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Static anti-windup design for nonlinear Markovian jump systems with multiple disturbances[☆]

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ABSTRACT

A static anti-windup compensation problem for Markovian jump systems with nonlinearity and multiple disturbances (one disturbance being an energy bounded signal, the other generated from a system expressed in a state-space expression) is studied in this paper. Our first objective is to design stabilizing composite hierarchical anti-disturbance controllers based on output-based disturbance observers, in the absence of actuator saturation, attenuating and rejecting the above two disturbances respectively. The aim is then to design anti-windup compensation gains for the aforementioned controllers such that the system can still be stabilized and the above mentioned two disturbances can continually be attenuated and rejected, respectively, regardless of whether control saturation exists. Sufficient conditions are derived for the existence of the desired disturbance observer gains, controller matrices, and anti-windup compensation gains, guaranteeing prescribed performances.

1. Introduction

Since the beginning of cybernetics, disturbance attenuation and rejection has been a hot issue, and remains an important and difficult topic [23,25,43]. In general, system disturbances in practical controlled process are caused by measurement noise, sensor and actuator error, modeling error, environment disturbance, structure variation, etc. In control theory, these can be classified into different disturbance types, such as norm-bounded, harmonic, non-Gaussian/Gaussian, neutral stable exogenous systems, etc. The $\mathscr{H}_\infty$ control scheme is suitable to attenuate norm-bounded disturbances [31], whereas the stochastic control scheme can attenuate non-Gaussian/Gaussian disturbances, and the output regulator theory can reject the disturbance that is produced by a neutral stable exogenous system [16]. The disturbance-observer-based control (DOBC) methodology can successfully address disturbances that can be generated by an exogenous system, which is able to represent harmonic, bounded, neutral stable, and other dynamic disturbances [3–5,11,17,38], and now has been successfully applied in practical engineering, in areas such as robotics [3] and table drive systems [17].

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On the other hand, control input saturation exists in almost all practical systems, and it always degrades system performance and even potentially drives dynamical systems to be unstable [1,15,34,44]. Hence, to design a controller such that the resulting closed-loop system maintains acceptable stability with desired performances against actuator saturation is of great importance, but is widely recognized as difficult. Analysis and synthesis for control systems under control input limitations always either directly considers the control limitation for the nonlinearity of saturation when designing the controller [13,14] or indirectly addresses the input saturation [9,10,12,19]. The detailed indirect methodology is as follows: first, ignore the control input limitation, and assume there exists a stabilizing controller (also named the main controller) with some specified performances; then, add an anti-windup compensator term into the aforementioned controller to reduce the negative effects brought about by saturation. This anti-windup compensation method is known as two-stage design and has been widely used in practical engineering [24,30,36]. Thus, it is worthwhile to address the actuation saturation problem by means of an anti-windup compensation approach.

Note that in these previous studies about the anti-windup compensation problem, either no disturbance or just one kind of disturbance has been assumed in the controlled plant, and only a single control method is used in the above two approaches against actuator saturation. However, this is not usually true in practice, as systems almost always encounter many kinds of disturbances, and a single control approach will be unsatisfactory [11]. To address the problem, a composite hierarchical anti-disturbance control (CHADC) strategy, which combines DOBC with another advanced anti-disturbance control strategy, such as $\mathscr{H}_\infty$ control [38], and passive control [39], were developed. Hence, a critical issue has been raised on whether the anti-windup compensation strategy in a single control framework can be extended to the composite control framework. The main characteristic of the CHADC scheme is to propose a disturbance observer that is qualified to estimate the disturbance that can be described in a state-space representation, and then design a composite control strategy by combining the estimation of the disturbance with a feedback control law.

In contrast, the essence of a single control methodology is just to design a feedback control law. Consequently, the difficulties of anti-windup compensation in a CHADC framework are as follows. (1) If the actuator is saturated, addition or subtraction between the estimation of the disturbance and feedback control is constrained, rather than the feedback control alone. Therefore, methods developed in [10,12,19,24,30] for single control schemes are difficult to apply to a CHADC framework. (2) The effectiveness of the anti-windup compensation scheme depends heavily upon the stabilizing composite controller with some prescribed performances in the absence of actuator saturation. In addition, if the system states and their estimation cannot be acquired, how can we design a CHADC scheme based on an output-based disturbance observer? Thus, it is challenging, but of great significance, to study anti-windup compensation strategies in the CHADC framework.

In engineering practice, many complicated systems suffer from abrupt variations in their structures owing to the following aspects: sudden environmental disturbances, repair of components, variations in subsystem interconnections, random failures, and so on. Markovian jump systems (MJSs), which are different from switched systems [41,42], offer an effective model to describe the above behaviors of these physical systems, whose coefficients vary randomly and abruptly. Successful results on MJSs have been presented in the literature, and for some significant work on this topic, the reader is referred to [2,6–8,18,20,21,26–29,33,35,37,40] and references therein.

Based the above observations, we can conclude that many practical systems can be modeled by nonlinear MJSs with input saturation and multiple disturbances. Motivated by these results, this paper is devoted to investigating the problem of anti-windup compensation for a class of nonlinear MJSs with input saturation and two types of disturbances: one represented by an exogenous system and the other norm bounded. Based on an improved version of the output-based disturbance observer, a CHADC strategy combining DOBC and a $\mathscr{H}_\infty$ control method, which can stabilize the nonlinear MJSs with attenuating and rejecting disturbances respectively, is first designed as the main controller, in the absence of actuator saturation. When saturation works, we propose a new method to design the anti-windup compensator by considering the saturation effects as a disturbance-like signal, and minimizing the negative effects on the controlled output caused by the saturation via a $\mathscr{H}_\infty$ control scheme, which is also the main contribution of this paper. With the CHADC and anti-windup compensation strategies, and by choosing a stochastic Lyapunov–Krasovskii functional, the expected disturbance observer gains, output-feedback controller gains, and anti-windup compensator gains can be computed through convex optimization algorithms via the two-stage design methodology. Finally, a numerical example is presented with the simulation results.

Notation. Notation used throughout the paper are standard:

- Superscript “T” denotes matrix transposition;
- $\mathbb{R}^n$ represents n-dimensional Euclidean space;
- $P > 0$ denotes that P is real symmetric and positive definite;
- $\|\cdot\|$ represents the Euclidean norm;
- diag$\{\cdots\}$ represents a block-diagonal matrix;
- a star ($\star$) represents the symmetry element of a matrix.

2. Problem formulation

Fig. 1 presents the structure of the static anti-windup compensation problem for a class of nonlinear MJSs subject to multiple disturbances and input saturation. We model the problem mathematically in detail in the subsequent procedure.