Control design for a class of nonlinear continuous-time systems

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Abstract

This paper addresses the control design problem for a certain class of continuous-time nonlinear systems subject to actuator saturations. The system under consideration consists of a system with two nested nonlinearities of different type: saturation nonlinearity and cone-bounded nonlinearity. The control law investigated for stabilization purposes depends on both the state and the cone-bounded nonlinearity. Constructive conditions based on LMIs are then provided to ensure the regional or global stability of the system. Different points, like other approaches issued from the literature, are quickly discussed. An illustrative example allows to show the interest of the approach proposed.

Keywords: Nonlinear systems; Saturations; Nonlinear feedback design; Nested nonlinearities; LMIs

1. Introduction

The stability and stabilization problems of dynamical systems subject to nonlinearities is of interest due to the fact that such systems include a wide variety of practical systems and devices, like servo systems, flexible systems, etc. Indeed, smooth and non-smooth nonlinearities often occur in real control process, due to physical, technological, safety constraints or imperfections, even inherent characteristic of considered controlled systems (Kapila & Grigoriadis, 2002; Kokotovic & Arcak, 2001; Tarbouriech, Garcia, & Glattfelder, 2007).

In the current paper, we consider a particular class of nonlinear systems consisting of a linear system affected by a state-dependent nonlinearity belonging to a general class of sectors and subject to amplitude saturation in the input. This class of systems includes as a special case the system without saturation studied in the context of absolute stability in de Oliveira, Geromel, and Hsu (2002) through the use of suitable Lur’e–Lyapunov functions. This class of systems without saturation but with uncertain parameters in the matrices is also studied in Montagner et al. (2007). The main objective of this paper is to design a saturating control law resulting from both the system states and the nonlinearity, through constant feedback gain matrices (Arcak & Kokotovic, 2001; Arcak, Larsen, & Kokotovic, 2003). The problem of the design of suitable feedback control gains is investigated. Thus, both regional and global stabilization results are proposed by considering a quadratic candidate Lyapunov function. Differently from Arcak et al. (2003), the objective of designing nonlinear feedback is to enlarge the region of stability of the closed-loop system subject to nested nonlinearities. Hence, this current paper can be viewed as a work complementary to Arcak et al. (2003) and Montagner et al. (2007). Based on the application to the current case of the modified sector conditions proposed in Tarbouriech, Prieur, and Gomes da Silva (2006), the conditions developed to address stabilization (in a regional or global context) appear under LMI forms and can directly be cast into convex optimization problems. Some discussions about the LDI-based approach, developed in Hu and Lin (2001), are provided. The numerical example intends to show that the considered control law can guarantee a larger closed-loop basin of attraction than in the case of a classical saturating state feedback.
Notation. Notation used in the paper is standard. Relative to a matrix $A \in \mathbb{R}^{m \times n}$, $A'$ denotes its transpose, and $A_{ij}$, $i = 1, \ldots, m$, denotes its $i$th row. If $A = A' \in \mathbb{R}^{m \times n}$, then $A < 0$ ($A \leq 0$) means that $A$ is negative (semi-)definite.

The components of any vector $x \in \mathbb{R}^n$ are denoted $x_i$, $i = 1, \ldots, n$. Inequalities between vectors are componentwise: $x \leq 0$ means that $x_i \leq 0$ and $x \leq y$ means that $x_i - y_i \leq 0$. $I_n$ denotes the $n \times n$ identity matrix.

2. Problem presentation

This paper focuses on the class of nonlinear systems consisting of a linear system affected by a state-dependent nonlinearity $\phi$ belonging to a general class of sectors and subject to amplitude saturation in the input. The considered continuous-time nonlinear system is then represented by:

$$\dot{x}(t) = Ax(t) + G\phi(z(t)) + B\text{sat}(u(t))$$
$$z(t) = Lx(t) + N\phi(z(t)) + M\text{sat}(u(t))$$ (1)

where $x(t) \in \mathbb{R}^n$, $u(t) \in \mathbb{R}^m$, $z(t) \in \mathbb{R}^p$ and $\phi(.) : \mathbb{R}^p \rightarrow \mathbb{R}^p$. $A$, $B$, $G$, $L$, $N$ and $M$ are real constant matrices of appropriate dimensions. The system is assumed to be well posed.

The additive vector $\phi(z(t))$ is a nonlinear vector depending on the output vector $z(t)$. Such an additive nonlinearity could represent state-space uncertainty or unmodelled dynamics (Turner, Hermann, & Postlethwaite, 2004) or could still represent some terms of interest resulting from a linearization or an approximation of a nonlinear system (Arcak et al., 2003). Thus, the nonlinearity $\phi(z(t))$ is continuous and verifies a cone-bounded sector condition (Johansson & Robertsson, 2002; Khalil, 2002), i.e. there exists a symmetric positive definite matrix $\Omega = \Omega' \in \mathbb{R}^{p \times p}$ such that

$$\phi'(z(t))\Delta\phi(z(t)) - \Omega z(t) \leq 0, \quad \forall z \in \mathbb{R}^p, \phi(0) = 0$$ (2)

where $\Delta \in \mathbb{R}^{p \times p}$ is any diagonal matrix defined by

$$\Delta = \begin{cases} \text{diag}(\delta_i), & \delta_i > 0, \forall i = 1, \ldots, p, \\ \delta I_p, & \text{if } \phi(.) \text{ is decentralized} \\ \delta > 0, \text{ otherwise}. \end{cases}$$

By definition, the nonlinearity globally satisfies the sector condition (2). The matrix $\Omega \in \mathbb{R}^{p \times p}$ is given by the designer, and therefore assumed to be known in the sequel. Moreover, the matrix $\Delta$ may represent a certain degree-of-freedom and then is a decision variable in what follows.

Furthermore, sat(.) is a componentwise saturation map $\mathbb{R}^m \rightarrow \mathbb{R}^m$ defined as:

$$\text{sat}(u_{ij}(t)) = \text{sign}(u_{ij}(t)) \min(\rho_{ij}, |u_{ij}(t)|)$$ (4)

where $\rho_{ij} > 0$ denotes the symmetric amplitude bound relative to the $i$th control input.

Throughout this work, assuming that $x(t)$ is available and that $\phi(z(t))$ is either available (as a signal) or known (its model is known), the following feedback control law is considered:

$$u(t) = Kx(t) + \Gamma \phi(z(t))$$ (5)

where $K \in \mathbb{R}^{m \times n}$ and $\Gamma' \in \mathbb{R}^{n \times p}$. The corresponding closed-loop system reads:

$$\dot{x}(t) = Ax(t) + G\phi(z(t)) + B\text{sat}(Kx(t) + \Gamma \phi(z(t)))$$
$$z(t) = Lx(t) + N\phi(z(t)) + M\text{sat}(Kx(t) + \Gamma \phi(z(t)))$$ (6)

System (6) is subject to nested nonlinearities since the saturation nonlinearity depends on the sector-bounded nonlinearity $\phi(z(t))$.

Note that in the absence of saturation, the stability of system (6) is related both to the stability property of the closed-loop matrix $A + BK$ and to the nonlinearity $\phi(z(t))$. In the presence of saturation, considering that the exact analytical determination of the basin of attraction of the system is, in general, not possible, we are concerned with the determination of estimates of this basin, i.e. regions in the state space in which the asymptotic stability of system (6) is guaranteed. Moreover, it is important to underline that although the cone-bounded sector condition (2) is globally satisfied, the global stabilization of system (6) could be studied only if the open-loop matrix $A$ satisfies some stability assumption (Sussmann, Sonntag, & Yang, 1994). Otherwise, only the regional stability of the closed-loop system can be investigated.

Thus we want to address the problem of designing a nonlinear feedback using the knowledge we have on the cone-bounded nonlinearity. The implicit objective is to design the gain matrices $K$ and $\Gamma'$ in order to maximize the basin of attraction of the resulting closed-loop system (6).

Problem 1. Determine feedback matrices $K$ and $\Gamma'$ and a region $S_0 \subseteq \mathbb{R}^n$ as large as possible, such that for any initial condition $x_0 \in S_0$ the origin of the closed-loop system (6) is asymptotically stable for any $\phi(.)$ verifying the sector condition (2).

To address Problem 1, quadratic Lyapunov functions and ellipsoidal regions of stability are exploited. In this case, the maximization of the region of stability can be accomplished by using any well-known size optimization criteria for ellipsoidal sets. On the other hand, when the open-loop system is asymptotically stable, it can be possible to search for $K$ and $\Gamma'$ in order to guarantee the global asymptotic stability of the closed-loop system. The region of stability $S_0$ is then the whole state space.

3. Nonlinear feedback design results

By defining the decentralized dead-zone nonlinearity $\psi(.) : \mathbb{R}^n \rightarrow \mathbb{R}^m$:

$$\psi(u(t)) = \text{sat}(u(t)) - u(t)$$ (7)

the closed-loop system reads:

$$\dot{x}(t) = (A + BK)x(t) + (G + B\Gamma)\phi(z(t)) + B\psi(u(t))$$
$$z(t) = (L + MK)x(t) + (N + M\Gamma)\phi(z(t)) + M\psi(u(t))$$ (8)

System (8) is then subject to two nonlinearities $\phi(z)$ and $\psi(u)$, the last one depending on the first one by definition.
3.1. Preliminary results

The nonlinearity $\psi(u(t))$, defined in (7) with (5), satisfies the following lemma, directly derived from Lemma 1 in Tarbouriech et al. (2006). Thus, by considering, with the notation in Tarbouriech et al. (2006), $w = E_1x + u = (E_1 + K)x + \Gamma \psi(z)$, one gets:

**Lemma 2.** Consider a matrix $E_1 \in R^{m \times n}$. If $x$ belongs to $S(\rho)$

$$S(\rho) = \{x \in R^n; -\rho \leq E_1x \leq \rho\}$$

then the nonlinearity $\psi(u)$ satisfies the following inequality:

$$\psi(u)^T (\psi(u) + (E_1 + K)x + \Gamma \psi(z)) \leq 0$$

or equivalently

$$\psi(u)^T (sat(u) + E_1x) \leq 0$$

for any diagonal positive definite matrix $T \in R^{m \times m}$.

3.2. Main results

Based on the use of Lemma 2, the following proposition allowing to compute gain matrices $K$ and $\Gamma$ can be stated.

**Proposition 3.** If there exist a symmetric positive definite matrix $W \in R^{m \times m}$, two positive diagonal matrices $S_{\Delta} \in R^{p \times p}$, $S \in R^{m \times m}$, three matrices $Z_1 \in R^{m \times n}$, $Y_1 \in R^{m \times n}$, and $Y_2 \in R^{m \times p}$ satisfying:

$$
\begin{bmatrix}
W^A + AW + Y_1^B + BY_1 & * & * \\
S_{\Delta} G^* + Y_2^B & (MY_2 + NS_{\Delta}) \psi' & * \\
+\Omega(LW + MY_2) & +\Omega(MY_2 + NS_{\Delta}) - 2S_{\Delta} & * \\
S^B - Y_1 - Z_1 & -Y_2 + SM \psi' & -2S
\end{bmatrix} < 0
$$

then the gains $K = Y_1 W^{-1}$ and $\Gamma = Y_2 S_{\Delta}^{-1}$ are solutions to Problem 1.

**Proof.** The satisfaction of relation (13) means that the ellipsoid $E(W)$ is included in $S(\rho)$ with the change of variables $E_1 = Z_1 W^{-1}$. Therefore the nonlinearity $\psi(u)$ satisfies the sector condition (10) or (11) of Lemma 2 for any $x \in E(W)$. Consider now the quadratic function $V(x) = x^T P x$, with $P = W^{-1}$. Its time-derivative along the trajectories of the closed-loop system (8) reads: $\dot{V}(x) = x^T (A + BK) P + P (A + BK) x + 2x^T P (G + B1) \psi + 2x^T P B \psi$. From the satisfaction of sector conditions (10) or (11) and (2), for $x \in E(W)$ it follows: $\dot{V}(x) \leq x^T (A + BK) P + P (A + BK) x + 2x^T P (G + B1) \psi + 2x^T P B \psi - 2\psi^T (\psi + (E_1 + K)x + \Gamma \psi(z)) - 2\psi^T \Delta(\psi - \Omega(L + MK) x - \Omega(M^\Gamma + N) \psi - \Omega M \psi)$. This inequality can be rewritten as $\dot{V}(x) \leq \xi^T M \xi$, with $\xi = [x^T \psi^T \psi^T]$ and $M =$

$$
\begin{bmatrix}
(A + BK) P + P (A + BK) & * & * \\
(G + B1) P & (M + N) \psi' \Delta & * \\
+\Delta \Omega (L + MK) & +\Delta \Omega (M^\Gamma + N) - 2\Delta & * \\
B^T P - T K - TE_1 & -T \Gamma + M^T \psi' \Delta & -2T
\end{bmatrix}.
$$

By pre- and post-multiplying the matrix $M$ above defined by the diagonal matrix diag($W; S_{\Delta}; S$), with $W = P^{-1}; S_{\Delta} = \Delta^{-1}; T = S^{-1}$, and with the change of variables $E_1 = Z_1 W^{-1}$. $K W = Y_1$ and $\Gamma S_{\Delta} = Y_2$, it follows that if relation (12) is satisfied, then one gets $M < 0$ and therefore $\dot{V}(x) < 0$, $\forall x \in E(W)$, $x \neq 0$. Hence, one can conclude that $E(W)$ is a contractive set along the trajectories of system (8) and then is a region of asymptotic stability for this system. □

The conditions given in Proposition 3 concern the stabilization problem in a local context. If the matrix $A$ is Hurwitz, the global asymptotic stabilization problem can be addressed by considering $Z_1 = 0$. Furthermore, see Tarbouriech et al. (2006) for some discussion about the multiplier $T$ and its structure. The following global stabilization result can be stated.

**Corollary 4.** If there exist a symmetric positive definite matrix $W \in R^{m \times m}$, two positive diagonal matrices $S_{\Delta} \in R^{p \times p}$, $S \in R^{m \times m}$, two matrices $Y_1 \in R^{m \times n}$ and $Y_2 \in R^{m \times p}$ satisfying:

$$
\begin{bmatrix}
W^A + AW + Y_1^B + BY_1 & * & * \\
S_{\Delta} G^* + Y_2^B & (MY_2 + NS_{\Delta}) \psi' & * \\
+\Omega(LW + MY_2) & +\Omega(MY_2 + NS_{\Delta}) - 2S_{\Delta} & * \\
S^B - Y_1 - Z_1 & -Y_2 + SM \psi' & -2S
\end{bmatrix} < 0
$$

then the gains $K = Y_1 W^{-1}$ and $\Gamma = Y_2 S_{\Delta}^{-1}$ globally asymptotically stabilize the closed-loop system (8).

**Remark 5.** In the control design, the designer is often faced to model uncertainty. For example, in the case where system (1) is subject to polytopic uncertainties (i.e. system matrices $A, B, G, L, N$ and $M$ belong to a polytope of matrices), relations of Problem 1 or Corollary 4 could be modified by using a similar framework as in Montagner et al. (2007).

3.3. LDI approach

By using the formalism developed in Hu and Lin (2001) and Hu, Teel, and Zaccarian (2006) and the LDI-based framework which uses a polytopic representation for the saturated closed-loop system, the following proposition to address Problem 1 can be stated.

**Proposition 6.** If there exist a symmetric positive definite matrix $W \in R^{m \times m}$, a positive diagonal matrix $S_{\Delta} \in R^{p \times p}$, three matrices $Z_1 \in R^{m \times n}$, $Y_1 \in R^{m \times n}$ and $Y_2 \in R^{m \times p}$ satisfying the equations given in Box I, where $D_j$ is a diagonal matrix with diagonal values equal to 0 or 1, then the gains $K = Y_1 W^{-1}$, $\Gamma = Y_2 S_{\Delta}^{-1}$ and the ellipsoid $E(W) = \{x \in R^n; x^T W^{-1} x \leq 1\}$, are solutions to Problem 1.

**Proof.** It follows the same lines as that one of Proposition 3. By using the formalism developed in Hu and Lin (2001) and Hu et al. (2006), one studies the conditions of nonlinear feedback
Proposition 6 which is valid in the set $R = \{W\}$ due to Proposition 6 and the one due to Proposition 3, denoted proportional to the specialized algorithms as in Klerk (2002), with complexity example, LMI conditions can be solved in polynomial time by LMIs to be solved considering Propositions 3 and 6 are compared.

Table 1
Number of decision variables and lines in both Propositions 3 and 6

<table>
<thead>
<tr>
<th>Proposition</th>
<th>Decision variables ($D$)</th>
<th>Lines ($L$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>$n(n+1)/2+ m(2n+p) + p+m$</td>
<td>$n+p+$ $m+m(n+1)$</td>
</tr>
<tr>
<td>6</td>
<td>$n(n+1)/2+ m(2n+p) + p$</td>
<td>$2^n(n+p)+$ $2^n m(n+p+1)$</td>
</tr>
</tbody>
</table>

design with respect to the following system:

$$\dot{x}(t) = \left( A + B \sum_{j=1}^{2^n} (D_j K + (I_m - D_j) H_1) \right) x(t) + \left( G + B \sum_{j=1}^{2^n} D_j \Gamma \right) \varphi(z(t))$$

$$z(t) = \left( L + M \sum_{j=1}^{2^n} (D_j K + (I_m - D_j) H_1) \right) x(t) + \left( N + M \sum_{j=1}^{2^n} D_j \Gamma \right) \varphi(z(t))$$

which is valid in the set

$$S(H_1, H_2, \rho) = \{x \in \mathbb{R}^n; -\rho \leq H_1 x \leq \rho\}$$

with $H_1 = Z_1 W^{-1}$. $\square$

Proposition 6 provides an alternative solution to Proposition 3. The number of variables and the number of lines in the LMIs to be solved considering Propositions 3 and 6 are compared in Table 1.

The numerical complexity of both approaches is closely related to the number of lines and decision variables. For example, LMI conditions can be solved in polynomial time by specialized algorithms as in Klerk (2002), with complexity proportional to $C = D^3 L$. When we study this quantity, one can observe that the numerical complexity associated to Proposition 3 increases much more slowly than that one associated to Proposition 6. The ratio between the quantity $D^3 L$ due to Proposition 6 and the one due to Proposition 3, denoted $R = \frac{D^3 L_{\text{Prop.6}}}{D^3 L_{\text{Prop.3}}}$, is depicted in Fig. 1, for the particular case $p = 1$ and various numbers of inputs $m$.

One can check that in all cases the complexity associated to Proposition 6 is larger than the one associated to Proposition 3.

Indeed, the ratio of complexity exponentially increases with $m$ due to the presence of the factor $2^m$ in the quantity $L$ resulting from Proposition 6.

Note that other ways to compare the accurate complexity could be investigated using other indexes, like for example the CPU-time.

Remark 7. In the uncertain context (in particular in the polytopic uncertainty case (Montagner et al., 2007)), the complexity associate to Proposition 6 increases even much quicker than that one associate to Proposition 3.

4. Numerical issues

4.1. Optimization issues

The implicit objective of Problem 1 consists in maximizing the estimate of the basin of attraction of the closed-loop system. Thus, when the open-loop matrix $A$ is asymptotically stable, if the conditions of Corollary 4 are feasible then the region of stability is the whole state space. Otherwise, by using Proposition 3, the problem of maximizing the region of stability consists in maximizing the size of $\mathcal{E}(W)$. Different linear optimization criteria $J(\cdot)$, associated to the size of $\mathcal{E}(W)$, can be considered, like the volume: $J = - \log(\det(W))$, or the size of the minor axis: $J = -\lambda$, with $W \geq \lambda I_n$.

A solution of Problem 1 can then be searched as follows:

$$\min_{W,S_D,S,F_1,F_2,Z_1} J(\cdot)$$

subject to LMIs (12) and (13).
Problem (17) can also be modified to consider additional convex constraints (for instance, associate to some constraints on norm gains or structural ones) or a different optimization criterion. Let us consider, for optimization of the size of set $\mathcal{S}_0 = \mathcal{E}(W)$, a given shape set $\mathcal{Z}_0 \in \mathbb{R}^n$ and a scaling factor $\beta$, where $\mathcal{Z}_0 = Co[v_r \in \mathbb{R}^n; r = 1, \ldots, n_r]$. The criterion may then be to maximize the scaling factor $\beta$ such that $\beta \mathcal{Z}_0 \subset \mathcal{E}(W)$ (Gomes da Silva & Tarbouriech, 2001). Moreover, let us also introduce a pole placement constraint in a circle centered in $-\sigma$ with radius $\eta$ (Garcia, Daafouz, & Bernussou, 1996). These requirements can then be accomplished by solving the following convex programming problem:

$$
\min_{\mu, v_r, \Sigma_1, \Sigma_2, \Sigma_3, \Sigma_4} \mu
$$

subject to LMI (12) and (13)

$$
\begin{align*}
\mu & \quad v_r^T \quad W_r & \geq 0, & \quad r = 1, \ldots, n_r \\
\mu & \quad -\eta^2 W & W(A + \alpha L_n)^T + Y_1'B' & < 0.
\end{align*}
$$

(18)

Thus, by considering $\beta = 1/\sqrt{\eta}$, the minimization of $\mu$ implies the maximization of $\beta$.

4.2. Illustrative example

Consider the unstable system (1) described by the following data:

$$
A = \begin{bmatrix} 1 & -1 \\ 1 & -3 \end{bmatrix}; \quad B = \begin{bmatrix} 2 \\ 1 \end{bmatrix}; \quad G = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \\
L = \begin{bmatrix} 1 & 1 \end{bmatrix}; \quad M = 1; \quad N = 0.5
$$

involving a nonlinearity $\varphi(z) = z(1 + \sin(z))/1.35$. This nonlinearity satisfies the sector condition (2) with $\Omega = 1.4$ (see Fig. 2).

Let us consider the limitation on the actuator given by $\rho = 5$. The optimization problem (18) is solved with $\mathcal{Z}_0$ being the hypercube centered in 0 and with vertices components equal to 1 or $-1$, and with the pole placement constraint $\sigma = 2.5$, $\eta = 2$. One obtains the solution:

$$
K = \begin{bmatrix} -1.8750 & 0.4323 \end{bmatrix}; \quad \Gamma = -1.1406
$$

which corresponds to an expansion of the shape set $\beta = 5.5644$, and for which the ellipsoid set $\mathcal{E}(W)$ is plotted in solid line on Fig. 3.

This domain may be compared with the solution obtained when only the matrix $K$ is computed (that is $\Gamma = 0$), plotted in dashed line on Fig. 3 and corresponding to enlarge the shape set with a factor $\beta = 3.7640$.

The same results, both in terms of the ellipsoids ($\mathcal{E}(W), \beta$) and control gains $K$, $\Gamma$, are obtained by using LDI conditions (Proposition 6). Typically, in various numerical conditions, the mere difference between both Propositions 3 and 6 comes from the numerical complexity (or CPU time) but this is relatively insignificant in small dimension examples.

5. Conclusion

The aim of this note was to design a nonlinear feedback using both the system states and the nonlinearity affecting the system, in order to enlarge the region of stability for the saturated closed-loop system. More precisely, we considered a particular class of nonlinear systems resulting from a saturation and cone-bounded nested nonlinearities. The main results are given in terms of constructive conditions since they are written in LMI form by using a quadratic Lyapunov function and a modified sector condition. An alternative solution using the LDI-based framework has been also developed and discussed. The additional degree-of-freedom due to the use of the nonlinearity $\varphi(z)$ in the control law allows to increase the size of the region of stability.

When dealing with such nested nonlinearities, several ways can be investigated: the first one is the design problem of output dynamic controllers for both the cases where the cone-bounded nonlinearity is available or not for feedback. A second problem is to provide some performance requirements for the nonlinear design purposes. Such problems are under study.
References


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