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Research Article

Novel Stabilization Conditions for Uncertain Singular Systems with Time-Varying Delay

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The problem of delay-dependent robust stabilization for continuously singular time-varying delay systems with norm-bounded uncertainties is investigated in this paper. First, based on some mathematical transform, the uncertain singular system is described in a form which involves the time-delay integral items. Then, in terms of the delay-range-dependent Lyapunov functional and the LMI technique, the improved delay-dependent LMIs-based conditions are established for the uncertain singular systems with time-varying delay to be regular, causal, and stable. Furthermore, by solving these LMIs, an explicit expression for the desired state feedback control law can be obtained; thus, the regularity, causality, and stability of the closed-loop system are guaranteed. In the end, numerical examples are given to illustrate the effectiveness of the proposed methods.

1. Introduction

During the past several decades, singular systems, which are known as descriptor systems, implicit systems, and differential-algebraic systems, received a considerable attention because of their applications in many areas, such as engineering systems, social systems, economic systems, network analysis, biological systems, and time-series analysis [1, 2]. As we all know, it is required to consider not only stability but also regularity and absence of impulses (for continuous singular systems) or causality (for discrete singular systems) simultaneously for singular systems; thus, the study on singular systems is much more complicated than that on the regular ones [3, 4]. Recently, many scholars have applied themselves to the research of singular system and many stability and stabilization conditions have been established for singular systems; see, for example, [5–11] and the references therein.

On the other hand, much attention has been paid to the study of time-delay systems in recent years, because time delays inevitably exist in a variety of practical systems, such as chemical processes, nuclear reactors, and biological systems, and lead to the instability and poor performance of systems [12–15]. Generally speaking, the existing results can be classified into two types: delay-independent results (see, e.g., [16, 17] and the references therein) and delay-dependent results (see, e.g., [18, 19] and the references therein). Furthermore, the delay-independent case is regarded as more conservative than the delay-dependent case, especially when the time delay is comparatively small. Thus, the delay-dependent stability and stabilization conditions for singular time-delay systems have received increasing attention during the past years. For example, by utilizing model transformation and bounding technique for cross-terms, Zhu et al. [20, 21] investigated the delay-dependent robust stabilization problem for uncertain singular time-delay systems. References [22, 23] also discussed the problem, and neither model transformation nor bounding technique for cross-terms is needed in the development of the results. Based on an improved Lyapunov functional, which includes some nonpositive items, Weng and Mao [24] discussed the delay-dependent robust stability and stabilization for uncertain singular time-delay systems, and some LMIs-based results were obtained. However, in the practical systems, most of those delays are time-varying because the external perturbances and uncertainties are always existing [25]. Thus, proposing some time-varying delay-tolerant results for the singular system is obviously more meaningful. In terms of Lyapunov stability theory and LMI technique, some results about the admissibility and dissipativity for discrete-time singular systems with mixed time-varying delays were proposed in [26]. Based on the probability idea, Weng and Mao [27] presented some delay-range-dependent and delay-distribution-independent stability criteria for discrete-time singular systems with time-varying delay, and several sufficient results were obtained. However, to the best of our knowledge, the stabilization conditions for singular time-varying delay systems still have not been fully investigated, and there is still much room for improvement.

This paper is concerned with the problem of robust stabilization for continuously singular time-varying delay systems with norm-bounded and time-varying parametric uncertainties. The focus of this paper is to design a state feedback controller such that the closed-loop system is regular, causal, and stable for all admissible uncertainties. The proposed sufficient robust stabilization conditions of the considered system are described in terms of strict LMIs, which are formulated in terms of all the coefficient matrices of the original system. Finally, numerical examples are provided to demonstrate the effectiveness of the proposed methods.

Notation 1. Throughout this paper, for real matrices X and Y, the notation $X \geq Y$ (resp., $X > Y$) means that the matrix $X-Y$ is semipositive definite (resp., positive definite). I is the identity matrix with appropriate dimensions; a superscript "T" represents transpose. $\|x\|$ refers to the Euclidean norm of the vector x. For a symmetric matrix, $*$ denotes the symmetric terms. $M+M^T$ is denoted as $\{M\}^H$ for simplicity.

2. Problem Formulation and Dynamic Models

Consider an uncertain singular system with time-varying delay described by Wu and Zhou [28]:

$$\begin{aligned} E\dot{x}_{(t)} &= (A+\Delta A)\,x_{(t)} + \left(A_d + \Delta A_d\right) x_{(t-d(t))} + Bu(t), \\ x_{(t)} &= \Phi_{(t)}, \quad t \in \left[-d_2, 0\right], \end{aligned} \tag{1}$$

where $x_{(t)} \in R^n$ is the state variable and $d_{(t)}$ is a time-varying delay satisfying $0 < d_1 \leq d_{(t)} \leq d_2$ and $\dot{d}_{(t)} \leq \mu$. $\Phi_{(t)}$ is a compatible initial value at t. The matrix $E \in R^{n\times n}$ may be singular and rank $E \leq n$ is assumed. A, A_d, and B are real constant matrices with appropriate dimensions. ΔA and ΔA_d are norm-bounded parametric matrices and are assumed to be of the following form:

$$\left[\Delta A \quad \Delta A_d\right] = MF_{(t)}\left[N_1 \quad N_2\right], \tag{2}$$

where $F_{(t)} \in R^{k\times s}$ is an unknown parameter matrix satisfying $F_{(t)}^T F_{(t)} \leq I$. M, N_1, and N_2 are known constant matrices with appropriate dimensions.

The nominal unforced singular time-delay system of (1) can be described as

$$\begin{aligned} E\dot{x}_{(t)} &= Ax_{(t)} + A_d x_{(t-d_{(t)})}, \\ x_{(t)} &= \Phi_{(t)}, \quad t \in \left[-d_2, 0\right]. \end{aligned} \tag{3}$$

The following definitions and lemmas will be used in the proof of the main results.

Definition 1 (see [29]). (i) The pair (E, A) is regular if $\det(SE-A)$ is not identically zero; (ii) the pair (E, A) is said to be impulse free if it is regular and $\deg\{\det(SE-A)\} = \operatorname{rank} E$.

Definition 2 (see [29]). (i) The system (3) is said to be regular and impulse free if $d_{(t)}$ satisfies $0 < d_1 \leq d_{(t)} \leq d_2$; the pair (E, A) is regular and impulse free. (ii) The system (3) is said to be stable if, for any $\varepsilon > 0$, there exists a scalar $\mu(\varepsilon)$, such that, for any compatible initial conditions $\sup_{-d_2 \leq t \leq 0}\|\Phi_{(t)}\|^2 < \mu(\varepsilon)$, when $t > 0$, the solution $x(t)$ of the system (3) satisfies $\|x(t)\| \leq \varepsilon$. Furthermore, $\lim_{t\to 0} x(t) = 0$. (iii) The system (3) is said to be admissible if it is regular, impulse free, and stable.

Definition 3. (i) The uncertain singular time-varying delay system (1) is said to be robustly admissible if the system (1) with $u(t) = 0$ is regular, impulse free, and stable for all admissible uncertainties satisfying (2) and any time-delay $d_{(t)}$ satisfying $0 < d_1 \leq d_{(t)} \leq d_2$. (ii) The singular time-varying delay system (1) is said to be stabilizable if there exists state feedback controller $u(t) = Kx(t)$ such that the closed-loop system is admissible for any time delay $d_{(t)}$ satisfying $0 < d_1 \leq d_{(t)} \leq d_2$. (iii) The uncertain singular time-varying delay system (1) is said to be robustly stabilizable if there exists state feedback controller $u(t) = Kx(t)$ such that the closed-loop system is robustly admissible for all admissible uncertainties satisfying (2) and any time-delay $d_{(t)}$ satisfying $0 < d_1 \leq d_{(t)} \leq d_2$.

After some mathematical transform, the systems (1) and (3) can be described in the following forms:

$$\begin{aligned} E\dot{x}_{(t)} &= \left(A+\Delta A + A_d + \Delta A_d\right) x_{(t)} \\ &\quad - \left(A_d + \Delta A_d\right) \sum_{i=0}^{m-1} \int_{t-((i+1)/m)d_1}^{t-(i/m)d_1} \dot{x}_{(s)} ds \\ &\quad - \left(A_d + \Delta A_d\right) \int_{t-d(t)}^{t-d_1} \dot{x}_{(s)} ds, \\ x_{(t)} &= \Phi_{(t)}, \quad t \in \left[-d_2, 0\right], \end{aligned} \tag{4}$$

$$E\dot{x}_{(t)} = \left(A + A_d\right) x_{(t)} - A_d \sum_{i=0}^{m-1} \int_{t-((i+1)/m)d_1}^{t-(i/m)d_1} \dot{x}_{(s)} ds$$

$$
\begin{aligned}
&- A_d \int_{t-d(t)}^{t-d_1} \dot{x}_{(s)} ds, \\
&x_{(t)} = \Phi_{(t)}, \quad t \in [-d_2, 0].
\end{aligned} \tag{5}
$$

For description in brevity, we define $\gamma = d_1/m$ and $d_{12} = d_2 - d_1$. This section is concluded by presenting a lemma, which will be used in the proof of our main results.

Lemma 4 (see [30, 31]). *Given matrices χ, μ, and ν with appropriate dimensions and with χ symmetrical, then $\chi + \mu F_{(t)} \nu + \nu^T F_{(t)}^T \mu^T < 0$ holds for any $F_{(t)} \in R^{k\times s}$ satisfying $F_{(t)}^T F_{(t)} \le I$, if and only if there exists a scalar $\sigma > 0$ such that $\chi + \sigma\mu\mu^T + \sigma^{-1}\nu^T\nu < 0$.*

3. Main Results

In this section, the delay-dependent conditions for system (1) to be stabilizable and robustly stabilizable are presented. As a basis, we first study system (5) and obtain the following Theorem 5.

Theorem 5. *For the prescribed scalars satisfying $0 < d_1 \le d_2$, the singular time-delay system (5) is admissible for any time-delay $d_{(t)}$ satisfying $0 < d_1 \le d_{(t)} \le d_2$ if there exist positive symmetric matrices P, U_i $(i = 1,2,3,4)$, Q_1, Q_2, matrices H_i $(i = 1,2)$, S_i $(i = 1,2,3,4,5,6,7)$, G_i $(i = 1,2,3,4,5,6,7,8)$, and L_i $(i = 1,2,3,4,5)$ satisfying the following LMIs:*

$$
\Psi_i = \begin{bmatrix}
\Psi_{111} & \Psi_{112} & G_1 & -G_1 & \Psi_{115} & \Psi_{116} & -L_1 + L_2^T & L_5^T \\
* & \Psi_{i22} & G_7 & -G_7 & \Psi_{125} & \Psi_{126} & -L_2^T - L_4 & -L_5^T \\
* & * & \Psi_{133} & \Psi_{134} & \Psi_{135} & \Psi_{136} & G_2^T & G_8^T \\
* & * & * & \Psi_{44} & \Psi_{145} & \Psi_{146} & -G_2^T & -G_8^T \\
* & * & * & * & \Psi_{155} & \Psi_{156} & LS_2^T - L_3 & LS_7^T \\
* & * & * & * & * & \Psi_{166} & -G_2^T - L_2^T & \Psi_{168} \\
* & * & * & * & * & * & \Psi_{i77} & \Psi_{i78} \\
* & * & * & * & * & * & * & \Psi_{i88}
\end{bmatrix} < 0, \quad i = 1, 2, \tag{6}
$$

where $L \in R^{n\times(n-r)}$ is any matrix with full columns and satisfies $E^T L = 0$ and

$$
\begin{aligned}
\Psi_{111} &= U_1 + U_2 + U_3 + U_4 + \{L_1 + H_1(A + A_d)\}^H, \\
\Psi_{112} &= -H_1 A_d - L_1 + L_4^T, \\
\Psi_{116} &= -mH_1 A_d - G_1 - L_1, \\
\Psi_{115} &= E^T P - H_1 + (H_2(A + A_d))^T + S_1 L^T + L_3^T, \\
\Psi_{122} &= -3E^T Q_2 E - L_4 - L_4^T, \\
\Psi_{126} &= -G_7 - L_4, \\
\Psi_{125} &= -(H_2 A_d)^T + S_6 L^T - L_3^T, \\
\Psi_{133} &= -U_1 + \{G_3\}^H, \qquad \Psi_{134} = -G_3 + G_4^T, \\
\Psi_{135} &= S_3 L^T + G_5^T, \qquad \Psi_{136} = -G_3 + G_6^T, \\
\Psi_{144} &= -U_2 - \{G_4\}^H, \qquad \Psi_{145} = S_4 L^T - G_5^T, \\
\Psi_{146} &= -G_4 - G_6^T, \qquad \Psi_{155} = \gamma^2 Q_1 + d_{12}^2 Q_2 - \{H_2\}^H, \\
\Psi_{156} &= -mH_2 A_d + LS_5^T - G_5 - L_3, \\
\Psi_{166} &= -E^T Q_1 E - \{G_6\}^H, \\
\Psi_{168} &= -G_8^T - L_5^T, \\
\Psi_{178} &= -L_5^T + E^T Q_2 E, \\
\Psi_{177} &= -(1-\mu) U_3 - \{L_2\}^H - E^T Q_2 E, \\
\Psi_{188} &= -U_4 - E^T Q_2 E, \\
\Psi_{222} &= -E^T Q_2 E - \{L_4\}^H, \\
\Psi_{277} &= -(1-\mu) U_3 - \{L_2\}^H - 3E^T Q_2 E, \\
\Psi_{278} &= -L_5^T + 3E^T Q_2 E, \\
\Psi_{288} &= -U_4 - 3E^T Q_2 E.
\end{aligned} \tag{7}
$$

Proof. Under the conditions of Theorem 5, it is first shown that the system (5) is regular and impulse free for any time-delay $d_{(t)}$ satisfying $0 < d_1 \le d_{(t)} \le d_2$. Define $H = [I_n \ \ I_n \ \ 0 \ \ 0 \ \ A^T \ \ 0 \ \ 0 \ \ 0]$. Then, by pre- and postmultiplying (6) by H and H^T, respectively, it is possible to obtain

$$
\begin{aligned}
&- E^T Q_2 E + A^T PE + E^T PA + A^T L (S_1 + S_6)^T \\
&+ (S_1 + S_6) L^T A < 0.
\end{aligned} \tag{8}
$$

Since rank $E = r \le n$, there exist two nonsingular matrices $\widetilde{M}$ and $\widetilde{N}$ such that $\widetilde{M} E \widetilde{N} = \left[\begin{smallmatrix} I_r & 0 \\ 0 & 0 \end{smallmatrix}\right]$. Accordingly, denote $\widetilde{M} A \widetilde{N} = \left[\begin{smallmatrix} A_1 & A_2 \\ A_3 & A_4 \end{smallmatrix}\right]$, $\widetilde{N}^T (S_1 + S_6) = \left[\begin{smallmatrix} S_{11} \\ S_{12} \end{smallmatrix}\right]$, $\widetilde{M}^{-T} L = \left[\begin{smallmatrix} 0 \\ L_1 \end{smallmatrix}\right]$, where

$\overline{L}_1 \in R^{(n-r)\times(n-r)}$ is any nonsingular matrix and $I_r \in R^{r\times r}$ is an identity matrix. Then, by pre- and postmultiplying inequalities (8) by $\widetilde{N}^T$and $\widetilde{N}$, respectively, it is possible to obtain

$$\begin{bmatrix} \diamond & \diamond \\ * & S_{12}L_1^T A_4 + A_4^T L_1 S_{12}^T \end{bmatrix} < 0. \tag{9}$$

Here, "$\diamond$" representing the matrix blocks are irrelevant to the following discussion; the real expression of these two variables is omitted here. From (9), it is possible to obtain that

$$S_{12}L_1^T A_4 + A_4^T L_1 S_{12}^T < 0. \tag{10}$$

It can be shown that A_4 is nonsingular. Thus, the pair (E, A) is regular and impulse free [29]; that is to say, system (5) is regular and impulse free.

Then, we are in a position to show that system (5) is stable under the conditions of Theorem 5. Choose a Lyapunov-Krasovskii functional candidate as

$$V(t) = V_1(t) + V_2(t) + V_3(t), \tag{11}$$

where

$$\begin{aligned} V_1(t) &= x_{(t)}^T E^T P E x_{(t)} + \sum_{i=0}^{m-1} \int_{t-i\gamma}^{t} x_{(s)}^T U_1 x_{(s)} ds \\ &\quad + \sum_{i=0}^{m-1} \int_{t-(i+1)\gamma}^{t} x_{(s)}^T U_2 x_{(s)} ds + \int_{t-d_t}^{t} x_{(s)}^T U_3 x_{(s)} ds \\ &\quad + \int_{t-d_2}^{t} x_{(s)}^T U_4 x_{(s)} ds, \end{aligned} \tag{12}$$

$$V_2(t) = \gamma \sum_{i=0}^{m-1} \int_{-\gamma}^{0} \int_{t-i\gamma+\varepsilon}^{t-i\gamma} x_{(s)}^T Q_1 x_{(s)} ds d\varepsilon,$$

$$V_3(t) = d_{12} \int_{-d_2}^{-d_1} \int_{t+\varepsilon}^{t} \dot{x}_{(s)}^T E^T Q_2 E \dot{x}_{(s)} ds d\varepsilon.$$

The derivative of $V(t)$ along the trajectories of (5) satisfies

$$\dot{V}(t) = \dot{V}_1(t) + \dot{V}_2(t) + \dot{V}_3(t), \tag{13}$$

where

$$\begin{aligned} \dot{V}_1(t) &= \dot{x}_{(t)}^T E^T P E x_{(t)} + m x_{(t)}^T U_1 x_{(t)} \\ &\quad - \sum_{i=0}^{m-1} x_{(t-i\gamma)}^T U_1 x_{(t-i\gamma)} + m x_{(t)}^T U_2 x_{(t)} \\ &\quad - \sum_{i=0}^{m-1} x_{(t-(i+1)\gamma)}^T U_2 x_{(t-(i+1)\gamma)} \\ &\quad + x_{(t)}^T U_3 x_{(t)} - (1-\mu) x_{(t-d(t))}^T U_3 x_{(t-d(t))} \\ &\quad + x_{(t)}^T U_4 x_{(t)} - x_{(t-d_2)}^T U_4 x_{(t-d_2)}, \end{aligned}$$

$$\begin{aligned} \dot{V}_2(t) &\le \gamma^2 \dot{x}_{(t)}^T E^T Q_1 E \dot{x}_{(t)} \\ &\quad - \sum_{i=0}^{m-1} \int_{t-(i+1)\gamma}^{t-i\gamma} \dot{x}_{(s)}^T ds E^T Q_1 E \int_{t-(i+1)\gamma}^{t-i\gamma} \dot{x}_{(s)} ds, \end{aligned}$$

$$\begin{aligned} \dot{V}_3(t) &= d_{12}^2 \dot{x}_{(t)}^T E^T Q_2 E \dot{x}_{(t)} \\ &\quad - d_{12} \int_{t-d_{(t)}}^{t-d_1} \dot{x}_{(s)}^T E^T Q_2 E \dot{x}_{(s)} ds \\ &\quad - d_{12} \int_{t-d_2}^{t-d_{(t)}} \dot{x}_{(s)}^T E^T Q_2 E \dot{x}_{(s)} ds \\ &\le d_{12}^2 \dot{x}_{(t)}^T E^T Q_2 E \dot{x}_{(t)} \\ &\quad - \frac{d_{12}}{d_{(t)} - d_1} \int_{t-d_{(t)}}^{t-d_1} \dot{x}_{(s)}^T ds E^T Q_2 E \int_{t-d_{(t)}}^{t-d_1} \dot{x}_{(s)} ds \\ &\quad - \frac{d_{12}}{d_2 - d_{(t)}} \int_{t-d_2}^{t-d_{(t)}} \dot{x}_{(s)}^T ds E^T Q_2 E \int_{t-d_2}^{t-d_t} \dot{x}_{(s)} ds. \end{aligned} \tag{14}$$

We have $-d_{12}/(d_{(t)} - d_1) - d_{12}/(d_2 - d_{(t)}) \le 4$; thus, when $d_1 \le d_{(t)} \le (d_1 + d_2)/2$, it is easy to obtain

$$\begin{aligned} &- \frac{d_{12}}{d_{(t)} - d_1} \int_{t-d_{(t)}}^{t-d_1} \dot{x}_{(s)}^T ds E^T Q_2 E \int_{t-d_{(t)}}^{t-d_1} \dot{x}_{(s)} ds \\ &\quad \le \left(-4 + \frac{d_{12}}{d_2 - d_{(t)}}\right) \int_{t-d_{(t)}}^{t-d_1} \dot{x}_{(s)}^T ds E^T Q_2 E \int_{t-d_{(t)}}^{t-d_1} \dot{x}_{(s)} ds. \end{aligned} \tag{15}$$

By defining $\theta_1(t) = 2 - d_{12}/(d_2 - d_{(t)})$ and according to $d_1 \le d_{(t)} \le (d_1 + d_2)/2$, we have $0 \le \theta_1(t) \le 1$. Thus, based on the convex theory, it is easy to obtain that

$$\begin{aligned} &\left(-4 + \frac{d_{12}}{d_2 - d_{(t)}}\right) \int_{t-d_{(t)}}^{t-d_1} \dot{x}_{(s)}^T ds E^T Q_2 E \int_{t-d_{(t)}}^{t-d_1} \dot{x}_{(s)} ds \\ &\quad - \frac{d_{12}}{d_2 - d_{(t)}} \int_{t-d_2}^{t-d_{(t)}} \dot{x}_{(s)}^T ds E^T Q_2 E \int_{t-d_2}^{t-d_{(t)}} \dot{x}_{(s)} ds \\ &= \left(\frac{1}{2} + \frac{\theta_1(t)}{2}\right) \\ &\quad \times \left(-3 \int_{t-d_{(t)}}^{t-d_1} \dot{x}_{(s)}^T ds E^T Q_2 E \int_{t-d_{(t)}}^{t-d_1} \dot{x}_{(s)} ds \right. \\ &\quad \left. - \int_{t-d_2}^{t-d_{(t)}} \dot{x}_{(s)}^T ds E^T Q_2 E \int_{t-d_2}^{t-d_{(t)}} \dot{x}_{(s)} ds \right) \\ &\quad + \left(1 - \left(\frac{1}{2} + \frac{\theta_1(t)}{2}\right)\right) \end{aligned}$$

$$\times \left(- \int_{t-d_{(t)}}^{t-d_1} \dot{x}_{(s)}^T ds E^T Q_2 E \int_{t-d_{(t)}}^{t-d_1} \dot{x}_{(s)} ds \right.$$
$$\left. -3 \int_{t-d_2}^{t-d_{(t)}} \dot{x}_{(s)}^T ds E^T Q_2 E \int_{t-d_2}^{t-d_{(t)}} \dot{x}_{(s)} ds \right). \tag{16}$$

When $(d_1 + d_2)/2 \le d_{(t)} \le d_2$, we have

$$- \frac{d_{12}}{d_2 - d_{(t)}} \int_{t-d_2}^{t-d_{(t)}} \dot{x}_{(s)}^T ds E^T Q_2 E \int_{t-d_2}^{t-d_{(t)}} \dot{x}_{(s)} ds$$
$$\le \left(-4 + \frac{d_{12}}{d_{(t)} - d_1} \right) \int_{t-d_2}^{t-d_{(t)}} \dot{x}_{(s)}^T ds E^T Q_2 E \int_{t-d_2}^{t-d_{(t)}} \dot{x}_{(s)} ds. \tag{17}$$

By defining $\theta_2(t) = 2 - d_{12}/(d_{(t)} - d_1)$ and according to $(d_1 + d_2)/2 \le d_{(t)} \le d_2$, we have $0 \le \theta_2(t) \le 1$. Based on convex theory, we achieve

$$- \frac{d_{12}}{d_{(t)} - d_1} \int_{t-d_{(t)}}^{t-d_1} \dot{x}_{(s)}^T ds E^T Q_2 E \int_{t-d_{(t)}}^{t-d_1} \dot{x}_{(s)} ds$$
$$+ \left(-4 + \frac{d_{12}}{d_{(t)} - d_1} \right) \int_{t-d_2}^{t-d_{(t)}} \dot{x}_{(s)}^T ds E^T Q_2 E \int_{t-d_2}^{t-d_{(t)}} \dot{x}_{(s)} ds$$
$$= \left(\frac{1}{2} + \frac{\theta_2(t)}{2} \right)$$
$$\times \left(- \int_{t-d_{(t)}}^{t-d_1} \dot{x}_{(s)}^T ds E^T Q_2 E \int_{t-d_{(t)}}^{t-d_1} \dot{x}_{(s)} ds \right.$$
$$\left. -3 \int_{t-d_2}^{t-d_{(t)}} \dot{x}_{(s)}^T ds E^T Q_2 E \int_{t-d_2}^{t-d_{(t)}} \dot{x}_{(s)} ds \right)$$
$$+ \left(1 - \left(\frac{1}{2} + \frac{\theta_2(t)}{2} \right) \right)$$
$$\times \left(-3 \int_{t-d_{(t)}}^{t-d_1} \dot{x}_{(s)}^T ds E^T Q_2 E \int_{t-d_{(t)}}^{t-d_1} \dot{x}_{(s)} ds \right.$$
$$\left. - \int_{t-d_2}^{t-d_{(t)}} \dot{x}_{(s)}^T ds E^T Q_2 E \int_{t-d_2}^{t-d_{(t)}} \dot{x}_{(s)} ds \right). \tag{18}$$

It is easy to obtain $0 \le (1 + \theta_1(t))/2 \le 1$ and $0 \le (1 + \theta_2(t))/2 \le 1$. Then, based on the analysis mentioned above, we can obtain that when $\theta(t)$ satisfies $0 \le \theta(t) \le 1$, there exists

$$- \frac{d_{12}}{d_{(t)} - d_1} \int_{t-d_{(t)}}^{t-d_1} \dot{x}_{(s)}^T ds E^T Q_2 E \int_{t-d_{(t)}}^{t-d_1} \dot{x}_{(s)} ds$$
$$- \frac{d_{12}}{d_2 - d_{(t)}} \int_{t-d_2}^{t-d_{(t)}} \dot{x}_{(s)}^T ds E^T Q_2 E \int_{t-d_2}^{t-d_{(t)}} \dot{x}_{(s)} ds$$
$$\le \theta(t) \left(-3 \int_{t-d_{(t)}}^{t-d_1} \dot{x}_{(s)}^T ds E^T Q_2 E \int_{t-d_{(t)}}^{t-d_1} \dot{x}_{(s)} ds \right.$$
$$\left. - \int_{t-d_2}^{t-d_{(t)}} \dot{x}_{(s)}^T ds E^T Q_2 E \int_{t-d_2}^{t-d_{(t)}} \dot{x}_{(s)} ds \right)$$
$$+ (1 - \theta(t))$$
$$\times \left(- \int_{t-d_{(t)}}^{t-d_1} \dot{x}_{(s)}^T ds E^T Q_2 E \int_{t-d_{(t)}}^{t-d_1} \dot{x}_{(s)} ds \right.$$
$$\left. -3 \int_{t-d_2}^{t-d_{(t)}} \dot{x}_{(s)}^T ds E^T Q_2 E \int_{t-d_2}^{t-d_{(t)}} \dot{x}_{(s)} ds \right). \tag{19}$$

By considering (5), it is obvious that

$$\left(x_{(t)}^T H_1 + \dot{x}_{(t)}^T E^T H_2 \right)$$
$$\times \sum_{i=0}^{m-1} \left((A + A_d) x_{(t)} - m A_d \int_{t-((i+1)/m)d_1}^{t-(i/m)d_1} \dot{x}_{(s)} ds \right.$$
$$\left. - A_d \int_{t-d(t)}^{t-d_1} \dot{x}_{(s)} ds - E \dot{x}_{(t)} \right) = 0. \tag{20}$$

Noting $E^T L = 0$, we obtain

$$2 \sum_{i=0}^{m-1} \left(x_{(t)}^T S_1 + x_{t-d(t)}^T S_2 + x_{t-i\gamma}^T S_3 \right.$$
$$+ x_{t-(i+1)\gamma}^T S_4 + \int_{t-(i+1)\gamma}^{t-i\gamma} \dot{x}_{(s)}^T ds S_5 \tag{21}$$
$$\left. + \int_{t-d_t}^{t-d_1} \dot{x}_{(s)}^T ds S_6 + x_{t-d_2}^T S_7 \right) L^T E \dot{x}_{(t)} = 0.$$

Furthermore, according to the free-weighting-matrix method, we have

$$\left(x_{(t)}^T G_1 + x_{t-d(t)}^T G_2 + x_{t-i\gamma}^T G_3 + x_{t-(i+1)\gamma}^T G_4 \right.$$
$$+ \dot{x}_{(t)}^T E^T G_5 + \int_{t-(i+1)\gamma}^{t-i\gamma} \dot{x}_{(s)}^T ds G_6$$
$$\left. + \int_{t-d_t}^{t-d_1} \dot{x}_{(s)}^T ds G_7 + x_{t-d_2}^T G_8 \right)$$
$$\times \left(x_{(t-i\gamma)} - x_{(t-(i+1)\gamma)} - \int_{t-(i+1)\gamma}^{t-i\gamma} \dot{x}_{(s)} ds \right) = 0,$$

$$\left(x_{(t)}^{T}L_1 + x_{t-d(t)}^{T}L_2 + \dot{x}_{(t)}^{T}E^{T}L_3 + \int_{t-d_t}^{t-d_1}\dot{x}_{(s)}^{T}ds L_4 + x_{t-d_2}^{T}L_5\right) \times \left(x_{(t)} - x_{(t-d_t)} - \int_{t-d_t}^{t-d_1}\dot{x}_{(s)}ds - \sum_{i=0}^{m-1}\int_{t-(i+1)\gamma}^{t-i\gamma}\dot{x}_{(s)}ds\right) = 0. \quad (22)$$

Then, combining manipulations (13)–(22) yields

$$\dot{V}(t) \le \sum_{i=0}^{m-1}\left(\theta(t)\,\xi_{(t)}^{T}\Psi_1\xi_{(t)} + (1-\theta(t))\,\xi_{(t)}^{T}\Psi_2\xi_{(t)}\right), \quad (23)$$

where

$$\xi_{(t)} = \left[x_{(t)}^{T} \quad \int_{t-d_{(t)}}^{t-d_1}\dot{x}_{(s)}^{T}ds \quad x_{t-i\gamma}^{T} \quad x_{t-(i+1)\gamma}^{T} \quad \dot{x}_{(t)}^{T}E^{T} \quad \int_{t-(i+1)\gamma}^{t-i\gamma}\dot{x}_{(s)}^{T}ds \quad x_{(t-d_t)}^{T} \quad x_{(t-d_2)}^{T}\right]^{T}. \quad (24)$$

Then, we can obtain $\dot{V}(t) < 0$ from (6). Thus, we can deduce that

$$\dot{V}(t) \le -\lambda_2\|\zeta_{(t)}\|^2 \le -\lambda_2\|x_{(t)}\|^2, \quad (25)$$

where $\lambda_2 = -\max\{\lambda_{\max}(\Psi_1), \lambda_{\max}(\Psi_2)\} > 0$. Therefore, the system (5) is stable based on Definition (2). This completes the proof. □

Theorem 6. *For the prescribed scalars satisfying $0 < d_1 \le d_2$, the singular system (1) is stabilizable for any time-delay $d_{(t)}$ satisfying $0 < d_1 \le d_{(t)} \le d_2$ if there exist positive symmetric matrices P, U_i $(i = 1,2,3,4)$, Q_1, Q_2 matrices $H_1 = Z^{-1}\left[\begin{smallmatrix}\overline{H}_{111} & 0\\ \overline{H}_{121} & \overline{H}_{22}\end{smallmatrix}\right]Z$, $H_2 = \beta Z^{-1}\left[\begin{smallmatrix}\beta^{-1}\overline{H}_{211} & 0\\ \beta^{-1}\overline{H}_{221} & \overline{H}_{22}\end{smallmatrix}\right]Z$, S_i $(i = 1,2,3,4,5,6,7)$, G_i $(i = 1,2,3,4,5,6,7,8)$, L_i $(i = 1,2,3,4,5)$, $T \in R^{p\times n}$, and scalar β satisfying the following LMIs:*

$$\widetilde{\Psi}_i = \begin{bmatrix} \widetilde{\Psi}_{111} & \Psi_{112} & G_1 & -G_1 & \widetilde{\Psi}_{115} & \Psi_{116} & -L_1 + L_2^{T} & L_5^{T}\\ * & \Psi_{i22} & G_7 & -G_7 & \Psi_{125} & \Psi_{126} & -L_2^{T} - L_4 & -L_5^{T}\\ * & * & \Psi_{133} & \Psi_{134} & \Psi_{135} & \Psi_{136} & G_2^{T} & \Psi_{138}\\ * & * & * & \Psi_{44} & \Psi_{145} & \Psi_{146} & -G_2^{T} & -G_8^{T}\\ * & * & * & * & \Psi_{155} & \Psi_{156} & LS_2^{T} - L_3 & LS_7^{T}\\ * & * & * & * & * & \Psi_{166} & -G_2^{T} - L_2^{T} & \Psi_{168}\\ * & * & * & * & * & * & \Psi_{i77} & \Psi_{i78}\\ * & * & * & * & * & * & * & \Psi_{i88} \end{bmatrix} < 0, \quad i = 1,2, \quad (26)$$

where $L \in R^{n\times(n-r)}$ is any matrix with full columns and satisfies $E^{T}L = 0$, $\overline{H}_{22} \in R^{p\times p}$ is any nonsingular matrix, $Z \in R^{n\times n}$ is any nonsingular constant matrix satisfying $ZB = \begin{bmatrix}0 & B_1^{T}\end{bmatrix}^{T}$, where $B_1 \in R^{p\times p}$ is nonsingular, and $\widetilde{\Psi}_{111} = U_1+U_2+U_3+U_4+\{L_1 + H_1(A + A_d) + BT\}^{H}$, $\widetilde{\Psi}_{115} = (H_2(A + A_d) + \beta BT)^{T} + E^{T}P - H_1 + S_1L^{T} + L_3^{T}$. Then, a suitable state feedback controller is described as $K = (\overline{H}_{22}B_1)^{-1}B_1T$.

Proof. By replacing A with $A + BK$ and choosing $K = (\overline{H}_{22}B_1)^{-1}B_1T$, $H_1 = Z^{-1}\left[\begin{smallmatrix}\overline{H}_{111} & 0\\ \overline{H}_{121} & \overline{H}_{22}\end{smallmatrix}\right]Z$, and $H_2 = \beta Z^{-1}\left[\begin{smallmatrix}\beta^{-1}\overline{H}_{211} & 0\\ \beta^{-1}\overline{H}_{221} & \overline{H}_{22}\end{smallmatrix}\right]Z$, it is easy to obtain $H_1BK = BT$ and $H_2BK = \beta BT$. Thus, we can obtain (6) from LMIs (26). This completes the proof. □

Theorem 7. *For the prescribed scalars satisfying $0 < d_1 \le d_2$, the singular system (1) is robustly stabilizable for any time-delay $d_{(t)}$ satisfying $0 < d_1 \le d_{(t)} \le d_2$ if there exist positive symmetric matrices P, U_i $(i = 1,2,3,4)$, Q_1, Q_2, matrices $H_1 = Z^{-1}\left[\begin{smallmatrix}\overline{H}_{111} & 0\\ \overline{H}_{121} & \overline{H}_{22}\end{smallmatrix}\right]Z$, $H_2 = \beta Z^{-1}\left[\begin{smallmatrix}\beta^{-1}\overline{H}_{211} & 0\\ \beta^{-1}\overline{H}_{221} & \overline{H}_{22}\end{smallmatrix}\right]Z$, S_i $(i = 1,2,3,4,5,6,7)$, G_i $(i = 1,2,3,4,5,6,7,8)$, L_i $(i = 1,2,3,4,5)$, $T \in R^{p\times n}$, and scalars β, $\lambda > 0$ satisfying the following LMIs:*

$$\begin{bmatrix} \widetilde{\Psi}_i & \widetilde{\Pi}_2^{T} & \lambda\widetilde{\Lambda}_2^{T}\\ * & -\lambda I & 0\\ * & * & -\lambda I \end{bmatrix} < 0, \quad i = 1,2, \quad (27)$$

where $\widetilde{\Psi}_1, \widetilde{\Psi}_2$, and L follow the same definitions as in Theorem 6 and $\overline{H}_{22} \in R^{p\times p}$ is any nonsingular matrix, $Z \in R^{n\times n}$ is any nonsingular constant matrix satisfying $ZB = \begin{bmatrix}0 & B_1^{T}\end{bmatrix}^{T}$, where $B_1 \in R^{p\times p}$ is nonsingular, and $\widetilde{\Pi}_2 = \begin{bmatrix}M^{T} & H_1^{T} & 0 & 0 & 0 & M^{T} & H_2^{T} & 0 & 0 & 0\end{bmatrix}$, $\widetilde{\Lambda}_2 = [N_1 + N_2 \quad -N_2 \quad 0 \quad 0 \quad 0 - mN_2 \quad 0 \quad 0]$. Then, a suitable state feedback control law is described as $K = (\overline{H}_{22}B_1)^{-1}B_1T$.

Proof. Replacing A and A_d with $A + \Delta A$ and $A_d + \Delta A_d$, respectively, (26) can be expressed as

$$\widetilde{\Psi}_i + \widetilde{\Lambda}_2^{T}F_{(t)}\widetilde{\Pi}_2 + \widetilde{\Pi}_2^{T}F_{(t)}^{T}\widetilde{\Lambda}_2 < 0, \quad i = 1,2. \quad (28)$$

Table 1: Comparisons of the upper bounds of d_2 with different d_1 of the system without uncertainties.

d_1	0.5	1	1.5	2
[32]	2.9056	2.9073	2.9103	2.9163
[33]	3.0401	3.0416	3.0441	3.0490
[34]	3.0401	3.0416	3.0441	3.0490
Theorem 5	3.0501	3.0540	3.0604	3.0724

By Lemma 4, LMIs (28) hold for any $F_{(t)}$ satisfying $F_{(t)}^T F_{(t)} \le I$ if and only if there exists scalar $\lambda > 0$ such that

$$\widetilde{\Psi}_i + \lambda \widetilde{\Lambda}_2^T \widetilde{\Lambda}_2 + \lambda^{-1} \widetilde{\Pi}_2^T \widetilde{\Pi}_2 < 0, \quad i = 1, 2. \tag{29}$$

Applying the Schur complement, (27) is equivalent to (29). This completes the proof.

□

4. Illustrative Examples

Example 1. Consider that the continuous singular time-varying delay system (5) has the system matrices of $E = \begin{bmatrix} 9 & 3 \\ 6 & 2 \end{bmatrix}$, $A = \begin{bmatrix} -13.1 & -13.7 \\ -15.4 & -23.8 \end{bmatrix}$, and $A_d = \begin{bmatrix} -18.6 & -10.4 \\ -25.2 & -16.8 \end{bmatrix}$. Set $\mu = 0.2$ and select $L = [2 \ \ -3]^T$. For the deferent lower bounds d_1, the upper bounds of d_2 for the system to be admissible are shown in Table 1. It is obvious that the delay-dependent stability results obtained in this paper are better than those in [32–34].

Example 2. Consider that the continuous singular time-varying delay system has the following system matrices [25]:

$$E = \begin{bmatrix} 1 & 1 & 0 \\ 1 & -1 & 1 \\ 2 & 0 & 1 \end{bmatrix}, \qquad A = \begin{bmatrix} 2 & 1 & 1 \\ -1 & 0 & 1 \\ 0.5 & 0 & 1 \end{bmatrix},$$
$$A_d = \begin{bmatrix} -1.5 & 0.5 & -0.8 \\ 1 & 1 & 0.5 \\ 0.7 & 0.5 & 1 \end{bmatrix}, \qquad B = \begin{bmatrix} 1 & 2 \\ 1.5 & 0 \\ 0 & 1 \end{bmatrix}. \tag{30}$$

Set $\mu = 0$ and select $L = [-1 \ \ 1 \ \ 2]^T$; Theorem 5 yields that the system is stable for any constant delay d satisfying $0 \le d \le 5$, which has less conservatism than $0 \le d \le 3.1$ which was obtained in [28]. Then, set $\mu = 0.2$ and select $L = [-1 \ \ 1 \ \ 2]^T$. For any time-varying delay $d_{(t)}$ satisfying $0.5 \le d_{(t)} \le 2$, the LMIs (26) are feasible, and a controller gain law can be obtained as follows:

$$K = \begin{bmatrix} -0.6466 & -0.1275 & -0.2681 \\ 0.2072 & 0.5078 & -0.1450 \end{bmatrix}. \tag{31}$$

Now, we consider the system uncertainties, and the uncertain system matrices have the following forms of $M = [0.4 \ \ 0.3 \ \ 0.1]^T$, $N_1 = [0.2 \ \ 0.4 \ \ 0.5]$, and $N_2 = [0.3 \ \ 0.7 \ \ 0.5]$. Set $\mu = 0.2$ and choose $L = [-1 \ \ 1 \ \ 2]^T$. For any time-varying delay $d_{(t)}$ satisfying $0.5 \le d_{(t)} \le 2$, the LMIs (27) are feasible, and a robust controller can be obtained as

$$K = \begin{bmatrix} -2.2790 & -0.4928 & -0.9442 \\ 0.7654 & 1.6355 & -0.4224 \end{bmatrix}. \tag{32}$$

5. Conclusion

In this research, the robustly delay-dependent stabilization for continuously singular time-varying delay systems with norm-bounded uncertainties is investigated. Based on Lyapunov stability theory and LMI technique, the new delay-dependent LMIs-based conditions are established for the singular time-varying delay system to be regular, impulse free, and stable. By solving these LMIs, the desired state feedback control law can be obtained, and the regularity, causality, and stability of the closed-loop system are guaranteed. Finally, simulation results are given to show the effectiveness of the proposed method.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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