Applied Science and Engineering Progress, Vol. 20, No. 4, 2027, 8397

Review Article

Recent Advances in Multi-Input Multi-Output (MIMO) H_∞ Control for Active Vibration Isolation in Semiconductor Metrology

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Received: 9 September 2026; Revised: 24 October 2026; Accepted: 10 November 2026; Published online: 24 November 2026
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Abstract
Semiconductor manufacturing increasingly demands a sub-nanometer positioning accuracy, imposing stringent requirements on active vibration isolation (AVI) in precision metrology systems. Among available strategies, multi-input multi-output (MIMO) H-infinity (H_∞) control has emerged as an effective framework for achieving robust disturbance rejection under modeling uncertainties. This paper explores recent advances in MIMO H_∞ control for semiconductor metrology. Other alternative control strategies are also compared to highlight the advantages and limitations of H_∞ control. Current technical challenges and the emerging research directions, such as data-driven modeling, intelligent control, and advanced sensing technologies, are outlined. The review also examines trade-offs involving controller bandwidth, model uncertainty, computational requirements, actuator limitations, and experimental validation. The reviewed studies indicate that the hybrid architectures combining H_∞ feedback with disturbance observers, feedforward compensation, or sensor fusion can improve disturbance rejection relative to standalone H_∞ feedback under specific operating conditions, although their benefits depend on model accuracy, sensing quality, and implementation constraints.

Keywords: Active vibration isolation, MIMO H-infinity control, Precision motion systems, Robust control, Semiconductor metrology

1 Introduction

The continuous scaling of semiconductor manufacturing has imposed increasingly stringent requirements on positioning accuracy and vibration suppression in advanced lithography and metrology systems [1]-[3]. Unlike conventional single-input single-output (SISO) systems, semiconductor positioning stages are inherently multiple-input multiple-output (MIMO) systems in which multiple actuators regulate several translational and rotational degrees of freedom [2], [4], [5]. Among robust control methodologies, H-infinity (H_∞) control has become an important framework for precision motion systems because it systematically addresses model uncertainties, external disturbances, and performance trade-offs [6], [7]. By minimizing the worst-case closed-loop gain, H_∞ control provides robust disturbance attenuation and stability for modeled uncertainties, making it well suited to semiconductor metrology and active vibration isolation (AVI) [6], [8].

Recent control strategies for AVI have increasingly integrated MIMO system identification, H_∞ control, disturbance observers (DOBs), feedforward compensation, and data-driven methods. These developments have improved multivariable modeling, decoupling, disturbance rejection, and tracking performance in wafer stages and precision vibration isolation platforms [1], [2], [5]. Although significant progress has been achieved, relatively few comprehensive reviews have focused specifically on MIMO H_∞ control for active vibration isolation in semiconductor metrology. Existing reviews also provide limited discussion of the integration of robust multivariable control with data-driven identification, sensor fusion, feedforward compensation, disturbance observers, and intelligent control. Consequently,

Applied Science and Engineering Progress, Vol. 20, No. 4, 2027, 8397

a comprehensive assessment of these complementary developments remains needed to better identify current challenges and future research opportunities. Figure 1 provides an overview of the review, illustrating the relationships between disturbance sources, 6-DOF active vibration isolation systems, MIMO modeling and decoupling, robust H_∞ controller design, complementary control strategies, and the resulting performance improvements.

The scope of this review primarily encompasses MIMO H_∞ control and closely related robust-control strategies for active vibration isolation and precision motion systems directly relevant to semiconductor metrology, including metrology frames, wafer/lithography stages, and multi-DOF positioning platforms. Studies on pneumatic isolators, seismic isolation platforms, general 6-DOF AVI systems, and nanopositioning systems are included selectively when their control architectures, disturbance-rejection strategies, sensing approaches, or implementation methods are transferable to semiconductor metrology. These supporting studies are not treated as having identical disturbance spectra, bandwidths, actuator/sensor configurations, or performance requirements; rather, they are used to identify control principles and implementation strategies relevant to semiconductor precision systems.

Relevant disturbance sources include floor-transmitted vibrations, reaction forces and torques generated by moving stages, and acoustic excitation. Sensor noise additionally affects the feedback measurements and can limit achievable isolation performance [1], [8].

2 Review Methodology

This review provides a narrative synthesis of recent advances in MIMO H_∞ control for active vibration isolation (AVI) in semiconductor metrology. The literature was identified through searches of major scientific databases, including IEEE Xplore, ScienceDirect, SpringerLink, and Scopus, using combinations of keywords such as MIMO H_∞ control, active vibration isolation, semiconductor metrology, precision motion systems, disturbance observer, feedforward control, system identification, and wafer stage. The complete database-specific search strings, search fields, filters, and search dates are provided in Supplementary Table S1.

The literature was categorized into (i) studies directly addressing semiconductor metrology and precision motion systems and (ii) supporting AVI/control studies from adjacent precision-engineering applications whose MIMO, H_∞, sensing, disturbance-rejection, or real-time implementation methods are transferable to semiconductor metrology. Emphasis was placed on peer-reviewed journal articles published primarily during the last decade, together with several widely recognized earlier studies that established the theoretical foundations of robust H_∞ control. English-language publications were considered to support theoretical foundations and contextual discussion. Full-text availability was required for detailed technical assessment.

The literature search was completed in August 2026 and primarily covered publications from 2016 to 2026. Earlier foundational sources were identified through backward citation searching of relevant publications and targeted searches for established control-theory references. These sources were included selectively to explain theoretical foundations, established control methods, and vibration-evaluation criteria, rather than to represent recent research advances. The 2016–2026 restriction applied to the main database searches, whereas these

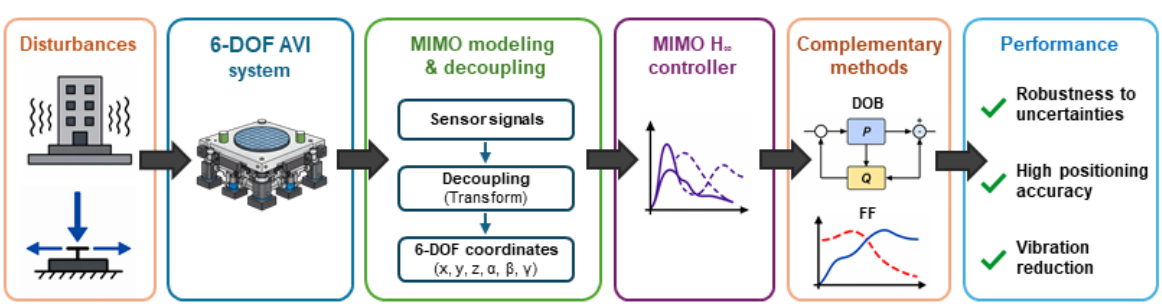


Figure 1: Overall framework of MIMO H_∞ control strategies for active vibration isolation in semiconductor precision motion systems.

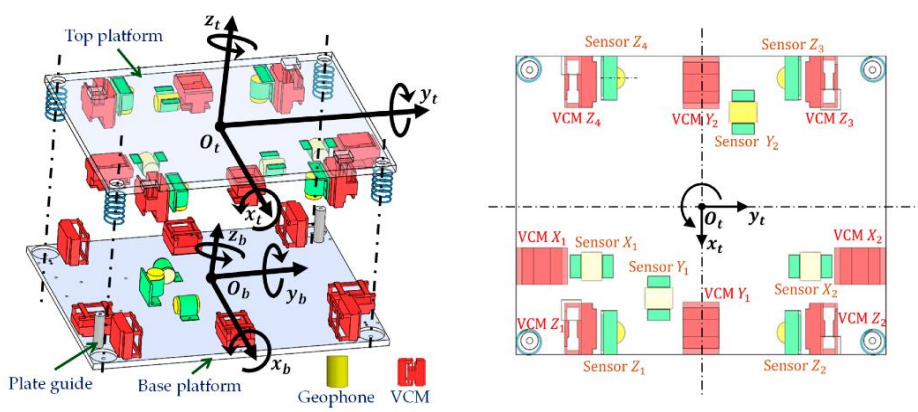
supplementary searches had no publication-year restriction. Studies were included if they addressed MIMO H_∞ control, AVI, or semiconductor precision motion, or presented modeling, sensing, disturbance-rejection, or implementation methods transferable to these applications. Publications were excluded if they lacked direct relevance or a transferable method, or provided insufficient technical information for the synthesis. Following duplicate removal, 70 records from the database searches were screened, of which 29 publications were included. Five earlier foundational publications were identified through supplementary searches, bringing the total number of publications included in the literature synthesis to 34. One additional supporting reference was cited for contextual discussion, bringing the total number of cited references to 35.

Semiconductor technology nodes (nm/μm) were recorded where explicitly reported in the selected publications. Studies without an explicit node designation were classified as "not reported," while general vibration-isolation studies without a semiconductor application were classified as "not applicable." Positioning accuracy, tracking error, and vibration amplitude were not used to infer technology nodes.

Duplicate records were identified by comparing titles, authors, and publication identifiers and removed before screening. Screening comprised an initial assessment of titles and abstracts, followed by full-text assessment of potentially eligible publications against the inclusion and exclusion criteria. The study-selection process, including the numbers excluded at each stage and the reasons for full-text exclusion, is presented in Supplementary Figure S1. The selected publications were analyzed with respect to modeling approaches, controller synthesis, experimental validation, disturbance rejection performance, implementation strategies, and practical limitations. Rather than providing a comprehensive bibliometric survey, this review synthesizes representative contributions to identify current research trends, compare alternative control approaches, highlight remaining technical challenges, and discuss future research directions for semiconductor precision motion systems.

3 Active vibration isolation in semiconductor metrology

Active vibration isolation (AVI) is a key technology to achieve sub-nanometer positioning accuracy in semiconductor metrology systems. Semiconductor metrology systems therefore require vibration suppression over a broad frequency range while maintaining robustness against modeling uncertainties and minimizing multiaxis coupling [1], [2]. Modern semiconductor equipment commonly employs six-degree-of-freedom (6-DOF) active vibration isolation platforms based on pneumatic actuators and precision mechatronic architectures to achieve high positioning stability and vibration suppression [9], [10]. Figure 2 shows a representative 6-DOF AVI system with



(**a**) (**b**)

Figure 2: Representative configuration of a 6-DOF AVI system. (**a**) Exploded view illustrating the main structural components, including the top and base platforms, voice-coil motors, geophones, and coordinate systems. (**b**) Top view showing the arrangement of the actuators and sensors on the upper platform. Reproduced under a CC BY 4.0 license [10].

Applied Science and Engineering Progress, Vol. 20, No. 4, 2027, 8397

its principal mechanical components, actuator layout, and sensor arrangement used for precision multiaxis motion control [10].

Recent developments have integrated active isolation with feedforward compensation, disturbance estimation, and data-driven control, which can lead to improved disturbance rejection and tracking performance [2], [5]. Multi-stage positioning architectures, which combine coarse and fine motion stages, have further improved the accuracy of positioning by simultaneously achieving large travel ranges and high dynamic performance [2].

Because semiconductor isolation platforms operate as MIMO systems, multiple sensors and actuators are distributed to regulate all controlled degrees of freedom simultaneously [9], [10], [11]. For further enhancing the measurement bandwidth and robustness against sensor noise, modern AVI systems increasingly employ sensor-fusion techniques that combine complementary sensing modalities [1], [7]. Accurate dynamic models are fundamental to high-performance AVI because semiconductor positioning platforms exhibit structural flexibility, multiaxis coupling, and position-dependent dynamics. Modern semiconductor systems therefore employ multivariable state-space and frequency-domain models, often developed using frequency response function (FRF) identification, to support robust controller design [1], [11], [12].

4 MIMO H_∞ control for active vibration isolation

The increasing complexity of semiconductor metrology systems has made robust MIMO control essential to achieve a sub-nanometer positioning accuracy [2]. By explicitly accounting for multivariable coupling, modeling uncertainties, and external disturbances, MIMO H_∞ control provides an effective framework for high-performance active vibration isolation (AVI) [8], [10].

4.1 *Fundamentals of H_∞ robust control*

H_∞ control achieves robust disturbance attenuation and stability by explicitly accounting for model uncertainties and performance objectives through mixed-sensitivity or frequency-shaped optimization, making it well suited to semiconductor metrology and AVI [6], [8]. For AVI, the plant is commonly represented by a generalized state-space model incorporating system dynamics, external disturbances, measurement noise, and model uncertainties [6]. A representative state-space formulation for an active vibration isolation system is given by [10]:

$$\dot{X} = AX + BU_v + DX_b + F_t, \tag{1}$$

$$Y = CX, \tag{2}$$

where, $\dot{X}$ denotes the time derivative of the state vector, X is the state vector, U_v is the control input, X_b represents the base-platform vibration, F_t denotes the external disturbances, and Y is the measured output. A, B, C, and D are the state, control-input, output, and base-vibration input matrices, respectively.

Controlled-output and manipulated-input selection defines the motions regulated by a MIMO controller and the available actuation channels. In semiconductor stages, controlled variables include task-relevant translational and rotational positions [1], whereas AVI systems may regulate platform velocities or accelerations [8], [10]. For example, [10] uses six-DOF velocity outputs and generalized force/torque inputs generated by voice-coil motors, while [6] uses a pneumatic-valve voltage command as the manipulated input. Sensor and actuator arrangements should support the targeted motions while accounting for cross-axis coupling, measurement noise, and actuator limitations [1], [6], [10]. In H_∞ synthesis, measured feedback signals are distinguished from weighted performance outputs, which express objectives such as vibration suppression and limits on control effort [6], [8].

The objective of H_∞ controller synthesis is to determine a robust controller that minimizes the worst-case effect of external disturbances and model uncertainties on the closed-loop system. This optimization problem can be expressed as [7], [13], [14]:

$$\inf_{K \in \mathcal{K}} \|T_{zw}(s;K)\|_\infty \tag{3}$$

where $\mathcal{K}$ denotes the set of internally stabilizing controllers, K is the controller, $T_{zw}(s;K)$ is the closed-loop transfer matrix from the exogenous input w to the weighted performance output z, and $\|\cdot\|_\infty$denotes the H_∞ norm. For a prescribed performance bound $\gamma > 0$, the corresponding suboptimal problem seeks a controller $\mathcal{K} \in \mathrm{K}$ satisfying $\|T_{zw}(s;K)\|_\infty < \gamma$. The H_∞ norm represents the maximum singular value of the system transfer function over all frequencies and is defined as [6], [7]:

$$\|G(s)\|_\infty = \sup_\omega \bar{\sigma}\big(G(j\omega)\big), \quad (4)$$

where $\bar{\sigma}(\cdot)$ denotes the maximum singular value of the transfer function matrix. A standard mixed-sensitivity formulation uses the output sensitivity matrix $S(s) = [I + G(s)K(s)]^{-1}$ and complementary sensitivity matrix $T(s) = I - S(s) = G(s)K(s)[I + G(s)K(s)]^{-1}$, where $G(s)$ is the plant transfer matrix and I is the identity matrix of appropriate dimension. These matrices are shaped using frequency-dependent weighting functions [14]. The corresponding performance requirement is:

$$\left\| \begin{bmatrix} W_1(s)S(s) \\ W_2(s)K(s)S(s) \\ W_3(s)T(s) \end{bmatrix} \right\|_\infty < \gamma \quad (5)$$

where $W_1(s)$, $W_2(s)$, and $W_3(s)$ are stable, proper weighting transfer functions or matrices of compatible dimensions.

They shape tracking and disturbance rejection through *S,* penalize control effort through *KS,* and shape noise attenuation and robustness through *T,* respectively. The positive scalar γ bounds the H_∞ norm of the stacked weighted transfer matrix, and synthesis seeks the smallest achievable bound subject to internal stability [14]. In semiconductor active vibration isolation systems, weighting functions are selected to suppress low-frequency floor vibrations and reaction-force disturbances while limiting actuator saturation, measurement-noise amplification, and high-frequency structural resonances. Consequently, the choice of weighting functions represents a critical design step that determines the achievable closed-loop performance, closed-loop bandwidth, and robustness of high-precision motion systems [13], [15]. In practice, H_∞ controllers are typically synthesized using the algebraic Riccati equation or linear matrix inequality (LMI)-based methods, while recent active vibration isolation systems commonly employ mixed-sensitivity H_∞ loop-shaping to improve closed-loop robustness and disturbance rejection [6], [7], [8], [16]. For systems with structured model uncertainties, μ-synthesis uses the structured singular value μ to guide controller design for robust stability and performance. A common solution approach is D–K iteration, where D denotes scaling matrices and K denotes the controller. The procedure alternates between controller synthesis with fixed scalings and updating the scalings to reduce an upper bound on μ [14], [17]. Riccati-based synthesis is computationally efficient for standard H_∞ control problems, whereas LMI-based synthesis provides greater flexibility for handling multiple design constraints and uncertainties [13], [18], [19].

From an implementation perspective, the practical deployment of MIMO H_∞ controllers requires balancing robust control performance with computational and real-time constraints. High-order controllers often require model reduction or computationally efficient implementations to satisfy the stringent sampling-rate and real-time requirements of precision motion systems [1], [3]. Also, practical controller design involves balancing controller complexity, robustness, control bandwidth, disturbance rejection, and actuator limitations while maintaining high positioning accuracy in the presence of flexible dynamics and model uncertainties [2], [5]. Collectively, mixed-sensitivity optimization and loop-shaping remain the dominant H_∞ synthesis approaches because they provide an effective balance among disturbance rejection, tracking performance, robustness, and control effort [6], [7].

4.2 *MIMO system modeling*

Mechanical degrees of freedom (DOF) denote independent motion coordinates, while controlled DOFs denote the coordinates actively regulated. An unconstrained rigid platform has six mechanical DOFs: three translations and three rotations, although a study may control only a subset. These counts differ from model order, which denotes the number of states in a state-space realization. A model with six second-order rigid-body motion coordinates typically contains 12 displacement and velocity states; actuator, sensor, and flexible dynamics can introduce additional states. Furthermore, a two-degree-of-freedom control architecture denotes separate reference and feedback paths, rather than two mechanical motion coordinates.

Accurate dynamic modeling is fundamental to the design of high-performance MIMO H_∞ controllers [1], [2]. State-space models are widely used to describe the coupled dynamics of AVI systems by incorporating actuator dynamics, sensor dynamics, flexible modes, and external disturbance inputs [1], [10]. As semiconductor motion systems exhibit complex structural dynamics, experimental system identification has become an essential step in the development of high-performance controllers [11],

Applied Science and Engineering Progress, Vol. 20, No. 4, 2027, 8397

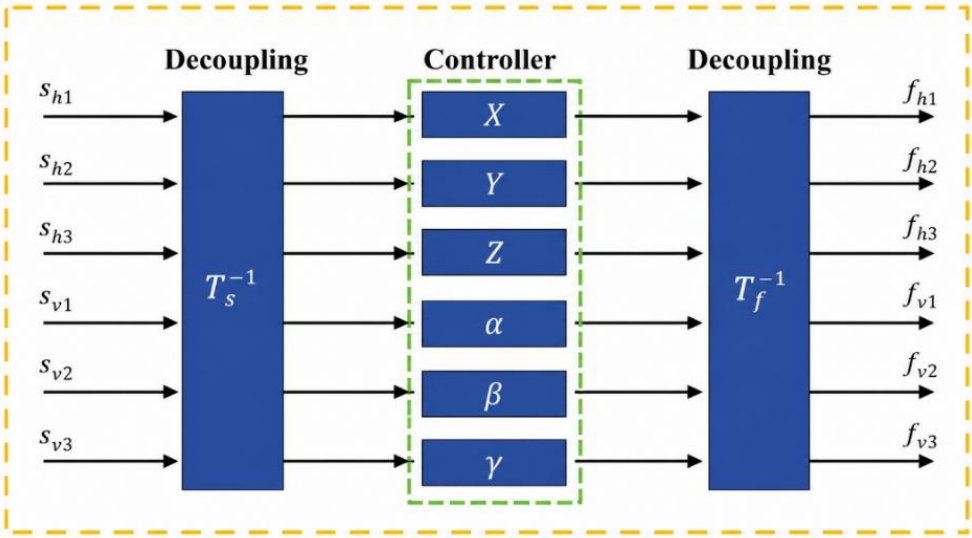


Figure 3: Representative MIMO-to-SISO decoupling framework for a 6-DOF AVI system. Sensor measurements are transformed into decoupled translational (X, Y, Z) and rotational (α, β, γ) coordinates for independent axis control before being mapped back to the physical actuators through inverse coordinate transformations. Adapted under the CC BY 4.0 license [20].

[12]. Figure 3 shows a representative MIMO-to-SISO decoupling strategy for a 6-DOF AVI system, where sensor signals are transformed into the decoupled motion coordinates for independent axis control before being mapped back to the actuators [20]. Here, s and f denote the sensor measurements and actuator commands, respectively, while T_s^{-1} and T_f^{-1} represent the coordinate transformation matrices that used for MIMO decoupling.

FRF identification is widely used for characterizing precision motion systems [12]. Recent frequency-domain identification methods, which employ physically structured model parameterizations, have further improved model accuracy [11], [12]. Recent approaches combine modal analysis with data-driven identification to model flexible dynamics across the operating workspace, improving vibration suppression in advanced wafer stages [11], [21]. Data-driven modeling and identification can improve MIMO control by providing more accurate representations of cross-axis coupling, flexible modes, and the position-dependent dynamics that are difficult to capture using fixed models. These approaches can improve the decoupling and provide more control-relevant dynamic models, while data-driven position-dependent compensation can enhance tracking performance under varying operating conditions [4], [11], [21], [22]. Such improvements can complement robust H_∞ control by reducing the mismatch between the nominal model and the actual system dynamics.

Reducing cross-axis coupling is another important aspect of MIMO modeling [2]. Recently conducted studies have introduced data-driven calibration methods that can significantly enhance tracking accuracy and disturbance rejection [4].

4.3 *Controller design and synthesis*

Through weighting-function design and mixed-sensitivity or loop-shaping optimization, H_∞ control provides a systematic framework to balance tracking performance, robustness, and control effort [6], [7]. Mixed-sensitivity optimization is one of the most commonly adopted H_∞ synthesis methods, as it can effectively balance disturbance rejection, robust performance, and control effort [6], [10].

Modern semiconductor motion systems normally use two-degree-of-freedom (2-DOF) control architectures that combine robust feedback with feedforward compensation [2]. Recently developed data-driven feedforward approaches have significantly enhanced the tracking accuracy in ultra-precision wafer stages [22]. Developments have integrated H_∞ control with disturbance observers (DOBs), virtual sensor fusion, and data-driven

techniques for further improving disturbance rejection and robustness [5], [7].

4.4 *Practical implementation*

The practical implementation of MIMO H_∞ controllers requires efficient real-time computation in addition to robust controller design. Because wafer scanners and AVI systems operate at high sampling rates, controller complexity, computational latency, and hardware constraints must be carefully considered to enable real-time implementation [2], [23]. The resulting controllers are typically implemented on field-programmable gate array (FPGA)-based or other real-time motion control platforms to achieve the computational efficiency and deterministic execution required for high-speed MIMO motion control [2], [23].

Recent developments in frequency-domain system identification, data-driven feedforward compensation, and FPGA-based acceleration have enhanced the model accuracy, tracking performance, and computational efficiency for advanced semiconductor manufacturing equipment [11], [22], [24].

Controller bandwidth should be assessed against model reliability, sensing quality, and implementation constraints. Increasing bandwidth can improve disturbance rejection but also increases sensitivity to noise, unmodeled flexible modes, and delay. For example, the wafer-stage example in [1] uses a 5 kHz sampling frequency, while its rigid-body approximation becomes inadequate beyond approximately 500 Hz. These values illustrate a system-specific limitation rather than a universal bandwidth or sampling requirement. Furthermore, [8] synthesizes its controller using a nominal model and checks stability afterward, identifying unmodeled high-frequency dynamics as a remaining robustness concern. Thus, nominal performance should not be interpreted as proof of robustness across operating conditions.

Controller order creates an additional implementation trade-off. In [8], the H_∞ controller has twice as many states as the physics-driven controller, motivating order reduction and further implementation work. Reduced controllers require renewed performance and stability checks, and sampling rates should accommodate the intended bandwidth together with computation and conversion delays [14]. Actuator limits also require explicit assessment: penalizing control effort does not guarantee compliance with hard saturation constraints, whereas [6] explicitly addresses valve-voltage saturation. Validation strength varies across studies: [8] evaluates controller performance through analysis and simulation using an experimentally characterized setup, while [6] and [10] report hardware experiments. The payload tests in [10] provide evidence of robustness to loading changes, but broader tests of operating conditions and disturbance spectra remain necessary before generalizing performance to semiconductor metrology.

5 Recent research and comparative analysis

Alternative control strategies, such as proportional–integral–derivative (PID) control, model predictive control (MPC), and adaptive or data-driven control, have also been studied for multivariable control systems [25] and precision motion applications [2], [5], [7], [11].

5.1 *Recent advances in MIMO H_∞ control*

The reviewed studies show that recent advances in MIMO H_∞ control have extended beyond improving theoretical robustness toward developing practical control architectures for semiconductor metrology [3], [5], [6], [7], [8], [10], [23]. Although these approaches share the common objective of improving disturbance rejection and positioning accuracy, they address different technical challenges via complementary strategies, such as improved system identification, disturbance observers (DOBs), feedforward compensation, virtual sensor fusion, and position-dependent modeling [3], [4], [5], [7], [11], [21], [22]. Rather than relying only on robust controller synthesis, recent research increasingly integrates these techniques for improving modeling accuracy, robustness, and real-time implementation under realistic operating conditions [3], [5], [7], [22], [24]. This trend can show a shift from standalone H_∞ controllers toward integrated control frameworks that better address the requirements of modern semiconductor manufacturing, including high positioning accuracy, computational efficiency, and real-time implementation. Despite these advances, challenges remain in addressing strong MIMO coupling, systematic weighting-function design, and robust controller implementation under varying operating conditions [6], [7], [16].

Applied Science and Engineering Progress, Vol. 20, No. 4, 2027, 8397

Table 1 distinguishes studies directly addressing semiconductor metrology or wafer-stage systems from supporting studies in adjacent applications. Supporting studies are included for their transferable control methods; their reported performance does not constitute direct validation for semiconductor metrology.

Vibration attenuation, trajectory tracking, and positioning accuracy represent distinct performance objectives. Vibration attenuation concerns the reduction of disturbance-induced motion and is assessed using transmissibility, frequency-dependent attenuation, or residual vibration RMS. Trajectory tracking concerns deviation from a time-varying

Table 1: Comparison of representative robust and complementary control strategies relevant to active vibration isolation and semiconductor precision motion systems.

Control Strategy	Application domain	Controlled DOF	Primary Objective	Reported Performance	Experimental Validation	Relevance to semiconductor metrology	Semiconductor technology node (nm/μm)	Ref. / Year
Mixed-sensitivity H_∞ feedback and feedforward	Metrology-frame active vibration isolation (AVI)	1-vertical	Floor vibration and disturbance-force rejection	Reduced sensor-noise amplification while maintaining disturbance rejection comparable to manually tuned controllers	Experimental metrology-frame model; controller evaluated by frequency-domain analysis and simulation.	Supporting-metrology-frame AVI; semiconductor application not explicitly established	Not applicable	[8] (2017)
H_∞ vs. PID	General hybrid AVI	6	Hybrid active-passive vibration isolation	Transmissibility of −10 to −48 dB at passive resonance; at least 4 dB better than acceleration-sensor systems	Experimental prototype	Supporting	Not applicable	[26] (2017)
Self-tuning MIMO disturbance feedforward	Precision 6-DOF AVI	6	Floor vibration rejection	Significant improvement in floor-vibration rejection with computationally efficient self-tuning finite-impulse-response (FIR) implementation	6-DOF Stewart platform	Supporting	Not applicable	[23] (2018)
Mixed-sensitivity H_∞ robust decoupling	General 6-DOF AVI	6	Robust decoupling and vibration isolation	Experimental comparison with passive and proportional–derivative (PD)-controlled systems demonstrated improved robustness and interaction suppression	Experimental AVI system	Supporting	Not applicable	[10] (2024)
Frequency-shaped H_∞ with input saturation	Pneumatic AVI	1	Low-frequency pneumatic vibration isolation	Effective suppression of 1–10 Hz disturbances while respecting actuator voltage limits	Pneumatic vibration isolator	Supporting	Not applicable	[6] (2024)

Table 1: (Continued) Comparison of representative robust and complementary control strategies relevant to active vibration isolation and semiconductor precision motion systems.

Control Strategy	Application domain	Controlled DOF	Primary Objective	Reported Performance	Experimental Validation	Relevance to semiconductor metrology	Semiconductor technology node (nm/μm)	Ref. / Year
Position-dependent flexible-mode compensation	EUV wafer-stage positioning	Multi-DOF	Compensation of flexible dynamics	Real-time implementation using computationally efficient position-dependent weighting functions for nanometer-level wafer-stage positioning	Extreme ultraviolet (EUV) wafer stage	Direct—semiconductor precision motion	Not reported	[3] (2025)
MIMO H_∞ + DOB control	Semiconductor precision-motion platform	6	Torque-disturbance rejection and decoupling	100-fold reduction in control error with ±0.09 μm translational and ±0.06 μrad rotational tracking error.	Semiconductor motion platform	Direct—semiconductor precision motion	Not reported	[5] (2026)
Enhanced H_∞ loop shaping with virtual sensor fusion	Seismic AVI	3	Seismic vibration isolation	Up to 65 dB vibration attenuation within the 0.1–10 Hz frequency band	3-DOF isolation platform	Supporting	Not applicable	[7] (2026)

Note: Direct denotes semiconductor equipment or wafer/lithography-stage studies; Supporting denotes transferable methods from adjacent applications. Direct relevance does not imply metrology-frame isolation validation. Technology node refers to the fabrication node, not motion accuracy or vibration amplitude. "Not reported" indicates an unspecified node in a semiconductor-specific study; "Not applicable" indicates no semiconductor-specific application beyond background motivation.

reference and is assessed using RMS or peak tracking error. Positioning accuracy concerns deviation from the intended position under specified operating conditions and should be distinguished from resolution and repeatability. Accordingly, the results in Table 1 are interpreted according to the objective and metric reported in each study; improvements in one objective do not automatically establish improvements in the others.

The studies in Table 1 span different application domains and test conditions; therefore, their reported performance values should not be interpreted as directly comparable. Metrics such as vibration attenuation, tracking error, and disturbance-rejection improvement depend on the disturbance type and frequency range, controlled variable, reference baseline, sensor/actuator configuration, and experimental conditions. Accordingly, the quantitative results in Table 1 are presented primarily to demonstrate the performance achieved within each study rather than to establish a direct ranking among the control strategies. The representative studies summarized in Table 1 show a broader evolution in robust and complementary control strategies for active vibration isolation and semiconductor precision motion systems. Earlier approaches emphasized systematic mixed-sensitivity feedback–feedforward design, robust decoupling, and disturbance rejection, whereas more recent studies increasingly integrate H_∞ control or conventional motion-control architectures with disturbance observers, virtual sensor fusion, frequency shaping, data-driven identification, self-tuning feedforward compensation, and position-dependent flexible-mode control [3], [5], [6], [7], [8], [10], [23]. Recent research also places greater emphasis on modeling accuracy, computational efficiency, and real-time implementation to address the increasingly stringent performance requirements of semiconductor manufacturing and precision engineering [2], [3], [11], [24]. Despite the reported improvements in vibration attenuation, positioning accuracy, and practical implementation, challenges remain in systematically addressing strong multivariable coupling, position-dependent dynamics, weighting-function selection, and computational complexity under varying operating conditions.

Applied Science and Engineering Progress, Vol. 20, No. 4, 2027, 8397

Overall, the available evidence suggests that future progress will depend on tighter integration of robust control with advanced system identification, sensing, disturbance estimation, and computationally efficient implementation rather than on further refinement of standalone controller synthesis.

5.2 *Comparison with alternative control strategies*

Although MIMO H_∞ control is a well-established robust control methodology for semiconductor motion systems, alternative control strategies have also been investigated in precision motion applications and other coupled MIMO systems, offering distinct advantages and limitations in terms of disturbance rejection, robustness, computational complexity, and implementation requirements [2], [27], [28].

Table 2 provides descriptive comparisons rather than a universal performance ranking. Quantitative comparison requires common test conditions and consistently reported indices, including frequency-dependent vibration attenuation or transmissibility, RMS motion or tracking error, settling time, control effort, and robustness margins. Because the reviewed studies differ in disturbance spectra, controlled variables, hardware, and evaluation procedures, their reported results cannot establish a consistent numerical ranking across control strategies.

Compared with standalone H_∞ feedback, conventional PID generally offers simpler implementation but does not explicitly optimize multivariable robustness [14]. Adding a disturbance observer can help recover nominal performance under plant uncertainty and external disturbances, but its benefits depend on observer-filter design and stability conditions. Increasing observer bandwidth introduces trade-offs involving measurement noise and unmodeled dynamics, so improvement over standalone H_∞ feedback is not automatic [29]. Standard online MPC explicitly handles state and input constraints but requires constrained optimization at each sampling instant, making computational feasibility an important consideration [30]. These approaches therefore involve different trade-offs among robustness, constraint handling, computational demands, and implementation complexity, rather than a universal performance ranking.

Table 2 shows that a single control strategy is not universally optimal, because each involves trade-offs among robustness, computational complexity, and implementation requirements. Compared with classical PID controllers, which are straightforward to implement but exhibit limited robustness to model uncertainty and multivariable coupling, H_∞ control provides a systematic framework for robust disturbance rejection and performance optimization in precision motion systems. Contrary to MPC, which offers effective constraint handling but requires computationally intensive online optimization, H_∞ control generally can achieve a practical balance between robustness and computational efficiency for real-time precision engineering and semiconductor applications. Likewise, adaptive and data-driven control approaches can enhance performance under varying operating conditions; however, their effectiveness depends on the quality of system adaptation, model identification, and available data. Consequently, recent research has increasingly explored hybrid H_∞-based architectures that integrate feedforward compensation, DOBs, virtual sensor fusion, and other complementary techniques for enhancing disturbance rejection, robustness, and practical implementation in complex precision motion systems [5], [6], [7].

Compared with other advanced control approaches, H_∞ control offers a practical balance between robustness, systematic design, and implementation complexity. While μ-synthesis can provide stronger robustness guarantees for explicitly structured uncertainties, D–K iteration generally results in greater design and computational complexity [14], [17]. Linear quadratic regulator (LQR) provides an efficient optimal-control framework but does not explicitly guarantee worst-case disturbance attenuation or robustness against model uncertainty. Adaptive control can accommodate the time-varying or uncertain dynamics through online parameter adjustment, but its performance depends on adaptation quality and may introduce additional implementation complexity. In contrast, H_∞ control directly minimizes worst-case disturbance amplification and provides explicit robustness against bounded model uncertainty without requiring online adaptation, making it particularly suitable for high-precision MIMO vibration-isolation systems.

Further than the qualitative comparison presented in Table 2, recent studies have reported significant improvements in the vibration isolation performance employing advanced H_∞-based control architectures. Recently conducted investigations have shown substantial improvements in the performance of H_∞-based active vibration isolation systems. The experimental results show that mixed-sensitivity

Table 2: Qualitative comparison of representative control strategies for active vibration isolation and semiconductor precision motion systems.

Control strategy	Low-frequency isolation	Robustness to model uncertainty	Computational complexity	Ease of implementation	Comparison with standalone H_∞ feedback	Ref.
Classical PID	Depends on tuning and plant dynamics	No explicit uncertainty treatment in standard PID design	Fixed controller with few parameters	Gain tuning; additional decoupling may be needed	May be comparable for simple, weakly coupled plants; less suited to explicitly addressing multivariable uncertainty.	[2], [10]
Pure H_∞ Feedback	Shaped through frequency-dependent performance weights	Explicit treatment of specified uncertainty models	Offline synthesis; online cost depends on controller order	Plant model, weighting-function selection, and validation	Reference strategy.	[6], [8], [10]
Hybrid H_∞ + DOB	Combines robust feedback with disturbance estimation	Depends on feedback design, observer bandwidth, and model accuracy	Feedback-controller and observer calculations	Coordinated controller/observer design and noise management	May improve rejection of disturbances within the observer bandwidth, subject to model accuracy and noise sensitivity.	[5], [29]
MPC	Depends on prediction model, horizon, and objective weights	Depends on whether nominal or robust MPC is used	Online constrained optimization	Prediction model, constraint specification, and real-time solver	May offer advantages when explicit actuator and motion constraints dominate; performance depends on model accuracy and available computation.	[2], [30]
Adaptive / Data-Driven Control	Depends on identification quality and adaptation design	Depends on the specific method and stability guarantees	Identification, learning, or parameter-update calculations	Suitable data, model validation, and method-specific tuning	May offer advantages under changing dynamics; robustness depends on the method and its stability guarantees.	[4], [21], [22]

Note: Comparisons indicate conditional advantages and limitations rather than a universal ranking. Classification as inferior, comparable, or better requires evaluation under common operating conditions and performance metrics.

and loop-shaping H_∞ controllers can effectively suppress the low-frequency disturbances while maintaining robustness against modeling uncertainties. For example, Xu *et al.,* [6] reported effective attenuation of vibrations in the frequency range of 1–10 Hz utilizing a frequency-shaped H_∞ controller with input-saturation constraints. Also, Yin *et al.,* [7] achieved up to 65 dB reduction in transmitted vibration within the 0.1–10 Hz band by integrating H_∞ loop-shaping with virtual sensor fusion.

In semiconductor motion systems, increasingly stringent positioning requirements demand sub-nanometer positioning accuracy together with robust multivariable control under disturbances and model uncertainties [2]. Practical implementation has also progressed considerably, with computationally efficient control structures enabling real-time

deployment on industrial EUV wafer stages [3]. Furthermore, systematic H_∞ controller design has been shown to reduce sensor-noise amplification and actuator drift while maintaining disturbance rejection performance comparable to manually tuned controllers [8]. Collectively, these studies demonstrate that modern H_∞-based control architectures provide an effective balance between disturbance attenuation, robustness, and practical implementation, which makes them well suited for high-precision motion-control applications, including semiconductor manufacturing systems.

The performance of the classical PID in precision wafer stages is often limited by the multivariable coupling, structural flexibility, and model uncertainties, which motivates the use of more advanced control strategies [2], [27]. The MPC explicitly accounts for multivariable system dynamics and input/state constraints via an online optimization framework, which can make it an attractive approach for high-performance precision motion control. Recent investigations have combined robust H_∞ feedback with feedforward compensation, while advances in frequency-domain system identification and data-driven calibration have further improved tracking accuracy and controller performance in precision motion systems [4], [8], [11], [22]. Consequently, integrated H_∞ control architectures combining robust feedback with complementary techniques, such as feedforward compensation, DOBs, and virtual sensor fusion, have emerged as an effective approach for semiconductor motion systems [5], [7], [8].

5.3 *Performance evaluation*

This subsection discusses control strategies relevant to semiconductor metrology, drawing on both semiconductor precision-motion studies and supporting vibration-isolation research. Findings from general isolation platforms are considered transferable control principles rather than direct evidence of performance in semiconductor equipment. The performance of AVI systems is commonly evaluated using vibration transmissibility, disturbance rejection, positioning accuracy, robustness, and computational efficiency. Experimental studies demonstrate that MIMO H_∞ control provides effective disturbance rejection under plant uncertainties and multivariable coupling, although the reported degree of improvement depends strongly on the disturbance characteristics, system configuration, and performance metric considered. The H_∞ control effectively suppresses structural resonances and cross-axis interactions, while hybrid architectures incorporating DOBs, feedforward compensation, and virtual sensor fusion further improve the low-frequency vibration attenuation and tracking performance [5], [7], [10]. MPC and adaptive control can offer advantages in constrained or time-varying applications, but they generally need online optimization or adaptive parameter tuning. Recent studies have integrated H_∞ control with data-driven processes, DOBs, and virtual sensor fusion for improving the robustness and positioning accuracy in semiconductor motion systems [5], [7], [22].

In industrial applications, vibration-isolation performance should also be considered in relation to established facility-level vibration criteria. Vibration-criterion (VC) curves provide widely used reference criteria for characterizing floor-vibration environments and assessing facilities intended for vibration-sensitive equipment, including applications in microelectronics, optics, and metrology [31]. However, the reviewed previous studies predominantly report system-specific metrics, such as transmissibility, vibration attenuation, and the positioning error, rather than explicitly benchmarking performance against common industrial criteria. More consistent reporting against recognized standards and vibration criteria would facilitate comparison among AVI systems and improve the industrial relevance of future studies.

6 Challenges and future directions

Despite considerable advancement in MIMO H_∞ control, several important research gaps remain in meeting the increasingly stringent requirements of semiconductor metrology. Existing studies continue to face challenges in accurately representing flexible structural dynamics, position-dependent behavior, and strong multivariable coupling using the computationally efficient models [2], [11], [21]. Although frequency-domain identification and data-driven modeling have significantly improved model fidelity, their systematic integration with robust H_∞ controller design under varying operating conditions remains an important open research challenge [4], [5], [22]. Few studies have investigated unified control frameworks that simultaneously address modeling accuracy, computational efficiency, disturbance rejection, and real-time implementation for

increasingly complex semiconductor motion systems. Addressing these limitations will be essential for enabling the next generation of high-throughput semiconductor metrology systems with sub-nanometer-level positioning accuracy.

Further improvements in H_∞ synthesis alone may be insufficient because achievable control performance is fundamentally constrained by the accuracy of the plant model and the quality of available feedback information. System identification is therefore needed to capture cross-axis coupling, flexible modes, and operating-condition-dependent dynamics, while advanced sensing provides reliable information on disturbances and system states [4], [11], [21], [22]. Integrating these capabilities with robust H_∞ control can reduce model–plant mismatch and sensing limitations, enabling the controller to exploit its disturbance-rejection and robustness capabilities more effectively.

Real-time implementation of MIMO H_∞ controllers can also be computationally demanding because controller complexity generally increases with the number of controlled DOFs and modeled flexible dynamics. High controller order can increase memory requirements and execution time, making it more difficult to meet the high sampling-rate and low-latency requirements of precision motion systems. Controller-order reduction, efficient numerical implementation, and hardware acceleration are therefore important for practical real-time deployment [24].

Virtual sensor fusion and the emerging intelligent sensing technologies can improve the measurement quality by combining complementary sensor information and estimating system states that are difficult to measure directly, thereby providing more reliable feedback for MIMO H_∞ control [7]. FPGA-based hardware acceleration can further enable efficient real-time implementation of advanced multivariable control and multisensor processing algorithms [24]. Within the scope of AVI, machine learning (ML) and other data-driven methods can complement H_∞ control by improving model accuracy, supporting parameter optimization and model updating, and adapting to position- or operating-condition-dependent dynamics [4], [21], [22], [32]. Physics-informed ML can further combine measured data with known physical dynamics to improve model fidelity and generalization under limited or noisy data [32], [33], [34]. In such hybrid frameworks, ML can help capture complex or changing system behavior, while H_∞ control provides the robust-control framework for disturbance rejection and model uncertainty. Digital twins can provide continuously updated virtual representations of the controlled system for model validation and controller evaluation [32], [33]. Event-triggered control and embedded artificial intelligence (AI) implemented on FPGA platforms may reduce computational demands and facilitate real-time intelligent control for next-generation semiconductor metrology systems [24], [35]. Future research should therefore investigate how these approaches can be integrated with robust H_∞ architectures while preserving stability and robustness guarantees under model uncertainty.

7 Conclusions

As semiconductor manufacturing demands ever-tougher positioning accuracy and vibration suppression, robust multivariable control has become essential for precision motion systems. The reviewed evidence indicates that future progress in semiconductor active vibration isolation will depend less on further refinement of standalone H_∞ controller synthesis and more on the effective integration of robust control with advanced system identification, intelligent sensing, and data-driven implementation strategies. Achieving the next generation of sub-nanometer-level positioning accuracy will therefore require integrated control frameworks that simultaneously address modeling accuracy, computational efficiency, real-time implementation, and robustness under increasingly complex operating conditions.

This review addresses the gap in the literature by providing a focused synthesis of MIMO H_∞ control developments relevant to active vibration isolation in semiconductor metrology, while distinguishing directly relevant semiconductor applications from transferable approaches reported in adjacent precision-engineering systems. The reviewed studies were critically assessed in terms of system modeling, controller architecture, disturbance-rejection performance, sensing, experimental validation, and implementation requirements. The comparison indicates that H_∞ control is particularly effective for systems with strong multivariable coupling and model uncertainty, while hybrid architectures incorporating disturbance observers, feedforward compensation, data-driven modeling, and sensor fusion can further address limitations associated with changing dynamics and sensing constraints. A key contribution of this review is therefore the integration of these previously dispersed developments into a unified perspective that

relates control design to modeling accuracy, sensing quality, and real-time implementation requirements in semiconductor precision-motion systems.

Abbreviations

2-DOF	Two-degrees-of-freedom
3-DOF	Three-degrees-of-freedom
6-DOF	Six-degrees-of-freedom
AI	Artificial intelligence
AVI	Active vibration isolation
DOB	Disturbance observer
EUV	Extreme ultraviolet
FF	Feedforward
FIR	Finite-impulse-response
FPGA	Field-programmable gate array
FRF	Frequency response function
H_∞	H-infinity
LMI	Linear matrix inequality
MIMO	Multi-input multi-output
MPC	Model predictive control
PD	Proportional–derivative
PID	Proportional-integral-derivative
SISO	Single-input single-output

Acknowledgments

This research received no external funding. The authors thank the anonymous reviewers for their constructive comments.

Author Contributions

T.B.: conceptualization, methodology, investigation, project administration, writing, reviewing and editing; M.O.: conceptualization, methodology, writing—reviewing and editing, supervision. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

The authors declare no conflict of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors utilized the ChatGPT tool to enhance the language and readability of the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online here.

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