Delay-dependent stability criteria for delay differential systems

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***Abstract*—This paper proposes an approach for the stability of delay differential systems. The key features of the approach is that to obtain generalized stability region, a parameterized model transformation with free weighting matrices is introduced. In fact, these techniques lead to generalized and less conservative stability condition that guarantee the wide stability region. The proposed stability conditions are demonstrated with numerical examples. Comparisons with other stability conditions in the literature shows the derived conditions are the more powerful ones to guarantee the widest stability region.**

Keywords— Delay differential Systems, Global asymptotic stability; Time-varying delays; Linear matrix inequality; Neural networks

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I. INTRODUCTION

Time delays are frequently encountered in many practical engineering systems, such as chemical processes, long transmission lines in pneumatic systems [1]-[8]. It has been shown that the presence of a time delay in a dynamical system is often a primary source of instability and performance degradation [9]. Delay-dependent robust stability criteria of uncertain fuzzy systems with state and input delays are presented in [10]. Dynamical systems with distributed time-varying delays have been of considerable interest for the fast few decades. In particular, the interest in stability analysis of various delay differential systems has been growing rapidly due to their successful applications in practical fields such as circuit theory, aircraft stabilization, population dynamics, distributed networks, manual control and so on. Current efforts on the problem of stability of distributed time-varying delays system can be divided into two categories, namely delay independent criteria and delay dependent criteria. Distributed delay systems have been considered in [11]-[14].

The issue of robust asymptotic stability for delay differential systems using Linear Matrix Inequalities (LMI) approach is remains open, which motivates this paper. In this paper, we establish a new LMI condition by using the Lyapunov-Krasovskii functional to guarantee the asymptotic stability of the system concerned. A sufficient condition for the solvability of this problem is proposed in terms of Linear Matrix Inequalities (LMIs) and the validity of this result is checked numerically using the effective LMI control toolbox in MATLAB.

NOTATIONS: Throughout this paper, for a matrix *B* and two symmetric matrices *A* and *C*,

$$\begin{bmatrix} A & B \\ & C \\ & \end{bmatrix}$$

denote the symmetric matrix, where the notation * represents the entries implied by symmetry. A^T and A^{-1} are denotes the matrix transpose and inverse of A respectively. We say $X>0$ for $X \in \Re^n$ means that the matrix X is real symmetric positive definite. $\|\cdot\|$ refers to the Euclidean norm for vectors. And I denotes the identity matrix with appropriate dimensions.

II. MAIN RESULTS

Consider the following delay differential system

$$\dot{x}(t) = -Ax(t) + Bf(x(t)) + Cf(x(t-\tau(t))), \qquad (1)$$

Where $x(t) = [x_1(t), x_2(t), \ldots, x_n(t)]^T \in R^n$ is the neural state vector. The matrices $A = diag\{a_1, a_2, \ldots, a_n\}$ is a diagonal matrix and $a_i > 0, i = 1, \ldots, n,\ B = [b_{ij}]_{n\times n},\ C = [c_{ij}]_{n\times n}$ are the connection weight matrices. Further $f(x(t)) = [f_1(x_1(t)), f_2(x_2(t)), \ldots, f_n(x_n(t))]^T \in R^n$ is the neuron activation function with $f(0)=0$. $\tau(t)$ is the time-varying delay which satisfies

$$0 \le \tau_1 \le \tau(t) \le \tau_2 and\ \dot{\tau}(t) \le d,\ forevery\, t \ge 0,$$

Where τ_1, τ_2 and d are known constants.

The following assumption is made on the neuron activation function.

(A) Each neuron activation functions $g(\cdot)$ in system (1) are bounded and satisfy the following condition

$$0 \le \frac{g_i(x) - g_i(y)}{x-y} \le L_i,$$

Where $L_i\ (i = 1, 2 \ldots, n)$ are some constants and they can be positive. So it is less restrictive than the descriptions on both the sigmoid activations and the Lipschitz type activation functions. Denote $L = diag\{L_1, \ldots, L_n\}$.

Note that the function $f(\cdot)$ satisfies Assumption (A), and we have

$$f^T(x(t))f(x(t)) \le x^T(t)L^T Lx(t).$$

Lemma 2.1 *[15] For any vectors* $x, y \in R^n$, *with* $P > 0$, *the following inequality holds*

$$2x^T y \le x^T P^{-1} x + y^T P y.$$

III. Global stability results

In this section, some sufficient conditions of stability for system (1) are obtained.

Theorem 3.1 Given scalars $\tau_1 > 0, \tau_2 > 0$ and $d > 0$, if there exist symmetric positive definite matrices $P > 0, Q_j > 0, S_i > 0, (i = 1,2,3), (j = 1,\ldots,4)$, and any matrices $N_a, M_a, O_a, N_i, M_i, O_i, (i = 1,2,\ldots,8)$ such that feasible solution exist for the following LMI.

$$\Omega = \begin{bmatrix}
\Omega_{11} & \Omega_{12} & \Omega_{13} & \Omega_{14} & \Omega_{15} & \Omega_{16} & \Omega_{17} & \Omega_{18} & \Omega_{19} & \Omega_{1,10} & \Omega_{1,11} \\
* & \Omega_{22} & \Omega_{23} & \Omega_{24} & \Omega_{25} & \Omega_{26} & \Omega_{27} & \Omega_{28} & \Omega_{29} & \Omega_{2,10} & \Omega_{2,11} \\
* & * & \Omega_{33} & \Omega_{34} & \Omega_{35} & \Omega_{36} & \Omega_{37} & \Omega_{38} & \Omega_{39} & \Omega_{3,10} & \Omega_{3,11} \\
* & * & * & \Omega_{44} & \Omega_{45} & \Omega_{46} & \Omega_{47} & \Omega_{48} & \Omega_{49} & \Omega_{4,10} & \Omega_{4,11} \\
* & * & * & * & \Omega_{55} & \Omega_{56} & \Omega_{57} & \Omega_{58} & \Omega_{59} & \Omega_{5,10} & \Omega_{5,11} \\
* & * & * & * & * & \Omega_{66} & \Omega_{67} & \Omega_{68} & \Omega_{69} & \Omega_{6,10} & \Omega_{6,11} \\
* & * & * & * & * & * & \Omega_{77} & \Omega_{78} & \Omega_{79} & \Omega_{7,10} & \Omega_{7,11} \\
* & * & * & * & * & * & * & \Omega_{88} & \Omega_{89} & \Omega_{8,10} & \Omega_{8,11} \\
* & * & * & * & * & * & * & * & \Omega_{99} & \Omega_{9,10} & \Omega_{9,11} \\
* & * & * & * & * & * & * & * & * & \Omega_{10,10} & \Omega_{10,11} \\
* & * & * & * & * & * & * & * & * & * & \Omega_{11,11}
\end{bmatrix} < 0, \tag{2}$$

$$\Omega_{11} = \Xi_0 - O_1A - A^TO_1 + O_1BL + L^TB^TO_1^T$$

$$\Omega_{12} = O_1CL - A^TO_2^T + L^TB^TO_2^T + PCL - M_1,$$

$$\Omega_{13} = -A^TN_a^T + L^TB^TN_a^T + M_1, \Omega_{14} = -N_1 - A^TO_3^T + L^TB^TO_3^T,$$

$$\Omega_{15} = N_1 - A^TO_4^T + L^TB^TO_4^T, \Omega_{16} = -A^TO_5^T + L^TB^TO_5^T,$$

$$\Omega_{17} = -A^TO_6^T + L^TB^TO_6^T,$$

$$\Omega_{18} = -A^TO_7^T + L^TB^TO_7^T,$$

$$\Omega_{19} = -O_1 - A^TO_8^T + L^TB^TO_8^T, \Omega_{1,10} = N_1, \Omega_{1,11} = M_1,$$

$$\Omega_{22} = -(1-d)Q_1 + O_2CL + L^TC^TO_2^T + X - M_2^T - M_2, \Omega_{23} = L^TC^TO_a^T + M_2 - M_a^T - X,$$

$$\Omega_{24} = -N_2 + L^TC^TO_3^T - M_3^T, \Omega_{25} = N_2 + L^TC^TO_4^T - M_4^T, \Omega_{26} = L^TC^TO_5^T - M_5^T,$$

$$\Omega_{27} = L^TC^TO_6^T - M_6^T, \Omega_{28} = L^TC^TO_7^T - M_7^T,$$

$$\Omega_{29} = -O_2 + L^TC^TO_8^T - M_8^T, \Omega_{2,10} = N_2, \Omega_{2,11} = M_2, \Omega_{33} = M_a + M_a^T + X - Q_4,$$

$$\Omega_{34} = -N_a + M_3^T, \Omega_{35} = M_a + M_4^T, \Omega_{36} = -U_{22}^T + M_5^T, \Omega_{37} = M_6^T, \Omega_{38} = M_7^T,$$

$$\Omega_{39}=-O_a+M_8^T,\Omega_{3,10}=N_a,\Omega_{3,11}=M_a,\Omega_{4,4}=-Q_2-N_3^T-N_3+W,\Omega_{4,5}=N_3-N_4^T-W,$$
$$\Omega_{4,6}=-N_5^T,\Omega_{4,7}=-V_{22}^T-N_6^T,\Omega_{4,8}=-N_7^T,\Omega_{4,9}=-O_3-N_8^T,\Omega_{4,10}=N_3,\Omega_{4,11}=M_3,$$
$$\Omega_{5,5}=N_4^T+N_4+W-Q_3,\Omega_{5,6}=N_5^T,\Omega_{5,7}=N_6^T,\Omega_{5,8}=N_7^T,\Omega_{5,9}=-O_4+N_8^T,$$
$$\Omega_{5,10}=N_4,\Omega_{5,11}=M_4,\Omega_{6,6}=-S_1,\Omega_{6,7}=0,\Omega_{6,8}=0,\Omega_{6,9}=-O_5,\Omega_{6,10}=N_5,\Omega_{6,11}=M_5,$$
$$\Omega_{7,7}=-S_2,\Omega_{7,8}=0,\Omega_{7,9}=-O_6,\Omega_{7,10}=N_6,\Omega_{7,11}=M_6,\Omega_{8,8}=-S_3,\Omega_{8,9}=-O_7,$$
$$\Omega_{8,10}=N_7,\Omega_{8,11}=M_7,\Omega_{9,9}=-O_8^T-O_8,\Omega_{9,10}=N_8,\Omega_{9,11}=M_8,\Omega_{10,10}=-W,\Omega_{10,11}=0,$$
$$\Omega_{11,11}=-X,\Xi_0=-A^TP-PA+Q_1+Q_2+Q_3+Q_4+\tau_a^2S_1+\tau_1^2S_2+\tau_2^2S_3+PBL+L^TB^TP,$$

$\tau_a=\frac{1}{2}(\tau_1+\tau_2)$, for then system (1) is asymptotically stable.

Proof: We use the following Lyapunov functional to derive the stability result .

$$V(t,x(t))=V_1(t,x(t))+V_2(t,x(t))+V_3(t,x(t))+V_4(t,x(t))+V_5(t,x(t))+V_6(t,x(t)), \tag{3}$$

Where

$$V_1(t,x(t))=x^T(t)\,P\,x(t),$$
$$V_2(t,x(t))=\int_{t-\tau(t)}^t x^T(s)\,Q_1\,x(s)ds+\int_{t-\tau_1}^t x^T(s)\,Q_2\,x(s)\,ds+\int_{t-\tau_2}^t x^T(s)\,Q_3x(s)\,ds+\int_{t-\tau_a}^t x^T(s)\,Q_4\,x(s)\,ds,$$
$$V_3(t,x(t))=\tau_a\int_{-\tau_a}^0\int_{t+\beta}^t x^T(s)S_1\,x(s)ds\,d\beta+\tau_1\int_{-\tau_1}^0\int_{t+\beta}^t x^T(s)\,S_2\,x(s)dsd\beta+\tau_2\int_{-\tau_2}^0\int_{t+\beta}^t x^T(s)\,S_3\,x(s)ds\,d\beta,$$
$$V_4(t,x(t))=\begin{bmatrix}x(t)\\ \int_{t-\tau_a}^t x(s)ds\end{bmatrix}^T\begin{bmatrix}U_{11} & U_{12}\\ * & U_{22}\end{bmatrix}\begin{bmatrix}x(t)\\ \int_{t-\tau_a}^t x(s)ds\end{bmatrix},$$
$$V_5(t,x(t))=\begin{bmatrix}x(t)\\ \int_{t-\tau_1}^t x(s)ds\end{bmatrix}^T\begin{bmatrix}V_{11} & V_{12}\\ * & V_{22}\end{bmatrix}\begin{bmatrix}x(t)\\ \int_{t-\tau_1}^t x(s)ds\end{bmatrix},$$
$$V_6(t,x(t))=\begin{bmatrix}x(t)\\ \int_{t-\tau_2}^t x(s)ds\end{bmatrix}^T\begin{bmatrix}W_{11} & W_{12}\\ * & W_{22}\end{bmatrix}\begin{bmatrix}x(t)\\ \int_{t-\tau_2}^t x(s)ds\end{bmatrix}.$$

We can calculate derivative of $V(t)$ along the trajectories of the system (1), then we have .

$$\dot V_1(t,x(t))\le 2x^T(t)P[-Ax(t)+Bf(x(t))+Cf(x(t-\tau(t)))], \tag{4}$$
$$\dot V_2(t,x(t))\le x^T(t)Q_1x(t)-(1-\dot\tau(t))x^T(t-\tau(t))Q_1x(t-\tau(t))+x^T(t)Q_2x(t)+x^T(t)Q_3x(t)$$
$$+x^T(t)Q_4x(t)-x^T(t-\tau_1)Q_2x(t-\tau_1)-x^T(t-\tau_2)Q_3x(t-\tau_2)-x^T(t-\tau_a)Q_4x(t-\tau_a), \tag{5}$$

$$\dot{V}_3(t,x(t)) \le \tau_a^2 x^T(t)S_1x(t) + \tau_1^2 x^T(t)S_2x(t) + \tau_2^2 x^T(t)S_3x(t)$$
$$-\tau_a\int_{t-\tau_a}^{t} x^T(s)S_1\ x(s)\ ds - \tau_1\int_{t-\tau_1}^{t} x^T(s)\ S_2\ x(s)\ ds - \tau_2\int_{t-\tau_2}^{t} x^T(s)\ S_3\ x(s)\ ds, \qquad (6)$$

Thus from, (4)-(7) and using Jensen's inequality [?] in (7)

$$\dot{V}(t,x(t)) \le \xi_4^T(t)\begin{bmatrix} (1,1) & (1,2) & \Xi_3 & \Xi_{13} & \Xi_{23} & \Xi_4 & \Xi_{14} & \Xi_{24} \\ * & (2,2) & \Xi_6 & \Xi_{16} & \Xi_{26} & \Xi_7 & \Xi_{17} & \Xi_{27} \\ * & * & (3,3) & 0 & 0 & \Xi_9 & 0 & 0 \\ * & * & * & (4,4) & 0 & 0 & \Xi_{19} & 0 \\ * & * & * & * & (5,5) & 0 & 0 & \Xi_{29} \\ * & * & * & * & * & (6,6) & 0 & 0 \\ * & * & * & * & * & * & (7,7) & 0 \\ * & * & * & * & * & * & * & (8,8) \end{bmatrix}\xi_4(t),$$

Where

$$(1,1) = \Xi_0 + \Xi_1 + \Xi_{11} + \Xi_{21}, \quad (1,2) = PCL + \Xi_2 + \Xi_{12} + \Xi_{22},$$
$$(2,2) = -(1-d)Q_1 + \Xi_5 + \Xi_{15} + \Xi_{25}, (3,3) = -Q_4 + \Xi_8, (4,4) = -Q_2 + \Xi_{18},$$
$$(5,5) = -Q_3 + \Xi_{28}, (6,6) = -S_1 + \Xi_{10}, (7,7) = -S_2 + \Xi_{20}, (8,8) = -S_3 + \Xi_{30},$$
$$\xi_4^T(t) = [x^T(t)\ x^T(t-\tau(t))\ x^T(t-\tau_a)\ x^T(t-\tau_1)\ x^T(t-\tau_2)(\int_{t-\tau_a}^{t} x(s)ds)^T(\int_{t-\tau_1}^{t} x(s)ds)^T(\int_{t-\tau_2}^{t} x(s)ds)^T].$$

According to Leibniz-Newton formula, for any matrices $N_a, N_i, (i=1,\ldots,8)$, the following equation holds

$$2[x^T(t)\ N_1 + x^T(t-\tau(t))\ N_2 + x^T(t-\tau_1)\ N_3 + x^T(t-\tau_2)\ N_4 + (\int_{t-\tau_a}^{t} x(s)ds)^T N_5$$
$$+(\int_{t-\tau_1}^{t} x(s)ds)^T N_6 + (\int_{t-\tau_2}^{t} x(s)ds)^T N_7 + \dot{x}^T(t)N_8 + x^T(t-\tau_a)\ N_a]$$
$$\times[x(t-\tau_2) - x(t-\tau_1) - \int_{t-\tau_1}^{t-\tau_2}\dot{x}(s)ds] = 0. \qquad (7)$$

It follows from Lemma 2.1 and by Leibniz-Newton formula that

$$-2[x^T(t)\ N_1 + x^T(t-\tau(t))\ N_2 + x^T(t-\tau_1)\ N_3 + x^T(t-\tau_2)\ N_4 + (\int_{t-\tau_a}^{t} x(s)ds)^T N_5$$
$$+(\int_{t-\tau_1}^{t} x(s)ds)^T N_6 + (\int_{t-\tau_2}^{t} x(s)ds)^T N_7 + \dot{x}^T(t)N_8 + x^T(t-\tau_a)\ N_a]\int_{t-\tau_1}^{t-\tau_2}\dot{x}(s)ds$$
$$\le \xi^T(t)\ N\ W^{-1}\ N^T\ \xi(t) + (\int_{t-\tau_1}^{t-\tau_2}\dot{x}(s)ds)^T\ W\ (\int_{t-\tau_1}^{t-\tau_2}\dot{x}(s)ds)$$

$$\leq \xi^T(t)\, N\, W^{-1}\, N^T\, \xi(t) + [x(t-\tau_2) - x(t-\tau_1)]^T\, W\, [x(t-\tau_2) - x(t-\tau_1)], \tag{8}$$

Where

$$\xi^T(t) = [x^T(t)\; x^T(t-\tau(t))\; x^T(t-\tau_a) x^T(t-\tau_1)\; x^T(t-\tau_2)\; (\int_{t-\tau_a}^{t} x(s)ds)^T\; (\int_{t-\tau_1}^{t} x(s)ds)^T (\int_{t-\tau_2}^{t} x(s)ds)^T\; \dot{x}^T(t)$$

$$and N^T = [N_1^T\; N_2^T\; N_a^T\; N_3^T\; N_4^T N_5^T\; N_6^T\; N_7^T\; N_8^T].$$

According to Leibniz-Newton formula, for any matrices $M_a, M_i, (i = 1, \ldots, 8)$, the following equation holds

$$\begin{aligned} &2[x^T(t)\, M_1 + x^T(t-\tau(t))\, M_2 + x^T(t-\tau_1)\, M_3 + x^T(t-\tau_2)\, M_4 + (\int_{t-\tau_a}^{t} x(s)ds)^T M_5 \\ &+ (\int_{t-\tau_1}^{t} x(s)ds)^T M_6 + (\int_{t-\tau_2}^{t} x(s)ds)^T M_7 + \dot{x}^T(t) M_8 + x^T(t-\tau_a)\, M_a] \\ &\times [x(t-\tau_a) - x(t-\tau(t)) - \int_{t-\tau(t)}^{t-\tau_a} \dot{x}(s)ds] = 0. \end{aligned} \tag{9}$$

It follows from Lemma 2.1 and by Leibniz-Newton formula that

$$\begin{aligned} &-2[x^T(t)\, M_1 + x^T(t-\tau(t))\, M_2 + x^T(t-\tau_1)\, M_3 + x^T(t-\tau_2)\, M_4 + (\int_{t-\tau_a}^{t} x(s)ds)^T M_5 \\ &+ (\int_{t-\tau_1}^{t} x(s)ds)^T M_6 + (\int_{t-\tau_2}^{t} x(s)ds)^T M_7 + \dot{x}^T(t) M_8 + x^T(t-\tau_a)\, M_a] \int_{t-\tau(t)}^{t-\tau_a} \dot{x}(s)ds \\ &\leq \xi^T(t)\, N\, W^{-1}\, N^T\, \xi(t) + (\int_{t-\tau_1}^{t-\tau_2} \dot{x}(s)ds)^T\, W\, (\int_{t-\tau(t)}^{t-\tau_a} \dot{x}(s)ds) \end{aligned}$$

$$\leq \xi^T(t)\, M\; X^{-1}\, M^T\, \xi(t) + [x(t-\tau_a) - x(t-\tau(t))]^T\; X\, [x(t-\tau_a) - x(t-\tau(t))], \tag{10}$$

Where $M^T = [M_1^T\; M_2^T\; M_a^T\; M_3^T\; M_4^T M_5^T\; M_6^T\; M_7^T\; M_8^T].$

According to equation (3), for any matrices $O_a, O_i, (i = 1, \ldots, 8)$, the following equation holds

$$\begin{aligned} &2[x^T(t)\, O_1 + x^T(t-\tau(t))\, O_2 + x^T(t-\tau_1)\, O_3 + x^T(t-\tau_2)\, O_4 + (\int_{t-\tau_a}^{t} x(s)ds)^T O_5 \\ &+ (\int_{t-\tau_1}^{t} x(s)ds)^T O_6 + (\int_{t-\tau_2}^{t} x(s)ds)^T O_7 + \dot{x}^T(t) O_8 + x^T(t-\tau_a)\, O_a] \\ &\times [-\dot{x}(t) + \{-Ax(t) + Bf(x(t)) + Cf(x(t-\tau(t)))\}] = 0. \end{aligned} \tag{11}$$

Then, we add the terms on the left sides of equation (8), (10), (12) to $\dot{V}(t)$ and consider the equation (9), (11), we obtain

$$\dot{V}(t) \le \xi^T(t)\,\Omega\,\xi(t).$$

This completes the proof.

IV. NUMERICAL EXAMPLES

Example 1. Consider the system (1) with time varying delays. The model of this system is of the following form:

$$\dot{x}(t) = -Ax(t) + Bf(x(t)) + Wf(x(t-\tau(t))),$$

and

$$A = \begin{bmatrix} 7 & 0 \\ 0 & 5 \end{bmatrix}, \quad B = \begin{bmatrix} -0.3 & -0.2 \\ 0.3 & 0.4 \end{bmatrix},$$

$$C = \begin{bmatrix} -0.5 & 0.7 \\ -0.8 & -1 \end{bmatrix} \quad L = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}.$$

By using the Matlab LMI toolbox, we solve the LMI (3) for $\tau_1 = 0.5, \tau_2 = 1.5$ and $d = 0.5$ the feasible solutions are

$$P = \begin{bmatrix} 0.6632 & 0.0127 \\ 0.0127 & 0.5652 \end{bmatrix},$$

$$Q_1 = \begin{bmatrix} 0.9233 & 0.0815 \\ 0.0815 & 1.3429 \end{bmatrix},$$

$$Q_2 = \begin{bmatrix} 0.8747 & 0.0017 \\ 0.0017 & 0.8365 \end{bmatrix},$$

$$Q_3 = \begin{bmatrix} 0.8742 & 0.0013 \\ 0.0013 & 0.8374 \end{bmatrix},$$

$$Q_4 = \begin{bmatrix} 0.9669 & 0.0036 \\ 0.0036 & 0.9270 \end{bmatrix},$$

$$S_1 = \begin{bmatrix} 0.7560 & 0.0019 \\ 0.0019 & 0.7387 \end{bmatrix},$$

$$S_2 = \begin{bmatrix} 0.7494 & 0.0007 \\ 0.0007 & 0.7477 \end{bmatrix},$$

$$S_3 = \begin{bmatrix} 0.7435 & 0.0025 \\ 0.0025 & 0.6968 \end{bmatrix}$$

Therefore, the concerned system with time-varying delays is asymptotically stable.

CONCLUSION

A new sufficient condition is derived to guarantee the stability of the equilibrium point for fuzzy cellular neural networks with interval time varying delays. A linear matrix inequality approach has been developed to solve the problem addressed. Our results can be easily verified and also less conservative than previously known criteria.

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