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Anti-windup-based dynamic controller synthesis for nonlinear systems under input saturation

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A B S T R A C T

This paper describes the design of dynamic controller and static anti-windup compensator (AWC) for Lipschitz nonlinear systems under input saturation. Global and local AWC-based control schemes for stabilization of the nonlinear systems are proposed, and necessary conditions for feasibility of the control approaches are investigated. A one-step approach for simultaneous design of H_∞ controller and AWC by means of linear matrix inequalities (LMIs) is presented herein, which supports multi-objective synthesis to attain stabilization or tracking, robustness against disturbance and noise, and penalization of large and high frequency control signals. This multi-objective synthesis can be accomplished by incorporating design weights, as commonly used in the standard H_∞ control theory, to design a performance-oriented anti-windup-based control scheme. LMIs for the global control of the nonlinear systems subject to input saturation are derived by application of a quadratic Lyapunov function, the Lipschitz condition, the global sector condition, L_2 gain reduction, substantial matrix algebra and variable transformation. In order to cope with unstable and oscillatory nonlinear systems, LMI-based local results are established using a local sector condition. Additional conditions are derived, by incorporating properties of the saturation function, to ensure well-posedness of the controller. Two simulation examples are provided to show the effectiveness of the proposed control schemes for control of stable and chaotic nonlinear systems under input saturation.

1. Introduction

Every input of a linear or a nonlinear system is bounded by an upper and a lower limit owing to physical restriction of actuators, which causes saturation of the control signal applied to achieve desired control objectives like stabilization, tracking and disturbance rejection. Actuator saturation, usually ignored to simplify the design of a control system, causes performance degradation, lag, overshoot, undershoot as well as instability in the closed-loop response of practical systems due to a well-known phenomenon called windup effect [1–5]. Due to inherent complexity of nonlinear systems, actuator saturation is particularly neglected in a control law derivation, which can cause serious troubles to physical systems and their surroundings, such as damage, plant failure and accidents [6–7]. In order to overcome the effects of actuator saturation, an anti-windup compensator (AWC) is applied in addition to an output feedback controller [3–10].

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One-step control approaches to deal with the windup effect and to ensure the closed-loop performance such as stability, tracking and disturbance rejection have been considered in the literature [11–15]. These schemes are utilizing the knowledge of actuator nonlinearity, for output or state feedback controller synthesis, to achieve global or local stability and robust performance. Recently, a one-step approach for simultaneous linear controller and static AWC design of linear systems, by extending the standard results of H_∞ control theory [16], has been proposed in the work [17] (see also Refs. [18–22]). Since both linear controller and AWC are simultaneously involved, in the design process, by incorporating the knowledge of actuator saturation, such one-step approaches for control of input constrained systems offer an attractive feature of more clear multi-objective synthesis. However, the one-step synthesis approach requires rigorous efforts for controller design of different types of stable, unstable and chaotic nonlinear systems under input saturation owing to difficulties in mathematical derivations for simultaneous controller and AWC synthesis and due to in-built complexity of nonlinear systems.

Some remarkable exceptions on AWC synthesis for different types of nonlinear systems are available in the literature. A full order AWC design methodology, based on parametric tuning, is proposed in [23] for feedback linearizable Euler–Lagrange systems. This nonlinear AWC scheme guarantees stabilization of the overall closed-loop system; though, it lacks in attaining the performance objectives in the presence of input saturation. In order to keep the state of a feedback controller in the presence of input saturation same as for the case of nominal closed-loop system (without input saturation), a dynamic linear AWC design scheme has been proposed in the work [24] for a specific class of feedback linearizable nonlinear systems. A preliminary analytical study on nonlinear decoupled-architecture-based AWC design has been carried out in [25]. This contribution addressed the aforesaid problem using nonlinear matrix inequalities for feedback linearizable asymptotically stable Lipschitz nonlinear systems with invertible dynamics. It is worth mentioning that the aforementioned studies on AWC design had proposed two-step control approaches for nonlinear systems under actuator saturation, in which the design of a nominal feedback controller (using existing techniques) by ignoring input saturation is followed by incorporation of an AWC in the closed-loop system to compensate the effects of saturation. Moreover, control of nonlinear systems under input saturation is an important and appealing research issue owing to the bounded-input limitation for every system, which unfortunately could not get the desired research attention due to complexity of the problem.

In this paper, simultaneous synthesis of dynamic controller and AWC, motivated by the results of multi-objective control methodology [16], linear AWC scheme [26] and linear one-step control approach [17], is studied for Lipschitz nonlinear systems under input saturation. The proposed one-step techniques can be applied to a more general class of nonlinear systems, which are not necessarily stable, containing both actuator saturation and Lipschitz nonlinearities in contrast to the recent work [17]. Design schemes for global and local output feedback stabilizing controllers and necessary conditions for feasibility of the design constraints are provided. Further, a global anti-windup-based H_∞ controller design approach utilizing linear matrix inequalities (LMIs) is developed by application of a quadratic Lyapunov function, the L_2 gain reduction, the global sector condition, considerable matrix algebra and enormous variable transformation. Furthermore, a one-step local H_∞ LMI-based control approach, to deal with nonlinear systems for which global design is not feasible, is derived by application of the local sector condition. With this local control approach, the acceptable bound on L_2 norm of exogenous input can be enlarged by means of an LMI-based optimization algorithm. Additional conditions are derived by employing properties of the saturation function to obtain a well-posed controller avoiding algebraic loops for numerical simulation and practical implementation. Numerical examples are provided to demonstrate the effectiveness of the proposed global and local anti-windup-based one-step control approaches.

In contrast to the aforementioned nonlinear AWC design schemes, the present work proposes a one-step approach for designing output feedback controller and AWC simultaneously. The key feature of the proposed one-step design approach, over the two-step schemes for nonlinear systems under actuator saturation, is involvement of the both controller and AWC, simultaneously, in synthesis process to achieve desired closed-loop performance objectives as well as prevention against windup effects. Therefore, the proposed one-step anti-windup-based control approach can assemble a better combination of feedback controller and AWC in terms of performance, robustness, stability, disturbance rejection and region of convergence. Consequently, the one-step approach for control of input constrained nonlinear systems can offer an attractive feature of more clear multi-objective synthesis. Performance weights for control error, noise, disturbance, control signal, input and output, as in the standard H_∞ multi-objective synthesis, can be incorporated to design a higher order performance-oriented anti-windup-based controller. For the local synthesis, this multi-objective synthesis can be advantageous in enlarging the tolerate-able bound on L_2 norm of exogenous input because a higher order controller, due to incorporation of proper design weights in the synthesis process, can have more degree of freedom to achieve the desired performance objectives. In addition, the present work deals with the design of a computationally simple static AWC rather than a dynamic AWC. The proposed controller and AWC can be designed and implemented without any requirement of the exact information of nonlinearity in a plant in contrast to the traditional nonlinear AWC methodologies. Further, our control schemes do not require measurement or estimation of the state of a system in addition to measured output.

This paper is organized as follows. Section 2 presents the system description. Section 3 derives LMI-based conditions for designing global and local stabilizing controllers. Section 4 presents the global and local conditions for simultaneous design of H_∞ controller and static AWC. Section 5 provides the simulation results for the proposed control schemes. Section 6 draws conclusions of the study.