Research Article

Filter Design for Continuous-Time Linear Systems Subject to Sensor Saturation

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This paper presents new sufficient conditions to cope with the filtering problem for continuous-time linear systems subject to sensor saturation. A generalized sector condition has been used to handle the saturation in the measured output. The $H_\infty$ performance was considered and a quadratic Lyapunov function was employed in order to derive the design conditions. The conditions are presented in terms of matrix inequalities that become linear when a scalar parameter is fixed. The efficiency of the proposed conditions and their capability to deal with different levels of saturation are illustrated by numerical examples.

1. Introduction

The study of nonlinear phenomena occurring in control systems has attracted a lot of attention in the last years, mainly because of the effects these types of phenomena may cause [1]. Among others, one may cite quantization, time-delay, polynomial systems, hysteresis, and saturation [2–6]. The presence of those effects can degrade the performance and even bring instability to the control systems. Therefore, one must be cautious when analyzing systems that are subjected to nonlinear effects. The saturation phenomenon is related to the physical limitations presented in actuators, sensors, and other systems components. When the presence of saturation is not taken into account in the design process, it can lead to very conservative performances [4, 7, 8].

In the control literature, one of the most studied topics is the filter design problem [9]. In the filtering problem, we are interested in obtaining a good approximation of a desired signal in the presence of noise. The filter to be designed makes use of the output measurements of the system to provide an estimation of the desired signal. The desired signal can be a combination of the states or the states themselves. The problems have been studied under different conditions such as linear systems [10], uncertain systems [11, 12], time-delay systems [13, 14], polynomial systems [2, 15], and 2D systems [16]. Although the filter design depends on the output measurements of the system, which are obtained by using sensors that can present saturation, this scenario has not been fully explored in the literature.

In [17], the $H_\infty$ filtering problem has been studied for continuous-time systems subject to sensor nonlinearities, including sensor saturation. The main difference between the proposed technique and the method presented in [17] resides in the sector condition that has been employed. This paper addresses the problem of robust linear filter design for continuous-time linear systems subject to sensor saturation. The $H_\infty$ performance will be used as performance criteria and a generalized sector condition will be employed to handle the saturation. A quadratic Lyapunov function is considered and the filter design is accomplished by partitioning the Lyapunov matrix and its inverse. New sufficient conditions in the form of matrix inequalities are presented for both nominal case and uncertain case. Numerical experiments from the literature illustrate the potential of the proposed conditions and indicate that the saturation in the measured output does affect the $H_\infty$ performance of the robust linear filter.

This paper is organized as follows. Section 2 introduces the problem under consideration and the main goal of this paper. Section 3 presents some preliminary results and the main results are given in Section 4. Section 5 is devoted to present the numerical experiments and Section 6 concludes the paper.
Notation 1. For two symmetric matrices of the same dimensions \(X\) and \(Y\), \(X > Y\) means that \(X - Y\) is positive definite. \(\mathbb{R}^n\) is the set of positive real numbers. For matrices and vectors, \(\top\) indicates the transpose. Identity matrices are denoted by \(I\) and null matrices are denoted by \(0\). The symbol \(*\) indicates a symmetric block in matrices.

2. Problem Statement

Consider the following continuous-time system:

\[
\begin{aligned}
\dot{x}(t) &= Ax(t) + Bw(t), \\
z(t) &= C_x x(t) + D_z w(t), \\
y(t) &= \text{sat}_{y_0}(C_y x(t)),
\end{aligned}
\]

where \(x \in \mathbb{R}^n\) is the state vector, \(w \in \mathbb{R}^n\) is the input, \(z \in \mathbb{R}^n\) is the signal to be estimated, \(y \in \mathbb{R}^n\) is the output, and \(t \in \mathbb{R}^+\) is the time domain. The constant matrices that describe the system have the following forms: \(A \in \mathbb{R}^{n \times n}, B \in \mathbb{R}^{n \times m}, C_x \in \mathbb{R}^{n \times n}, D_z \in \mathbb{R}^{n \times m},\) and \(C_y \in \mathbb{R}^{n \times n}\). The matrix \(A\) is supposed to be Hurwitz stable. Due to physical limitations, the sensor output \(y\) is supposed to be bounded in amplitude; that is,

\[
-y_0(i) \leq y(i) \leq y_0(i), \quad y_0(i) > 0, \quad i = 1, \ldots, n_y.
\]

Furthermore, the signal \(w\) is suggested to be energy bounded; that is, \(w \in L_2\). Without loss of generality, we assume that the signal \(w\) is \(L_2\)-normalized; that is, it satisfies

\[
\|w\|_2^2 = \int_0^\infty w^T(t)w(t)\,dt \leq 1. \tag{3}
\]

The problem to be addressed in this paper is finding a full order stable robust continuous-time linear filter given by

\[
\begin{aligned}
\dot{z}_f(t) &= A_f z_f(t) + B_f y(t), \\
\dot{z}_j(t) &= C_f z_f(t) + D_f y(t),
\end{aligned}
\]

where \(x_f \in \mathbb{R}^n, n_f = n, \) is the estimated state and \(z_f \in \mathbb{R}^n\) is the estimated output, and the filtering matrices are \(A_f \in \mathbb{R}^{n_f \times n_f}, B_f \in \mathbb{R}^{n_f \times n}, C_f \in \mathbb{R}^{n \times n_f},\) and \(D_f \in \mathbb{R}^{n \times n_n}.\) As a consequence of the bounds (2), the output \(y\) that will be used by the filter is a saturated one

\[
y(t) = \text{sat}_{y_0}(C_y x(t)) \tag{5}
\]

and each component of \(\text{sat}(C_y x(t))\) is defined, \(\forall i = 1, \ldots, n_y,\) by

\[
\text{sat}(C_y x(t)) = \text{sign}(C_y x(t)) \min(\|C_y x(t)\|^2, y_0(i)). \tag{6}
\]

Defining the decentralized dead-zone nonlinearity \(\phi \in \mathbb{R}^n\) as

\[
\phi(x) = \text{sat}_{y_0}(C_y x(t)) - C_y x(t), \tag{7}
\]

system (1) reads

\[
\begin{aligned}
\dot{x}(t) &= Ax(t) + Bw(t), \\
z(t) &= C_x x(t) + D_z w(t), \\
y(t) &= \phi + C_y x(t).
\end{aligned}
\]

Connecting filter (4) with system (8) and defining the augmented state vector \(\tilde{x}(t) = [x^T(t), y^T(t)]\) and the output error \(e(t) = z(t) - z_f(t),\) one has

\[
\begin{aligned}
\dot{\tilde{x}}(t) &= \tilde{A}\tilde{x}(t) + \tilde{B}w(t) + \tilde{B}_f\phi, \\
e(t) &= [C_z - D_f C_y - C_f] \begin{bmatrix} x(t) \\ y_f(t) \end{bmatrix} + [D_z] w(t) + [-D_f]\phi,
\end{aligned}
\]

that can be written in a compact form with

\[
\begin{aligned}
\dot{\tilde{x}}(t) &= \tilde{A}\tilde{x}(t) + \tilde{B}w(t) + \tilde{B}_f\phi, \\
e(t) &= \tilde{C}\tilde{x}(t) + \tilde{D}w(t) + \tilde{D}_f\phi,
\end{aligned}
\]

where

\[
\tilde{A} = \begin{bmatrix} A & 0 \\ B_f C_y & A_f \end{bmatrix} \in \mathbb{R}^{2n \times 2n},
\tilde{B} = \begin{bmatrix} B \\ 0 \end{bmatrix} \in \mathbb{R}^{2 \times n},
\tilde{B}_f = \begin{bmatrix} 0 \\ B_f \end{bmatrix} \in \mathbb{R}^{2 \times n},
\tilde{C} = \begin{bmatrix} C_z - D_f C_y - C_f \end{bmatrix} \in \mathbb{R}^{n \times 2n},
\tilde{D} = \begin{bmatrix} D_z \end{bmatrix} \in \mathbb{R}^{n \times 2n},
\tilde{D}_f = \begin{bmatrix} -D_f \end{bmatrix} \in \mathbb{R}^{n \times 2n}.
\]

The \(H_\infty\) performance will be used as the performance criteria, assuring that the augmented system (10) is asymptotically stable and the energy gain from the disturbance input \(w(t)\) to the error \(e(t) = z(t) - z_f(t)\) is minimized.

Definition 2 (see [18]). If there exists a Lyapunov function \(V(\tilde{x}(t)) > 0,\) then a bound \(\gamma^2\) to the \(H_\infty\) performance of the augmented system (10), from the noise input \(w(t)\) to the error output \(e(t),\) can be obtained by

\[
\dot{V}(\tilde{x}(t)) + \frac{1}{\gamma^4} e(t)^T e(t) - w(t)^T w(t) < 0. \tag{12}
\]

3. Preliminaries

The preliminary results presented here follow the lines in [19, 20].
Proposition 3. If there exist a matrix $Q = Q^T > 0 \in \mathbb{R}^{2n \times 2n}$, a diagonal matrix $S_1 > 0 \in \mathbb{R}^{n \times n}$, and $F \in \mathbb{R}^{n \times 2n}$ such that the inequalities

$$
\begin{bmatrix}
    Q \tilde{A}^T + \tilde{A}Q & \tilde{B} \tilde{S}_1 - Q \tilde{C}_s^T - F^T \\
    * & -I_{n_w} & 0 \\
    * & * & -2S_1 \\
    * & * & -\gamma^2 I_{n_z}
\end{bmatrix} < 0,
$$

are satisfied, then the $H_{\infty}$ performance is limited by $\gamma$ for every initial condition belonging to $\mathcal{E}(Q^{-1}) = \{\bar{x}(t) \in \mathbb{R}^{2n}; \bar{x}(t)Q^{-1}\bar{x}(t) \leq 1\}$.

Proof. Consider the quadratic Lyapunov function $V(\bar{x}(t)) = \bar{x}(t)Q^{-1}\bar{x}(t)$, with $Q = Q^T > 0$. The $H_{\infty}$ performance bound from $w(t)$ to $e(t)$ for system (10) can be obtained by

$$
\dot{V}(\bar{x}(t)) + \frac{1}{y_0^2}e(t)^T e(t) - w(t)^T w(t) < 0.
$$

By using equations from system (10), one can write

$$
\begin{bmatrix}
    \bar{x}(t) \\
    w(t) \\
    \phi
\end{bmatrix}^T
\begin{bmatrix}
    \tilde{A}Q^{-1} + Q^{-1}\tilde{A} & Q^{-1}\tilde{B} & Q^{-1}\tilde{B}_1 \\
    \tilde{B}^T Q^{-1} & -I_{n_w} & 0 \\
    \tilde{B}_1^T Q^{-1} & 0 & 0 \\
    \gamma^2 I_{n_z} & \tilde{C} & \tilde{D}_s
\end{bmatrix}
\begin{bmatrix}
    \bar{x}(t) \\
    w(t) \\
    \phi
\end{bmatrix} < 0.
$$

Given that $\bar{x}(t) \in S(y_0)$ with $S(y_0) = \{\bar{x}(t) \in \mathbb{R}^{2n}; -y_0 \leq FQ^{-1}\bar{x}(t) \leq y_0\}$, one can use Lemma 1 from [6], to verify that

$$
-2\phi^T S_1^{-1} \left( \phi + \gamma^2 \bar{x}(t) - FQ^{-1}\bar{x}(t) \right) \geq 0,
$$

where $S_1$ is a positive diagonal matrix. It is possible to rewrite (17) as

$$
-2\phi^T S_1^{-1} \left( \phi + \gamma^2 \bar{x}(t) - FQ^{-1}\bar{x}(t) \right) \geq 0,
$$

where $\bar{C}_s = \begin{bmatrix} C_y & 0_{n \times n} \end{bmatrix}$. Applying a Schur complement on inequality (14), one can write

$$
Q - F^T \frac{1}{y_0^2} F \geq 0.
$$

Pre- and postmultiplying the last inequality by $Q^{-1}$, one has

$$
Q^{-1} - Q^{-1} F \frac{1}{y_0^2} F Q^{-1} \geq 0
$$

or equivalently

$$
\bar{x}(t)^T Q^{-1} \bar{x}(t) \geq \bar{x}(t)^T F \frac{1}{y_0^2} F Q^{-1} \bar{x}(t).
$$

In this way, one concludes that the ellipsoid $\mathcal{E}(Q^{-1}) = \{\bar{x}(t) \in \mathbb{R}^{2n}; \bar{x}(t)Q^{-1}\bar{x}(t) \leq 1\}$ is contained in $S(y_0)$. Moreover, if (18) is positive definite, one can write

$$
\dot{V}(\bar{x}(t)) + \frac{1}{y_0^2}e(t)^T e(t) - w(t)^T w(t) 
\leq \dot{V}(\bar{x}(t)) + \frac{1}{y_0^2}e(t)^T e(t) - w(t)^T w(t) 
- 2\phi^T S_1^{-1} \left( \phi + \bar{C}_s \bar{x}(t) - FQ^{-1}\bar{x}(t) \right).
$$

To ensure that (15) holds, it suffices to verify that the right side of inequality (22) is negative definite. This fact can be guaranteed by the following inequality:

$$
\begin{bmatrix}
    Q^{-1}\bar{x}(t) \\
    w(t) \\
    \phi
\end{bmatrix}^T
\begin{bmatrix}
    R_1 & \tilde{B} & R_2 \\
    B^T & -I_{n_w} & 0 \\
    S_1^{-1} \phi
\end{bmatrix}
\begin{bmatrix}
    Q^{-1}\bar{x}(t) \\
    w(t) \\
    \phi
\end{bmatrix} < 0,
$$

where

$$
R_1 = Q\tilde{A}^T + \tilde{A}Q, \\
R_2 = \tilde{B}S_1 - Q\tilde{C}_s^T - F^T.
$$

By applying Schur complement in (23), one has condition (13):

$$
\begin{bmatrix}
    R_1 & \tilde{B} & Q\tilde{C}_s^T \\
    * & -I_{n_w} & 0 \\
    * & * & -2S_1
\end{bmatrix} < 0.
$$

4. Main Results

The following theorem presents a sufficient condition for the filter design problem based on Proposition 3.

Theorem 4. If there exist positive definite symmetric matrices $Z \in \mathbb{R}^{2n \times 2n}$ and $X \in \mathbb{R}^{2n \times 2n}$, a positive definite diagonal matrix $S_1 \in \mathbb{R}^{n \times n}$, matrices $G \in \mathbb{R}^{n \times n}$, $H \in \mathbb{R}^{n \times n}$, $L \in \mathbb{R}^{n \times n}$, $W_1 \in \mathbb{R}^{2n \times 2n}$, $W_2 \in \mathbb{R}^{2n \times 2n}$, and $D_1 \in \mathbb{R}^{n \times 2n}$, and a scalar $\gamma$ such that the following inequalities are satisfied,
\[
\begin{bmatrix}
A'Z + ZA & A'X + ZA + C'_yL' + G' & ZB & -C'_y - W_1 & C'_z - C'_yD'_f - H'

* & A'X + XA + C'_yL' + LC'_y & XB & LS_1 - C'_y - W_2 & C'_z - C'_yD'_f

* & * & -I_{n_w} & 0 & D'_z

* & * & * & -2S_1 & -S'_1D'_f

* & * & * & * & -\gamma^2I_{n_w}
\end{bmatrix} < 0, \quad (26)
\]

\[
\begin{bmatrix}
Z & Z & W_{1(\psi)} & * & X & W_{r(\psi)} & * & * & \gamma^2_{0(\psi)}
\end{bmatrix} > 0, \quad (27)
\]

Define the matrices
\[
S = \begin{bmatrix} Y & I \\ V & 0 \end{bmatrix},
\]
\[
S^{-1} = \begin{bmatrix} 0 & V^{-1} \\ I & -VV^{-1} \end{bmatrix},
\]
\[
R = \begin{bmatrix} Y & 0 \\ 0 & I \end{bmatrix},
\]
\[
R^{-1} = \begin{bmatrix} Y^{-1} & 0 \\ 0 & I \end{bmatrix}.
\]

By multiplying (13) on the left by \(T_1 = \text{diag}(R^{-1}S'Q^{-1}, I, I, I)\) and on the right by \(T_1'\), one has condition (26) where
\[
Z = Y^{-1},
\]
\[
L = U'B_f,
\]
\[
G = U'A_fVZ,
\]
\[
H = C_fVZ,
\]
\[
W_1 = Z\gamma^2_{1},
\]
\[
W_2 = X\gamma^2_{1} + U'\gamma^2_2.
\]

By multiplying (14) on the left by \(T_2 = \text{diag}(R^{-1}S'Q^{-1}, I)\) and on the right by \(T_2'\), one has condition (27). For details about the filter reconstruction, the reader is referred to [21]. \(\square\)

**Remark 5.** Note that Theorem 4 presents a bilinear matrix inequality condition, because the variable \(S_1\) appears multiplying some other variables of the problem. However, since matrix \(S_1\) is diagonal, this problem can be overcome by considering
\[
S_1 = \text{diag}(\lambda, \lambda, \ldots, \lambda), \quad \lambda > 0 \quad (33)
\]

and performing a line search in \(\lambda > 0\). In this way, condition (26) becomes a linear matrix inequality for each fixed value of \(\lambda\).
of $\lambda$. Moreover, since matrix $S_1$ is precisely known, matrix $D_f$ will be recovered directly from condition (26) and no change of variables is necessary in this case.

The proposed approach can also be extended to deal with time-varying uncertainties and state-dependent polytopic uncertainties as introduced in [22]. In this case, the system is described as

$$
\dot{x}(t) = A(\sigma)x(t) + B(\sigma)w(t), \\
z(t) = C_x(\sigma)x(t) + D_z(\sigma)w(t), \\
y(t) = \phi + C z(t).
$$

(34)

The matrices in (34) belong to a polytopic domain parameterized in terms of the states $x(t)$ and in terms of a time-varying parameter $\sigma$, being generically represented by

$$
Z(\sigma) = \sum_{i=1}^{N} \sigma_i(x^i, \alpha^i) Z_i, \quad \sigma \in \Lambda_N,
$$

(35)

where $Z(\sigma)$ represents any matrix of the system in (34), $Z_i$, $i = 1, \ldots, N$, are the vertices, $N$ is the number of vertices of the polytope, and $\Lambda_N$ is the unit simplex, given by

$$
\Lambda_N = \left\{ \sigma \in \mathbb{R}^N : \sum_{i=1}^{N} \sigma_i(x^i, \alpha^i) = 1, \quad \sigma_i(x^i, \alpha^i) \geq 0, \quad i = 1, \ldots, N \right\}.
$$

(36)

Connecting the filter as in (4) with system (34), one can use the same procedure as presented before to obtain sufficient conditions to design a robust filter for system (34). The next theorem presents the conditions.

**Theorem 6.** If there exist positive definite symmetric matrices $Z \in \mathbb{R}^{n \times n}$ and $X \in \mathbb{R}^{n \times n}$, a positive definite diagonal matrix $S_1 \in \mathbb{R}^{n \times n}$, matrices $G \in \mathbb{R}^{n \times n}$, $H \in \mathbb{R}^{n \times n}$, $L \in \mathbb{R}^{n \times n}$, $W_i \in \mathbb{R}^{n \times n}$, $W_2 \in \mathbb{R}^{n \times n}$, and $D_f \in \mathbb{R}^{n \times n}$, and a scalar $\gamma$ such that inequality (27) and the following inequalities are satisfied

$$
\begin{bmatrix}
A_f'Z +ZA_f & A_f'X +ZA_f + C_{y_f}L' + G' & ZB_1 & -C_{y_f}' - W_1 & C_{z_f}' - C_{y_f}'D_f - H' \\
* & A_f'X +XA_f + C_{y_f}L' + LC_{y_f} & XB_1 + LD_{y_f} & LS_1 - C_{y_f}' - W_2 & C_{z_f}' - C_{y_f}'D_f \\
* & * & * & * & C_{z_f}' - C_{y_f}'D_f \\
* & * & * & * & \gamma^2 I_{n_z}
\end{bmatrix} < 0
$$

(37)

for $i = 1, \ldots, N$, then

$$
A_f = \left( U' \right)^{-1} G (VZ)^{-1}, \\
B_f = \left( U' \right)^{-1} L, \\
C_f = H (VZ)^{-1},
$$

(38)

are the matrices of the robust filter that guarantee an $\mathcal{H}_{\infty}$ performance bounded by $\gamma^2$. The matrices $U$ and $V$ are obtained from the relation $XY + U'V = I$.

Proof. Multiplying condition (37) by $\sigma_i$ for $i = 1, \ldots, N$ and summing up, one has a parameter dependent condition. Then, the proof follows the same steps as the ones in proof of Theorem 4.

The comments presented in Remark 5 are also valid for this case.

## 5. Numerical Experiments

The main goal of the experiments is to illustrate the potential of the proposed conditions and show the effect of the saturation level $y_0$ in the $\mathcal{H}_{\infty}$ performance of the robust filter designed by Theorems 4 and 6. The routines were implemented in Matlab, version 7.1.0.246 (R14) SP 3 using the packages Yalmip [23] and SeDuMi [24].

**Example 7.** Consider the continuous-time system borrowed from [25] that describes the longitudinal dynamics of the F-8 aircraft, whose system matrices are

$$
A = \begin{bmatrix}
-2.4701 & 0.3430 & -1.2680 & -4.3661 \\
-2.5618 & 0.0539 & -17.2462 & -36.5734 \\
-2.0172 & 0.0698 & -2.5839 & -5.1006 \\
1 & 0 & 0 & 0
\end{bmatrix},
$$

$$
B = \begin{bmatrix}
1 & 0 \\
0 & 1 \\
0 & 0 \\
0 & 0
\end{bmatrix},
$$

(39)

$$
C_x = \begin{bmatrix}
0 & 0 & 0 & 1 \\
0 & 0 & -1 & 1
\end{bmatrix},
$$

$$
C_z = \begin{bmatrix}
0 & 0 & 1
\end{bmatrix},
$$

$$
D_z = 0.
$$
In this example, the matrix $S_1$ has been considered as $S_1 = \text{diag}(\lambda, \lambda)$, $\lambda > 0$, and three different situations for the saturation level $y_0$ have been considered:

\[
\begin{align*}
C_1 & \rightarrow y'_0 = \begin{bmatrix} 10^{-1} & 10^{-1} \end{bmatrix}, \\
C_2 & \rightarrow y'_0 = \begin{bmatrix} 10^{-2} & 10^{-2} \end{bmatrix}, \\
C_3 & \rightarrow y'_0 = \begin{bmatrix} 10^{-3} & 10^{-3} \end{bmatrix}.
\end{align*}
\]

Figure 1 presents the behavior of $y$ with the variation of $\lambda$ for a strictly proper filter (i.e., considering $D_f = 0$) obtained with Theorem 4, considering three different levels of sensor saturation in the measured output $y$. For this system, the method in [17] provides a proper filter with $\gamma = 0.4693$ for $y'_0 = \begin{bmatrix} 1 & 1 \end{bmatrix}$. It can be seen that Theorem 4 can provide smaller bounds to the $H_{\infty}$ performance than [17] even for more restrictive situations in the output $y(t)$. Moreover, for each fixed value of $\lambda$, the curve for $C_1$ yields the small values for $\gamma$. This is expected since the case $C_1$ is the less restrictive situation.

In order to perform a time-domain simulation, let us consider the following input noise:

\[
w(t) = \sin(0.5t) \exp(-0.1t) \begin{bmatrix} 1 \\ 1 \end{bmatrix}.
\]

Figure 2 shows the error signal obtained with a time simulation of the augmented system (10) considering two different levels of sensor saturation. The dashed red line depicts the error for a filter obtained with Theorem 4 with $C_1$ and $\lambda = 0.7$, while the solid blue line shows the error-time response for a filter designed by Theorem 4 with $C_3$ and $\lambda = 0.8$. It can be noted that the sensor saturation in the output $y$ can affect directly the performance of the augmented system. Moreover, the filter obtained for $C_1$ provides a more attenuated error signal.

Figure 3 shows the behavior of the saturated output $y(t)$ considering case $C_1$ with $\lambda = 0.7$ in Theorem 4. Note that the component $y_2(t)$ is the most affected by the saturation level.

**Example 8.** Consider the following example adapted from [22] with matrices:

\[
A_1 = \begin{bmatrix} -9.1 & 50 \\ -1 & -10 \end{bmatrix},
A_2 = \begin{bmatrix} -0.1 & 50 \\ -1 & -10 \end{bmatrix}.
\]
to be efficient in taking into account the sensor saturation in the filter design problem. As future research, the author is investigating how to consider LPV filters to treat the systems with time-varying uncertainties.

Conflicts of Interest

The author declares that there are no conflicts of interest regarding the publication of this paper.

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