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Quasi-LPV control of a magnetic levitation system using geometric interpolation

Control quasi-LPV de un sistema de levitación magnética mediante interpolación geométrica

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Abstract

This article presents a gain-scheduling control strategy for constant reference tracking in a magnetic levitation system, utilizing a quasi-LPV model and a distance-based geometric interpolation mechanism. The system, involving the suspension of a metallic sphere, is characterized by highly nonlinear, inherently unstable open-loop dynamics where only position is measurable. These nonlinearities are embedded into an endogenous parameter vector that varies within a bounded domain defined by physical operating limits. Consequently, the plant is represented as a family of linear time-invariant models at the parametric vertices. At these vertices, local tracking controllers are designed via state feedback and pole placement, integrated with full-order observers to estimate unmeasurable states. The global controller and observer are synthesized through geometric interpolation, where weights are derived from the Euclidean distance between the estimated parameter vector and each vertex. This approach ensures convex combinations and positive weights across the operating range, simplifying implementation compared to traditional analytical methods. MATLAB/Simulink simulations on the full nonlinear model demonstrate satisfactory tracking performance, bounded control effort, and robustness against input disturbances and measurement noise, validating the efficacy of the proposed control architecture.

Keywords: Magnetic levitation, quasi-LPV systems, gain-scheduling, geometric interpolation, nonlinear systems, state observers, United Nations SDG 9.

Resumen

Este artículo presenta una estrategia de control por programación de ganancias para el seguimiento de referencias constantes en un sistema de levitación magnética, utilizando un modelo quasi-LPV y un mecanismo de interpolación geométrica. El sistema consiste en la suspensión de una esfera metálica caracterizada por una dinámica no lineal e inestabilidad a lazo abierto, donde solo la posición es medible. Las no linealidades se incorporan en un vector de parámetros endógenos que varía en un dominio acotado por los límites físicos, permitiendo representar la planta como una familia de modelos lineales invariantes en el tiempo en los vértices del dominio. En dichos vértices, se diseñan controladores locales mediante realimentación de estado y asignación de polos, integrados con observadores de orden completo para estimar los estados no medibles. El controlador y observador globales se sintetizan mediante interpolación geométrica, donde los pesos se derivan de la distancia euclidiana entre el parámetro estimado y cada vértice. Este enfoque garantiza combinaciones convexas y pesos positivos en todo el rango operativo, simplificando la implementación frente a métodos analíticos tradicionales. Simulaciones en MATLAB/Simulink sobre el modelo no lineal completo demuestran un seguimiento satisfactorio, esfuerzo de control acotado y robustez ante perturbaciones y ruido de medición, validando la eficacia de la arquitectura propuesta.

Palabras clave: Levitación magnética, sistemas quasi-LPV, programación de ganancias, interpolación geométrica, sistemas no lineales, observadores de estado, ODS 9 de las Naciones Unidas.

1 Introduction

Magnetic levitation systems constitute a widely used benchmark plant in the field of automatic control due to the combination of pronounced nonlinearities, open-loop instability, and limitations in the measurement of state variables (Kuo, 1996; Khalil, 2002; Sira-Ramirez et al., 2005; Ogata, 2010). These characteristics make them a natural testbed for the evaluation of advanced control methodologies, particularly those aimed at nonlinear and inherently unstable systems, both in academic research and industrial-oriented applications (Bidikli, 2020; Wang et al., 2021; Teppa-Garran & Faggioni, 2023).

A common approach to the control of magnetic levitation systems consists of linearizing the plant around a fixed operating point and subsequently designing a linear controller (Lee et al., 2007; Hypiusova & Kozakova, 2017; Rusar et al., 2017). Although this approach yields satisfactory performance in small neighborhoods of the equilibrium point, its effectiveness degrades rapidly when the system operates over wider position ranges or is subjected to significant disturbances. This limitation has motivated the development of nonlinear, adaptive, sliding-mode, and predictive control strategies, which usually involve increased modeling effort and implementation complexity (Muthairi & Zribi, 2004; Shieh et al., 2010; Wang et al., 2021).

In this context, the theory of Linear Parameter-Varying (LPV) systems provides an attractive intermediate framework, as it allows nonlinear systems to be represented as families of linear models that depend on a bounded parameter vector (Rugh & Shamma, 2000; Rotondo, 2018; Bombois et al., 2021). In particular, quasi-LPV models, where the scheduling parameters are endogenous and depend on the system states, enable nonlinearities to be embedded directly into the parametric dependence of the model without relying on disconnected local linearizations (Robles et al., 2019).

Recent works have demonstrated the effectiveness of quasi-LPV formulations for modeling and control of nonlinear systems in a variety of applications, including aerospace systems, robotics, and industrial processes (Tan et al., 2000; Cisneros et al., 2018; Li et al., 2023). Moreover, the quasi-LPV paradigm has proven to be particularly suitable for gain-scheduling control designs based on state-space techniques, where classical linear tools such as pole placement, optimal control, or robust synthesis can be exploited (Teppa-Garrán & Andrade-Da Silva, 2009; Teppa-Garrán et al., 2025).

Within the LPV and quasi-LPV framework, gain-scheduling strategies require an interpolation mechanism to coherently combine the controllers designed at the vertices of the parametric domain. Analytical interpolation approaches, in which the interpolation weights are obtained by solving a system of linear equations enforcing the exact reconstruction of the parameter vector, have been proposed and successfully applied to inherently stable processes such as coupled tank systems (Teppa-Garrán & Andrade-Da Silva, 2009; Teppa-Garrán et al., 2025). However, when unstable systems with physical constraints on the control signal are considered, as is the case in magnetic levitation, analytical interpolation may present practical difficulties, particularly due to the possibility of negative interpolation weights or the need for additional conditioning.

In this scenario, distance-based geometric interpolation mechanisms offer a conceptually simpler alternative, as they naturally yield convex combinations of the local controllers and guarantee positive weights throughout the parametric domain (Leith & Leithead, 2000). These properties make geometric interpolation especially attractive for practical implementations, where actuator saturation and unidirectional control signals must be explicitly considered.

Motivated by these considerations, this work proposes the application of a quasi-LPV control scheme with Euclidean distance-based geometric interpolation to the magnetic levitation of a spherical object. Unlike previous quasi-LPV applications focused on stable or weakly nonlinear systems, this work explicitly addresses a nonlinear and open-loop unstable plant and consistently integrates the design of tracking controllers and full-order state observers using a single interpolation mechanism based on estimated parameters.

The main contribution of this article lies in demonstrating that geometric interpolation constitutes an effective and practical mechanism for the implementation of quasi-LPV controllers in magnetic levitation systems, offering a favorable trade-off between simplicity, robustness, and performance. Simulation results validate the proposed approach and highlight its potential as a practical alternative to more complex interpolation schemes or nonlinear control methodologies with higher computational cost.

Finally, this work is aligned with Sustainable Development Goal 9 (Industry, Innovation, and Infrastructure), as it contributes to the development of advanced modeling and control methodologies applicable to nonlinear systems of technological and industrial interest. In particular, the use of quasi-LPV control with geometric interpolation promotes more flexible and efficient automation solutions, supporting the strengthening of innovative industrial infrastructures.

2 Magnetic levitation system and quasi-LPV modeling

This section presents the mathematical modeling of the magnetic levitation system considered in this work and introduces its representation within the quasi-LPV framework. First, the nonlinear dynamic model of the plant is derived in state-space form, highlighting the main sources of nonlinearity and instability. Then, an equivalent quasi-LPV formulation is developed by embedding the nonlinear terms into an endogenous, bounded parameter vector. This representation provides the basis for the subsequent gain-scheduling control design and the geometric interpolation scheme described in the following sections.

2.1 Nonlinear model of the magnetic levitation system

The magnetic levitation system considered in this work consists of a metallic sphere suspended vertically by the electromagnetic force generated by a single coil. This system is widely used as a benchmark in control engineering due to its strongly nonlinear dynamics and intrinsic open-loop instability, as well as the practical limitation that only the vertical position of the levitated object is directly measurable (Kuo, 1996; Khalil, 2002; Sira-Ramirez et al., 2005).

The dynamic behavior of the plant results from the coupling between the electrical dynamics of the electromagnet and the mechanical dynamics of the sphere (see Fig. 1). The electrical subsystem can be described by applying Kirchhoff's voltage law to the coil circuit, while the mechanical subsystem follows from Newton's second law applied to the vertical motion of the sphere. The electromagnetic force acting upon the sphere scales with the square of the coil current and is inversely proportional to the sphere's displacement, thereby exhibiting pronounced nonlinearity and inherent open-loop instability (Kuo, 1996; Bidikli, 2020).

By defining the state vector as

$$\boldsymbol{x}(t) = [x_1(t) \quad x_2(t) \quad x_3(t)]^T,$$

where $x_1(t)$ denotes the vertical position of the sphere, $x_2(t)$ its vertical velocity, and $x_3(t)$ the current flowing through the electromagnet, the nonlinear model of the magnetic levitation system can be expressed in state-space form as

$$\dot{x}_1(t) = x_2(t),$$

$$\dot{x}_2(t) = g - \frac{q{x_3}^2(t)}{mx_1(t)},$$

$$\dot{x}_3(t) = -\frac{Rx_3(t)}{L} + \frac{u(t)}{L},$$

where $u(t)$ represents the voltage applied to the electromagnet, g is the gravitational acceleration, m is the mass of the levitated sphere, R and L are the electrical resistance and inductance of the coil, respectively, and q is a constant that characterizes the magnetic force generated by the actuator.

The strong nonlinear coupling between the electrical and mechanical subsystems, together with the rational dependence on the position state $x_1(t)$, makes the system unstable and highly sensitive to variations in operating conditions and disturbances. These characteristics motivate the adoption of modeling frameworks capable of capturing nonlinear behavior over a wide operating range without relying on linearization around a single equilibrium point.

The physical parameters of the magnetic levitation system used throughout this study, along with their numerical values, are summarized in Table 1. These parameters correspond to a standard laboratory-scale magnetic levitation setup and are employed consistently in the modeling and simulation results reported in this work.

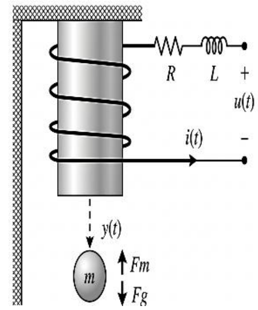

Figure 1. Magnetic levitation system.

Table 1. Physical parameters of the magnetic levitation system

Parameter	Description	Value	Units
g	Gravitational acceleration	9.81	$\mathrm{m/s^2}$
L	Coil inductance	0.01	H
R	Coil resistance	1.00	Ω
q	Electromagnetic force constant	1.00	$\mathrm{Nm/A^2}$
m	Mass of the levitated sphere	1.00	Kg
x_{eq}	Desired equilibrium position of the ball	0.50	m
u_{eq}	Equilibrium input	2.20	V

2.2 Quasi-LPV representation of the magnetic levitation system

To overcome the limitations associated with linearization around a single operating point, the nonlinear model of the magnetic levitation system described in Section 2.1 is reformulated within the quasi-LPV framework. In this approach, the nonlinear dynamics are embedded into a parameter-dependent linear structure, where the scheduling parameters are endogenous and depend explicitly on the system states.

Starting from the nonlinear model, the mechanical equation can be algebraically rearranged without altering the system dynamics as

$$\dot{x}_2(t) = g\frac{1}{x_1(t)}x_1(t) - \frac{q}{m}\frac{x_3(t)}{x_1(t)}x_3(t).$$

This manipulation allows the rational nonlinearities to be isolated in a vector of scheduling parameters, while preserving a linear dependence on the state variables. Accordingly, the endogenous parameter vector is defined as

$$\boldsymbol{\theta}(t) = [\theta_1(t) \quad \theta_2(t)]^T = \begin{bmatrix}\frac{1}{x_1(t)} & \frac{x_3(t)}{x_1(t)}\end{bmatrix}^T.$$

With this definition, the nonlinear magnetic levitation system can be written in the quasi-LPV form

$$\dot{\boldsymbol{x}}(t) = \boldsymbol{A}(\boldsymbol{\theta}(t))\boldsymbol{x}(t) + \boldsymbol{B}\boldsymbol{u}(t), \qquad \boldsymbol{y}(t) = \boldsymbol{C}\boldsymbol{x}(t),$$

where the parameter-dependent state matrix is given by

$$\boldsymbol{A}(\boldsymbol{\theta}(t)) = \begin{bmatrix} 0 & 1 & 0 \\ g\theta_1(t) & 0 & -\frac{q}{m}\theta_2(t) \\ 0 & 0 & -\frac{R}{L} \end{bmatrix},$$

and the constant input and output matrices are

$$\boldsymbol{B} = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{L} \end{bmatrix}, \qquad \boldsymbol{C} = [1 \quad 0 \quad 0].$$

In this representation, all nonlinear effects of the magnetic levitation system are fully captured by the dependence of the matrix $\boldsymbol{A}(\boldsymbol{\theta}(t))$ on the endogenous parameters $\theta_1(t)$ and $\theta_2(t)$, while the model remains linear in the state and input variables. Notably, the gravitational term appears multiplied by the first scheduling parameter, which is consistent with the physical structure of the system and with the adopted quasi-LPV modeling strategy.

The scheduling parameters are naturally bounded due to physical constraints on the admissible position and current of the levitated sphere. These bounds define a compact parametric domain, whose vertices are used to generate the local linear models required for the gain-scheduling control and observer design presented in the following section.

2.3 Parametric domain and local linear models

The quasi-LPV representation derived in Section 2.2 depends on the endogenous scheduling parameter vector

$$\boldsymbol{\theta}(t) = \begin{bmatrix} \theta_1(t) \\ \theta_2(t) \end{bmatrix} = \begin{bmatrix} \frac{1}{x_1(t)} \\ \frac{x_3(t)}{x_1(t)} \end{bmatrix},$$

whose components are functions of the system states. Since the magnetic levitation system operates within physical constraints on position and current, the scheduling parameters are naturally bounded. These bounds define a compact parametric domain that contains all admissible trajectories of $\boldsymbol{\theta}(t)$ during operation.

Let the position and current of the levitated sphere be constrained to the intervals

$$x_1(t) \in [x_{1,min}, x_{1,max}], \quad x_3(t) \in [x_{3,min}, x_{3,max}],$$

where the limits are selected according to physical restrictions and the desired operating range around the nominal equilibrium point. From these bounds, the corresponding intervals for the scheduling parameters are obtained as

$$\theta_1(t) \in \left[\frac{1}{x_{1,max}}, \frac{1}{x_{1,min}}\right], \quad \theta_2(t) \in \left[\frac{x_{3,min}}{x_{1,max}}, \frac{x_{3,max}}{x_{1,min}}\right].$$

The Cartesian product of these intervals defines a compact rectangular region

$$\Omega = \{\theta \in \mathbb{R}^2 : \theta_1^- \leq \theta_1 \leq \theta_1^+, \theta_2^- \leq \theta_2 \leq \theta_2^+\},$$

which represents the admissible parametric domain of the quasi-LPV system.

The extreme combinations of the bounds of Ω define a finite set $\boldsymbol{\theta}^{(i)}, i = 1, \ldots, N$, where $N = 4$ for the two-parameter case considered in this work. Evaluating the parameter-dependent matrix $A(\boldsymbol{\theta})$ at each vector yields a collection of linear time-invariant models of the form

$$\dot{\boldsymbol{x}}(t) = \boldsymbol{A}^{(i)}\boldsymbol{x}(t) + \boldsymbol{B}\boldsymbol{u}(t), \quad \boldsymbol{y}(t) = \boldsymbol{C}\boldsymbol{x}(t),$$

with

$$\boldsymbol{A}^{(i)} = A\left(\boldsymbol{\theta}^{(i)}\right), \quad i = 1, \ldots, N.$$

These local linear models constitute the basis for the gain-scheduling control design. A local controller and a corresponding state observer are designed for each vertex, ensuring the desired tracking performance and stability properties at the extreme parameter combinations. The global controller and observer are subsequently obtained by interpolating the local designs as a function of the instantaneous value of the scheduling parameters, as detailed in the next section.

3 Control design

This section presents the design of the gain-scheduled control strategy for the magnetic levitation system based on the quasi-LPV model developed in Section 2. The objective is to achieve accurate tracking of constant reference positions while ensuring stability and bounded control effort over the entire admissible operating region. To this end, local tracking controllers and state observers are designed at the vertices of the parametric domain and subsequently combined through a geometric interpolation mechanism.

3.1 Tracking control problem formulation

The control objective considered in this work is the tracking of constant reference trajectories for the vertical position of the levitated sphere. Let the tracking error be defined as

$$e(t) = r(t) - y(t),$$

where $r(t)$ denotes the reference position and $y(t) = x_1(t)$ is the measured output. For constant reference inputs, zero steady-state error is achieved by incorporating integral action into the control law.

Following a state-space tracking control approach, an augmented system is constructed by including the error dynamics. Taking the time derivative of the tracking error yields

$$\dot{e}(t) = -\dot{y}(t) = -\boldsymbol{C}\dot{\boldsymbol{x}}(t).$$

For each local linear model associated with a vertex of the quasi-LPV parametric domain, the augmented state vector is defined as

$$\boldsymbol{z}(t) = \begin{bmatrix} e(t) \\ \dot{\boldsymbol{x}}(t) \end{bmatrix}.$$

This formulation transforms the tracking problem into a regulation problem for an augmented linear system, enabling the systematic application of linear state-feedback design techniques.

3.2 Local tracking controller design

For each vertex of the parametric domain, a local tracking controller is designed using state feedback on the augmented system. The auxiliary control input is defined as

$$u_0(t) = -\boldsymbol{K}^{(i)}\boldsymbol{z}(t) = -\begin{bmatrix} k_e^{(i)} & \boldsymbol{K}_x^{(i)} \end{bmatrix}\boldsymbol{z}(t),$$

where $k_e^{(i)}$ is the gain associated with the integral of the tracking error, and $\boldsymbol{K}_x^{(i)}$ is the state-feedback gain vector. Integrating the auxiliary input yields the actual control signal applied to the plant,

$$u(t) = -k_e^{(i)}\int_0^t e(\tau)\,d\tau - \boldsymbol{K}_x^{(i)}\boldsymbol{x}(t)$$

The controller gains are computed independently at each vertex using pole placement techniques, selecting the closed-loop poles to satisfy predefined transient performance requirements while ensuring robustness across the operating region.

At each vertex, the resulting local tracking control structure consists of the plant model, the augmented state-feedback controller, and the reference input, as conceptually illustrated in Figure 2.

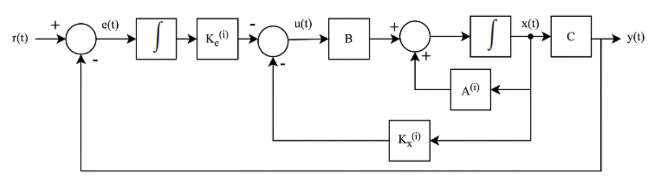

Figure 2. Local tracking control structure associated with a vertex of the quasi-LPV parametric domain.

3.3 Local state observer design

Since only the position of the levitated sphere is directly measurable, full state information must be reconstructed through state estimation. For this purpose, a full-order state observer is designed for each local linear model.

For the i-th vertex, the observer dynamics are given by

$$\dot{\hat{\boldsymbol{x}}}(t) = \boldsymbol{A}^{(i)}\hat{\boldsymbol{x}}(t) + \boldsymbol{B}u(t) + \boldsymbol{L}^{(i)}\big(y(t) - \boldsymbol{C}\hat{\boldsymbol{x}}(t)\big),$$

where $\hat{\boldsymbol{x}}(t)$ is the estimated state vector and $\boldsymbol{L}^{(i)}$ is the observer gain matrix. The observer gains are selected such that the estimation error dynamics are significantly faster than the closed-loop system dynamics, ensuring rapid convergence of the estimated states.

The estimated state vector is used both for state-feedback control and for the computation of the scheduling parameters required by the interpolation mechanism

3.4 Geometric interpolation of controllers and observers

The global control and observer gains are obtained by interpolating the local designs as functions of the instantaneous value of the scheduling parameter vector. The scheduling parameters are computed from the estimated state variables in order to ensure consistency between control and estimation.

For each vertex $\boldsymbol{\theta}^{(i)}$, the Euclidean distance to the current scheduling estimated parameter vector $\hat{\boldsymbol{\theta}}(t)$ is computed as

$$d_i(t) = \left\|\hat{\boldsymbol{\theta}}(t) - \boldsymbol{\theta}^{(i)}\right\|_2.$$

The Euclidean distance was selected due to its simplicity and its ability to provide smooth and intuitive weighting of the local designs within the parametric domain. The interpolation weights are then defined using a normalized complementary distance measure,

$$\alpha_i(t) = \frac{1 - d_i(t)/\sum_{j=1}^{N} d_j(t)}{\sum_{k=1}^{N}\left(1 - d_k(t)/\sum_{j=1}^{N} d_j(t)\right)}, \quad i = 1, \dots, N,$$

which satisfies the convexity conditions

$$\alpha_i(t) \geq 0, \quad \sum_{j=1}^{N} \alpha_i(t) = 1.$$

Using these weights, the global controller and observer gains are obtained as

$$\boldsymbol{K}(t) = \sum_{i=1}^{N} \alpha_i(t)\boldsymbol{K}^{(i)}, \quad \boldsymbol{L}(t) = \sum_{i=1}^{N} \alpha_i(t)\boldsymbol{L}^{(i)}.$$

This interpolation scheme ensures continuous gain variations as the operating point evolves, a behavior that is illustrated in the simulation results presented in Section 4. The overall quasi-LPV control architecture, illustrating the interaction between the nonlinear plant, the local controllers and observers, and the geometric interpolation mechanism, is depicted in Figure 3.

4 Results

This section presents numerical simulation results obtained using the full nonlinear model of the magnetic levitation system. The objective of these simulations is to evaluate the tracking performance, control effort, state estimation accuracy, and robustness of the proposed quasi-LPV control strategy with geometric interpolation.

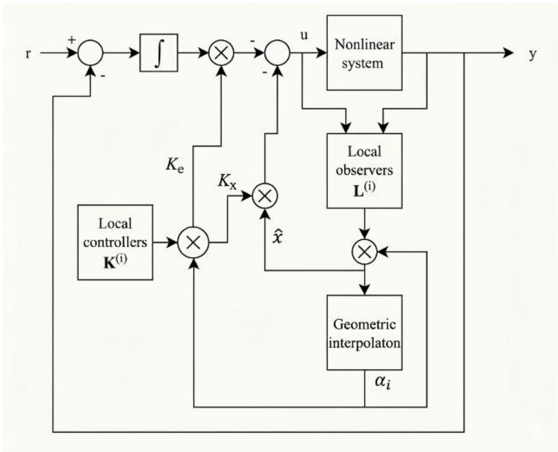

Figure 3. Overall quasi-LPV control architecture with geometric interpolation of local controllers and observers.

4.1 Simulation setup and test scenarios

All simulations were carried out in MATLAB/Simulink using the full nonlinear state-space model of the magnetic levitation system described in Section 2, with the physical parameters listed in Table 1. The control law and the computation of the scheduling parameters were executed using the estimated states derived from the local observers. To ensure consistency within the admissible operating range of the parametric domain, all initial conditions were set identically to zero.

The local tracking controllers were designed to satisfy time-domain performance specifications defined during the control synthesis stage. In particular, the desired closed-loop behavior was characterized by a limited overshoot and a specified settling time, which guided the selection of the closed-loop poles at each vertex of the quasi-LPV polytope. These specifications were chosen to ensure a fast and well-damped transient response while avoiding excessive control effort. The performance specifications were consistently met in all test scenarios.

The reference signal applied to the system consisted of constant position commands with successive step changes around the nominal equilibrium point. This test scenario was selected to evaluate the ability of the proposed control strategy to achieve accurate reference tracking and smooth transitions between operating points.

In addition to nominal tracking conditions, robustness-oriented simulations were conducted. These included external disturbances applied to the control input and additive noise in the position measurement, allowing assessment of the closed-loop behavior under non-ideal operating conditions.

4.2 Reference tracking performance

The tracking performance of the proposed control strategy is illustrated in Figure 4. This figure shows the time evolution of the sphere position $x_1(t)$ compared with the reference signal for a sequence of step changes.

As observed in the figure, the closed-loop system achieves accurate tracking of the reference position with zero steady-state error. The transient response remains well behaved, with no excessive overshoot or oscillatory behavior, despite the intrinsic open-loop instability and strong nonlinearities of the plant. These results confirm the effectiveness of the local tracking controllers and the geometric interpolation mechanism in achieving consistent performance across the operating range.

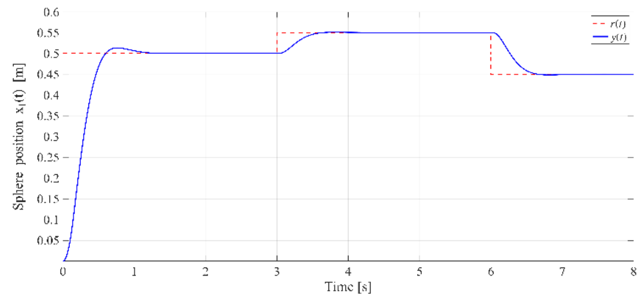

Figure 4. Reference tracking performance of the magnetic levitation system under the proposed quasi-LPV control scheme.

4.3 Control effort and actuation behavior

The corresponding control input $u(t)$ generated during the tracking experiment is shown in Figure 5. The control signal remains bounded throughout the simulation and exhibits smooth variations as the reference changes.

The absence of high-frequency oscillations or large control peaks indicates that the interpolated controller does not introduce aggressive or impractical actuation demands. This behavior is particularly relevant for magnetic levitation systems, where actuator saturation and unidirectional input constraints must be considered. The results demonstrate that the proposed control strategy achieves the desired tracking performance while maintaining a reasonable control effort.

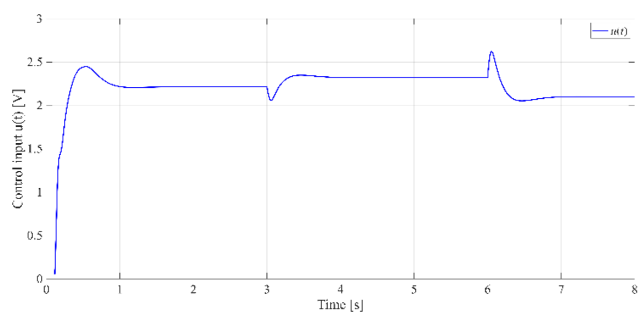

Figure 5. Control input corresponding to the reference tracking experiment.

4.4 Scheduling parameters and interpolation weights

The evolution of the scheduling parameters and the corresponding interpolation weights is shown in Figures 6 and 7, respectively. The parameters vary continuously within their prescribed bounds as the operating point of the system changes.

The interpolation weights remain positive and sum to unity at all times, confirming that the geometric interpolation mechanism produces convex combinations of the local controllers and observers. The smooth variation of the weights ensures gradual transitions between local designs and prevents abrupt changes in the control law, contributing to the overall robustness and numerical stability of the closed-loop system.

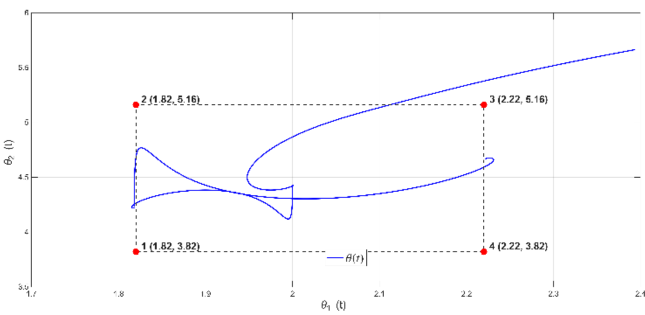

Figure 6. Time evolution of the scheduling parameter vector $\boldsymbol{\theta}(t)$ during the reference tracking experiment.

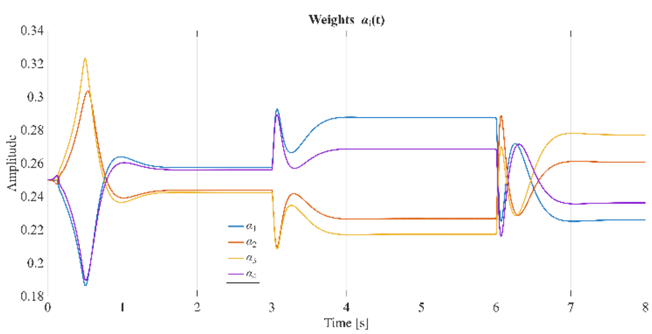

Figure 7. Time evolution of the geometric interpolation weights $\alpha_i(t)$ associated with the quasi-LPV controller.

4.5 Robustness assessment

The robustness of the proposed quasi-LPV control strategy was evaluated through simulation experiments addressing two representative non-ideal operating conditions: external disturbances applied to the control input and measurement noise affecting the system output. These scenarios are particularly relevant in magnetic levitation applications, where actuator imperfections and noisy sensing are commonly encountered.

The closed-loop response of the system under an external disturbance acting on the control input is shown in Figure 8. In this experiment, a constant additive disturbance of 0.21 V was applied to the control input starting at $t = 4.5$ s while the system was tracking a constant reference position. The disturbance produces a transient deviation in the output; however, the controller rapidly compensates for its effect and restores accurate reference tracking. No sustained oscillations or instability are observed after the disturbance is applied, indicating effective disturbance rejection capability.

The robustness of the proposed scheme with respect to measurement noise is analyzed next. In this case, additive noise was introduced in the measurement of the sphere position, which is the only directly measured output of the system. The noise signal corresponds to band-limited white noise with zero mean and finite variance, representing sensor noise and electronic measurement imperfections commonly encountered in practical implementations. The resulting closed-loop response of the system in the presence of measurement noise is shown in Figure 9. Despite the noisy measurement, the system remains stable and preserves satisfactory reference tracking. Small fluctuations in the output are observed as a consequence of the measurement noise; however, these oscillations remain bounded and do not compromise the overall tracking performance. The corresponding control signal generated under noisy measurement conditions is depicted in Figure 10. As expected, the control input exhibits oscillatory behavior associated with the observer-based compensation of the noisy output signal. Nevertheless, the control effort remains bounded and does not exhibit drift or instability, confirming that the observer and the geometric interpolation mechanism operate coherently in the presence of measurement noise.

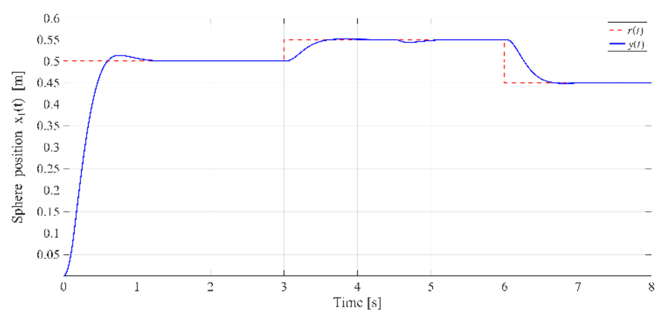

Figure 8. Closed-loop response under an input disturbance during reference tracking.

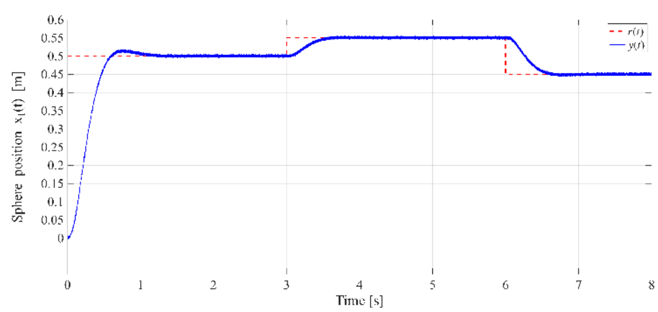

Figure 9. Closed-loop response under output measurement noise during reference tracking.

Overall, the robustness results indicate that the proposed quasi-LPV control strategy with geometric interpolation maintains stability and acceptable performance under both input disturbances and output measurement noise. The separation between control and estimation dynamics, together with the smooth interpolation of local controllers and observers, contributes to the reliable behavior of the closed-loop system under non-ideal operating conditions.

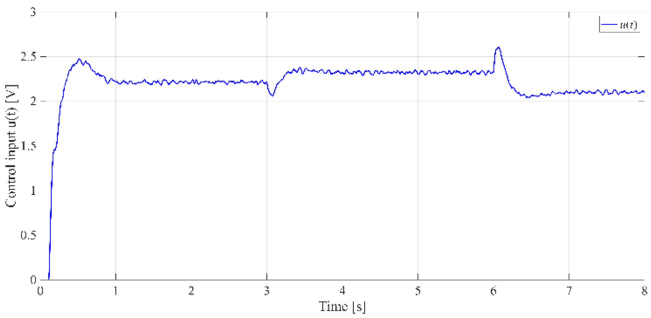

Figure 10. Control input under output measurement noise

5 Conclusions

This article has presented a gain-scheduling control strategy for a magnetic levitation system based on a quasi-LPV modeling framework and a geometric interpolation mechanism. By incorporating the nonlinear dynamics of the plant into an endogenous and bounded parameter vector, the original nonlinear system was represented as a family of linear time-invariant models evaluated over a compact parametric domain. This formulation enabled the systematic design of local tracking controllers and state observers using linear state-space techniques.

A central contribution of this work is the adoption of a distance-based geometric interpolation scheme to combine the local designs into a global controller and observer. Unlike analytical interpolation approaches, the proposed mechanism guarantees convex combinations and strictly positive interpolation weights throughout the operating region, which is particularly advantageous for magnetic levitation systems subject to physical constraints on the control input. This feature simplifies the implementation while preserving smooth gain variations and consistent closed-loop behavior.

Simulation results obtained using the full nonlinear model confirmed that the proposed control strategy achieves accurate tracking of constant reference positions with bounded control effort, despite the intrinsic open-loop instability of the plant and the presence of disturbances and measurement noise. The use of full-order state observers provided reliable estimation of the non-measurable states and ensured coherent scheduling parameter computation for the interpolation process.

Overall, the results demonstrate that geometric interpolation constitutes an effective and practically attractive alternative to analytical interpolation methods within quasi-LPV control schemes, particularly for nonlinear and open-loop unstable systems such as magnetic levitation plants. The proposed approach achieves a favorable balance between modeling fidelity, implementation simplicity, and control performance.

Future work will focus on experimental validation using a laboratory-scale magnetic levitation setup, the extension of the methodology to discrete-time implementations, and the incorporation of actuator and state constraints within the quasi-LPV framework.

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