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Delay-range-dependent observer-based control of nonlinear systems under input and output time-delays

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ABSTRACT

The problem of designing observer-based controller for a class of nonlinear time-delay systems subjected to input and output time-varying delays is addressed in this paper. More incisively, a delay-range-dependent criterion, incorporating variation of delays between known lower and upper bounds, is established for control of nonlinear time-delay systems. The proposed methodology ensures asymptotic stability of the closed-loop system's state and the estimation error between states of the system and observer. By application of a Lyapunov–Krasovskii functional, Jensen's inequality, standard matrix inequality procedures, Luenberger-type observer, delay-interval bounds and delay-derivative limits, observer-based controller synthesis approach using nonlinear matrix inequalities for the nonlinear time-delay systems is provided. Further, a decoupling approach is employed to render a simpler condition for the observer and the controller synthesis. A novel observer-based control scheme for the linear time-delay systems with interval time-varying input as well as output lags is derived from the proposed control strategy. The traditional delay-dependent controller design, incorporating zero lower bound of the delay, for the time-delay systems is a particular scenario of the projected delay-range-dependent approach. The proposed decoupled observer-based controller synthesis condition is cast into linear matrix inequalities by means of the cone complementary linearization approach. Finally, a numerical simulation example of control of one-link flexible joint robotic arm is provided to verify the proposed design methodology.

1. Introduction

In physical systems, unmeasured states are retrieved from the knowledge of inputs and outputs due to unavailability of sensors and owing to infeasibility of measurement schemes. Such observers along with the state-feedback control theory have been applied for monitoring and, specially, to control dynamical systems, when system states are not directly measureable. Two major problems sprang up, for the famous high-gain observer, when used for feedback stabilization of nonlinear systems by employing an estimated state vector. Firstly, such an observer might fail in estimation of observable states of a nonlinear system because these observers are very sensitive to measurement noises and delays [1–4]. Secondly, stability of the closed-loop system using an observer-based controller is not guaranteed, since the observer and the controller designs are independent to each other, resulting into an incompatible control strategy for an open-loop plant [5]. For an efficacious solution to the stabilization

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problem, observer-based controls by designing an observer and a feedback controller, simultaneously, are frequently employed to attain stabilization and to enhance the constancy and performance of unstable systems [6,7].

Control of nonlinear time-delay systems is a theme of both practical and theoretical interests that has experienced much research attention in the past years. Several methods including the sampled-data control, dynamic control, adaptive control and so on (see, for instance, [8–13]) are developed for control of time-delay systems. Sampled-data control technique is adapted for observer design to address limitations of emerging digital hardware and communication technologies. The work in [10] incorporates estimation of states of delayed neural network by employing the sampled-data systems under stochastic sampling. Asymptotic robust synchronization of uncertain chaotic systems with stochastic time-varying sampling intervals by involving the sampled-data control has been explored in [11]. Dynamic control strategies are developed for synchronization of complex nonlinear multiple systems with switching technology (see, for instance [12]). The linear case for the observer-based controller synthesis with strong convergence attributes is well probed. Whereas for the nonlinear counterpart, the design is still thought-provoking and perplexed as it does not include systematic solution and depends on the nature of nonlinear system dynamics. In various engineering applications, command signals are generated for a far stationed physical process, sensors are placed at a significantly large distance, and the quantified data are imparted via a low-rate communication system. Therefore, the control signals and the measured outputs encounter a non-negligible time-delay producing inadequate performance, which, further, may cause oscillations and instability. Various engineering applications, for example, chemical processes, nuclear reactors, neural networks, transmission lines, aircraft systems, pneumatic arrangements, microwave appliances, traffic control equipment, ship steering units, turbojet engines *etc*., are vulnerable to the time-delay imbalances in input or/and output signals [14–22]. This captivates considerable attention of dynamic control researchers in both the linear and the nonlinear domains and, accordingly, various stabilization and state vector identification criteria have been presented. Observer and controller designs have been investigated for the linear delayed systems to ensure stability and robustness, see, for instant, [7,20,22–24], and references therein.

Observer-based control approaches have been investigated for nonlinear dynamic systems in continuous-time as well as discrete-time domains and multiple designs have been introduced for dealing with time-varying delays (see, for example, [5,14,23,24–26], *etc*.). Delay-independent and delay-dependent overtures of observer and controller constructions are available in the literature [27] for state estimation and stabilization of time-delay systems. Recently, diverse delay-dependent proficiencies have been projected, for investigation of stability of time-delay systems, to subdue the conservatism introduced by delays. The intention of exploring the delay-dependent stability includes development of measures to provide the sustainable delay treatment and to ensure handling of complexity by the evolution of few decision variables. Practically, a trade-off subsists between both the conservatism and the complexity of stability investigation approaches considering time-delay bounds, although both of them serve as criteria [28]. Lyapunov–Krasovskii (LK) functional took part immensely to explore the nonlinear systems' controller designs involving time-delays, namely linear matrix inequality (LMI) methods [29,30], free weighting matrix approaches [28,31–33], integral inequality approaches [34] and so forth. An LMI-based optimization approach is projected for the robust control of an uncertain time-delay system and the maximal allowable bound is studied in [28]. In [31], the free weighting matrix technique along with the average dwell-time approach is introduced for obtaining sufficient criteria for the desired disturbance observer and the state feedback controller designs. It is notable that the free weighting matrix method is computationally complex technique to tackle the time-delays. Another work [34] explores the integral inequality and the delay decomposition approach to reduce the conservatism for the state feedback stabilization of time-varying delayed uncertain systems. However, beside these recent works, a lot of problems for the observer-based control of nonlinear time-delay systems are required to be figured out. To the best of our knowledge, observer-based control of nonlinear systems with input and output time-delays belonging to an interval ranging between a non-negative lower limit and a finite upper value has not been addressed in the previous works. It should be noted that the input and the output delays are practically unavoidable owing to the distant positions of actuators from the controller and sensors from the processing units and, by the way, observer-based control is utilitarian to deal with the additional complication of inaccessibility of the full state vector.

This paper specifically addresses the observer-based control of a class of nonlinear systems under input as well as output time-varying delays. Based on a Lyapunov–Krasovskii functional, various delay-range-dependent observer and controller synthesis conditions are derived. The proposed observer-based stabilization conditions are developed by involving the time-derivative of the LK functional, working out the matrix inequality procedures, and considering both the zero and the nonzero lower and finite upper bounds of both the input and the output delays. A Luenberger-type observer-based stabilization controller synthesis scheme guaranteeing asymptotic estimation of states of the delayed Lipschitz nonlinear plants is established. However, the designed condition entangled nonlinear matrix inequality because it incorporates two gain matrices in the design procedure, namely, the controller and the observer gains, causing difficulties in their computations. To address this situation, a sufficient condition for the observer-based controller synthesis is derived, by following the decoupling techniques [35–37], to incur an LMI-based simple solution. The proposed decoupled observer-based control condition can be resolved using a recursive LMI approach by virtue of cone complementary linearization algorithm. As far our cognizance, a delay-range-dependent observer-based control of nonlinear systems, engaging time-varying input and output delays, has been addressed for the first time. A numerical simulation example for the observer-based control of a one-link flexible joint robot under measurement and actuation delays is provided to demonstrate effectiveness of the proposed design approach.

This paper is organized as follows. Section 2 provides description of nonlinear systems with input and output delays. Main results on delay-range-dependent observer-based control are detailed in Section 3. Simulation results on a one-link flexible joint robot are outlined in Section 4 . Section 5 draws conclusions of the study.