H_∞ control of nonlinear fuzzy descriptor system via LMI

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Abstract—this paper deals with the H_∞ control of nonlinear fuzzy descriptor system described by Takagi-Sugeno fuzzy models. In the first step, we present a stability analysis of nonlinear fuzzy descriptor system. The stability conditions are given in LMI form. In the second step, we have developed H_∞ PDC control law in order to reject the effects of external disturbances submitted to the system. Finally, a simulation example is presented to illustrate the mains results.

Keywords— fuzzy descriptor systems; stability; PDC control; H_∞ control; LMI approach.

I. INTRODUCTION

During last decade, the control of nonlinear fuzzy system described by Takagi-Sugeno fuzzy models attracted much attention [8] [9] [10] [11]. The main advantages of this type of fuzzy control are their simplicity and efficiency to complete other nonlinear control technique. Furthermore, the descriptor systems have become a research center for nonlinear fuzzy systems since they involve dynamic relationships and algebraic relations [1] [4] [7] [14]. However, the stability conditions are given in the form of LMI (Linear Matrix Inequality) and LME (Linear Matrix Equality) [5] [12] [13] which present a constraint during programming and solving LMI problem.

In this paper, we present fuzzy descriptor systems and a study about the stability of this class of systems then we propose H_∞ control law that allows a rejection external disturbance presented in strict LMI design. To validate our results a simulation example is presented [4][6][8].

II. FUZZY DESCRIPTOR SYSTEM

We consider the T-S fuzzy descriptor systems described by r fuzzy rules as follows.

$$\left\{ \begin{array}{l} \text{If } z_1(t) \text{ is } M_{i1} \text{ and } \dots z_g(t) \text{ is } M_{ig} \\ \text{Then } E\dot{x}(t) = h_i(z(t))A_i x(t) \end{array} \right.$$

Where $x(t) \in \mathbb{R}^n$ and $y(t) \in \mathbb{R}^n$ are respectively the state vector and output. $A_i \in \mathbb{R}^{n \times n}$ is the local state matrix that present the i -th local model et E is a singular matrix with

$rank(E) \leq n$. $z_j(t)$ and $M_{ij} (1 \dots n)$ are the premise variables and their fuzzy sets, respectively.

By assuming that $\forall t$:

$$z(t) = [z_1(t) \dots z_g(t)]$$

$$w_i(z(t)) = \prod_{j=1}^g M_{ij}(z_j(t)) ; w_i(z(t)) \geq 0, i = 1 \dots r.$$

and

$$h_i(z(t)) = \frac{w_i(z(t))}{\sum_{i=1}^r w_i(z(t))}$$

The global fuzzy descriptor system can be written in the following form:

$$E\dot{x}(t) = \sum_{i=1}^r h_i(z(t))A_i x(t) \quad (1)$$

We consider the Singular Value Decomposition (SVD) of the matrix E . There are two non-singular matrixes U and V such that:

$$\bar{E} = UEV = \begin{bmatrix} I_r & 0 \\ 0 & 0 \end{bmatrix}, \quad \bar{A} = UAV = \begin{bmatrix} \bar{A}_{11} & \bar{A}_{12} \\ \bar{A}_{21} & \bar{A}_{22} \end{bmatrix}.$$

We define the following matrix:

$$\begin{aligned} E^\perp &= V(I - UEV)U, \\ E^\dagger &= U^T(I - UEV)U^{-T} \\ E^\dagger &= U^{-1}(I - UEV)U. \end{aligned}$$

It is noted that: $EE^\perp = 0$; $E^T E^\dagger = 0$; $E^\dagger E = 0$

Definition 1. [2]

The pair (E, A_i) is said to be regular if $\det(sE - A_i)$ is not identically zero.

Definition 2. [2]

The pair (E, A_i) is said to be impulse-free if $\deg(\det(sE - A_i)) = \text{rang}(E)$.

It is worth noting that the stability properties for conventional systems are no longer sufficient for singular systems, unless they are completed by the regularity condition and the absence of impulses, which leads to the introduction of the notion of admissibility.

Definition 3. [2]

The descriptor system (1) is said to be admissible if it is regular, impulse-free and Hurwitz stable.

III. STABILITY OF FUZZY DESCRIPTORS SYSTEMS

In this section, we will introduce two different types of stability conditions, the first is given by (Taniguchi and al. (1999)) and second is given by (Chaabane et al., 2006) which we will build the following work.

Theorem 1: (Taniguchi and al. (1999))

The fuzzy descriptor system (1) is stable if and only if there exist a symmetric matrix P such that:

$$\begin{cases} E^T P = P^T E \geq 0 \\ A_i^T P + P^T A_i < 0; i=1 \dots r \end{cases} \quad (2)$$

$$A_i^T P + P^T A_i < 0; i=1 \dots r \quad (3)$$

Proof : view [2]

(Taniguchi and al. (1999)) used, during the stability study, the Lyapunov function $V(x(t)) = x^T E^T P x$ with $E^T P = P^T E \geq 0$ which P is a matrix which satisfies the above condition. To eliminate the equality $E^T P = P^T E \geq 0$, we propose the theorem 2.

Theorem 2: (Chaabane and al, 2006)

The fuzzy descriptor system (1) is admissible if and only if there exist a symmetric matrix X and two matrices Q and Z such that the following LMI is feasible:

$$EXE^T + \text{sym}\{E^+ Z\} > 0 \quad (4)$$

$$\text{sym}\{A_i^T (XE + E^+ Q)\} < 0 \quad (5)$$

Proof: view [2]

Theorem 2 has two strict LMI conditions (4) and (5). Indeed, the condition (5) is similar to the condition (3) when we replace $P = XE + E^+ Q$, we obtain $E^T P = E^T XE$ which is symmetric and the condition of positivity of $E^T P = P^T E \geq 0$ is assured by (4) as a strict condition [2].

IV. H_∞ CONTROL OF FUZZY DESCRIPTOR SYSTEMS

We consider the fuzzy descriptor system described as follows:

$$\begin{aligned} E\dot{x}(t) &= \sum_{i=1}^r h_i(z(t)) [A_i x(t) + B_i u(t) + D_i w(t)] \\ y(t) &= \sum_{i=1}^r h_i(z(t)) C_i x(t) \end{aligned} \quad (6)$$

which $x(t)$, $y(t)$, $u(t)$ and $w(t)$ are respectively the state, output, control and disturbances vectors. A_i , B_i , C_i and D_i are the matrix appropriates for the local model and E is a singular matrix with $\text{rang}(E) \leq n$.

The conditions of H_∞ admissibility of the autonomous fuzzy descriptor system is presented in the next theorems (We take $u(t) = 0$).

Theorem 3:

The fuzzy descriptor system (6) is admissible and allows a performance H_∞ in external disturbance rejection if and only if there exist a symmetric matrix X , two matrices Q and Z and a scalar $\gamma > 0$, such as the following LMI is feasible:

$$\begin{aligned} & EXE^T + \text{sym}\{E^+ Z\} > 0 \\ & \begin{bmatrix} \text{sym}\{A_i^T (XE + E^+ Q)\} & * & * \\ D_i^T (XE + E^+ Q) & -\gamma I & * \\ C_i & 0 & -\gamma I \end{bmatrix} < 0 \end{aligned} \quad (7)$$

Proof:

We consider the following Lyapunov function:

$$V(x(t)) = x^T E^T P x > 0$$

$$\dot{V}(x(t)) = \dot{x}^T E^T P x + x^T E^T P \dot{x}$$

We suppose it exist a scalar $\gamma > 0$ such that:

$$\dot{V}(x(t)) + y^T y - \gamma^2 w^T w < 0$$

$$\begin{aligned} \dot{V}(x(t)) + y^T y - \gamma^2 w^T w &= \dot{x}^T E^T P x + x^T P^T E \dot{x} + y^T y - \gamma^2 w^T w \\ &= \sum_{i=1}^r h_i(z(t)) [x^T A_i^T P x + w^T D_i^T P x + x^T P^T A_i x \\ &\quad + w^T P^T D_i x + x^T C_i^T C_i x - \gamma^2 w^T w] < 0 \\ &\Leftrightarrow [x^T A_i^T P x + w^T D_i^T P x + x^T P^T A_i x + w^T P^T D_i x + x^T C_i^T C_i x - \gamma^2 w^T w] < 0 \\ &\Leftrightarrow \begin{bmatrix} x^T \\ w^T \end{bmatrix} \begin{bmatrix} A_i^T P + P A_i + C_i^T C_i & P D_i \\ D_i^T P & -\gamma^2 I \end{bmatrix} \begin{bmatrix} x \\ w \end{bmatrix} < 0 \\ &\Leftrightarrow \begin{bmatrix} A_i^T P + P A_i + C_i^T C_i & P D_i \\ D_i^T P & -\gamma^2 I \end{bmatrix} < 0 \end{aligned} \quad (8)$$

Using the theorem 2 and replacing $P = XE + E^+ Q$, we can rewrite the inequality (8) by the following two conditions:

$$\Leftrightarrow \begin{cases} EXE^T + \text{sym}\{E^+Z\} > 0 \\ \text{sym}\{A_i^T(XE + E^+Q)\} + C_i^T C_i & (XE + E^+Q)^T D_i \\ D_i^T(XE + E^+Q) & -\gamma^2 I \end{cases} < 0 \quad (9)$$

The condition (9) can be written as:

$$\begin{bmatrix} \text{sym}\{A_i^T(XE + E^+Q)\} & (XE + E^+Q)^T D_i \\ D_i^T(XE + E^+Q) & -\gamma^2 I \end{bmatrix} + \begin{bmatrix} C_i^T \\ 0 \end{bmatrix} I [C_i \ 0] < 0 \quad (10)$$

Multiplying the expression (10) by γ^{-1} and using Schur lemma, with $X = \gamma^{-1}X$ and $Q = \gamma^{-1}Q$ we obtain:

$$\begin{bmatrix} \text{sym}\{A_i^T(XE + E^+Q)\} & * & * \\ D_i^T(XE + E^+Q) & -\gamma I & * \\ C_i & 0 & -\gamma I \end{bmatrix} < 0 \quad (11)$$

A second approach has been proposed for the analysis of the stability based on the lemma of elimination. The advantage of this method is that it could be less conservative; it involves a new matrix to add a free weighting matrix useful in the synthesis of control law.

Theorem 4:

The fuzzy descriptor system (6) is admissible and allows a performance H_∞ in external disturbance rejection if and only if there exist a symmetric matrix X , three matrices Q , Z and G and a scalar $\gamma > 0$, such as the following LMI is feasible:

$$EXE^T + \text{sym}\{E^+Z\} > 0$$

$$\text{sym}\{(XE + E^+Q)\} > 0$$

$$\begin{bmatrix} 0 & * & * & * \\ D_i^T(XE + E^+Q) & -\gamma I & * & * \\ C_i & 0 & -\gamma I & * \\ (XE + E^+Q) & 0 & 0 & 0 \end{bmatrix} + \text{sym} \left\{ \begin{bmatrix} A_i^T \\ 0 \\ 0 \\ -I \end{bmatrix} G [I \ 0 \ 0 \ I] \right\} < 0 \quad (12)$$

Proof:

$$\begin{bmatrix} I & 0 & 0 & A_i^T \\ 0 & I & 0 & 0 \\ 0 & 0 & I & 0 \end{bmatrix} \text{ is the orthogonal vector of } \begin{bmatrix} A_i^T \\ 0 \\ 0 \\ -I \end{bmatrix}$$

$$\begin{bmatrix} -I \\ 0 \\ 0 \\ I \end{bmatrix}^T \text{ is the orthogonal vector of } \begin{bmatrix} I \\ 0 \\ 0 \\ I \end{bmatrix}$$

Applying the lemma elimination at (12), we obtain:

$$\begin{cases} \begin{bmatrix} I & 0 & 0 & A_i^T \\ 0 & I & 0 & 0 \\ 0 & 0 & I & 0 \end{bmatrix} \begin{bmatrix} 0 & * & * & * \\ D_i^T(XE + E^+Q) & -\gamma I & * & * \\ C_i & 0 & -\gamma I & * \\ (XE + E^+Q) & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} I & 0 & 0 \\ 0 & I & 0 \\ 0 & 0 & I \end{bmatrix} < 0 \\ \\ \begin{bmatrix} -I & 0 & 0 & I \end{bmatrix} \begin{bmatrix} 0 & * & * & * \\ D_i^T(XE + E^+Q) & -\gamma I & * & * \\ C_i & 0 & -\gamma I & * \\ (XE + E^+Q) & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} I \\ 0 \\ 0 \\ I \end{bmatrix} < 0 \\ \\ \Leftrightarrow \begin{cases} \begin{bmatrix} \text{sym}\{A_i^T(XE + E^+Q)\} & * & * \\ D_i^T(XE + E^+Q) & -\gamma I & * \\ C_i & 0 & -\gamma I \end{bmatrix} < 0 \\ \text{sym}\{(XE + E^+Q)\} > 0 \end{cases} \end{cases}$$

It is noted that if a descriptor system defined by the pair (E, A_i) is stable then its dual defined by the pair (E^T, A_i^T) is stable [3].

So we can rewrite the previous theorem also as follows:

Corollary 1

The fuzzy descriptor system (6) is admissible and allows a performance H_∞ in external disturbance rejection if it exists a symmetric matrix X , three matrices Q , Z and G and a scalar $\gamma > 0$, such as the LMI following solvent:

$$EXE^T + \text{sym}\{E^+Z\} > 0$$

$$\text{sym}\{(XE^T + E^+Q)\} > 0$$

$$\begin{bmatrix} 0 & * & * & * \\ D_i^T(XE^T + E^+Q) & -\gamma I & * & * \\ C_i & 0 & -\gamma I & * \\ (XE^T + E^+Q) & 0 & 0 & 0 \end{bmatrix} + \text{sym} \left\{ \begin{bmatrix} A_i^T \\ 0 \\ 0 \\ -I \end{bmatrix} G [I \ 0 \ 0 \ I] \right\} < 0 \quad (13)$$

Let the PDC control law given by the following form:

$$u(t) = \sum_{j=1}^r h_j(z(t)) F_j x(t) \quad (14)$$

Theorem 5:

The fuzzy descriptor system (6) is admissible in closed loop and allows a performance H_∞ in external disturbance rejection if it exists a symmetric matrix X , four matrices Q , G , Z and R_j and a scalar $\gamma > 0$, such as the LMI following solvent:

$$EXE^T + \text{sym}\{E^+Z\} > 0$$

$$\text{sym}\{(XE^T + E^\perp Q)\} > 0$$

$$\begin{bmatrix} \text{sym}\{A_iG+B_iR_j\} & * & * & * \\ D_i^T(XE^T+E^\perp Q) & -\gamma I & * & * \\ C_i & 0 & -\gamma I & * \\ (XE^T+E^\perp Q)+(A_iG+B_iR_j)^T-G & 0 & 0 & -G-G^T \end{bmatrix} < 0 \quad (15)$$

with

$$R_j = F_j G$$

Hence the PDC control law is given by:

$$u(t) = \sum_{j=1}^r h_j(z(t)) R_j G^{-1} x(t)$$

Proof:

We can write the equation (13) in the following form:

$$\begin{bmatrix} 0 & * & * & * \\ D_i^T(XE^T+E^\perp Q) & -\gamma I & * & * \\ C_i & 0 & -\gamma I & * \\ (XE^T+E^\perp Q) & 0 & 0 & 0 \end{bmatrix} + \text{sym} \left\{ \begin{bmatrix} A_i+B_iF_j \\ 0 \\ 0 \\ -I \end{bmatrix} G \begin{bmatrix} I & 0 & 0 & I \end{bmatrix} \right\} < 0$$

$\Leftrightarrow$

$$\begin{bmatrix} 0 & * & * & * \\ D_i^T(XE^T+E^\perp Q) & -\gamma I & * & * \\ C_i & 0 & -\gamma I & * \\ (XE^T+E^\perp Q) & 0 & 0 & 0 \end{bmatrix} + \text{sym} \left\{ \begin{bmatrix} A_iG+B_iR_j & 0 & 0 & A_iG+B_iR_j \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -G & 0 & 0 & -G \end{bmatrix} \right\} < 0$$

$\Leftrightarrow$

$$\begin{bmatrix} \text{sym}\{A_iG+B_iR_j\} & * & * & * \\ D_i^T(XE^T+E^\perp Q) & -\gamma I & * & * \\ C_i & 0 & -\gamma I & * \\ (XE^T+E^\perp Q)+(A_iG+B_iR_j)^T-G & 0 & 0 & -G-G^T \end{bmatrix} < 0$$

V. SIMULATION EXAMPLE

We consider a nonlinear descriptor system given by the set of differential algebraic equations (DAE). The model describes a disk rolling on a surface without slipping Figure (1). The disk is connected to a fixed wall via a nonlinear spring and a linear damper. The spring has a positive coefficient k . The damping coefficient is given by b , which is also positive. The disc radius is denoted by r , its inertia is given by J and its mass is denoted m [6].

Fig. 1. A roller disc

The state vector of this model is then:

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \dot{x}(t) = \begin{bmatrix} 0 & 1 & 0 & 0 \\ \frac{-K}{m(1+x_1^2)} & \frac{-b}{m} & 0 & \frac{1}{m} \\ 0 & 1 & -r & 0 \\ 0 & \frac{-b}{m} & \frac{-K}{m(1+x_3^2)} & \frac{-r^2}{J} + \frac{1}{m} \end{bmatrix} x(t) + \begin{bmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 0 \\ 0 & \frac{-r}{J} \end{bmatrix} u(t) + \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix} d(t)$$

$$y(t) = \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix} x(t)$$

$x_1(t)$: Position of disk center,

$x_2(t)$: The speed of translation of the disk,

$x_3(t)$: The angular speed of the disk,

$x_4(t)$: Contact force between the disc and the surface.

This nonlinear model can be approximated by a multi-model composed of local models defined around three operating points. Multi-models rolling disk representation is given by the following state:

$$E\dot{x}(t) = \sum_{i=1}^3 h_i(z(t)) [A_i x(t) + B_i u(t) + D_i w(t)]$$

$$y(t) = \sum_{i=1}^3 h_i(z(t)) C_i x(t)$$

The numerical values of those matrices are:

$$A_1 = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -2.508 & -0.75 & 0 & 0.025 \\ 0 & 1 & -0.4 & 0 \\ 0 & -0.75 & -4.1329 & -0.075 \end{bmatrix};$$

$$A_2 = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -3.2532 & -0.75 & 0 & 0.025 \\ 0 & 1 & -0.4 & 0 \\ 0 & -0.75 & -2.8267 & -0.075 \end{bmatrix}$$

$$A_3 = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -2.7147 & -0.75 & 0 & 0.025 \\ 0 & 1 & -0.4 & 0 \\ 0 & -0.75 & -3.6904 & -0.075 \end{bmatrix};$$

$$B_i = B = \begin{bmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 0 \\ 0 & -0.125 \end{bmatrix}, D_i = D = \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix}$$

$$E = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}, C_i = C = \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{bmatrix}.$$

The membership functions are defined as follows:

$$h_i(x_3(t)) = \frac{\mu_i(x_3(t))}{\sum_{i=1}^3 \mu_i(x_3(t))}$$

Which are themselves defined by:

$$\mu_1(x_3(t)) = \exp\left(\frac{-1}{2\left(\frac{x_3+5}{2}\right)^2}\right)$$

$$\mu_2(x_3(t)) = \exp\left(\frac{-1}{2\left(\frac{x_3}{2}\right)^2}\right)$$

$$\mu_3(x_3(t)) = \exp\left(\frac{-1}{2\left(\frac{x_3-5}{2}\right)^2}\right)$$

The curves of states evolution $x_1(t)$, $x_2(t)$, $x_3(t)$ and $x_4(t)$ in open loop are given in Fig.2. We note that the state $x_4(t)$ is subjected to a quite important disturbance. Those curves are obtained by using the Matlab Simulink toolbox.

Fig. 2. Curves of states evolution $x_1(t)$, $x_2(t)$, $x_3(t)$ and $x_4(t)$ in open loop.

By solving the LMI (4) and (15) of Theorem 5 using the Matlab toolbox, we obtain:

For simulation, we set: $\gamma = 1.44$

$$X = \begin{bmatrix} 0.8653 & -0.6426 & 0.3596 & 0.0091 \\ -0.6426 & 1.8403 & 0.2750 & 0.2915 \\ 0.3596 & 0.2750 & 0 & 0 \\ 0.0091 & 0.2915 & 0 & 0 \end{bmatrix}$$

$$Q = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1.9320 & -0.0856 \\ 0 & 0 & 0.0856 & 2.9497 \end{bmatrix} 10^3$$

$$G = \begin{bmatrix} 0.0025 & 0.0025 & 0.0012 & -0.0000 \\ -0.0033 & 0.0039 & -0.0021 & 0.0000 \\ -0.0020 & 0.0029 & 1.5417 & -0.1428 \\ 0.0000 & -0.0000 & 0.1215 & 1.2769 \end{bmatrix} 10^3$$

$$R_1 = \begin{bmatrix} 0.0009 & -0.0010 & 0.0001 & -0.0033 \\ 0.0078 & -0.0105 & -4.3218 & 1.6656 \end{bmatrix} 10^4$$

$$R_2 = \begin{bmatrix} 0.0009 & -0.0010 & 0.0001 & -0.0033 \\ 0.0078 & -0.0105 & -4.3218 & 1.6656 \end{bmatrix} 10^4$$

$$R_3 = \begin{bmatrix} 0.0009 & -0.0010 & 0.0001 & -0.0033 \\ 0.0078 & -0.0105 & -4.3218 & 1.6656 \end{bmatrix} 10^4$$

While the feedback gains matrices are given by:

$$F_1 = R_1 G^{-1} = \begin{bmatrix} -1.1036 & -3.4067 & -0.0011 & -0.0256 \\ 1.0383 & -4.8634 & -28.8140 & 9.8222 \end{bmatrix}$$

$$F_2 = R_2 G^{-1} = \begin{bmatrix} -1.1036 & -3.4067 & -0.0011 & -0.0256 \\ 1.0383 & -4.8634 & -28.8140 & 9.8222 \end{bmatrix}$$

$$F_3 = R_3 G^{-1} = \begin{bmatrix} -1.1036 & -3.4067 & -0.0011 & -0.0256 \\ 1.0383 & -4.8634 & -28.8140 & 9.8222 \end{bmatrix}$$

The curves of states evolution $x_1(t)$, $x_2(t)$, $x_3(t)$ and $x_4(t)$ in closed loop with a PDC controller are given in Fig.3. We note that the evolution curves of states are stable.

Fig. 3. Curves of states evolution $x_1(t)$, $x_2(t)$, $x_3(t)$ and $x_4(t)$ in closed loop.

VI. CONCLUSION

In this work, we addressed on the problem of the H_∞ control fuzzy descriptor systems. In the first place, we proposed the stability conditions of fuzzy descriptors systems, formed into strict LMIs. Then, we have developed a H_∞ control law permits the rejection of external disturbances. A simulation example is given to valid our resultants. In future work, we will establish a control law that allows a H_∞ control of uncertain fuzzy descriptor systems

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