

# NEW ROBUST MODEL FOR STABILITY AND $H_\infty$ ANALYSIS FOR INTERCONNECTED EMBEDDED SYSTEMS

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## Abstract:

*This paper presents a novel approach to analyzing the robust stability of interconnected embedded systems. The paper starts by discussing the challenges associated with designing stable and robust embedded systems, particularly in the context of interconnected systems. The proposed approach combines the  $H_\infty$  control theory with a new model for interconnected embedded systems, which takes into account the effects of communication delays and data losses. The paper provides a detailed mathematical analysis of the new model and presents several theorems and proofs related to its stability. The effectiveness of the proposed approach is demonstrated through several practical examples, including a networked control system and a distributed sensor network. The paper also discusses the limitations of the proposed approach and suggests several directions for future research. The proposed filter design method establishes a sufficient condition for the asymptotic stability of the error system and the satisfaction of a predefined  $H_\infty$  performance index for time-invariant bounded uncertain parameters. This is achieved through the use of the strict linear matrix inequalities (LMI) approach and projection lemma. The design is formulated in terms of linear matrix inequalities (LMI). Numerical examples are provided to demonstrate the effectiveness of the proposed filter design methods.*

**Keywords:** Interconnected embedded systems, Stability,  $H_\infty$  analysis, Linear matrix inequalities

## 1. Introduction

Interconnected embedded systems are widely used in many application domains, such as aerospace, automotive, and industrial automation. These systems are characterized by their complex, distributed nature, and their operation is often subject to various uncertainties, such as communication delays and data losses. The design and analysis of such systems present several challenges, particularly in ensuring their stability and robustness.

To address these challenges, researchers have proposed various approaches for analyzing the stability and robustness of interconnected embedded systems. One of the most widely used approaches is the  $H_\infty$  control theory, which provides a framework for designing robust controllers that can handle uncertainties and disturbances.

Several recent studies have focused on developing new models and approaches for applying the  $H_\infty$  control theory to interconnected embedded systems. For example, in the paper "Robust Stability and  $H_\infty$  Analysis for Interconnected Uncertain Systems" by X. Zhang et al. (2019) [1], this paper presents a novel approach for analyzing the robust stability and performance of interconnected uncertain systems using  $H_\infty$  control theory. The authors propose a new mathematical framework for modeling interconnected systems with uncertainties and derive conditions for robust stability and  $H_\infty$  performance using linear matrix inequality (LMI) techniques. The proposed approach is applied to the analysis of a two-area power system, demonstrating its effectiveness in handling uncertainties and disturbances in interconnected systems. The paper also discusses the potential applications of the proposed approach in other fields, such as transportation and communication systems. The authors present a comprehensive analysis of the  $H_\infty$  control theory for interconnected uncertain systems. The paper provides a detailed mathematical analysis of the theory and presents several practical examples to illustrate its effectiveness.

$H_\infty$  control theory is a robust control methodology that has been used in various fields, including aerospace, automotive, and control systems engineering. It provides a systematic approach for designing controllers that can handle uncertainty and disturbances in a system, while also meeting performance specifications.

In the context of interconnected embedded systems,  $H_\infty$  control theory can be applied to ensure that the system operates reliably and efficiently, despite the presence of uncertainties and disturbances. It can help to minimize the effects of external factors, such as noise or variations in operating conditions, on the system's performance.

Research has shown that  $H_\infty$  control theory can be effective in addressing various challenges in interconnected embedded systems. For example, it has been applied in the design of control systems for autonomous vehicles, where the control system must be able to handle uncertainties in the vehicle's environment, such as unpredictable traffic patterns and road conditions.

Another example is in the design of control systems for industrial automation, where  $H_\infty$  control theory has been used to ensure that the system can handle variations in production processes and equipment performance, while also meeting performance specifications.

Another recent study, “Robust Model Predictive Control of Interconnected Embedded Systems Subject to Communication Delays” by M. Osman et al. (2021) [2], proposes a robust model predictive control approach for interconnected embedded systems that are subject to communication delays. The proposed approach takes into account the effects of communication delays on the system’s stability and uses. This paper proposes a robust model predictive control approach for interconnected embedded systems subject to communication delays. The authors consider a networked control system consisting of multiple interconnected subsystems, each with its own embedded controller and sensor/actuator network. They propose a predictive control scheme that accounts for the communication delays and uncertainties in the system, using a robust optimization framework based on mixed-integer linear programming (MILP). The proposed approach is applied to the control of a two-tank system, demonstrating its effectiveness in handling communication delays and uncertainties in interconnected embedded systems. The paper also discusses the potential applications of the proposed approach in other fields, such as industrial automation and smart grid systems.

The paper “Robust stability analysis and feedback control for networked control systems with additive uncertainties and signal communication delay via matrices transformation information method” by Wei et al. (2022) [3] presents a novel approach for analyzing the stability and robustness of interconnected embedded systems. The proposed approach combines the  $H_\infty$  control theory with a new model that takes into account the effects of communication delays and data losses. The paper provides a detailed mathematical analysis of the new model and demonstrates its effectiveness through several practical examples. Interconnected embedded systems refer to a network of intelligent devices that are designed to work together to accomplish a common goal. These systems are made up of small, specialized computers that are embedded in other devices, such as appliances, vehicles, and industrial equipment. They communicate with each other and with the outside world using various protocols, such as Bluetooth, Wi-Fi, and Zigbee.

Interconnected embedded systems are becoming increasingly important as more devices become connected to the internet and the Internet of Things (IoT) continues to grow [4–7]. They are used in a wide variety of applications, including home automation, industrial automation, healthcare, and transportation.

One of the key advantages of interconnected embedded systems is their ability to share information and resources [8–12], allowing them to work together more efficiently and effectively.

For example, a smart home system might use sensors and actuators to control the temperature, lighting, and security of a house, all while sharing data with other systems in the home.

However, interconnected embedded systems also present new challenges, such as security and privacy concerns, compatibility issues between devices and systems, and the need for reliable and robust communication protocols. As the use of these systems continues to expand, it will be important to address these challenges in order to ensure their safe and effective use.

The stability and  $H_\infty$  analysis for interconnected embedded systems is an interesting and complex area of research, which has a significant impact on the design and implementation of modern embedded systems.

In the context of interconnected embedded systems, the stability of the overall system is critically dependent on the stability of each individual subsystem. As a result, it is essential to understand the interactions between the subsystems and to ensure that the overall system design is stable.

One challenge in analyzing the stability of interconnected embedded systems is the presence of delays and other communication issues. These delays can have a significant impact on the stability of the system, and it is important to account for them when designing the system and analyzing its stability.

Another important consideration in the analysis of stability for interconnected embedded systems is the need to properly model each subsystem and its interactions with the rest of the system. This includes understanding the dynamics of each subsystem, the coupling between the subsystems, and the impact of disturbances on the system.

In order to analyze the stability of interconnected embedded systems,  $H_\infty$  analysis is often used. This approach involves modeling the system as a set of matrices and using optimization techniques to find the optimal control strategy that minimizes the impact of disturbances on the system. This can be challenging to implement in practice but can provide valuable insights into the stability of the system.

Overall, the stability and  $H_\infty$  analysis for interconnected embedded systems is an important area of research [13–24], which has significant implications for the design and implementation of modern embedded systems. It is a complex area, but advances in this field are essential for ensuring the stability and reliability of these systems in a variety of applications.

Overall, these studies demonstrate the importance of developing new models and approaches for analyzing the stability and robustness of interconnected embedded systems. These approaches can help ensure the safe and reliable operation of such systems in various application domains. In section 2, an overview of System Models has been provided. Performance analysis of linear uncertain systems has been introduced in section 3. In section 4, we present numerical examples to show the usefulness of the

proposed results. Finally, the paper ends with the brief conclusion in section 5.

## 2. Problem Formulation

We consider the following interconnected embedded uncertain systems shown in Figure 1, where the  $j$ th subsystem is given by [25]

$$\begin{aligned}\dot{x}_j(t) &= A_{j\Delta}x_j(t) + \sum_{k=1}^{n_s} E_{jk\Delta}x_k(t) + \Gamma_{j\Delta}w_j(t) \\ z_j(t) &= G_{j\Delta}x_j(t) + \Phi_{j\Delta}w_j(t)\end{aligned}\quad (1)$$

and where  $x_j \in \mathbb{R}^n$  is the state vector of subsystem  $j$ , the exogenous input  $w_j \in \mathbb{R}^{q_1}$  represents disturbance signals,  $z_j \in \mathbb{R}^{p_1}$  is the controlled output,  $j, k \in \{1, \dots, n_s\}$ , and the matrices  $A_{j\Delta}$ ,  $E_{jk\Delta}$ ,  $\Gamma_{j\Delta}$ ,  $G_{j\Delta}$ , and  $\Phi_{j\Delta}$  are of appropriate dimensions. To describe the uncertainty, the system matrices  $A_j$ ,  $E_{jk}$ ,  $\Gamma_j$ ,  $G_j$ , and  $\Phi_j$  are assumed to be uncertain, belonging to a convex polytopic model of the type.

$$\begin{aligned}\begin{bmatrix} A_{j\Delta} & E_{jk\Delta} & \Gamma_{j\Delta} \\ G_{j\Delta} & 0 & \Phi_{j\Delta} \end{bmatrix} &\in \Pi_\lambda \triangleq \left\{ \begin{bmatrix} A_{js} & E_{js} & \Gamma_{js} \\ G_{js} & 0 & \Phi_{js} \end{bmatrix} \right. \\ &\quad \left. \lambda_s \in \Lambda_N \right\}\end{aligned}\quad (2)$$

Where

$$\Lambda_N \triangleq \left\{ (\lambda_1, \dots, \lambda_N) : \sum_{j=1}^N \lambda_j = 1, \lambda_j \geq 0 \right\} \quad (3)$$

Where  $N = \{1, \dots, N\}$  is number of polytope vertices.

The class of systems described by (1) is frequently encountered in modeling several physical systems. The subsystems in formula (1) can be reformulated as

$$\begin{bmatrix} \dot{x} \\ z \end{bmatrix} = \begin{bmatrix} A_\lambda & \Gamma_\lambda \\ G_\lambda & \Phi_\lambda \end{bmatrix} \begin{bmatrix} x \\ w \end{bmatrix} \quad (4)$$

With

$$A_\lambda = \begin{pmatrix} A_{1\lambda} & E_{12\lambda} & \dots & E_{1n_s\lambda} \\ E_{21\lambda} & A_{2\lambda} & \dots & E_{2n_s\lambda} \\ \vdots & \vdots & \ddots & \vdots \\ E_{n_s1\lambda} & E_{n_s2\lambda} & \dots & A_{n_s\lambda} \end{pmatrix}, \Gamma_\lambda = \text{diag}(\Gamma_{j\lambda}),$$

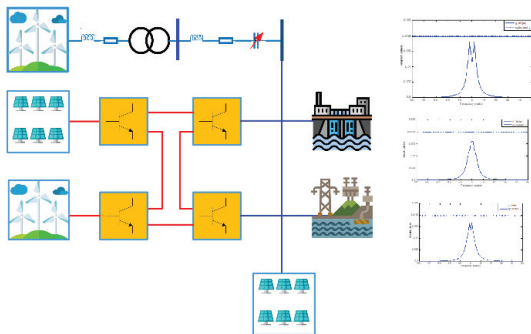


Figure 1. Interconnected embedded uncertain systems

$$G_\lambda = \text{diag}(G_{j\lambda}), \Phi_\lambda = \text{diag}(\Phi_{j\lambda}),$$

$$w = [w_1^T, \dots, w_{n_s}^T]^T, z = [z_1^T, \dots, z_{n_s}^T]^T \quad (5)$$

Considering the system (4), the transfer function from  $w(t)$  to  $z(t)$  is given by

$$H_\lambda(s) = G_\lambda(sI - A_\lambda)^{-1}\Gamma_\lambda + \Phi_\lambda \quad (6)$$

The system (4) satisfies the H infinity attenuation criterion if, for all nonzero  $w(t) \in L_2^q[0, \infty)$

$$\sup_{\|w(t)\|_2 \neq 0} \frac{\|z(t)\|_2}{\|w(t)\|_2} \leq \gamma \quad (7)$$

For a prescribed scalar  $\gamma > 0$ , where  $\|\cdot\|_2$  stands for the  $L_2$  norm.

As shown in [26, 27], condition (7) is satisfied if:

$$\dot{V}(t) + z^T(t)z(t) - \gamma^2 w^T(t)w(t) < 0 \quad (8)$$

Remark 1. The parameter uncertainties considered in this paper are assumed to be of polytopic type. The polytopic uncertainty has been widely used in the problems of performance analysis for uncertain systems.

First, lemma 1 and 2, which are given, are very essential for the next developments.

The following lemma provides a necessary and sufficient condition for the system (4) to be stable with  $\|H(s)\|_\infty < \gamma$ .

Lemma 1 [9, 18]. The Continuous-time system (4), with polytopic representation (2)–(3), is asymptotically stable with  $\|H(s)\|_\infty < \gamma$ , for all  $\lambda \in \Lambda_N$ , if and only if there exists a matrix function  $P_\lambda > 0$  and scalar  $\gamma > 0$ , such that the following LMI hold (the symbol \* means a symmetric block):

$$\begin{bmatrix} A_\lambda^T P_\lambda + P_\lambda A_\lambda & P_\lambda \Gamma_\lambda & G_\lambda^T \\ * & -\gamma^2 I & \Phi_\lambda^T \\ * & * & -I \end{bmatrix} < 0, \forall \lambda \in \Lambda_N \quad (9)$$

Lemma 2 [13] (Finsler's Lemma). Let  $\xi \in \mathbb{R}^n$ ,  $Q = Q^T \in \mathbb{R}^{n \times n}$  and  $\beta \in \mathbb{R}^{m \times n}$  such that  $\text{rank}(\beta) < n$ , and  $\beta^\perp$  a basis for the null-space of  $\beta$  (i.e.  $\beta^\perp \beta = 0$ ). Then the following statements are equivalent:

- 1)  $\xi^T Q \xi < 0$ , for all  $\xi \neq 0$ ,  $\beta \xi = 0$ ;
- 2)  $\beta_\perp^T Q \beta_\perp < 0$ ;
- 3)  $\exists \chi \in \mathbb{R}^{n \times m} : Q + \chi \beta + \beta^T \chi^T < 0$

## 3. Main Result

In this section, we present a stability and  $H_\infty$  performance of interconnected uncertain systems.

### 3.1. New Robust Stability Condition for Polytopic Embedded Systems

In this section, a new robust stability conditions for the polytopic embedded system (4) is developed. The main result for uncertain embedded system is stated in the following theorem with  $w(t) \equiv 0$ .

**Theorem 1.** The polytopic embedded system (4) is asymptotically stable, for all  $\lambda \in \Lambda_N$ , if and only if there exists matrices  $P_\lambda > 0$ ,  $M$ ,  $F$  and  $\mu < 0$  such that the following LMIs are feasible.

$$\begin{bmatrix} MA_\lambda + A_\lambda^T M^T - \mu I & P_\lambda - M + A_\lambda^T F^T \\ * & -F - F^T - \mu I \end{bmatrix} < 0, \quad (10)$$

**Proof**

The LMIs (10) are obtained by considering

$$\chi = \begin{bmatrix} M \\ F \end{bmatrix}, \quad (11)$$

$$\beta = [A_\lambda \quad -I], \quad (12)$$

$$Q = \begin{bmatrix} 0 & P_\lambda \\ P_\lambda & 0 \end{bmatrix}, \quad (13)$$

in condition (3) of Lemma 2, with

$$\beta_\perp = \begin{bmatrix} I \\ A_\lambda \end{bmatrix} \quad (14)$$

### 3.2. $H_\infty$ Performance Analysis of Polytopic Embedded Systems

**Theorem 2.** The uncertain embedded system (4) is asymptotically stable with  $\|H(s)\|_\infty < \gamma$ , for all  $\lambda \in \Lambda_N$ , if and only if there exists matrices  $P_\lambda > 0$ ,  $X_1$ ,  $X_2$ ,  $X_3$ , and  $X_4$ , such that the following LMIs are feasible.

$$\begin{bmatrix} \Psi_{11} & \Psi_{12} & \Psi_{13} & \Psi_{14} \\ * & \Psi_{22} & \Psi_{23} & \Psi_{24} \\ * & * & \Psi_{33} & \Psi_{34} \\ * & * & * & -I \end{bmatrix} < 0, \quad (15)$$

Where

$$\begin{aligned} \Psi_{11} &= X_1 A_\lambda + A_\lambda^T X_1^T \\ \Psi_{12} &= P_\lambda - X_1 + A_\lambda^T X_2^T \\ \Psi_{13} &= X_1 \Gamma_\lambda + A_\lambda^T X_3^T \\ \Psi_{14} &= G_\lambda^T + A_\lambda^T X_4^T \\ \Psi_{22} &= -X_2 - X_2^T \\ \Psi_{23} &= X_2 \Gamma_\lambda - X_3^T \\ \Psi_{24} &= -X_4^T \\ \Psi_{33} &= -\gamma^2 I + X_3 \Gamma_\lambda + \Gamma_\lambda^T X_3^T \\ \Psi_{34} &= \Phi_\lambda^T + \Gamma_\lambda^T X_4^T \end{aligned} \quad (16)$$

**Proof**

Choose a lyapunov function candidate to be

$$V(x) = x^T(t) P_\lambda x(t) \quad (17)$$

$P_\lambda$  given by  $P_\lambda = \sum_{j=1}^N \lambda_j P_j$ , where  $P_{j\lambda} \in \Re^{n \times n}$  are constant symmetric matrices must be determined.

Calculating the derivative of  $V(x)$  from (8), we obtained

$$\dot{x}^T(t) P x(t) + x^T(t) P \dot{x}(t) + z^T(t) z(t) - \gamma^2 w^T(t) w(t)$$

$$= \zeta^T Q \zeta < 0 \quad (18)$$

Where

$$\zeta = [x^T(t) \quad \dot{x}^T(t) \quad \omega^T(t) \quad z^T(t)]^T, \quad (19)$$

$$Q = \begin{bmatrix} 0 & P_\lambda & 0 & G_\lambda^T \\ * & 0 & 0 & 0 \\ * & * & -\gamma^2 I & \Phi_\lambda^T \\ * & * & * & -I \end{bmatrix}, \quad (20)$$

The LMIs (15) is obtained by considering

$$\chi = \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \end{bmatrix}, \quad (21)$$

$$\beta = [A_\lambda \quad -I \quad \Gamma_\lambda \quad 0], \quad (22)$$

in condition (3) of Lemma 2, with

$$\beta_\perp = \begin{bmatrix} I & 0 & 0 \\ A_\lambda & \Gamma_\lambda & 0 \\ 0 & I & 0 \\ 0 & 0 & I \end{bmatrix} \quad (23)$$

which provides, by calculation and using condition (ii) of lemma 2, the equality between  $\beta_\perp^T Q \beta_\perp < 0$  and the LMIs in (9). Thus, (9) is equivalent to (15) using Lemma 2.

This completes the proof of the theorem 2.  $\square$

## 4. Numerical Example

In this section, an example is given to illustrate the efficiency of the proposed method. We consider a class of linear embedded systems consisting of three interconnected subsystems shown as

Subsystem 1:

$$\dot{x}_1(t) = A_{1\lambda} x_1(t) + \sum_{k=1, k \neq 1}^3 E_{1k\lambda} x_k(t) + \Gamma_{1\lambda} w_1(t)$$

$$z_1(t) = G_{1\lambda} x_1(t) + \Phi_{1\lambda} w_1(t)$$

Subsystem 2:

$$\dot{x}_2(t) = A_{2\lambda} x_2(t) + \sum_{k=1, k \neq 2}^3 E_{2k\lambda} x_k(t) + \Gamma_{2\lambda} w_2(t)$$

$$z_2(t) = G_{2\lambda} x_2(t) + \Phi_{2\lambda} w_2(t)$$

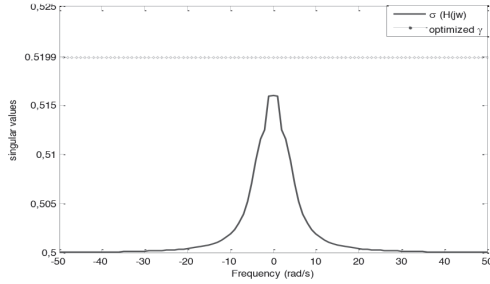
Subsystem 3:

$$\dot{x}_3(t) = A_{3\lambda} x_3(t) + \sum_{k=1, k \neq 3}^3 E_{3k\lambda} x_k(t) + \Gamma_{3\lambda} w_3(t)$$

$$z_3(t) = G_{3\lambda} x_3(t) + \Phi_{3\lambda} w_3(t)$$

**Table 1.** Comparison of Minimum  $H_\infty$  performance,  $\gamma_{\min}$ 

Method	$\gamma_{\min}$
Schule for Decentralized state feedback control for interconnected systems in [9]	$63.78 \times 10^{-2}$
By theorem 2	$51.99 \times 10^{-2}$

**Figure 2.** Interconnected embedded system: first vertex

With the following parameters:

$$A_{1\lambda} = \begin{bmatrix} -2 + \delta_1 & 0 \\ -2 & -1 + \delta_2 \end{bmatrix}, \Gamma_{1\lambda} = \begin{bmatrix} 0.2 \\ 0.2 \end{bmatrix},$$

$$G_{1\lambda} = \begin{bmatrix} 0.2 & 0.1 \end{bmatrix}, \Phi_{1\lambda} = 0.5$$

$$A_{2\lambda} = \begin{bmatrix} -1 + \delta_1 & 0 \\ -1 & -4 + \delta_2 \end{bmatrix}, \Gamma_{2\lambda} = \begin{bmatrix} 0.1 \\ 0.3 \end{bmatrix},$$

$$G_{2\lambda} = \begin{bmatrix} 0.2 & 0.1 \end{bmatrix}, \Phi_{2\lambda} = 0.2$$

$$A_{3\lambda} = \begin{bmatrix} \delta_1 & 1 \\ -1 & -2 + \delta_2 \end{bmatrix}, \Gamma_{3\lambda} = \begin{bmatrix} 0.1 \\ 0.5 \end{bmatrix},$$

$$G_{3\lambda} = \begin{bmatrix} 0.1 & -0.1 \end{bmatrix}, \Phi_{3\lambda} = 0.1$$

Where  $-1 \leq \delta_1 \leq 0.1$ ,  $-0.1 \leq \delta_2 \leq 0.2$

Couplings:

$$E_{12\lambda} = \begin{bmatrix} 1 & 0 \\ 1 & 0 \end{bmatrix}, E_{13\lambda} = \begin{bmatrix} 0 & -1 \\ 0 & -1 \end{bmatrix},$$

$$E_{21\lambda} = \begin{bmatrix} -1 & -2 \\ 3 & 6 \end{bmatrix}, E_{23\lambda} = \begin{bmatrix} -1 & 1 \\ 3 & -2 \end{bmatrix},$$

$$E_{31\lambda} = \begin{bmatrix} 1 & 2 \\ 1 & 2 \end{bmatrix}, E_{32\lambda} = \begin{bmatrix} 0 & 0 \\ 0 & -1 \end{bmatrix},$$

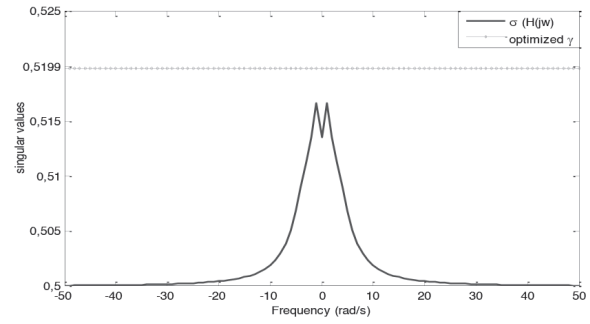
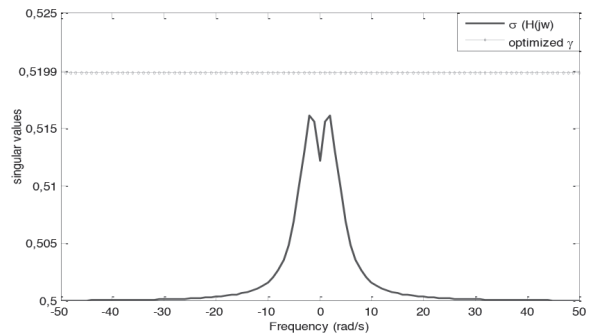
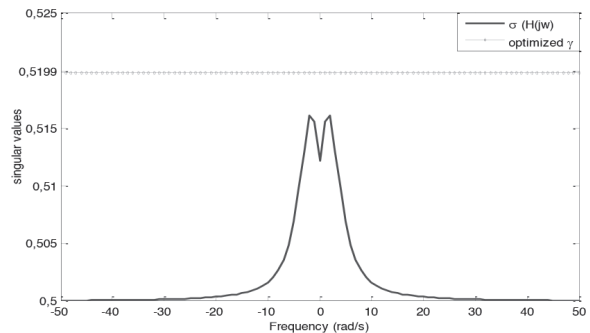
According to Lemma 1 and Theorem 2, the obtained guaranteed performances are listed in Table 1.

Table 1 shows clearly that Lemma 1 is less conservative than Theorem 2 for this example.

For the analysis of interconnected embedded systems, the  $H_\infty$  norms computed at the four vertices of interconnected embedded system are obtained from the Figures 2 to 5: all the obtained norms under the guaranteed the 0.5199 bound.

## 5. Conclusion

The conclusion of the study on stability and  $H_\infty$  analysis for interconnected embedded systems is that it is critical to consider the stability of the overall system when designing interconnected embedded systems.

**Figure 3.** Interconnected embedded system: second vertex**Figure 4.** Interconnected embedded system: third vertex**Figure 5.** Interconnected embedded system: fourth vertex

The interconnection of multiple subsystems can lead to instability and the possibility of system failure, which can have serious consequences in safety-critical applications such as automotive or aerospace systems.  $H_\infty$  control theory provides a powerful framework for designing robust control systems that can mitigate the effects of disturbances and uncertainties. By using  $H_\infty$  control techniques, it is possible to design controllers that guarantee stability and performance despite uncertain or unknown system parameters. The study highlights the importance of considering the interconnection structure of embedded systems when applying  $H_\infty$  control techniques. In particular, the study emphasizes the need to account for the coupling between different subsystems and the effect of external disturbances on the system.



Overall, the study concludes that the use of  $H_\infty$  control techniques can significantly improve the stability and performance of interconnected embedded systems, and it is essential to consider these techniques in the design of safety-critical embedded systems.

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