H∞ Control Design for Nonlinear Systems via Multimodel Approach

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***Abstract*—Nonlinear systems are integral to contemporary engineering applications, yet their regulation remains a significant challenge due to complex and highly dynamic behaviors. Robust control frameworks, particularly H∞ methods, provide systematic tools to ensure stability and performance in the presence of disturbances and modeling uncertainties. This study proposes an integrated design methodology that combines H∞ loop-shaping techniques with multimodel approaches to achieve resilient control of nonlinear systems. The control law is structured around the H∞ loop-shaping scheme, which shapes the open-loop dynamics to meet desired robustness and performance specifications. The multimodel strategy further enhances adaptability by accommodating diverse operating conditions and capturing variations in system behavior. Several control architectures are presented that unify H∞ loop-shaping with multimodel representations, offering a flexible framework for nonlinear system control. The design methodology also ensures desirable transient responses, thereby improving practical applicability for complex systems. A study is conducted to validate the proposed approaches. Simulation results confirm the effectiveness of multimodel H∞ control systems, underscoring their potential as a robust solution for complex nonlinear applications.**

***Keywords*—Nonlinear systems; H∞ loop shaping control; multimodel**

I. Introduction

Nonlinear systems are pervasive across engineering and scientific domains, naturally arising in mechanical structures [1], electrical circuits, chemical processes, aerospace vehicles, and biological networks. Unlike linear systems, which benefit from analytical tractability and the principle of superposition, nonlinear systems [2] often exhibit complex phenomena such as bifurcations [3], limit cycles, chaotic dynamics [4], and strong coupling effects [5]. These behaviors significantly complicate analysis and control, yet their regulation remains essential for ensuring stability and performance in modern applications. Classical control strategies, including feedback linearization [6], Lyapunov-based methods [7], and sliding mode control [8], have provided effective tools for nonlinear regulation. However, these techniques typically depend on stringent modeling assumptions and may lose reliability in the presence of uncertainties, disturbances, or parameter variations. In practice, nonlinear systems are rarely known with complete accuracy [9], necessitating robust control frameworks to guarantee performance under imperfect knowledge [10] and [11].

Within this context, H∞ control has emerged as a powerful methodology [12]. Its primary objective is to minimize the worst-case impact of disturbances on system performance, thereby ensuring both stability and robustness against uncertainties. Although originally formulated for linear systems, H∞ control has been extended to nonlinear dynamics through various approaches, offering a systematic means of addressing external perturbations and modeling errors. This makes H∞ particularly attractive for safety-critical applications such as aerospace flight control [13], robotics [14], and power systems [15].

Despite its advantages, direct application of H∞ control to nonlinear systems often proves analytically intractable and computationally intensive. To mitigate these challenges, researchers have introduced multimodel approaches [16], in which a nonlinear system is represented by a collection of local models, typically linear or weakly nonlinear, valid within specific operating regions [17]. By switching between or blending these models, multimodel strategies provide a tractable representation of complex nonlinear dynamics [18]. This framework facilitates the design of controllers that adapt to varying operating conditions [19], thereby enhancing robustness and performance without resorting to overly conservative assumptions [20].

The integration of multimodel representations with H∞ control offers a promising pathway toward resilient regulation of nonlinear systems. While multimodel structures reduce complexity by decomposing nonlinear behavior into manageable local models, H∞ design ensures robustness against uncertainties and disturbances. Together, they enable the synthesis of controllers capable of maintaining stability and performance across diverse operating regimes. This study contributes to this growing field by presenting a comprehensive study of H∞ control for nonlinear systems using multimodel approaches, aiming to bridge theoretical rigor with practical applicability in complex engineering contexts.

The remainder of this study is structured as follows: In Section II, we provide a preliminary study on H∞ loop-shaping techniques, highlighting their theoretical foundations and relevance for robust control of nonlinear systems. Section III introduces the multimodel approaches, where nonlinear dynamics are represented through sets of local models to facilitate analysis and controller design. In Section IV, we present an integrated scheme that combines H∞ loop-shaping techniques with multimodel strategies, demonstrating how the synergy between these methods strengthens robustness and flexibility in control system design. Proposed approaches are formulated within this composite methodology to ensure that stability and performance objectives are simultaneously satisfied, and four distinct architectures based on this concept are introduced. The effectiveness of the developed structures is examined in Section V through rigorous simulation studies, highlighting their robustness and feasibility for real systems implementation. Finally, Section VI concludes the study by summarizing the main contributions and outlining potential perspectives for future research.

II. Preliminary Study of H∞ Loop-Shaping Techniques for Robust Control

A. Foundations of H∞ Loop-Shaping

H∞ loop-shaping control design offers a systematic approach to achieving robust performance in uncertain systems. By shaping the open-loop frequency response to meet desired performance objectives and subsequently applying H∞ optimization, the method ensures stability margins and resilience against modeling errors. This integration of classical intuition with modern robust control theory makes H∞ loop-shaping particularly effective for complex multi-input multi-output systems.

The robust stability problem in the H∞ framework is to determine a controller K(s) that stabilizes the plant G(s) while ensuring that the closed-loop system satisfies prescribed performance and robustness criteria. Specifically, the objective is to design K(s) such that the weighted closed-loop transfer functions achieve a bounded H∞ norm, thereby guaranteeing stability margins in the presence of model uncertainties and external disturbances.

The robust stability H_∞ problem is to find $\gamma_{\min}$ as defined in Eq. (1) and *K(s)* in Eq. (7) in order to stabilize the studied plan *G(s),* such as:

$$\gamma min = \sqrt{1 + \lambda(YX)_{sup}} \tag{1}$$

where, $\boldsymbol{\lambda_{sup}}$ is the largest eigenvalue and the matrices X and Y are respectively the solutions of the following Riccati equations given by Eq. (2):

$$\begin{cases} XA + A^T X - XBB^T X + C^T C = 0 \\ YA^T + A^T Y - YC^T CY + BB^T = 0 \end{cases} \tag{2}$$

with (A, B, C) is the state space representation of the shaped plant *G denoted* $G_s(S)$, defined by Eq. (3):

$$G_s(s) = W_1(s)G(s)W_2(s) \tag{3}$$

A controller $K_\infty(s)$ stabilizing all the models is described by the state space representation Eq. (4) and Eq. (5):

$$\begin{cases} \dot{x}_c(t) = A_C x_c(t) + B_C y_c(t) \\ u(t) = C_c\, x_c(t) \end{cases} \tag{4}$$

where,

$$\begin{cases} A_c = A - BB^T X + \gamma^2 Z\gamma Y C^T C \\ B_c = \gamma^2 Z\gamma Y C^T \\ C_c = B^T X \\ Z_\gamma = (I + YX - \gamma^2 I)^{-1} \end{cases} \tag{5}$$

Using Eq. (5), the H∞ controller is given in Eq. (6) as follows:

$$K_\infty(s) = C_C(sI - A_C)^{-1} B_C \tag{6}$$

The final feedback controller $K(s)$, is obtained by combining controller $K_\infty(s)$ with the shaping functions $W_1(S)$ and $W_2(S)$, which is described by the relation Eq. (7):

$$K(s) = W_1(s)K_\infty(s)W_2(s) \tag{7}$$

B. Architecture of H∞ Loop-Shaping Control Systems

H∞ loop-shaping control provides a systematic framework that combines classical frequency-domain design with modern robust optimization. The method begins by shaping the open-loop transfer function with appropriate weighting functions to achieve desired performance characteristics such as bandwidth, disturbance rejection, and noise attenuation. Once the loop is shaped, H∞ optimization is applied to guarantee robustness against model uncertainties and unmodeled dynamics. This architecture in Fig. 1 is particularly effective for both Single-Input/ Single-Output (SISO) and Multiple-Input/Multiple-Output (MIMO) systems, as it balances intuitive design with rigorous mathematical guarantees, making it a widely applicable framework in robust control engineering.

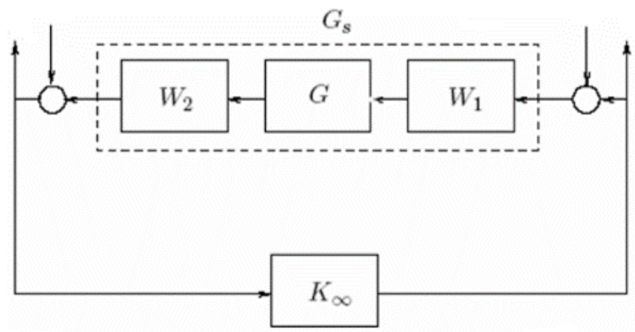

Fig. 1. Architecture of H∞ loop-shaping control systems.

The H∞ loop-shaping control design framework provides a rigorous and principled methodology for achieving robust performance by integrating intuitive frequency-domain shaping with formal optimization techniques. By simultaneously enhancing stability margins and accommodating model uncertainties, this framework is particularly well-suited for the control of complex nonlinear systems. Building upon this foundation, the subsequent section introduces multimodel approaches, which serve as complementary tools for representing nonlinear dynamics through collections of local models. Such representations enable computationally feasible analysis and facilitate systematic controller synthesis, thereby extending the applicability of robust control methods to a broader class of nonlinear systems.

III. Multimodel Approaches for Nonlinear System Representation and Controller Design

A. Multimodel Control for Nonlinear System

The principal objective is the synthesis of a global control law u(t) described by Eq. (8) for the considered nonlinear system Eq. (9), constructed on the basis of the multimodel representation. The resulting control input, designated as the multimodel command, is obtained through the aggregation of partial control signals generated by each local model.

$$u(t) = \sum_{i=1}^{n} v_i(t) u_i(t) \tag{8}$$

$$\begin{cases} \dot{x}(t) = \sum_{i=1}^{n} v_i(t)(A_i x(t) + B_i u_i(t)) \\ y(t) = \sum_{i=1}^{n} v_i(t) C_i x(t) \end{cases} \quad (9)$$

where,

$$\sum_{i=1}^{n} v_i = 1$$

υ_i (t) denotes the validity coefficient corresponding to the i^{th} local model, ensuring that the global control law is obtained as a weighted fusion of the partial commands u_i.

In the multimodel representation, A_i denotes the state matrix of the i^{th} local model, characterizing the intrinsic dynamics of the system states. The matrix B_i represents the input matrix, mapping the control signal u_i into the state space and thereby defining the influence of external commands. Similarly, C_i is the output matrix, which relates the internal state vector x(t) to the measurable output y(t).

B. Multimodel Architecture for Nonlinear Systems

The multimodel structure constitutes a comprehensive analytical framework that employs multiple local linear time-invariant (LTI) models, expressed in either linear or affine form. This methodology is predicated on the assumption that a complex nonlinear system can be effectively approximated by a structured combination of simpler local models, thereby establishing a representative model base. Each constituent model delineates the system dynamics at a specific operating point, while the global nonlinear behavior emerges from the coordinated interaction of these local models M_i through normalized activation functions. Consequently, the multimodel approach mitigates system complexity by facilitating the investigation of dynamic behavior under rigorously defined operating conditions. The conceptual foundation of this methodology is schematically illustrated in Fig. 2.

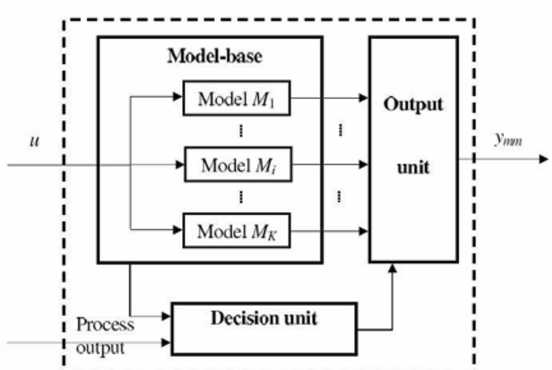

Fig. 2. Architecture of a multimodel approach for control systems.

The multimodel framework is organized into three core components. The model base consists of a library of local or generic models, which may vary in form and order but collectively provide simplified representations of the system across distinct operating regimes. The decision unit governs the selection and activation of these models, ensuring that the most appropriate local representation contributes to the global system defined by M in Eq. (10), given that each model is valid only within a specific operating region. Finally, the output unit synthesizes the overall system response by processing the validity vector associated with the model base. Two strategies are typically employed: commutation, which switches models according to operating conditions, and fusion, which aggregates outputs through a weighted combination. In this study, the fusion approach is adopted and formally defined in the following section.

$$M = \sum_{i=1}^{n} v_i(t) M_i(t) \quad (10)$$

With

$$\sum_{i=1}^{n} v_i = 1$$

IV. H∞ SYNTHESIS UNDER MULTIMODEL CONTROL DESIGN

A. General Principles of H∞ Loop-Shaping Synthesis in Multimodel Control

The integration of H∞ synthesis within a multimodel control paradigm aims to achieve robust performance for nonlinear systems by combining the advantages of multiple local linear models. In this framework, each local model contributes a partial control law derived from H∞ design, ensuring attenuation of disturbances and preservation of stability margins. The global control input is then obtained through a fusion mechanism, where the partial commands are weighted according to the validity coefficients associated with each model. This methodology facilitates seamless transitions among local controllers while ensuring robustness with respect to parameter variations and inherent system nonlinearities. On the basis of this principle, the proposed control architecture is structured around a set of local H∞ controllers, each associated with its corresponding base model. A validity estimation mechanism operates in real time to determine the weighting coefficients that quantify the relevance of each local model. These coefficients are subsequently employed within a fusion module, which synthesizes the global control input delivered to the plant. In the following sections, four distinct architectural configurations of this multimodel H∞ control strategy are introduced and analyzed.

B. Synthesis of Partial H∞ Loop- Shaping controller

For each local model Mi (i = 1, .., n), an H∞ Loop- Shaping controller $K_{\infty i}(s)$ is associated. The corresponding partial control law $K_i(s)$ is then derived by using local shaping $W_{1i}(S)$ and $W_{2i}(s)$, as expressed in Eq. (11):

$$K_i(s) = W_{1i}(s) K_{\infty i}(s) W_{2i}(s) \quad \text{, for i=1..n} \quad (11)$$

The synthesis procedure ensures that each controller attains the desired performance objectives while maintaining stability margins specifically adapted to the dynamic characteristics of its associated local model. By configuring the loop-shaping design to individual operating regimes, the resulting set of partial controllers provides localized robustness and performance guarantees across the multimodel framework. This localized design not only enhances the fidelity of control in each regime but also establishes a foundation for constructing a global control law capable of maintaining robustness under parameter variations, nonlinearities, and external perturbations. Consequently, the multimodel H∞ synthesis approach enables a systematic balance between local precision and global stability, ensuring reliable performance across the entire operating domain.

C. Synthesis of Global H∞ Loop- Shaping Controller

Once the parameters of the partial controllers have been identified, the subsequent step consists of deducing the global control law to be applied to the nonlinear system under study. A fusion-based control strategy is adopted, as it provides a coherent and effective framework for the proposed multimodel representation. In situations where the system can be accurately approximated by a weighted aggregation of local models, the global controller K(s) is constructed through the fusion of the elementary controllers $K_i(s)$, described by Eq. (12):

$$K(s) = \sum_{i=1}^{n} v_i \, K_i(s) \qquad (12)$$

υ_i (k) denotes the validity coefficient corresponding to the i^{th} local model.

With,

$$\sum_{i=1}^{n} v_i = 1$$

Based on the multimodel H∞ Loop-shaping synthesis framework, four representative architectures are proposed to illustrate different design philosophies and implementation strategies. The following subsection introduces four architectural configurations developed under the multimodel H∞ synthesis framework, highlighting their structural characteristics and the control strategies employed.

D. Proposed Architectures for Multimodel H∞ Control

a) Architecture 1 – Aggregated local controllers: The global control law is synthesized as the summation of local H∞ controllers, each designed with respect to its corresponding local model. The resulting global system is thus formed by the collective contribution of all local models. The architecture is illustrated in Fig. 3 below:

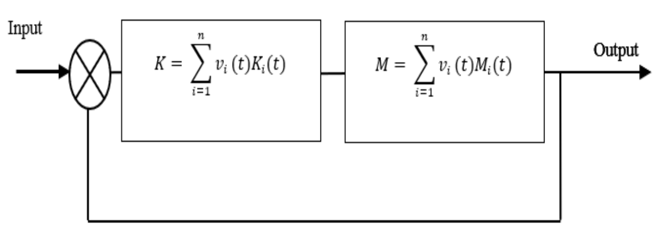

Fig. 3. Architecture 1- Aggregated local controllers.

b) Architecture 2 – Decentralized local control: Each local model is paired with its dedicated H∞ controller, operating independently. The control action applied to the plant is determined by the validity of the associated local model, ensuring model-specific regulation. The subsequent Fig. 4 depicts the structure of the proposed architecture.

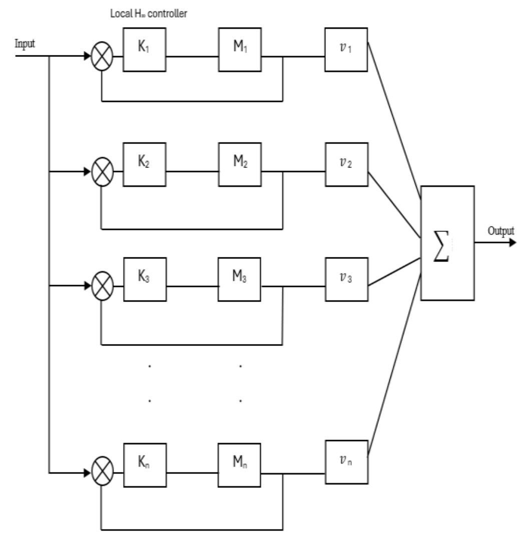

Fig. 4. Architecture 2 - Decentralized local control.

c) Architecture 3 – Global controller from multimodel representation: A single H∞ Loop-shaping controller, denoted K, is designed directly from the global multimodel representation. This controller is then connected to the aggregated global model formed by the ensemble of local models. This architecture is provided in Fig. 5.

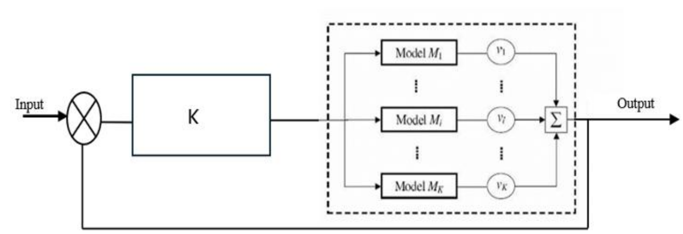

Fig. 5. Architecture 3- Global controller from multimodel representation.

d) Architecture 4 – Global controller applied to the real nonlinear system: The global H∞ Loop-shaping controller K, synthesized from the multimodel framework, is directly implemented on the real nonlinear system. Simulation studies are conducted to evaluate its robustness and performance under practical operating conditions.This architecture is schematically shown in Fig. 6 that follows.

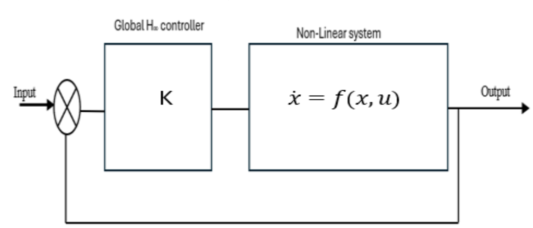

Fig. 6. Architecture 4 - Global controller applied to the real nonlinear system.

V. Numerical Validation of Proposed Methods

To evaluate the effectiveness of the proposed multimodel H∞ loop-shaping framework, a comparative validation of four distinct architectural configurations is conducted. Each architecture is examined with respect to its structural characteristics, control synthesis methodology, and resulting performance indices. The numerical simulations highlight the effectiveness of the individual designs to ensure robustness and stability margins under varying operating conditions [16].

Consider the nonlinear system given by Eq. (13):

$$y + (15 - 10y)\dot{y} = (36y(y-1) + 10)u \quad (13)$$

Through the multimodel approach, a set of four linear models has been formulated, with the corresponding transfer functions presented in the following Eq. (14), Eq. (15), Eq. (16) and Eq. (17):

$$G_1(s) = \frac{1}{1+5s} \quad (14)$$

$$G_2(s) = \frac{1}{1+15s} \quad (15)$$

$$G_3(s) = \frac{10}{1+5s} \quad (16)$$

$$G_4(s) = \frac{10}{1+15s} \quad (17)$$

Following the definition of the models, the design of the multimodel controller is undertaken, beginning with the partial H∞ loop-shaping approach and subsequently extending to the global H∞ loop-shaping controller. The design criterion is established to ensure an overshoot D=10%. The transfer function expressions and the value of γ_{min} corresponding to each partial model are summarized in Table I below.

We consider W_{2i}=1.

TABLE I. Partial H∞ Loop-Shaping Controller

System Models	Partial H∞ loop-shaping controller $Ki\infty$	W_{1i}	γ_{min}
M_1	$\frac{3.297s + 1.197}{s^2 + 3.43s + 1.96}$	$\frac{s+1}{s}$	*1.7634*
M_2	$\frac{1.08s + 0.102}{s^2 + 0.87s + 0.58}$	$\frac{0.25s + 0.25}{s}$	*1.9254*
M_3	$\frac{4.47s + 1.43}{s^2 + 3.88s + 2.35}$	$\frac{0.12s + 0.12}{s}$	*1.7618*
M_4	$\frac{1.08s + 0.102}{s^2 + 0.87s + 0.58}$	$\frac{0.025s + 0.025}{s}$	*1.9254*

The step responses of the four models, depicted in Fig. 7, Fig. 8, Fig. 9 and Fig. 10, confirm that the partial H∞ loop-shaping controller fulfills the prescribed performance objectives while ensuring robustness across all models.

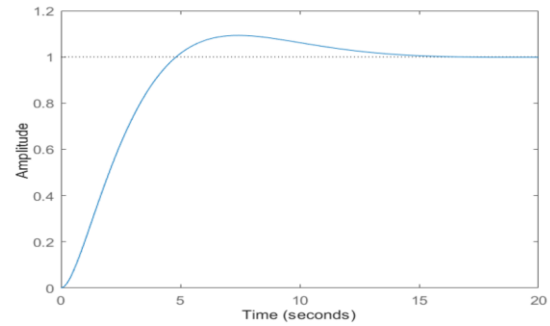

Fig. 7. Step response of the controlled model 1 using K_1.

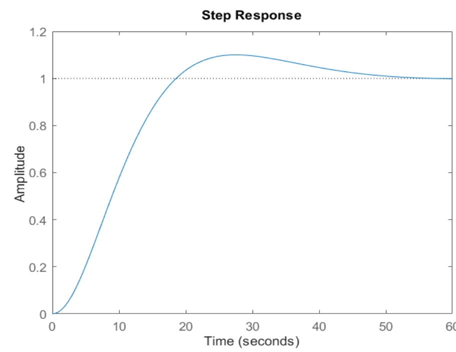

Fig. 8. Step response of the controlled model 2 using K_2.

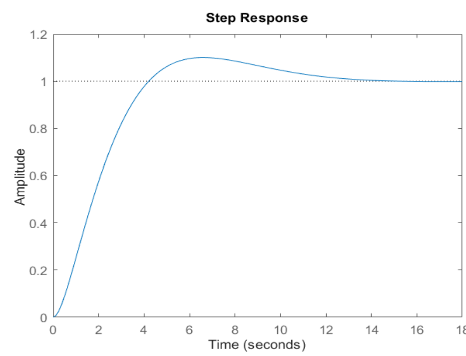

Fig. 9. Step response of the controlled model 3 using K_3.

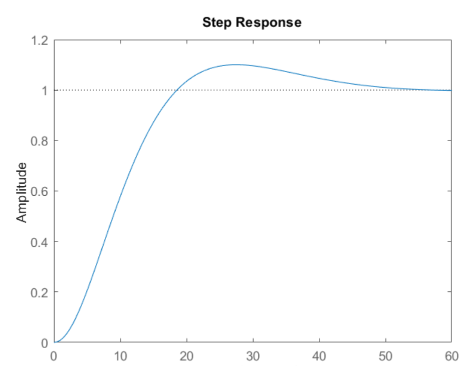

Fig. 10. Step response of the controlled model 4 using K_4.

While the first simulation demonstrates the behavior of a single partial controller, the second extends this concept by integrating the partial controllers within the four-architecture control framework to evaluate their performance.

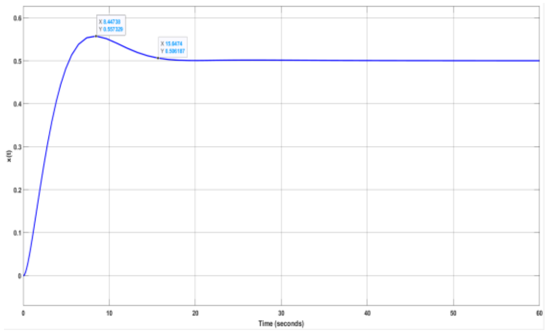

Fig. 11. Step response using architecture 1 - Aggregated local controllers.

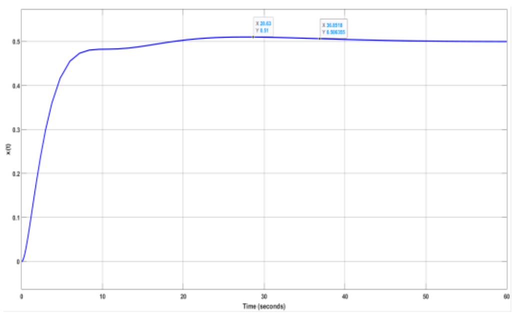

Fig. 12. Step response using architecture 2- Decentralized local control.

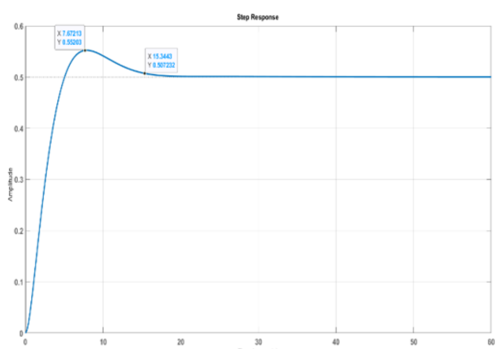

Fig. 13. Step response using architecture 3- Global controller from multimodel representation.

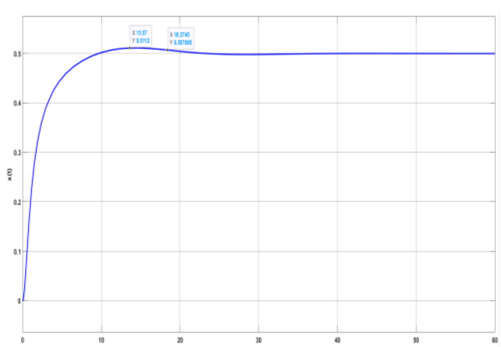

Fig. 14. Step response using architecture 4- Global controller applied to the real nonlinear system.

The comparative analysis of the four control architectures highlights the classical performance limitation between rapid response and system stability, particularly when applied to uncertain, disturbed, or otherwise complex systems. Architecture 1, the Aggregated Local Controllers (Fig. 11), achieves a rapid response time of 15 units but suffers from a significant overshoot of 10%, which compromises stability and makes it unsuitable for systems exposed to external perturbations or parameter uncertainties. Architecture 2, the Decentralized Local Control (Fig. 12), provides excellent precision with only 1% overshoot; however, its slow response time of 36 s limits its applicability in dynamic environments where rapid adaptation is essential. Architecture 3, the Global Controller based on a multimodel representation (Fig. 13), integrates these conflicting objectives by delivering the fastest response at 15 s with minimal overshoot of 1%, thereby offering the most efficient theoretical design under complex operating regimes. Finally, Architecture 4, the Global Controller implemented on the physical system (Fig. 14), demonstrates slightly slower dynamics at 18 s while maintaining the same low overshoot, thus confirming the robustness and practical effectiveness of the global approach in applied system contexts characterized by uncertainty and external disturbances. Overall, Architectures 3 and 4 provide the most favorable balance between speed and stability, ensuring reliable performance across a wide range of complex system scenarios, whereas Architectures 1 and 2 exemplify the extremes of this performance limitation.

Although standard H_∞ and H_2 control have been combined with multimodel frameworks in several earlier studies, these approaches generally rely on applying classical robust controllers to each local model or on implementing multimodel switching and scheduling strategies, often without guaranteeing global robustness across the entire operating domain. In contrast, the present work introduces a fundamentally different integration by embedding H_∞ loop-shaping within a multimodel architecture. Rather than designing loop-shaped controllers independently for each model, our methodology performs a joint synthesis that enforces a global robustness objective over the full multimodel set. This results in a coherent, system-wide loop-shaping design that departs from existing standard H_∞/H_2 multimodel formulations both in purpose and in structural organization.

VI. Conclusion

This study has presented an integrated design methodology that unifies H_∞ loop-shaping with multimodel architectures to address a central challenge in robust nonlinear control: achieving global performance guarantees without relying solely on locally valid controllers. Beyond the comparative evaluation of four architectures, the results highlight a broader conceptual contribution—global multimodel coordination can effectively overcome the classical speed-stability trade-off that constrains traditional local or single-model designs.

Architectures 3 and 4 demonstrate that embedding H_∞ loop shaping within a global multimodel framework yields controllers capable of maintaining fast dynamics, minimal overshoot, and robust stability across the full operating envelope. This positions multimodel H_∞ control as a scalable and practically deployable strategy for nonlinear systems subject to uncertainty, disturbances, and complex regime transitions. The successful experimental validation of Architecture 4 further confirms that the proposed methodology is not only theoretically sound but also operationally reliable in real-world conditions. Conceptually, this work shifts the perspective in robust nonlinear control from isolated local designs toward globally coherent control structures that preserve robustness throughout the entire state space. By bridging advanced linear robust control tools with nonlinear multimodel representations, the methodology contributes a systematic pathway for designing controllers that are both high-performance and globally robust.

Future research may advance this framework along several significant directions. A promising line of inquiry concerns its extension to large-scale interconnected systems, where multimodel representations arise naturally from subsystem interactions and where uncertainty is both structural and pervasive. Furthermore, the integration of adaptive and data-driven mechanisms within the multimodel architecture offers considerable potential for enhancing real-time performance in highly dynamic environments. Particular attention should be directed toward the incorporation of machine-learning-based modules capable of augmenting or partially replacing the controller, provided that their deployment is accompanied by rigorous guarantees of stability and robustness.

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