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Brief paper

Guaranteeing preselected tracking quality for uncertain strict-feedback systems with deadzone input nonlinearity and disturbances via low-complexity control ☆

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ABSTRACT

A continuous, low-complexity, static, state-feedback controller is proposed for strict-feedback systems with deadzone input nonlinearity and disturbances, utilizing the Prescribed Performance Control methodology. The scheme achieves *preselected* bounds on the transient and steady state output error performance despite the uncertainty in system nonlinearities and deadzone characteristics. Regarding the latter, a general class of admissible deadzones is considered compared to the current state-of-the-art, permitting nonsmooth and even locally decreasing behavior outside the dead-band. Furthermore, approximating structures, i.e., neural networks, fuzzy systems, etc., are not utilized and, moreover, the backstepping "explosion of complexity" issue is eliminated without residing in filtering, thus deriving a low-complexity design. The proposed controller evades the construction of a deadzone inverse and does not employ a special analytical deadzone representation. Simulations are performed to verify the theoretical findings.

1. Introduction

Deadzone actuation is among the most commonly encountered sources of nonlinearity in real control systems, with typical examples including mechanical connections, hydraulic servo valves, piezoelectric translators, electronic circuits and many others. Its existence is directly related to closed-loop performance deterioration, severe oscillations and even worse, instability phenomena. Therefore, the deadzone input nonlinearity compensation is an imperative to address task. Additionally, from a control viewpoint it constitutes a very challenging issue, as even linear systems are rendered nonsmooth and nonaffine.

Research in this direction is traced back to Tao and Kokotovic (1994) where a deadzone inverse function was constructed using adaptive techniques. In fact, the implicit or explicit utilization of a deadzone inverse has been the main line of effort in many related works, e.g., Cho and Bai (1998), Oh and Park (1998), Tao and Kokotovic (1994), Zhou, Wen, and Zhang (2006), and Zhou (2008). To avoid the utilization of a deadzone inverse, other compensation mechanisms emerged and evolved (Ibrir, Xie, & Su, 2007; Lewis, Kam Tim, Wang, & Li, 1999; Selmic & Lewis, 2000; Wang, Su, & Hong, 2004; Zhang & Ge, 2007). A Fuzzy Logic Precompensator was designed in Lewis et al. (1999) for industrial positioning systems with linear deadzones. A general procedure to compensate for nonlinear deadzones using neural networks was proposed in Selmic and Lewis (2000). Further, Wang et al. (2004) proposed the representation of the deadzone output as a linear system with a time-varying gain and a bounded disturbance term, under the assumption that the deadzone outside the dead-band is linear with equal slopes. The aforementioned assumption was relaxed in Ibrir et al. (2007). However, maximum and minimum bounds on the deadzone slopes were required to be known. This requirement was further relaxed in Zhang and Ge (2007) where an adaptive neural control scheme was developed for unknown nonlinear deadzones, assuming differentiability outside the dead-band.

A common characteristic of the aforementioned works is that transient performance cannot be *prescribed*; only the convergence of the tracking error to a residual set is established. There are currently two methodologies in the literature, namely the Prescribed Performance Control (PPC) and the Funnel Control, which achieve prescribed performance bounds on the transient

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and steady state behavior of the output tracking error. The Funnel Control was introduced in Ilchmann, Ryan, and Sangwin (2002) as an advancement of the adaptive high-gain control methodology, which replaces the monotonically increasing control gain in the latter by a time-varying function admitting higher values as the output error approaches the funnel boundary. For further details the reader is referred to Ilchmann and Ryan (2008). On the other hand, the so-called Prescribed Performance Control (PPC), introduced in Bechlioulis and Rovithakis (2008), utilizes appropriately defined functions to transform the original system into one that incorporates the desired performance criteria; then, a controller is designed to guarantee the boundedness of the transformed system trajectories. As discussed in Bechlioulis and Rovithakis (2008) this is a sufficient condition to achieve the desired performance specifications. In the context of PPC, solutions have been proposed for various classes of nonlinear systems (Bechlioulis & Rovithakis, 2008, 2009, 2010, 2011; Hua, Zhang, & Guan, 2014; Wang & Wen, 2010).

Very recently, inspired by Bechlioulis and Rovithakis (2008, 2009), an adaptive prescribed performance backstepping controller was proposed in Na (2013). The scheme therein guarantees prescribed transient and steady state performance in the presence of unknown nonlinear deadzones. However, it suffers from the "explosion of complexity", a well-documented issue in the backstepping literature, and, moreover, utilizes neural networks that further complicate design and implementation. In addition, it is discontinuous and cannot handle deadzones lacking differentiability outside the dead-band or exhibiting locally decreasing behavior. In Theodorakopoulos and Rovithakis (2013) preliminary results on employing the prescribed performance control methodology in the problem of controlling a class of uncertain strict-feedback systems having deadzone input nonlinearities with strictly increasing branches outside the dead-band, were provided. In the presence, however, of input disturbances the analysis presented in Theodorakopoulos and Rovithakis (2013)does not guarantee stability of the closed loop.

This paper considers the problem of guaranteeing *preselected* bounds on the transient and steady state output error performance for a fairly general class of uncertain strict-feedback systems with known but arbitrary relative degree, under the presence of a deadzone input nonlinearity and disturbances. Emphasis is placed on the admissible class of deadzones which is wider compared to the current state-of-the-art. Specifically, the deadzone branches are not required to be differentiable and are even allowed to exhibit locally decreasing behavior, thus generalizing the results obtained in Theodorakopoulos and Rovithakis (2013). The aforementioned attributes are attained via a continuous, static, state-feedback control law that exhibits remarkably low complexity levels.

Specifically, the proposed controller does not utilize derivatives of the intermediate control signals, thus evading the major source of complexity present in relevant controllers obtained via traditional backstepping procedures. Further, despite the uncertainty in system nonlinearities and deadzone characteristics, the proposed controller does not incorporate approximating structures, i.e., neural networks, fuzzy systems, etc., which complicate the controller design and implementation. Furthermore, contrary to the controllers reported in the relevant literature, the proposed control scheme can be *directly* implemented even in applications when the derivatives of the desired tracking trajectory are not available beforehand, e.g., when the tracking trajectory can only be measured in real time. Therefore, the extra cost and effort of utilizing additional mechanisms that produce approximations of the desired trajectory derivatives is completely evaded. Finally, it is worth noting that the proposed scheme does not construct a deadzone inverse or utilize a special deadzone analytical representation.

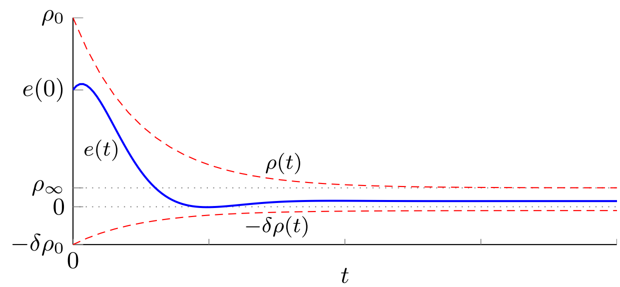

Fig. 1. Graphical representation of (1a) for $\rho(t) = (\rho_0 - \rho_\infty)e^{-\lambda t} + \rho_\infty$.

To design the aforementioned controller the PPC methodology was utilized rather than the Funnel Control. This choice is supported by the fact that a low-complexity control solution has already been reported in Bechlioulis and Rovithakis (2011) for a relevant system class of arbitrary relative degree following the PPC methodology, in the absence, however, of deadzone input nonlinearity. On the contrary, to the best of the authors' knowledge, no simple controller designed via the Funnel Control approach has been proposed to handle the considered system class.

The rest of the paper is organized as follows: In Section 2, preliminary knowledge on the Prescribed Performance Control methodology is provided, while in Section 3, the main problem addressed is stated. In Section 4, the main result of this work is presented and qualitatively analyzed. Further, in Section 5, a simulation study is performed to demonstrate the effectiveness of the proposed scheme. Conclusions are provided in Section 6. Finally, the main result of this work is proven in the Appendix.

2. Prescribed Performance Control preliminaries

It will be clearly demonstrated that the control design is based on the Prescribed Performance Control methodology which was pioneered in Bechlioulis and Rovithakis (2008) and utilized in Bechlioulis and Rovithakis (2009, 2010, 2011, 2014), Theodorakopoulos and Rovithakis (2014), and Bechlioulis, Theodorakopoulos, and Rovithakis (2013) to design controllers capable of *a priori* guaranteeing prescribed performance bounds on the transient and steady state output error for a range of nonlinear system classes. Seeking a complete and self-contained presentation, this section summarizes preliminary knowledge on the concept of prescribed performance control.

In this direction, consider a generic tracking error $e(t) \in \mathbb{R}$. Prescribed performance is achieved if the following inequalities are satisfied for all $t \geq 0$:

$$-\delta\rho(t) < e(t) < \rho(t), \quad \text{if } e(0) \geq 0, \tag{1a}$$

$$-\rho(t) < e(t) < \delta\rho(t), \quad \text{if } e(0) < 0, \tag{1b}$$

where δ is a non-negative design constant and $\rho : \mathbb{R}_{\geq 0} \to \mathbb{R}_{>0}$ is a continuous design function satisfying $\underline{\rho} \leq \rho(t) \leq \bar{\rho}, \ \forall t \geq 0$ for some constants $\underline{\rho}, \bar{\rho} > 0$, called *performance function* (Bechlioulis & Rovithakis, 2008). Constant δ and function ρ are utilized to incorporate the desired performance metrics of $e(t)$. To clearly illustrate the aforementioned statement, Fig. 1 depicts (1a) for an exponentially decaying performance function defined as

$$\rho(t) = (\rho_0 - \rho_\infty)e^{-\mu t} + \rho_\infty \tag{2}$$

and a constant $\delta \in [0, 1]$. The constant $\rho_\infty > 0$ corresponds to the maximum allowable tracking error at steady state and $\mu > 0$ to the minimum admissible convergence rate; the maximum overshoot is prescribed less than $\delta\rho(0) = \delta\rho_0$, which may even become zero by setting $\delta = 0$.

Furthermore, consider a continuous function $T : (L, U) \to \mathbb{R}$ that is strictly increasing and satisfies $\lim_{z\to U^-} T(z) = +\infty$ and