$$

The definition of ∇ is extended to $\mathcal{E}$ by

$$\mathrm{d}(x(t-k)) = \nabla^k \mathrm{d}x.$$

Denote $\mathcal{K}[\nabla]$ the ring of polynomials of ∇, and let $\mathcal{M}$ be the formal left module over the ring $\mathcal{K}[\nabla]$, more precisely

$$\mathcal{M} = \mathrm{span}_{\mathcal{K}[\nabla]}\{\mathrm{d}\xi \mid \xi \in \mathcal{K}\}.$$

Let $\{\omega_1, \ldots, \omega_k\}$ be a set of vectors of $\mathcal{E}$. Then, denote $\mathrm{span}_{\mathcal{K}[\nabla]}\{\omega_1, \ldots, \omega_k\}$ as the submodule of $\mathcal{M}$ spanned by $\{\omega_1, \ldots, \omega_k\}$.

The set of all the polynomials in ∇ with coefficients in $\mathbb{R}$ is a subring of $\mathcal{K}[\nabla]$, and will be denoted by $\mathbb{R}[\nabla]$.

Now, the notions of relative degree and relative shift are recalled.

Definition 1. ([8]) The time-delay system Σ is said to have a relative degree ρ if there exists a non negative integer ρ such that

$$\rho = \min\left\{k \in \mathbb{N} \,\middle|\, \frac{\partial y^{(k)}(t)}{\partial u(t-\tau)} \neq 0\right\}, \text{ for some } \tau \in \mathbb{N}.$$

If, for all $(k, \tau) \in \mathbb{N}^2$, $\partial y^{(k)}(t)/\partial u(t-\tau) = 0$, we set $\rho = \infty$.

Definition 2. ([8]) Assume that system Σ has a finite relative degree ρ. Then, this time-delay system is said to have a relative shift μ given by

$$\mu = \min\left\{\tau \in \mathbb{N} \,\middle|\, \frac{\partial y^{(\rho)}(t)}{\partial u(t-\tau)} \neq 0\right\}.$$

The notion of closure of a submodule, introduced in [2] for linear systems over a commutative ring is now recalled.

Definition 3. Let M be a module defined over a ring R. The closure over R of a submodule $A \subset M$, denoted $cls_R\, A$, is given by

$$cls_R\, A := \{x \in M \,|\, \exists p \in R,\, px \in A\}.$$

In what follows, we will consider the closure over the ring $\mathbb{R}[\nabla]$. The module M to be considered is given by

$$M := \mathrm{span}_{\mathbb{R}[\nabla]}\{\xi \,|\, \xi \in \mathcal{E}\}.$$

2.3. Causal compensators

The compensators to be considered are the so-called *pure-shift* causal compensators, and dynamic compensators, both introduced in [8]. Pure-shift compensators are written under the form

$$\begin{aligned} u(t) &= \alpha(x(\cdot), z(\cdot)) + \beta(x(\cdot))\, v(t) \\ z(t+1) &= \alpha(x(\cdot), z(\cdot)) + \beta(x(\cdot))\, v(t) \end{aligned} \tag{1}$$

and the general dynamic compensators are given by

$$\left\{\begin{array}{rcl} \dot{\eta}(t) & = & M_\eta(X(\cdot), z(\cdot), \eta(\cdot)) + \sum_{i=0}^{m'} (N_{\eta,i}(\cdot), z(\cdot), \eta(\cdot))\, v(t-i) \\ z(t+1) & = & M_z(X(\cdot), z(\cdot), \eta(\cdot)) + \sum_{i=0}^{m'} (N_{z,i}(\cdot), z(\cdot), \eta(\cdot))\, v(t-i) \\ u(t) & = & \alpha(x(\cdot), z(\cdot), \eta(\cdot)) + \sum_{i=0}^{m'} \beta_i(x(\cdot), z(\cdot), \eta(\cdot))\, v(t-i) \end{array}\right. \tag{2}$$

where $x(\cdot)$ stands for $\{x(t), x(t-1), \ldots, x(t-m')\}$. These compensators belong to the class of *pure shift* causal compensators, introduced in [8], which may be considered as a nonlinear extension of the Roesser model, which has been used for studying linear time-delay systems, viewed as 2-D systems [10].

3. PROBLEM STATEMENT

The problem of output tracking is now formally stated.

Definition 4. (Trajectory tracking) Consider system Σ with output y, and let $\tilde{y}$ be a continuous reference function. Find, if possible, a causal compensator C, such that y_c, the output of the compensated system, tends asymptotically to $\tilde{y}$; in other words, such that the error function $e(t) := y_c(t) - \tilde{y}(t)$ is stable at the origin.

Recall from nonlinear systems without delays, that a natural approach to solve this problem goes through a linearization of the system [4], and a basic solution consists in the following steps:

1. definition of an error function e between system's output y and reference output $\tilde{y}$:
$$e(t) := y(t) - \tilde{y}(t),$$
2. time derivation of the output up to relative degree ρ:
$$y^{(\rho)}(t) = a(x(t)) + b(x(t))\, u(t) \tag{3}$$
3. and choosing
$$u(t) = (v(t) - a(x(t)) - \sum_{i=0}^{\rho-1} \alpha_i y^{(i)}(t))/b(x(t)) \tag{4}$$
where v is the new control input, and the coefficients α_i are such that $s^\rho + \sum_{i=0}^{\rho-1} \alpha_i s^{(i)}$ is Hurwitz;

4. finally, by setting $v(t) = \tilde{y}^{(\rho)} + \sum_{i=0}^{\rho-1} \alpha_i \tilde{y}^{(i)}(t)$ the closed-loop error dynamics becomes
$$e^{(\rho)}(t) + \sum_{i=0}^{\rho-1} \alpha_i e^{(i)}(t) = 0 \tag{5}$$
which together with (4) imply that $y_c \to \tilde{y}$ as $t \to \infty$.

In the next section, this approach is adapted for time-delay systems.

4. TRAJECTORY TRACKING

When dealing with time-delay systems, the problem is complicated due to their infinite-dimensional nature and, for causality reasons, the approach recalled in previous section may not be directly used. Hence, for the delayed case, (3) becomes

$$\begin{aligned} y^{(\rho)}(t) &= a(\cdot) + b_0(\cdot)\, u(t) + \cdots + b_s(\cdot)\, u(t-s) \\ &= a(\cdot) + b(\nabla)\, u(t) \end{aligned}$$

with $b(\nabla) := b_0(\cdot) + b_1(\cdot)\nabla + \cdots + b_s(\cdot)\nabla^s$. All arguments of $a(\cdot), b_0(\cdot), \ldots, b_s(\cdot)$ are $x(t)$ and a finite number of its time delays.

The equation
$$b(\nabla)\, u(t) = v(t) - a(\cdot) - \Sigma \alpha_i y^{(i)}$$
has a causal solution of type (1) for arbitrary $\alpha_i \in \mathbb{R}[\nabla]$ if, and only if, $b_0(\cdot) \neq 0$, and by a static compensator with delayed state if $b(\nabla) = b_0(\cdot)$. In fact, there special cases have already been considered in the literature [1, 3, 11], and can be recalled in our framework as follows.

4.1. Case $b(\nabla) = b_0(\cdot)$ [11]

1. As in the case without delays, define the error
$$e(t) := y(t) - \tilde{y}(t).$$

2. Differentiate the output with respect to time up to relative degree ρ:
$$y^{\rho}(t) = a(\cdot) + b_0(\cdot)\, u(t)$$

3. and set
$$u(t) = \frac{v(t) - a(\cdot) - \sum_{i=0}^{\rho-1} \alpha_i y^{(i)}(t)}{b_0(\cdot)}$$
which defines a static state feedback with delays;

4. finally, by setting $v(t) = \tilde{y}^{(\rho)} + \sum_{i=0}^{\rho-1} \alpha_i \tilde{y}^{(i)}(t)$ the closed-loop error dynamics becomes
$$e^{(\rho)}(t) + \sum_{i=0}^{\rho-1} \alpha_i e^{(i)}(t) = 0$$
which implies that $y_c \to \tilde{y}$ as $t \to \infty$.

4.2. Case $b_0(\cdot) \neq 0$ [1, 3]

1. As in the case without delays, define the error

$$e(t) := y(t) - \tilde{y}(t).$$

2. Differentiate the output with respect to time up to relative degree ρ:

$$y^{\rho}(t) = a(\cdot) + b_0(\cdot)\, u(t) + \cdots + b_s(\cdot)\, u(t-s)$$

3. Set

$$\begin{aligned} z_1(t+1) &= \left[v(t) - a(\cdot) - \sum_{j=1}^{s} b_j(\cdot) z_j(t) - \sum_{i=0}^{\rho-1} \alpha_i y^{(i)}(t) \right] / b_0(\cdot) \\ z_2(t+1) &= z_1(t) \\ &\vdots \\ z_s(t+1) &= z_{s-1}(t) \\ u(t) &= \left[v(t) - a(\cdot) - \sum_{j=1}^{s} b_j(\cdot) z_j(t) - \sum_{i=0}^{\rho-1} \alpha_i y^{(i)}(t) \right] / b_0(\cdot) \end{aligned}$$

which defines a pure-shift causal compensator.

4. Finally, by setting $v(t) = \tilde{y}^{(\rho)} + \sum_{i=0}^{\rho-1} \alpha_i \tilde{y}^{(i)}(t)$ the closed-loop error dynamics becomes

$$e^{(\rho)}(t) + \sum_{i=0}^{\rho-1} \alpha_i e^{(i)}(t) = 0$$

which implies that $y_c \to \tilde{y}$ as $t \to \infty$.

4.3. General case: sufficient conditions

Now consider the more general case, where $b_0(\cdot)$ may be zero (i.e., $\mu > 0$). Under this condition, the previously presented contributions cannot be applied, since it is not possible to apply the standard linearization, which yields maximal loss of observability. In our approach, we will not look for a special form of state representation as in [1, 3, 11], but only to obtain a linear input-output response, which will be referred to as the Input-Output Linearization Problem. The closed loop system will be linear with respect to a non trivial zero dynamics (in general). To do so, let us extend the results presented in [7] as follows.

Let $\{\Phi_0, \ldots, \Phi_\rho\}$ be some functions such that

$$\mathrm{span}_{\mathbb{R}[\nabla]}\{\mathrm{d}\Phi_0, \ldots, \mathrm{d}\Phi_i\} = cls_{\mathbb{R}[\nabla]}\{\mathrm{d}y, \ldots, \mathrm{d}y^{(i)}\}, \quad i = 0, \ldots, \rho$$

so $y^{(\rho)}$ may be written as

$$y^{(\rho)}(t) = \sum_{i=0}^{\rho} a_i \Phi_i, \quad a_i \in I\!R.$$

From the definitions of relative degree and relative shift, $a_\rho \Phi_\rho$ is a function of the present and past values of the state and the control input:

$$a_\rho \Phi_\rho := \varphi(x(t), x(t-1), \ldots, x(t-\mu), u(t-\mu), \ldots, x(t-s), u(t-s)).$$

Now, define α and β as follows

$$\begin{aligned} \alpha(t) &:= \varphi(0, \ldots, 0, x(t-\mu), u(t-\mu), \ldots, x(t-s), u(t-s)) \\ \beta(t) &:= y^{(\rho)}(t) - \alpha(t). \end{aligned} \tag{6}$$

We have the following result.

Theorem 1. Consider system Σ, and the two functions α and β defined by (6). Then, the input-output linearization problem has a causal solution if $\mathrm{d}\beta \in \mathrm{span}_{\mathcal{K}[\nabla]}\{\mathrm{d}x\}$ and there is an integer k such that

$$\mathrm{d}\beta^{(k)} \in cls_{I\!R[\nabla]}\{\mathrm{d}y, \mathrm{d}\dot{y}, \ldots, \mathrm{d}y^{(\rho+k+1)}, \mathrm{d}\alpha, \mathrm{d}\dot{\alpha}, \ldots, \mathrm{d}\alpha^{(k-1)}.$$

This theorem is easy to prove, by solving in $u(t)$ the equation

$$\alpha(t) = v(t-\mu).$$

For more details, the reader is referred to [7]. □

Now consider that the Input-Output Linearization Problem has been solved by a causal dynamic compensator (2), and the resulting system may be written under the form

$$\begin{aligned} & y^{(\rho+k)}(t) + \sum_{i=0}^{\rho+k-1} a_i(\nabla) y^{(i)} = \nabla^\mu \sum_{j=0}^{k-p} b_j(\nabla)\, v^{(j)}(t), \\ & a_i(\nabla), b_j(\nabla) \in I\!R[\nabla], \quad b_{k-\rho}(0) \neq 0. \end{aligned} \tag{7}$$

We may now state our main result.

Theorem 2. Consider system Σ, with output y and let $\tilde{y}$ be the desired output trajectory. Assume that the conditions of Theorem 1 are fulfilled, and (7) holds. Then, the problem of output tracking has a causal solution if there exist some coefficients $a_0'(\nabla), \ldots, a_{\rho+k-1}(\nabla) \in I\!R[\nabla]$ such that all the roots of the quasi-polynomial

$$s^{(\rho+k)} + \sum_{i=0}^{\rho+k-1} a_i(e^{-s}) s^i + e^{-\mu s} \sum_{i=0}^{\rho+k-1} a_i{'}(e^{-s}) s^i \tag{8}$$

are in the left side of the complex plane.

Proof. Let the coefficients $b_j(\nabla)$ be defined by (7), and write

$$b_{k-\rho}(\nabla) = \bar{b}_0 + \sum_{\ell=1}^{s'} \bar{b}_\ell \nabla^\ell,$$

where s' is the polynomial degree of $b_{k-\rho}(\nabla)$. Define the following compensator

$$\begin{aligned}
v(t) &= \eta_1(t)\\
\dot{\eta}_1(t) &= \eta_2(t)\\
&\vdots\\
\dot{\eta}_{k-\rho-1}(t) &= \eta_{k-\rho}(t)\\
\dot{\eta}_{k-\rho}(t) &= \bar{b}_0^{-1}\left(\bar{v}(t) - \sum_{i=0}^{\rho+k-1} a'_i(\nabla) y^{(i)}(t) - \sum_{j=0}^{k-\rho-1} b_j(\nabla)\eta_j(t) - \sum_{\ell=1}^{s'} \bar{b}_\ell \nabla^{\ell-1} z(t)\right)\\
z(t+1) &= \bar{b}_0^{-1}\left(\bar{v}(t) - \sum_{i=0}^{\rho+k-1} a'_i(\nabla) y^{(i)}(t) - \sum_{j=0}^{k-\rho-1} b_j(\nabla)\eta_j(t) - \sum_{\ell=1}^{s'} \bar{b}_\ell \nabla^{\ell-1} z(t)\right)
\end{aligned}$$

where the coefficients $a'_i(\nabla), b_i(\nabla) \in \mathbb{R}[\nabla]$ are taken from (7) and (8). Up to this point, the closed-loop system satisfies

$$y^{(\rho+k)}(t) + \sum_{i=0}^{\rho+k-1} (a_i(\nabla) + a'_i(\nabla)) y^{(i)} = \bar{v}(t-\mu)$$

with $\lim_{t\to\infty} y(t) = 0$ if $\bar{v}(t) \equiv 0$.

One solution is given by

$$\bar{v}(t) = \tilde{y}^{(\rho+k)}(t+\mu) + \sum_{i=0}^{\rho+k+1} (a_i(\nabla) + a'_i(\nabla)) \tilde{y}^{(i)}(t+\mu)$$

where $\tilde{y}^{(i)}(t+\mu)$ represents the ith time derivative of the reference function $\tilde{y}$, evaluated at time $t+\mu$. Remark that this dependence on the future values of the reference function is not a problem for practical implementation of the compensator, since $\tilde{y}$ is known in advance. The error $e(t)$ is solution of

$$e^{\rho+k}(t) + \sum_{i=0}^{\rho+k-1} (a_i(\nabla) + a'_i(\nabla)\nabla^\mu) e^{(i)}(t) = 0$$

which, from (8), is stable [6]. □

Example 1. Consider the system

$$\begin{aligned}\dot{x}_1(t) &= 0.1x_1(t) + x_2(t-2)\,u(t-1)\\ \dot{x}_2(t) &= x_1(t) - x_2^3(t)\\ y(t) &= x_1(t) + x_2(t-1)\end{aligned}$$

for which the Output Tracking cannot be achieved by the methods proposed in [1, 3, 11].

The relative degree is 1, because one needs to time-differentiate the output only once, to obtain explicit dependence on u :

$$\dot{y}(t) = 0.1x_1(t) + x_2(t-2)\,u(t-1) + x_1(t-1) - x_2^3(t-1).$$

To compute the closure over $\mathbb{R}[\nabla]$ of $\text{span}_{\mathbb{R}[\nabla]}\{\mathrm{d}y, \mathrm{d}\dot{y}\}$ we write

$$\begin{bmatrix}\mathrm{d}y\\ \mathrm{d}\dot{y}\end{bmatrix} = \overbrace{\begin{bmatrix}1 & \nabla & 0\\ 0.1 & 0 & \nabla\end{bmatrix}}^{T}\begin{bmatrix}\mathrm{d}x_1\\ \mathrm{d}x_2\\ \mathrm{d}[x_1(t) + x_2(t-1)\,u(t) - x_2^3(t)]\end{bmatrix}.$$

Let S denote the Smith's form of T:

$$S = \text{Smith}(T) = \begin{bmatrix}1 & 0 & 0\\ 0 & \nabla & 0\end{bmatrix}.$$

Since one invariant polynomial is not scalar, $\text{span}_{\mathbb{R}[\nabla]}\{\mathrm{d}y, \mathrm{d}\dot{y}\}$ is not closed over $\mathbb{R}[\nabla]$. Let U and V be two unimodular matrices satisfying $S = U \cdot T \cdot V$. A basis $\{\mathrm{d}\Phi_1, \mathrm{d}\Phi_2\}$ for the closure is given by:

$$\begin{aligned}\begin{bmatrix}\mathrm{d}\Phi_1\\ \mathrm{d}\Phi_2\end{bmatrix} &= S^{-1}\cdot U\cdot T\begin{bmatrix}\mathrm{d}[x_1(t)]\\ \mathrm{d}[x_2(t)]\\ \mathrm{d}[x_1(t) + u(t)x_2(t-1) - x_2^3(t)]\end{bmatrix}\\ &= \begin{bmatrix}\mathrm{d}[x_1(t) + x_2(t-1)]\\ \mathrm{d}[-0.1x_2(t) + x_1(t) + u(t)x_2(t-1) - x_2^3(t)]\end{bmatrix}.\end{aligned}$$

Since conditions of Theorem 1 are fulfilled, we can construct the following causal compensator:

$$u(t) = (v(t) + 0.1x_2(t) - x_1(t) + x_2^3(t))/x_2(t-1)$$

which yields

$$\dot{y}(t) = 0.1y(t) + v(t-1).$$

Now define

$$\dot{s}e^s - 0.1e^s + a_0'.$$

Using Proposition 4 from [9] we find that $a_0' = 1$ satisfies the condition of Theorem 2, so we set

$$v(t) = (\bar{v}(t) - y(t)).$$

Finally, we define

$$\bar{v}(t) = \dot{\tilde{y}}(t+1) - 0.1\tilde{y}(t+1) + \tilde{y}(t)$$

and we obtain, in closed loop, that the error between the output and the reference function $y(t) - \tilde{y}(t)$ tends asymptotically to 0. Figure 1 shows a reference function $\tilde{y}(t) = 2 + \sin 2\pi t$ and the output of the system using this controller, simulated in Matlab–Simulink.

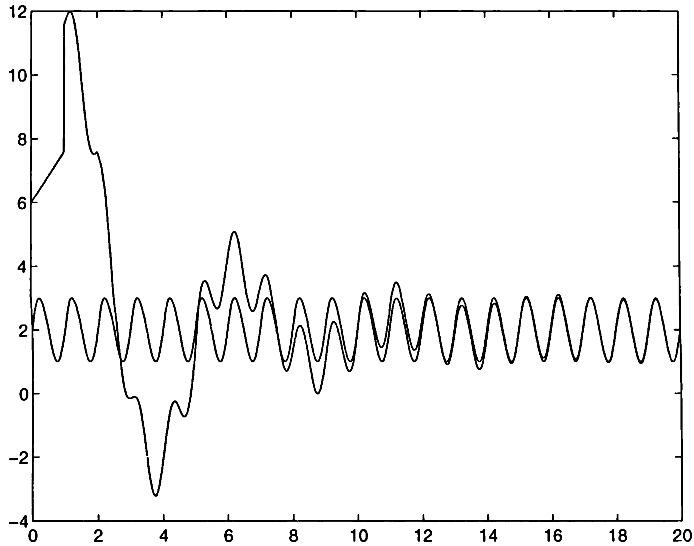

Fig. 1. Output tracking of reference signal $\tilde{y}(t) = 2 + \sin 2\pi t$.

5. CONCLUSIONS

The problem of output tracking for nonlinear time-delay systems has been defined, and a causal solution proposed.

The proposed methodology consists in finding a causal compensator such that the input-output relationship is linear, apply the results available in the theory of linear time-delay systems to stabilize it. The resulting stable input-output dynamics is then used to obtain an error dynamics which is also stable at the origin.

Some of the advantages of the proposed approach are that it is valid on a wide class of nonlinear systems, and they are weaker than other results available in the literature, among other reasons, because it does not require the full input to state linearization.

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