Delay-Independent Closed-Loop Stabilization of Neutral System with Infinite Delays
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Abstract—In this paper, the problem of stability and stabilization for neutral delay-differential systems with infinite delay is investigated. Using Lyapunov method, new delay-independent sufficient condition for the stability of neutral systems with infinite delay is obtained in terms of linear matrix inequality (LMI). Memory-less state feedback controllers are then designed for the stabilization of the system using the feasible solution of the resulting LMI, which are easily solved using any optimization algorithms. Numerical examples are given to illustrate the results of the proposed methods.

Keywords—Infinite delays, Lyapunov method, linear matrix inequality, neutral systems, stability.

I. INTRODUCTION

DIFFERENTIAL equations are important model for harnessing different components into a single system and analyse the inter-relationship that exist between these components which otherwise might continue to remain independent of each other [1]. The most commonly encountered models in the theory of differential equations are those physical systems which express the present states of a situation. However, more realistic physical system models take into account the past states or history of the system, otherwise referred to as time delays, as well as the present state of situations.

Differential equations which involve the present as well as the past states are called delay differential equations or functional differential equations. Delay differential equations are of two broad types: retarded functional differential equations and neutral functional differential equations see [1] and references therein. This paper focuses on the later type, in which the derivatives of the past history or derivatives of functional of the past history are involved as well as the present states of the system.

The existence of time delays in a dynamical system has been the source of poor system performances and even instability. Studies involving different time delays can be found in ship stabilization, control processes for pressure, and heat transfer regulation, but, they are sometimes deliberately introduced into feedback systems to improve system performances see [2] and references therein for details.

II. Organization of the Paper

The rest of the paper is organized as follows: Section II contains mathematical notations, preliminaries and definition...
on the subject of research. In Section III, the stability results are presented as theorems and proofs which are based on LMI and the Lyapunov-Krasovskii approach. Section IV contains result derived from stabilization conditions and memory-less state feedback designed for the system using the same methods as in Section III. Finally, Section V contains numerical examples which are an illustration of the design procedure and effectiveness of the theoretical results prior to the conclusions.

II. NOTATIONS AND PRELIMINARIES

A. Notations

Suppose, $h > 0$ is a given number, $E = (-\infty, \infty)$, $E^n$ is a real $n$-dimensional Euclidean space with norm $|\cdot|$. $C C([-h, 0], E^n)$ is the space of continuous function mapping the interval $[-h, 0]$ into $E^n$ with the norm $\|\cdot\|$, where $\|\phi\| = \sup_{-h < s < 0} |\phi(s)|$. I denotes the identity matrix order, and $*$ represents the elements below the main diagonal of a symmetric block matrix.

B. Preliminaries

Consider neutral system

$$\dot{x}(t) - A_0 \dot{x}(t-h) = A_1 x(t) + A_2 x(t-h).$$

This system is based on its extension to neutral functional integrodifferential system with infinite delays of the form

$$\dot{x}(t) - A_0 \dot{x}(t-h) = A_1 x(t) + A_2 x(t-h) + Bu(t) + \int_{-\infty}^{0} G(t, x(t)) dt$$

and its control base system

$$\dot{x}(t) - A_0 \dot{x}(t-h) = A_1 x(t) + A_2 x(t-h) + Bu(t) + \int_{-\infty}^{0} G(t, x(t)) dt$$

where $x(t) \in E^n$ is the state vector, $u(t) \in E^m$ is a control variable, and the following assumptions: $H_0$: $A_0, A_1$, and $A_2$ are $n \times n$ constant matrices, $H_1$: $B$ is an $n \times m$ constant matrix, $H_2$: $G: (-\infty, 0) \times (-\infty, 0) \times \mathcal{C} \rightarrow E^n$ is a continuous matrix function which satisfies $\|G(t, x)\| \leq M(t, s)\|x\|$ for all $(t, s) \in (-\infty, 0) \times \mathcal{C}$, where $\int_{-\infty}^{0} M(s) ds = -l < \infty$.

It is assumed that $G$ satisfy enough smoothness conditions to ensure that a solution of (2) exists through each $(t_0, \phi)$, $t \geq t_0 \geq 0$, is unique, and depends continuously upon $(t_0, \phi)$ and can be extended to the right as long as the trajectory remains in a bounded set $[t_0, \infty) \times \mathcal{C}$. These conditions are given in [4].

**Lemma 1.** For any real vector $D$ and $Z$ with appropriate dimension and any positive scalar $\tau$, then

$$DZ + Z^T D^T \leq \tau DD^T + \tau^{-1} Z^T Z$$

**Proof:** See [17].

**Lemma 2.** The linear matrix inequality

$$\begin{pmatrix} Z(x) & Y(x) \\ Y^T(x) & W(x) \end{pmatrix} > 0$$

is equivalent to $W(x) > 0$, $Z(x) - Y(x) W^{-1}(x) Y^T(x) > 0$, where $Z(x) = Z^T(x)$, $W(x) = W^T(x)$ and $Y(x)$ depend affinely on $x$.

**Proof:** See [18].

III. STABILITY OF NEUTRAL SYSTEM WITH INFINITE DELAYS

Here, a delay-independent criterion for the asymptotic stability of (2) in terms of LMI using the standard Lyapunov-Krasovskii approach will be developed and proved.

**Theorem 1.** The neutral functional integrodifferential system with infinite delays described by (2) is asymptotically stable for all $h \geq 0$ if there exists positive symmetric matrices $P, R > 0$, and some positive scalars $\tau_0, \tau_1, \tau_2 > 0$ which satisfy the following LMI

$$\begin{pmatrix} Z(P, R, \tau_0, \tau_1, \tau_2) \\ Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{pmatrix} = \begin{pmatrix} (2A_2 + 2XA_2^T A_2) & (2A_0 + 2XA_0^T A_0) \\ (2A_2 + 2XA_2^T A_2) & 2A_0^2 \end{pmatrix}$$

$$< 0$$

where,

$$Z_{11} = XA_1^T + A_1 X - 2IX,$$

$$Z_{12} = \begin{pmatrix} XA_1^T \\ \tau_0 XA_1^T \end{pmatrix} \begin{pmatrix} X \end{pmatrix} \begin{pmatrix} 0 \end{pmatrix},$$

$$Z_{22} = \text{diag}(-\tau_0, -\tau_0, -R, -I, -\tau_0 I, -\tau_1 I, -\tau_2 I),$$

**Proof:** Let the Lyapunov function candidate be given by

$$V = V_1 + V_2 + V_3$$

where,

$$V_1 = x^T(t) P x(t), \quad V_2 = \int_{-h}^{0} \dot{x}(t+s) \dot{x}(t+s) ds$$

Taking the derivative of $V$ along the solution of (2) gives

$$\dot{V}_1 = x^T \left( A_1^T P + P A_1 \right) x + 2x^T P A_2 \dot{x} + 2x^T P A_0 \dot{x} + 2x^T P \int_{-\infty}^{0} G(t, x(t)) ds$$

$$\dot{V}_2 = \dot{x}^T \dot{x} - \dot{x}^T \dot{x} = x^T A_1^T A_1 x + x^T A_2^T A_2 x + \dot{x}^T A_0^T A_0 \dot{x} +$$

$$\left( \int_{-\infty}^{0} G(t, x) ds \right) x^T \int_{-\infty}^{0} G(t, x) ds + 2x^T A_1^T A_2 x + 2x^T A_1^T \int_{-\infty}^{0} G(t, x) ds +$$

$$2x^T A_2^T A_0 \dot{x} + 2x^T A_2^T \int_{-\infty}^{0} G(t, x) ds +$$

$$\dot{V}_3 = x^T R x - x^T R x.$$
where \( x, x_h \) and \( \dot{x}_h \) denote \( x(t), x(t-h) \) and \( \dot{x}(t-h) \) respectively. The term \( \int_{-\infty}^{0} G(t, x)ds \) in (6) can be simplified using Jensen’s Inequality\(^{[19]} \) as follows,

\[
\left( \int_{-\infty}^{0} G(t, x)ds \right)^\top \int_{-\infty}^{0} G(t, x)ds \leq \left( \int_{-\infty}^{0} m(s)ds \right)^\top \int_{-\infty}^{0} m(s)ds \times \|x\|^2 \]

Applying Lemma 1 with (8) to the following terms in (5) and (6) gives;

\[
2x^TP\int_{-\infty}^{0} G(t, x)ds \leq -2x^TPlx
\]

(9)

\[
2x^T A^T_1 \int_{-\infty}^{0} G(t, x)ds
\]

\[
\leq \tau_0 x^T A^T_1 A_1 x + \tau_1^{-1} \left( \int_{-\infty}^{0} G(t, x)ds \right)^\top \int_{-\infty}^{0} G(t, x)ds
\]

(10)

\[
\leq \tau_0 x^T A^T_1 A_1 x + \tau_0^{-1}l^2 x^T x
\]

\[
2x^T A^T_0 \int_{-\infty}^{0} G(t, x)ds
\]

\[
\leq \tau_1 x^T A^T_2 A_2 x + \tau_1^{-1} \left( \int_{-\infty}^{0} G(t, x)ds \right)^\top \int_{-\infty}^{0} G(t, x)ds
\]

(11)

\[
\leq \tau_1 x^T A^T_2 A_2 x + \tau_1^{-1}l^2 x^T x
\]

\[
2x^T A^T_0 \int_{-\infty}^{0} G(t, x)ds
\]

\[
\leq \tau_2 x^T A^T_0 A_0 x + \tau_2^{-1} \left( \int_{-\infty}^{0} G(t, x)ds \right)^\top \int_{-\infty}^{0} G(t, x)ds
\]

(12)

\[
\leq \tau_2 x^T A^T_0 A_0 x + \tau_2^{-1}l^2 x^T x
\]

The task here is to ensure that (14) is closed-loop asymptotically stable.

**Theorem 2.** Consider (3) and all its assumptions; if there exists positive symmetric matrices \( P, R > 0 \), some positive scalars \( \tau_4, \ldots, \tau_6 > 0 \) and a positive-definite symmetric matrix \( X \in E^{m \times n} \) which satisfy the following LMI

\[
\begin{bmatrix}
Z_{11} & Z_{12} & Z_{13} & Z_{14} \\
Z_{12}^\top & Z_{22} & Z_{23} & 2A^T_2 A_0 \\
Z_{13}^\top & Z_{23} & Z_{33} & A^T_0 A_0 - I + \tau_2 A^T_0 A_0 \\
Z_{14}^\top & 2A^T_2 A_0 & A^T_0 A_0 - I + \tau_2 A^T_0 A_0 & 0
\end{bmatrix} < 0
\]

(15)

so that,

\[
Z_{11} = XA^T_1 + A_1 X - 2BB^T - 2IX - 2XA^T_1 BB^T + 2BB^T Ix,
\]

\[
Z_{12} = [XA^T_1 BB^T \tau_4 A^T_1 X \tau_5 A^T_1 XLX LX LX LX],
\]

\[
Z_{13} = 2A_2 + 2XA^T_1 A_2 - 2BB^T A_2
\]
\[ Z_{14} = 2A_0 + 2XA_1^TA_0 - 2BB^TA_0 \]
\[ Z_{22} = \text{diag}(-I, -I, -\tau_4I, -R, -I, -\tau_4I, -\tau_6I), \]
\[ Z_{33} = A_1^TA_2 - R + \tau_5A_2^TA_2 \]
where \( X = P^{-1} \). Then, (3) is closed-loop asymptotically stable, and the input \( u(t) = -B^T \) is a controller for (3).

**Proof:** Let the Lyapunov function be given by
\[ V = V_1 + V_2 + V_3 \]
where,
\[ V_1 = x^T(t)Px(t), \quad V_2 = \int_0^t x^T(s + x)ds, \]
and
\[ V_3 = \int_0^t x^T(s + x)ds, \]
Taking the derivative of \( V \) along the solution of (3) gives
\[ \dot{V}_1 = x^T(A_1^TP + PA_1 - 2BB^TP)x + 2x^TPA_1x + 2x^TPA_1\dot{x} + 2x^T(P\int_0^t g(t, x)ds) \]
\[ \dot{V}_2 = x^T \dot{x} - x^T A_1 x + x^T PBB^TPx + x^T A_1^TA_1 x + x^T A_1^TA_2 x + x^T A_1 A_2 x \]
\[ + \int_0^t g(t, x)ds - 2x^T A_1^TA_2 x + 2x^T A_2 \int_0^t g(t, x)ds - 2x^T PBB^TPx \]
\[ \dot{V}_3 = \int_0^t x^T(s + x)ds, \]
Applying Lemma 1 with (8) to the term \( x^T \) gives
\[ \dot{V} = \sum_{i=1}^n \left( \begin{array}{c} \dot{V}_1 \\ \dot{V}_2 \\ \dot{V}_3 \end{array} \right) \]
Using (19) and inequalities (8) – (12), and by replacing the constants \( \tau_0, \tau_2, \tau_6 \) by \( \tau_4, \tau_6, \tau_6 \) respectively, the overall derivative of \( V \) along the solution of (3) can be expressed as
\[ \dot{V} = \sum_{i=1}^n M_i \dot{\lambda}(t), \]
where
\[ M_{11} = A_1^TP + PA_1 - 2BB^TP - 2P + 2A_1^TA_1I + 2PBB^TP \]
\[ M_{12} = 2PA_1 + 2A_1^TA_2 - 2BB^TA_2 \]
\[ M_{22} = A_1^TA_2 - R + \tau_5A_2^TA_2 \]
\[ M_{23} = A_1^TA_2 - R + \tau_5A_2^TA_2 \]
Pre and most multiplying \( M(\cdot) \) by \( \Gamma^{-1} \) and \( \Gamma \), and now using the Schur complement gives \( Z(X, R, \tau_4, \tau_5, \tau_6) \) where
\[ \Gamma = \begin{pmatrix} X & 0 \\ 0 & I \end{pmatrix} \]
It follows then that \( \dot{V} \) is negative definite since \( M(\cdot) < 0 \) is equivalent \( Z(\cdot) < 0 \), which implies that (3) is closed-loop asymptotically stable see [20].

**Remark 1.** The problems in Theorem 1 and 2 are feasibility problems. The solution can be found by solving it in the form of a generalized eigenvalue problem, see [18] for details. In this paper, the solution was found by utilizing the MATLAB’s LMI Control Toolbox [21], which implements interior point algorithm.

**V. NUMERICAL EXAMPLES**

Here, numerical examples will be given to illustrate the proposed methods

**A. Example 1**
Consider the neutral system with infinite delay given by
\[ \dot{x}(t) - A_0 x(t - h) = A_1 x(t) + A_2 x(t - h) + \int_0^t g(t, x(s))ds \]
where, \( A_0 = (0 \ 0.4), A_1 = (-1 \ 0 \ -1), A_2 = \alpha(0 \ 1), \)
\[ G(t, x(t)) = \text{exp}(-3) \sin x(t) \cdot x(t) \]
Note that, the function \( G(t, x) \) satisfies its conditions with
\[ M(t) = -\text{exp}(-3) \cdot \sin x(t); \]
\[ \int_0^t M(t) dt = -\text{exp}(-3)/2 = l = -0.02489. \]
Now the bound of \( \alpha \) for the asymptotic stability for neutral systems without infinite delay as given in Example 2 of [8] is as follows, [22]: \( |\alpha| \leq 0.2 \), [23]: \( |\alpha| \leq 0.2 \), [8]: \( |\alpha| \leq 0.9165 \),
This paper (Theorem 1): \( |\alpha| \leq 23700 \).

The solutions of the LMI (4) for \( \alpha = 23700 \) are given as
\[ \tau_0 = 0.6662, \tau_1 = 0.0066, \tau_2 = 0.0375, X = \begin{pmatrix} 10006 & 0 \\ 0 & 10006 \end{pmatrix}, \]
\[ R = \begin{pmatrix} 9.9862 \times 10^8 & 0 \\ 0 & 9.9862 \times 10^8 \end{pmatrix} \]
It is observed that Theorem 1 gives a less conservative bound of \( \alpha \) than all the proposed methods in [8].

**B. Example 2**
Using (20) with the assumption that the systems matrices are equivalent to
where \( G \) is as defined in Example 1 above. Solving the LMI (15) gives \( \tau_1 = 0.1692, \tau_2 = 257.3315, \tau_3 = 1.5197, X = (0.1011 \ 0) \) and \( R = \begin{pmatrix} 1778 & 0 \\ 0 & 0 \\ 0 & 1778 \end{pmatrix} \).

Therefore the stabilizing feedback controller \( u(t) \) for (20) is

\[
u(t) = -B^T P x(t) = -B^T X^{-1} x(t) = \begin{pmatrix} 9.8949 \\ 9.8949 \end{pmatrix} x(t)\]

**VI. CONCLUSION**

In this paper, new sufficient conditions are derived for the stability and stabilization of neutral systems with infinite delays. The new stability conditions were obtained by using the Lyapunov stability approach which are then expressed in terms of LMI and solved by using the MATLAB's LMI Toolbox. The stabilization of the system was obtained by designating a memory-less state feedback control law which is provided to demonstrate the effectiveness of the new sufficient conditions.

**REFERENCES**


