IJARSCT

International Journal of Advanced Research in Science, Communication and Technology

International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal

ISSN: 2581-9429

Volume 6, Issue 2, February 2026

Impact Factor: 8.2

# Global Exponential Stabilization for a Class of Uncertain Nonlinear Systems through a Single Non-Fragile Input Control

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**Abstract:** *In this paper, the robust stabilization for a class of uncertain nonlinear systems with single input is explored. Using time-domain analysis combined with differential and integral inequalities, a non-fragile linear controller is designed to enable the closed-loop system to achieve global exponential stability. Simultaneously, the exponential convergence rate of the proposed systems is precisely calculated. This paper not only presents several numerical simulation examples, but also provides the circuit implementation of the controller to verify and illustrate the correctness and practicality of the main result..*

**Keywords*:*** nonlinear system, uncertain systems, global exponential stabilization, non-fragile control

## I. INTRODUCTION

As we know, the analysis, controller design, and related research of nonlinear systems have been explored and studied in depth in recent years. It is worth mentioning that chaotic systems are highly sensitive to initial conditions, so that they are not easily stabilized. Furthermore, since chaotic systems are nonlinear systems, they are more difficult to analyse and design than linear systems. In recent years, several well-known chaotic systems have been proposed by scholars and have been widely analysed and applied, such as Lorenz system, generalized Lorenz chaotic system, Lü chaotic system, generalized Chen chaotic system, unified chaotic system, and Zhu chaotic system. For related research, applications, and results on chaotic systems; see, for instance, [1]-[11] and the references therein.

On the other hand, since controllers, when implemented in hardware, inevitably contain uncertain parameters of components, non-fragile controllers are better able to reflect real-world conditions. In the past, many scholars have worked on the design of non-fragile controllers for various systems; see, for instance, [12]-[18] and the references therein. Research results show that systems equipped with non-fragile controllers do indeed perform better than those equipped with traditional controllers.

Considering the aforementioned factors and motivations, our team proposes to design a non-fragile, linear, and single controller for a class of uncertain nonlinear control systems encompassing several well-known chaotic systems, enabling the closed-loop system to achieve global exponential stability. Furthermore, we meticulously calculate the exponential convergence rate for the proposed system. We will also provide several numerical simulation results and construct the circuit architecture of the linear controller to verify and demonstrate the correctness and practicality of the main theorems.

## II. DESCRIPTION AND MAIN RESULTS OF UNCERTAIN NONLINEAR SYSTEMS

Terminology and notation

$\Re^n$ the n-dimensional Euclidean space;


DOI: 10.48175/IJARSCT-31250

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
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ISSN: 2581-9429 Volume 6, Issue 2, February 2026 Impact Factor: 8.2

$\|x\|$ the Euclidean norm of the vector $x \in \Re^n$;

$R^{m\times n}$ the set of all real $m$ by $n$ matrices;

$\lambda_{\min}(Q)$ the minimum eigenvalue of the matrix $Q$ with real eigenvalues.

Consider the following uncertain nonlinear control system with only a single and non-fragile input source, whose dynamic equations are as follows:

$$\dot{x}_1 = \Delta a x_1 + \Delta d_1 x_2 + \Delta d_2 x_3 + f_1(x_1, x_2, x_3), \tag{1a}$$

$$\dot{x}_2 = \Delta d_3 x_1 + \Delta d_4 x_2 + \Delta d_5 x_3 + f_2(x_1, x_2, x_3) + u, \tag{1b}$$

$$\dot{x}_3 = \Delta d_6 x_1 + \Delta d_7 x_2 + \Delta b x_3 + f_3(x_1, x_2, x_3), \tag{1c}$$

where $x(t) := [x_1(t) \quad x_2(t) \quad x_3(t)]^T \in \Re^{3\times 1}$ is the state vector, $u \in \Re$ is a non-fragile controller as

$$u = (K + \Delta K)x_2, \tag{1d}$$

where $K$ is the control gain and $\Delta K$ represents the uncertainties. In addition, $f_i$ is nonlinear term with $\Delta f_i(0,0,0) = 0,\ \forall\, i \in \{1,2,3\}$, and $\Delta a,\ \Delta b,\ \Delta d_i$ are uncertain parameters. In order for the above dynamic system to have at least one solution, we assume that $f_1,\ f_2$, and $f_3$ are all continuous functions.

For the uncertain parameters and nonlinear functions of the aforementioned uncertain nonlinear dynamic systems, the following two assumptions are made.

**(A1)** There exist constants $\overline{a}, \underline{a}, \overline{b}, \underline{b}, \overline{K}$, and $\overline{d_i}$ such that

$$-\overline{a} \le \Delta a \le -\underline{a} < 0, \quad -\overline{b} \le \Delta b \le -\underline{b} < 0, \quad |\Delta K| \le \overline{K},$$

$$|\Delta d_i| \le \overline{d_i}, \quad \forall\, i \in \{1,2,3,4,5,6,7\}.$$

**(A2)** There exist positive numbers $\alpha_1, \alpha_2$, and $\alpha_3$ such that

$$\sum_{i=1}^{3} \alpha_i^2 \cdot x_i \cdot f_i(x_1, x_2, x_3) = 0.$$

**Remark 1.** Some well-known chaotic systems are special cases of uncertain nonlinear systems (1) without input; such as the generalized Lorenz chaotic system [10], Lü chaotic system [10], generalized Chen chaotic system [10], unified chaotic system [10], and Zhu chaotic system [11]. Moreover, the above-mentioned chaotic systems also satisfy both assumptions (A1) and (A2).

The global exponential stabilization and exponential convergence rate of uncertain nonlinear control systems (1) are defined as follows.

**Definition 1.** The uncertain nonlinear systems (1) are said to be globally exponentially stable if there exist a control $u$ and positive numbers $\alpha$ and $k$, such that

$$|x_i(t)| \le k \cdot e^{-\alpha t}, \quad \forall\, t \ge 0,\ i \in \{1,2,3\}.$$

In this situation, the positive number $\alpha$ is called exponential convergence rate.

This paper primarily seeks a suitable non-fragile linear controller of (1d) to enable system (1) to achieve global exponential stability. Furthermore, the exponential convergence rate of this system is precisely calculated.

For the sake of brevity, let us define the following parameters:

$$l_1 = \frac{\alpha_1^2 \cdot \overline{d_2} + \alpha_3^2 \cdot \overline{d_6}}{2\alpha_1\alpha_3}, \quad l_2 = \frac{\alpha_1^2 \cdot \overline{d_1} + \alpha_2^2 \cdot \overline{d_3}}{2\alpha_1\alpha_2}, \quad l_3 = \frac{\alpha_2^2 \cdot \overline{d_5} + \alpha_3^2 \cdot \overline{d_7}}{2\alpha_2\alpha_3}. \tag{2}$$

Now we present the main theorem. Essentially, it is derived by using Lyapunov-like theorems and combining differential and integral inequalities to derive the control gain of a non-fragile linear controller as (1d) that guarantees global exponential stability of uncertain systems (1).


DOI: 10.48175/IJARSCT-31250

ISSN: 2581-9429 Volume 6, Issue 2, February 2026 Impact Factor: 8.2

**Theorem 1.** Uncertain nonlinear systems (1) with (A1)-(A2), and supplemented with the control gain

$$K = -\bar{r} - \overline{K} - \overline{d_4} \tag{3}$$

with

$$\bar{r} > \frac{2l_1 l_2 l_3 + l_2^2 \underline{b} + l_3^2 \underline{a}}{\underline{a}\underline{b} - l_1^2}, \tag{4}$$

are globally exponentially stable systems, provided that

$$\underline{a}\underline{b} > l_1^2. \tag{5}$$

Furthermore, the guaranteed exponential convergence rate is given by

$$\lambda_{\min}\left(\begin{bmatrix} \underline{a} & -l_1 & -l_2 \\ -l_1 & \underline{b} & -l_3 \\ -l_2 & -l_3 & \bar{r} \end{bmatrix}\right). \tag{6}$$

**Proof.** Based on (A1), (4), and (5), it is easy to obtain that

$$\det([\underline{a}]) > 0, \quad \det\left(\begin{bmatrix} \underline{a} & -l_1 \\ -l_1 & \underline{b} \end{bmatrix}\right) > 0, \quad \det\left(\begin{bmatrix} \underline{a} & -l_1 & -l_2 \\ -l_1 & \underline{b} & -l_3 \\ -l_2 & -l_3 & \bar{r} \end{bmatrix}\right) > 0.$$

It follows that the matrix of $Q := \begin{bmatrix} \underline{a} & -l_1 & -l_2 \\ -l_1 & \underline{b} & -l_3 \\ -l_2 & -l_3 & \bar{r} \end{bmatrix}$ is positive definite. Let

$$V(x(t)) := \alpha_1^2 \cdot x_1^2(t) + \alpha_2^2 \cdot x_2^2(t) + \alpha_3^2 \cdot x_3^2(t). \tag{7}$$

The time derivative of $V(x(t))$ along the trajectories of uncertain nonlinear systems (1), with (2)-(7), (A1), and (A2), is given by

$$\begin{aligned}
\dot{V}(x(t)) &= 2\alpha_1^2 \cdot x_1\dot{x}_1 + 2\alpha_2^2 \cdot x_2\dot{x}_2 + 2\alpha_3^2 \cdot x_3\dot{x}_3 \\
&= 2\alpha_1^2 x_1(\Delta a x_1 + \Delta d_1 x_2 + \Delta d_2 x_3 + f_1) \\
&\quad + 2\alpha_2^2 x_2[\Delta d_3 x_1 + \Delta d_4 x_2 + \Delta d_5 x_3 + f_2 + (K + \Delta K)x_2] \\
&\quad + 2\alpha_3^2 x_3(\Delta d_6 x_1 + \Delta d_7 x_2 + \Delta b x_3 + f_3) \\
&\le -2\alpha_1^2 \underline{a} x_1^2 + 2\alpha_1^2 \overline{d_1}|x_1||x_2| + 2\alpha_1^2 \overline{d_2}|x_1||x_3| \\
&\quad + 2\alpha_2^2 \overline{d_3}|x_1||x_2| + 2\alpha_2^2 \overline{d_4} x_2^2 + 2\alpha_2^2 \overline{d_5}|x_2||x_3| \\
&\quad + 2\alpha_3^2 \overline{d_6}|x_1||x_3| + 2\alpha_3^2 \overline{d_7}|x_2||x_3| - 2\alpha_3^2 \underline{b} x_3^2 \\
&\quad + 2(\alpha_1^2 x_1 f_1 + \alpha_2^2 x_2 f_2 + \alpha_3^2 x_3 f_3) \\
&\quad + 2\alpha_2^2 x_2(K + \Delta K)x_2 \\
&= -2\alpha_1^2 \underline{a} x_1^2 + 2(\alpha_1^2 \overline{d_1} + \alpha_2^2 \overline{d_3})|x_1||x_2| + 2(\alpha_1^2 \overline{d_2} + \alpha_3^2 \overline{d_6})|x_1||x_3| \\
&\quad + 2\alpha_2^2 \overline{d_4} x_2^2 + 2(\alpha_2^2 \overline{d_5} + \alpha_3^2 \overline{d_7})|x_2||x_3| - 2\alpha_3^2 \underline{b} x_3^2 + 2\alpha_2^2 x_2 K x_2 \\
&\quad + 2\alpha_2^2 x_2 \Delta K x_2 \\
&\le -2\alpha_1^2 \underline{a} x_1^2 + 2(\alpha_1^2 \overline{d_1} + \alpha_2^2 \overline{d_3})|x_1||x_2| + 2(\alpha_1^2 \overline{d_2} + \alpha_3^2 \overline{d_6})|x_1||x_3| \\
&\quad + 2\alpha_2^2 \overline{d_4} x_2^2 + 2(\alpha_2^2 \overline{d_5} + \alpha_3^2 \overline{d_7})|x_2||x_3| - 2\alpha_3^2 \underline{b} x_3^2 - 2\alpha_2^2(\bar{r} + \overline{K} + \overline{d_4})x_2^2 \\
&\quad + 2\alpha_2^2 \overline{K} x_2^2
\end{aligned}$$


DOI: 10.48175/IJARSCT-31250

$$= -2\alpha_1^2 \underline{a} x_1^2 + 2\left(\alpha_1^2 \overline{d_1} + \alpha_2^2 \overline{d_3}\right)|x_1||x_2| + 2\left(\alpha_1^2 \overline{d_2} + \alpha_3^2 \overline{d_6}\right)|x_1||x_3|$$
$$+ 2\left(\alpha_2^2 \overline{d_5} + \alpha_3^2 \overline{d_7}\right)|x_2||x_3| - 2\alpha_3^2 \underline{b} x_3^2 - 2\alpha_2^2 \bar{r} x_2^2$$
$$= -2\left[\alpha_1|x_1| \quad \alpha_3|x_3| \quad \alpha_2|x_2|\right] Q \left[\alpha_1|x_1| \quad \alpha_3|x_3| \quad \alpha_2|x_2|\right]^T$$
$$\le -2\left[\lambda_{\min}(Q)\right] \cdot \left\|\left[\alpha_1|x_1| \quad \alpha_3|x_3| \quad \alpha_2|x_2|\right]\right\|^2$$
$$= -2\left[\lambda_{\min}(Q)\right] \cdot V, \quad \forall\, t \ge 0.$$

Hence, we can further deduce that

$$e^{2[\lambda_{\min}(Q)]t} \cdot \dot{V} + e^{2[\lambda_{\min}(Q)]t} \cdot 2\left[\lambda_{\min}(Q)\right] \cdot V = \frac{d}{dt}\left[e^{2[\lambda_{\min}(Q)]t} \cdot V\right] \le 0, \quad \forall\, t \ge 0.$$

It results that

$$\int_0^t \frac{d}{d\tau}\left[e^{2[\lambda_{\min}(Q)]\tau} \cdot V(x(t))\right] d\tau = e^{2[\lambda_{\min}(Q)]t} \cdot V(x(t)) - V(x(0)) \le \int_0^t 0\, d\tau = 0, \quad \forall\, t \ge 0. \tag{8}$$

According to (7) and (8), it can be readily obtained that

$$\alpha_i^2 x_i^2(t) \le \alpha_1^2 x_1^2(t) + \alpha_2^2 x_2^2(t) + \alpha_3^2 x_3^2(t)$$
$$= V(x(t)) \le e^{-2[\lambda_{\min}(Q)]t} V(x(0)), \ \forall\, t \ge 0, \ i \in \{1,2,3\},$$

As a consequence, we can deduce that

$$|x_i(t)| \le \frac{\sqrt{V(x(0))}}{\alpha_i} \cdot e^{-[\lambda_{\min}(Q)]t} \le \frac{\sqrt{V(x(0))}}{\min_i \{\alpha_1, \alpha_2, \alpha_3\}} \cdot e^{-[\lambda_{\min}(Q)]t}, \quad \forall\, t \ge 0, \ i \in \{1,2,3\}.$$

Thus, the proof is complete.□

**Remark 2.** It is worth mentioning that the proposed controller (1d) is not only linear, but its dimension is also lower than that of the state variables. It should be emphasized that, merely by a single and non-fragile input controller, the global exponential stabilization of the uncertain nonlinear systems (1) with (A1) and (A2) can be achieved.

## III. COMPUTER SIMULATION RESULTS AND CIRCUIT IMPLEMENTATION

The following examples are offered to show the usefulness of the proposedtheoretical results.

**Example 1.**Consider the uncertain nonlinear systems of (1) with

$$-1 \le \Delta d_i \le 1, \quad \forall\, i \in \{1,2,3,4,5,6,7\}, \tag{9a}$$

$$-4 \le \Delta a \le -2, \quad -3 \le \Delta b \le -1, \quad -1 \le \Delta K \le 1, \tag{9b}$$

$$f_1 = 6x_2x_3^2, \quad f_2 = -5x_1x_3^2, \quad f_3 = -x_1x_2x_3. \tag{9c}$$

By selecting the parameters $\underline{a} = 2$, $\underline{b} = \alpha_1 = \alpha_2 = \alpha_3 = \overline{K} = 1$, and $\overline{d_i} = 1, \forall\, i \in \{1,2,3,4,5,6,7\}$, (A1) and (A2) are evidently satisfied. From (2), one has $l_1 = l_2 = l_3 = 1$. It follows that $\underline{a}\underline{b} = 2 > 1 = l_1^2$ and $\frac{2l_1l_2l_3 + l_2^2\underline{b} + l_3^2\underline{a}}{\underline{a}\underline{b} - l_1^2} = 5$.

Therefore, by Theorem1 with the choice $\bar{r} = 6$, we conclude that the uncertain systems (1)with (9) and $K = -8$, are globally exponentially stable. Moreover, according to (6), the guaranteed exponential convergence rate can be precisely calculated as

$$\alpha = \lambda_{\min}\left(\begin{bmatrix} 2 & -1 & -1 \\ -1 & 1 & -1 \\ -1 & -1 & 7 \end{bmatrix}\right) = 0.06.$$

The state trajectories of the uncontrolled system and the feedback-controlled system are displayed in Figure 1 and Figure 2, respectively. Furthermore, the control signal and the electronic circuit that implements this control law are shown in Figure 3 and Figure4, respectively.

**Example 2.** Consider the uncertain nonlinear systems of (1) with

$$-36 \le \Delta d_1 \le 36, \quad -1 \le \Delta d_i \le 1, \quad \forall\, i \in \{2,6,7\},, \tag{10a}$$

$$-20 \le \Delta d_5 \le 20, \quad -28 \le \Delta d_i \le 28, \quad \forall\, i \in \{3,4\},, \tag{10b}$$

$$-12 \le \Delta a \le -10, \quad -\frac{14}{3} \le \Delta b \le -\frac{8}{3}, \quad -1 \le \Delta K \le 1, \tag{10c}$$

$$f_1 = 0, \quad f_2 = -x_1 x_3, \quad f_3 = x_1 x_2. \tag{10d}$$

By selecting the parameters $\underline{a} = 10,\ \underline{b} = \frac{8}{3},\ \alpha_1 = \alpha_2 = \alpha_3 = \overline{K} = 1,\ \overline{d_1} = 36,\ \overline{d_3} = \overline{d_4} = 28,\ \overline{d_5} = 20,$ and $\overline{d_i} = 1,\ \forall\, i \in \{2,6,7\}$, (A1) and (A2) are evidently satisfied. From (2), one has $l_1 = 1, l_2 = 32, l_3 = 10.5$. It results that $\underline{ab} = \frac{80}{3} > 1 = l_1^2$ and $\frac{2l_1 l_2 l_3 + l_2^2 \underline{b} + l_3^2 \underline{a}}{\underline{ab} - l_1^2} = \frac{27031}{154} \approx 175.5$. Therefore, by Theorem1 with the choice $\overline{r} = 176$, we conclude that the uncertain systems (1)with (10) and $K = -205$ , are globally exponentially stable. Moreover, according to (6), the guaranteed exponential convergence rate can be precisely calculated as

$$\alpha = \lambda_{\min}\left(\begin{bmatrix} 10 & -1 & -32 \\ -1 & \frac{8}{3} & -10.5 \\ -32 & -10.5 & 176 \end{bmatrix}\right) = 0.01 .$$

The state trajectories of the uncontrolled system and the feedback-controlled system are displayed in Figure 5 and Figure 6, respectively. Furthermore, the control signal and the electronic circuit that implements this control law are shown in Figure7 and Figure 8, respectively.

**Example 3.** Consider the uncertain nonlinear systems of (1) with

$$-1.5 \le \Delta d_1 \le 1.5, \quad -2.5 \le \Delta d_4 \le 2.5, \quad -1 \le \Delta d_i \le 1, \quad \forall\, i \in \{2,3,5,6,7\}, \tag{11a}$$

$$-3 \le \Delta a \le -1, \quad -5.9 \le \Delta b \le -4.9, \quad -1 \le \Delta K \le 1, \tag{11b}$$

$$f_1 = x_2 x_3, \quad f_2 = -x_1 x_3, \quad f_3 = x_1 x_2. \tag{11c}$$

By selecting the parameters $\underline{a} = 1,\ \underline{b} = 4.9,\ \alpha_1 = \alpha_3 = \overline{K} = 1,\ \alpha_2 = \sqrt{2},\ \overline{d_1} = 1.5,\ \overline{d_4} = 2.5,$ and $\overline{d_i} = 1,\ \forall\, i \in \{2,3,5,6,7\}$, (A1) and (A2) are evidently satisfied. From (2), one has $l_1 = 1, l_2 = \frac{7\sqrt{2}}{8}, l_3 = \frac{3\sqrt{2}}{4}$. It results that $\underline{ab} = 4.9 > 1 = l_1^2$ and $\frac{2l_1 l_2 l_3 + l_2^2 \underline{b} + l_3^2 \underline{a}}{\underline{ab} - l_1^2} = \frac{277}{96} \approx 2.9$ . Therefore, by Theorem1 with the choice $\overline{r} = 3$, we conclude that the uncertain systems

(1) with (11) and $K = -6.5$ , are globally exponentially stable. Moreover, according to (6), the guaranteed exponential convergence rate can be precisely calculated as

$$\alpha = \lambda_{\min}\left(\begin{bmatrix} 1 & -1 & \frac{-7\sqrt{2}}{8} \\ -1 & 4.9 & \frac{-3\sqrt{2}}{4} \\ \frac{-7\sqrt{2}}{8} & \frac{-3\sqrt{2}}{4} & 3 \end{bmatrix}\right) = 0.02 .$$

The state trajectories of the uncontrolled system and the feedback-controlled system are displayed in Figure 9 and Figure 10, respectively. Furthermore, the control signal and the electronic circuit that implements this control law are shown in Figure11 and Figure 12, respectively.

## IV. CONCLUSION

In this paper, the robust stabilization for a class of uncertain nonlinear systems with single input has been explored. Using time-domain analysis combined with differential and integral inequalities, a non-fragile linear controller has been designed to enable the closed-loop system to achieve global exponential stability. Meanwhile, the exponential convergence rate of the proposed systems has been precisely calculated. This paper not only presents several numerical simulation examples, but also provides the circuit implementation of the controller to illustrate and verify the practicality and correctness of the obtained results.

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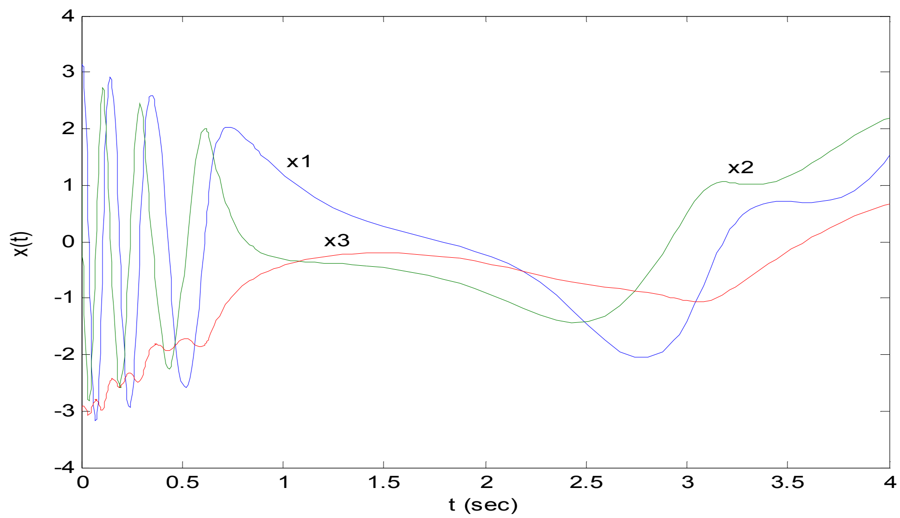


**Figure 1:**The state trajectories of the uncontrolled systems of Example 1.

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 6, Issue 2, February 2026
Impact Factor: 8.2

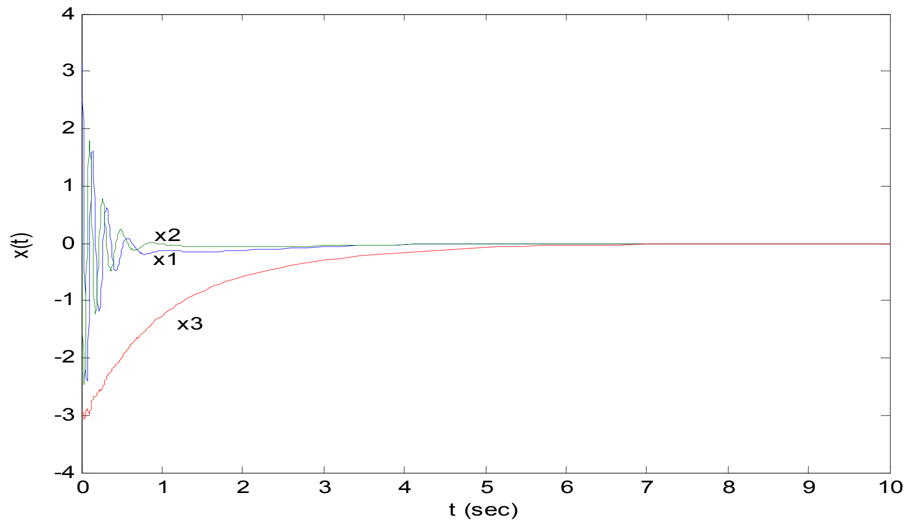


**Figure 2:**The state trajectories of the feedback-controlled systems of Example 1

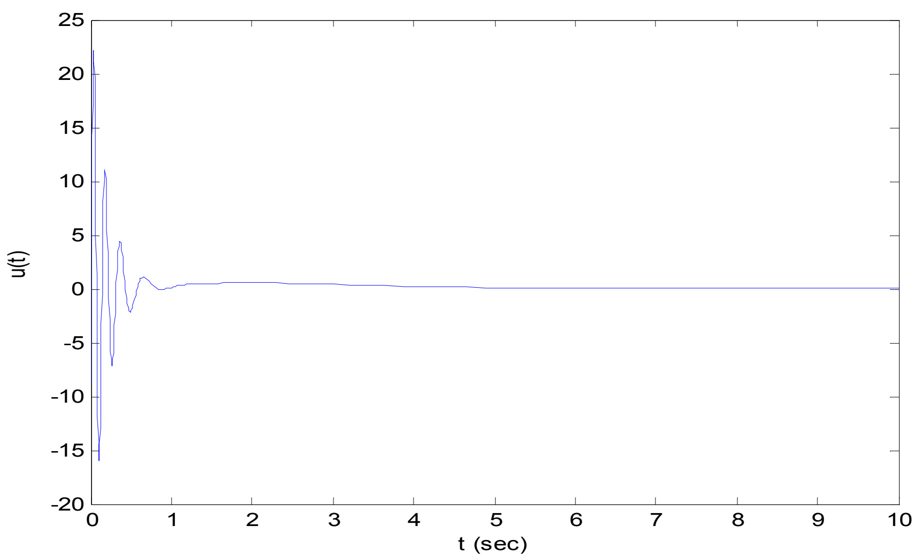


**Figure 3:** Control signal of Example 1.

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International Journal of Advanced Research in Science, Communication and Technology
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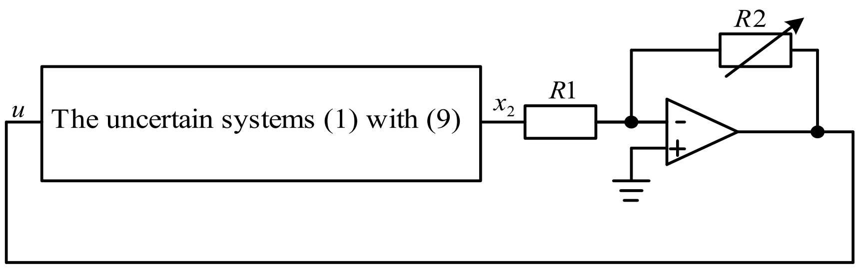


**Figure 4:**The diagram of implementation of Example 1, where $R1 = 10k\Omega$ and $R2 = 80k\Omega$.

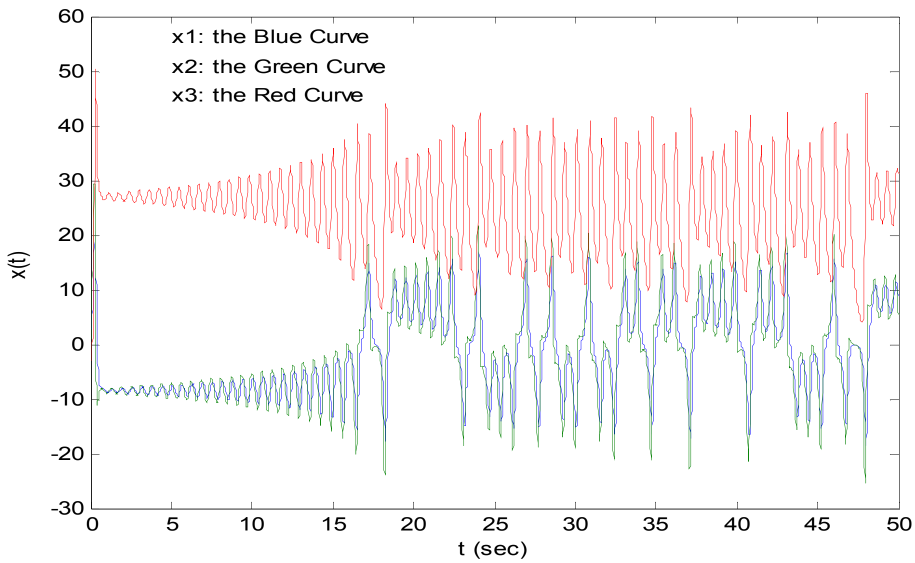


**Figure 5:** The state trajectories of the uncontrolled systems of Example 2.

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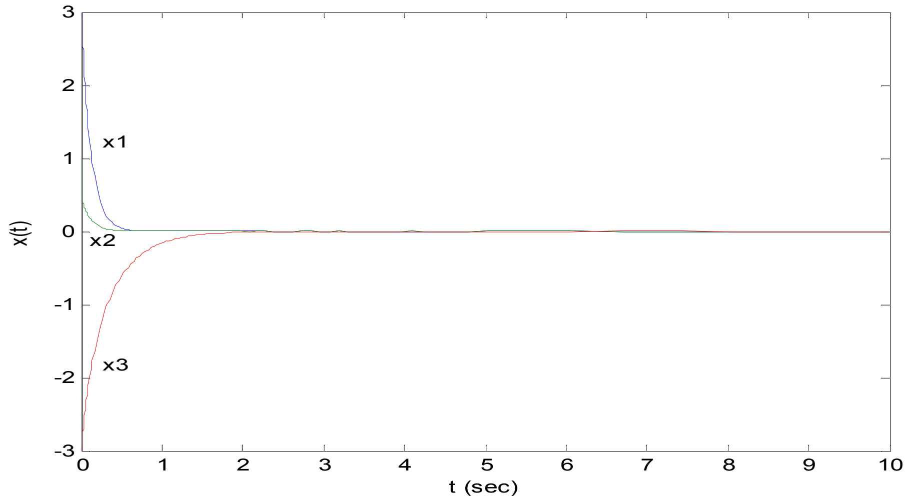


**Figure 6:** The state trajectories of the feedback-controlled systems of Example 2

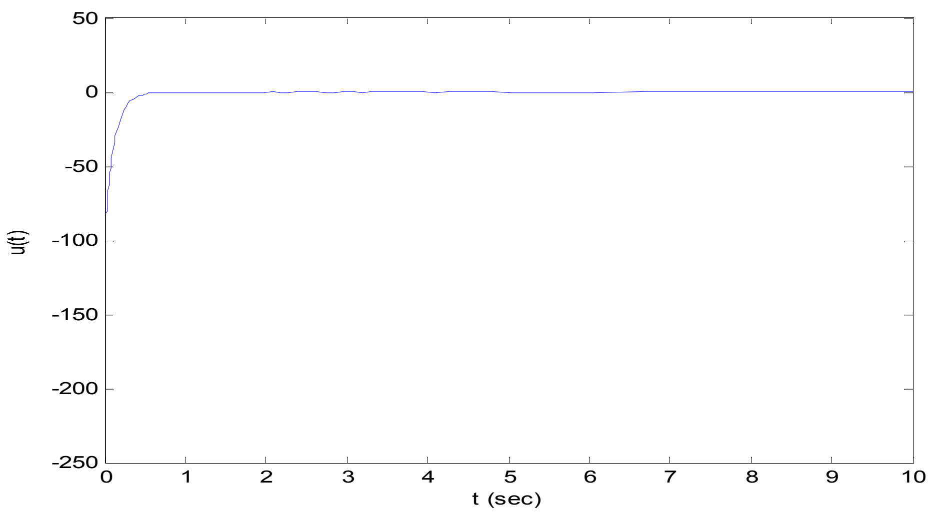


**Figure 7:** Control signal of Example 2.



DOI: 10.48175/IJARSCT-31250

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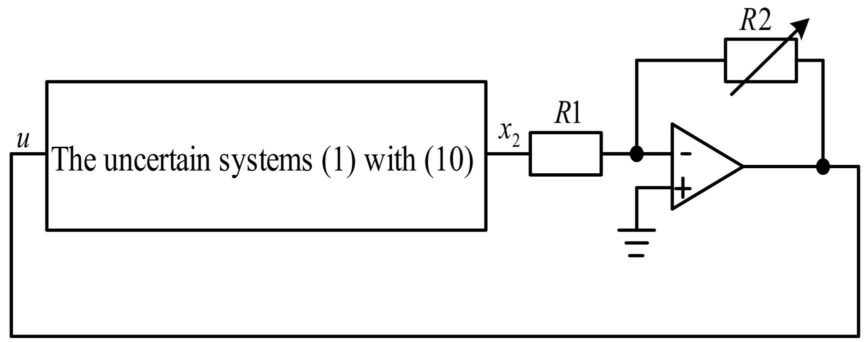


**Figure 8:**The diagram of implementation of Example 2, where $R1 = 1k\Omega$ and $R2 = 205k\Omega$.

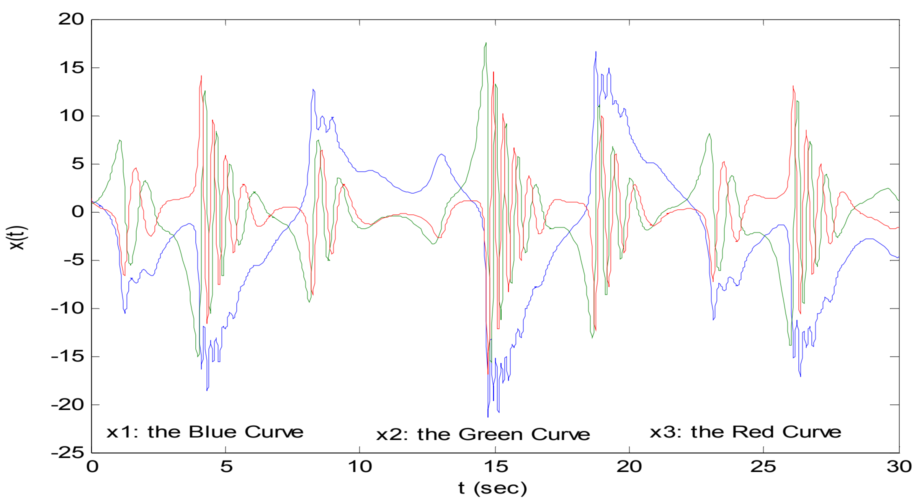


**Figure 9:**The state trajectories of the uncontrolled systems of Example 3.

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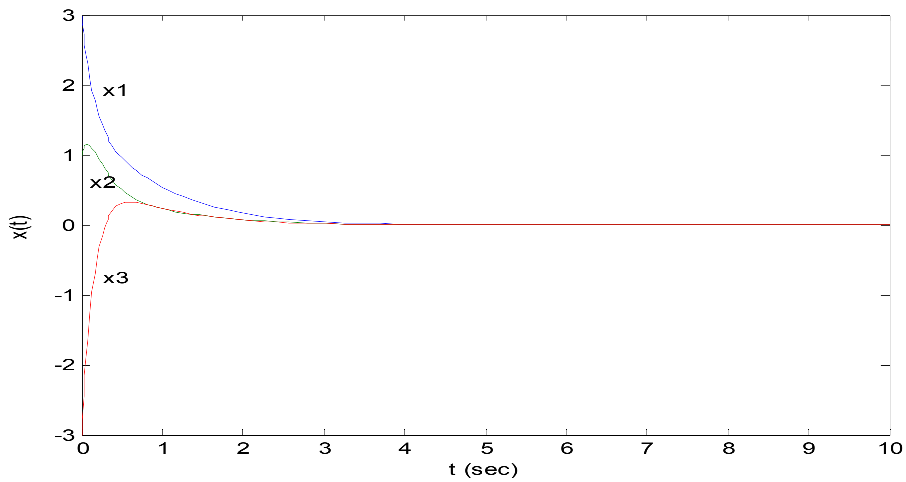


**Figure 10:**The state trajectories of the feedback-controlled systems of Example 3

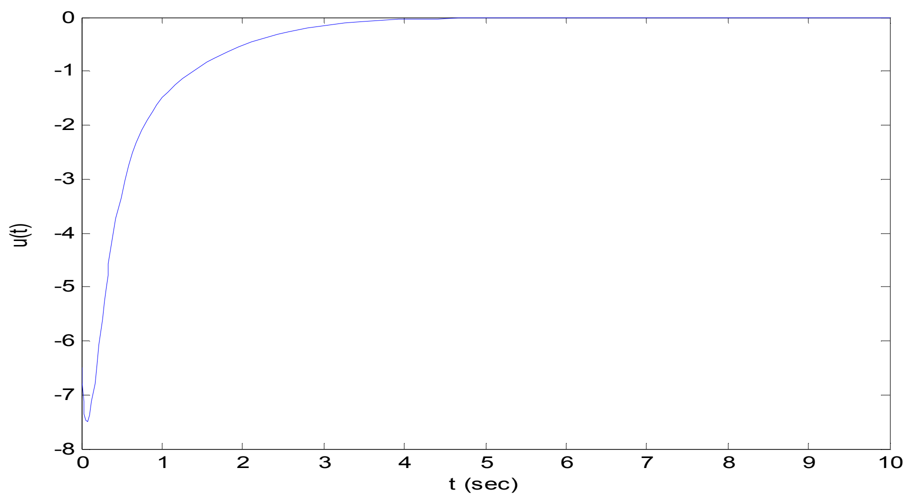


**Figure 11:**Control signal of Example 3.

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Impact Factor: 8.2

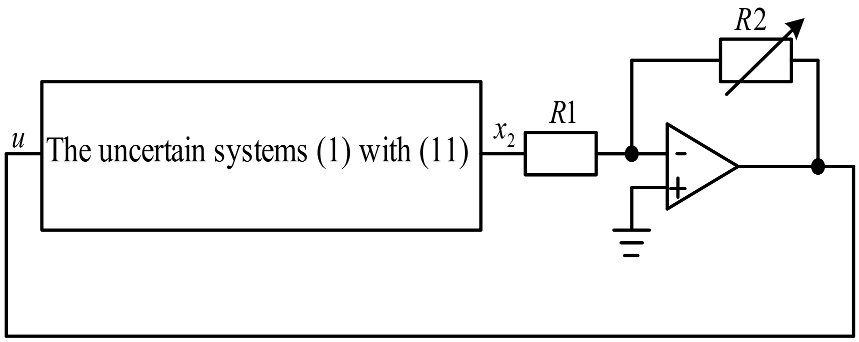


**Figure 12:**The diagram of implementation of Example 3, where $R1 = 1k\Omega$ and $R2 = 6.5k\Omega$.