

High-precision Air-bearing Linear Motor Positioning Platform: Modeling, Sensing Integration, and Control Performance Evaluation

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In this study, we present the design, dynamic modeling, sensing integration, and control performance evaluation of a high-precision positioning platform driven by a permanent magnet linear synchronous motor and supported by an air-bearing guideway. The platform is developed to fulfill the dual requirements of long travel range and nanometer-level positioning resolution, with broad applicability in precision manufacturing and metrology. An optical incremental linear encoder is integrated as the primary displacement sensing element, providing high-resolution position feedback essential for closed-loop control. The system dynamics are rigorously modeled and verified in MATLAB/Simulink, and a proportional–integral–derivative controller is designed and tuned to evaluate baseline control performance. Simulation results demonstrate a stable step response with satisfactory rise time, settling time, and steady-state positioning accuracy. The proposed sensing–actuation architecture is designed with structural expandability toward multi-axis motion control. These findings establish a systematic design and evaluation framework that serves as a foundation for the subsequent implementation of advanced control strategies, including active disturbance rejection control, to further enhance dynamic stiffness and robustness under high-speed, high-precision operating conditions.

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1. Introduction

The rapid advancement of precision engineering and nanotechnology has driven increasing demand for positioning systems capable of combining long travel range with high resolution. Such systems are indispensable in semiconductor lithography, optical alignment, MEMS assembly, and biomedical instrumentation, where both motion accuracy and sensing fidelity are critical.⁽¹⁾

For example, semiconductor lithography wafer stages must reposition across a 300 mm wafer while maintaining overlay accuracy at the nanometer level to keep pace with sub-10 nm process nodes, photonic-packaging alignment stations must traverse centimeter-scale distances to locate a fiber or waveguide and then hold sub-100 nm alignment during active coupling, and automated biomedical micromanipulation platforms must transport a sample carrier across a multi-centimeter working area while positioning a probe or injection needle with sub-micrometer accuracy relative to a target cell. In each case, a platform confined to the sub-millimeter stroke of conventional piezoelectric flexure stages cannot cover the required working area, motivating the long-travel, nanometer-resolution permanent magnet linear synchronous motor (PMLSM)/air-bearing architecture developed in this study.

Conventional rotary-motor-driven stages relying on ball screws or belt transmissions suffer from mechanical backlash, friction, and transmission compliance, which fundamentally limit positioning accuracy and dynamic bandwidth.⁽²⁾ Linear motors, with their direct-drive architecture, eliminate intermediate transmission elements and offer superior thrust response, reduced friction, and enhanced repeatability—making them the preferred actuator for high-performance precision stages. When combined with air-bearing guideways, which provide frictionless, wear-free support, the resulting platform achieves exceptional motion smoothness and long-term dimensional stability, both essential for nanometer-level positioning tasks.

Accurate displacement sensing is equally essential to positioning performance. Laser interferometers, offering sub-nanometer resolution and traceability to international length standards, serve as the metrological backbone of closed-loop precision systems.⁽³⁾ Over the past two decades, multi-DOF positioning platforms have been extensively investigated across a range of actuation principles. Piezoelectric-actuated flexure-based platforms have demonstrated remarkable resolution: Kim *et al.* achieved tracking errors within ± 5 nm at 40 $\mu\text{m/s}$ using a decoupled parallel compliant mechanism with PII control.⁽⁴⁾ Yuan *et al.* reported closed-loop positioning errors below 0.5% in a two-dimensional platform with a three-stage amplification structure.⁽⁵⁾ Systems combining flexible hinges with model-based optimization have further improved performance—Li and Xu achieved 0.038 μm accuracy through PSO-optimized flexure design,⁽⁶⁾ whereas Zhang *et al.* demonstrated a six-DOF parallel system with 30 nm closed-loop resolution across translational and rotational axes.⁽⁷⁾

Research has progressively shifted toward integrating advanced control strategies. Tang *et al.* implemented a linear active disturbance rejection controller in a large-stroke nano-positioning system, achieving average tracking errors within ± 100 nm over a 1 mm travel range.⁽⁸⁾ Parallel to these efforts, serial-parallel hybrid mechanisms, stacked nano-positioning structures,⁽⁹⁾ and

bridge-amplifier-enhanced platforms^(10,11) have collectively expanded the design space for high-precision multi-DOF motion systems.

This study is closely related to the field of physical/mechanical sensors, as the closed-loop positioning performance reported herein is directly enabled by a Renishaw optical incremental linear encoder, which serves as the primary displacement-sensing element. The sensing fidelity of this optical encoder directly determines the achievable control bandwidth and, in the active disturbance rejection control framework, the accuracy of the extended-state-observer-based disturbance estimation.

Despite these advances, most reported platforms rely on piezoelectric actuation and are inherently constrained to short travel ranges (typically < 1 mm). Achieving simultaneous long travel range (>100 mm), nanometer-level resolution, and high dynamic bandwidth in a single platform—while maintaining robust closed-loop performance under real-world disturbances—remains a significant challenge. To address this gap, we develop a PMLSM-driven air-bearing positioning platform integrated with a laser interferometer as the primary sensing element. System dynamics are modeled and validated in MATLAB/Simulink, and a proportional–integral–derivative (PID) controller is designed and evaluated as the baseline control strategy, providing a systematic framework for the subsequent implementation of advanced disturbance-rejection methods.

2. Experimental Method

2.1 Linear motor platform design

The single-axis positioning platform developed in this study employs an Aerotech BLMC-142 brushless PMLSM⁽¹²⁾ as the primary actuator, paired with an MTC350P high-performance “U-channel” rare-earth magnet track (350 mm travel range), as illustrated in Fig. 1. The BLMC-142 features a compact cross section of 57.2×31.8 mm², a continuous thrust of 120.3 N (with 1.4 bar forced-air cooling), and a peak thrust of 481.2 N. Its nonmagnetic forcer coil eliminates cogging forces and magnetic attraction, ensuring exceptionally smooth velocity control and high

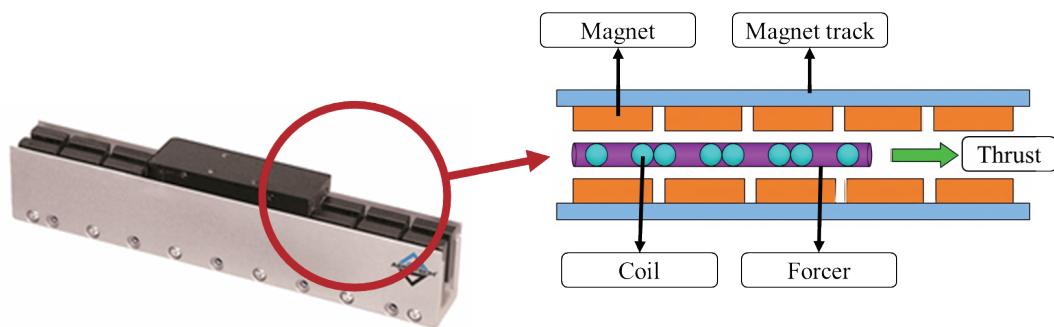


Fig. 1. (Color online) Linear motor and schematic of driving mechanism.⁽¹²⁾

positioning repeatability. The direct-drive architecture removes the need for ball screws, couplings, or belts, thereby eliminating backlash, mechanical compliance, and maintenance-related wear. Frictionless, wear-free linear guidance is provided by precision air bearings, which suppress motion-induced tilt and ensure smooth traversal across the full travel range—particularly critical during high-acceleration operation.

Position feedback is realized through a Renishaw TONiC™ T3031-15A optical incremental linear encoder readhead,⁽¹³⁾ operating in conjunction with a stainless steel RTLC20-S tape scale (20 μm grating pitch, scale accuracy $\pm 5 \mu\text{m}/\text{m}$). When paired with the Ti interpolation interface, the system achieves a displacement sensing resolution of 1 nm, a signal output jitter of $< \pm 0.5 \text{ nm}$ root mean square (*RMS*), and a sub-divisional error (*SDE*) of $< \pm 30 \text{ nm}$, supporting closed-loop operation at traversal speeds up to 10 m/s. The encoder signal is fed directly to the controller to form a single-axis closed-loop positioning loop. This sensing–actuation architecture integrates a 350-mm-long-stroke capability with nanometer-level feedback resolution, establishing the hardware foundation for the control strategies described in subsequent sections.

2.2 Precision positioning platform architecture

Figure 2 presents the overall hardware architecture of the single-axis air-bearing linear motor positioning platform developed in this study. The system comprises five principal components: a host personal computer (PC), an ACS Motion Control SPiiPlus CMhp multi-axis motion controller with an integrated digital drive, the BLMC-142/MTC350P linear motor platform, a precision air compressor, and a Renishaw TONiC™ T3031-15A optical incremental linear encoder.

The host PC serves as the supervisory interface for trajectory planning, parameter configuration, and real-time monitoring, communicating with the SPiiPlus CMhp controller via Ethernet. The SPiiPlus CMhp executes the servo control loop at a high sampling rate, generates the drive current commands for the BLMC-142 PMLSM forcer, and processes encoder feedback signals. The air compressor supplies regulated pneumatic pressure to the air-bearing guideway, establishing a frictionless, noncontact support condition between the moving carriage and the guide rail, thereby eliminating Coulomb friction and mechanical wear over the full 350 mm

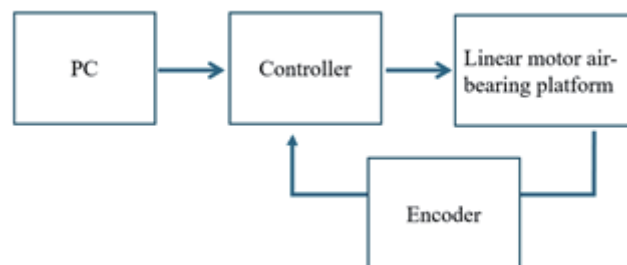


Fig. 2. (Color online) Overall architecture of the platform.

travel range. Displacement feedback is provided by the Renishaw TONiC™ T3031-15A encoder at a resolution of 1 nm, closing the position loop at the controller level. The resulting closed-loop system enables the implementation and comparative evaluation of control strategies, including PID control as the baseline and active disturbance rejection control (ADRC) as the advanced strategy, as detailed in the subsequent sections.

The ACS Motion Control SPiiPlus CMhp is selected as the motion controller for this study,⁽¹⁴⁾ as shown in Fig. 3. The SPiiPlus CMhp is a high-performance, standalone EtherCAT-based motion controller with up to three integrated digital servo drives, capable of coordinating up to 32 axes across an EtherCAT network. It is powered by single- or three-phase AC input (24–265 V_{AC}), with a separate 24 V_{DC} control supply that maintains signal integrity during emergency conditions.⁽¹⁴⁾ The controller supports a wide range of position feedback devices, including digital incremental (AqB), Sin-Cos analog, and absolute encoders, enabling direct interfacing with the Renishaw TONiC™ T3031-15A linear encoder used in this platform. Motion programs are developed and executed in real time using the ACSPL+ multitasking programming language, which supports advanced servo algorithms, including proportional–integral–velocity (PIV) cascaded control loops, dual-loop configurations, and disturbance-rejection control. Host communication with the supervisory PC is established via Ethernet (10/100 Base-T), ensuring low-latency command transmission and real-time data acquisition. These features collectively provide the computational capability and communication bandwidth required to implement and evaluate the PID and ADRC control strategies described in this study.



Fig. 3. (Color online) ACS Motion Control ECMsa controller.⁽¹⁴⁾

2.3 Platform simulation

To support the design and simulation-based evaluation of the closed-loop control system, in this section, we systematically derive the kinematic and dynamic models of the single-axis air-bearing PMLSM positioning platform. The platform exhibits a single translational degree of freedom (1-DOF) along the direction of motor thrust. Since the direct-drive configuration eliminates intermediate transmission elements, the kinematic relationship between the motor force and the commanded position reference is linear and backlash-free. The instantaneous position, velocity, and acceleration of the moving carriage are therefore fully described by the scalar kinematic equation expressed in Eq. (1):

$$X_d = F(r), \quad (1)$$

where X_d denotes the displacement of the motor forcer along the translational axis and r denotes the reference position command. Since the direct-drive configuration provides a unity-ratio correspondence between actuator displacement and carriage position, no transmission correction term is required in the kinematic model.

The dynamic model of the platform is derived by applying Newton's second law of motion along the single translational axis, as expressed in Eq. (2):

$$M\ddot{x} + C\dot{x} + Kx = F(f), \quad (2)$$

where M , C , and K denote the mass, damping, and stiffness matrices, respectively, and $F(f)$ represents the force or torque applied by the actuator.

A PID controller is implemented as the baseline closed-loop control strategy for the single-axis positioning platform. The PID architecture is selected for its structural simplicity, well-established tuning methodology, and proven effectiveness in precision motion control applications. In this configuration, the proportional term provides immediate corrective action proportional to the instantaneous position error, the integral term eliminates steady-state tracking error through accumulated error compensation, and the derivative term improves transient response by damping overshoot and suppressing rapid error variations. The control output $u(t)$ is formulated as expressed in Eq. (3):

$$u(t) = K_p e(t) + K_i \int e(t) dt + K_d \frac{de(t)}{dt}. \quad (3)$$

In this equation, $e(t) = r(t) - y(t)$ denotes the instantaneous position tracking error, defined as the difference between the reference position command $r(t)$ and the encoder-measured displacement $y(t)$ obtained from the Renishaw TONiC™ T3031-15A feedback loop. The proportional gain K_p , integral gain K_i , and derivative gain K_d were determined through an iterative simulation-based tuning procedure in MATLAB/Simulink: an initial gain set was obtained using the closed-loop

tuning rule applied to the linearized plant model of Eq. (2), after which the gains were manually fine-tuned within the sensing-in-the-loop simulation to jointly satisfy target specifications.

A simulation framework is constructed in MATLAB/Simulink on the basis of the dynamic model derived in Eq. (2) to evaluate the closed-loop control performance of the single-axis air-bearing PMLSM positioning platform. Both open-loop step response and closed-loop PID-controlled positioning tests are conducted to characterize the platform's dynamic behavior. The simulation systematically examines key performance metrics under representative step displacement commands. The PID controller gains K_p , K_v , and K_d are tuned iteratively within the Simulink environment to satisfy the target dynamic specifications.

2.4 Disturbance rejection control

ADRC is a model-independent control methodology that estimates and actively compensates for both internal uncertainties and external disturbances in real time.⁽¹⁵⁾ Unlike conventional model-based approaches, ADRC treats the combined effect of unknown system dynamics, parameter variations, and external perturbations as a generalized disturbance—referred to as the total disturbance—and employs an extended state observer to estimate it online without requiring an explicit system model. The estimated disturbance is then canceled within the control law, effectively reducing the plant to a chain of pure integrators that a simple linear feedback controller can stabilize.

Consider the second-order nonlinear plant model given in Eq. (4):

$$\ddot{y}(t) = f(y, \dot{y}, t) + d(t) + bu(t), \quad (4)$$

where $y(t)$ is the system output (platform displacement), $u(t)$ is the control input (thrust command), $f(y, \dot{y}, t)$ represents the lumped internal nonlinear dynamics including model uncertainties and parameter perturbations, $d(t)$ is the external disturbance force, and b is the input gain. The total disturbance $w(t)$ is defined as the aggregation of all unmodeled and uncertain terms, as expressed in Eq. (5):

$$w(t) = f(y, \dot{y}, t) + d(t). \quad (5)$$

By substituting Eq. (5) into Eq. (4), the plant simplifies to the disturbance-augmented form expressed in Eq. (6):

$$\ddot{y}(t) = w(t) + bu(t). \quad (6)$$

To enable the online estimation of $w(t)$, ADRC extends the system state vector by treating $w(t)$ as an additional state variable $x_3 = w(t)$. By defining the augmented state vector as $x = [x_1, x_2, x_3]^T = [y, \dot{y}, w]^T$, the augmented state-space representation is expressed in Eq. (7):

$$\dot{x} = Ax + Bx + E\dot{w}, \quad (7)$$

where A , B , and E are the augmented system matrices defined accordingly. The extended state observer is designed to track the augmented state x , yielding the observer dynamics expressed in Eq. (8):

$$\dot{\hat{x}} = A\hat{x} + Bx + L(y - x_1), \quad (8)$$

where $\hat{x}$ denotes the estimated state vector and L is the observer gain matrix, tuned to ensure the convergence of the estimation error to zero. Once the total disturbance estimate $x_3 \cong w(t)$ is obtained, the control law cancels the disturbance and reduces the plant to a double-integrator, upon which a linear PD feedback law is applied for trajectory tracking. ADRC has been successfully applied to precision linear motor positioning systems, demonstrating strong robustness against thrust ripple, payload variation, and friction-induced disturbances.⁽¹⁶⁾

3. Results and Discussion

3.1 Experimental setup of the linear motor platform

Figure 4 presents the physical hardware configuration of the single-axis air-bearing PMLSM positioning platform constructed in this study. The primary actuator is an Aerotech BLMC-142 brushless PMLSM forcer, operating in conjunction with an MTC350P high-performance “U-channel” rare-earth magnet track (350 mm effective travel range), which provides a peak thrust of 481.2 N and a continuous thrust of 120.3 N under forced-air cooling. The nonmagnetic forcer coil eliminates cogging forces, ensuring smooth, ripple-minimized thrust generation throughout the full stroke. Frictionless linear guidance is provided by a precision air-bearing

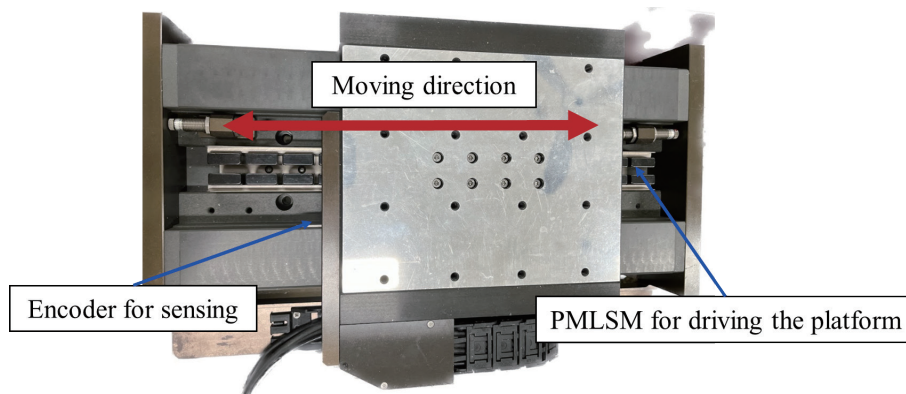


Fig. 4. (Color online) Air-bearing PMLSM positioning platform.

guideway supplied with regulated pneumatic pressure, which establishes a noncontact interface between the moving carriage and the guide rail, effectively eliminating Coulomb friction and mechanical wear.

Displacement sensing is realized through a Renishaw TONiC™ T3031-15A optical incremental linear encoder readhead, mounted beneath the moving stage and operating in conjunction with a stainless steel RTLC20-S tape scale (grating pitch: 20 μm ; scale accuracy: $\pm 5 \mu\text{m/m}$). The TONiC™ readhead employs third-generation filtering optics with Auto Gain Control (AGC) and Auto Offset Control (AOC) signal processing, delivering a position feedback resolution of 1 nm, a signal output jitter of $< \pm 0.5 \text{ nm RMS}$, and *SDE* of $< \pm 30 \text{ nm}$ at traversal speeds up to 10 m/s. The encoder output is transmitted directly to the ACS SPiiPlus CMhp motion controller, closing the position feedback loop at the servo level. This sensing architecture provides the high-fidelity, low-latency displacement signals essential for evaluating closed-loop control performance under the step-tracking and disturbance-rejection test conditions described in the following section.

3.2 Simulation of the linear motor platform

Figure 5 presents the MATLAB/Simulink block diagram of the closed-loop PID control system for the single-axis air-bearing PMLSM positioning platform. The simulation model comprises four principal subsystems: (i) a PID controller block implementing the control law defined in Eq. (3); (ii) a plant model derived from the equation of motion in Eq. (2), parameterized with the actual hardware specifications of the BLMC-142 motor; (iii) a displacement sensing model representing the Renishaw TONiC™ T3031-15A encoder, implemented as a quantization block with a resolution of 1 nm to accurately reproduce the discretization and signal noise characteristics of the physical feedback device; and (iv) a feedback summation block that computes the real-time position error between the reference command and the encoder-measured

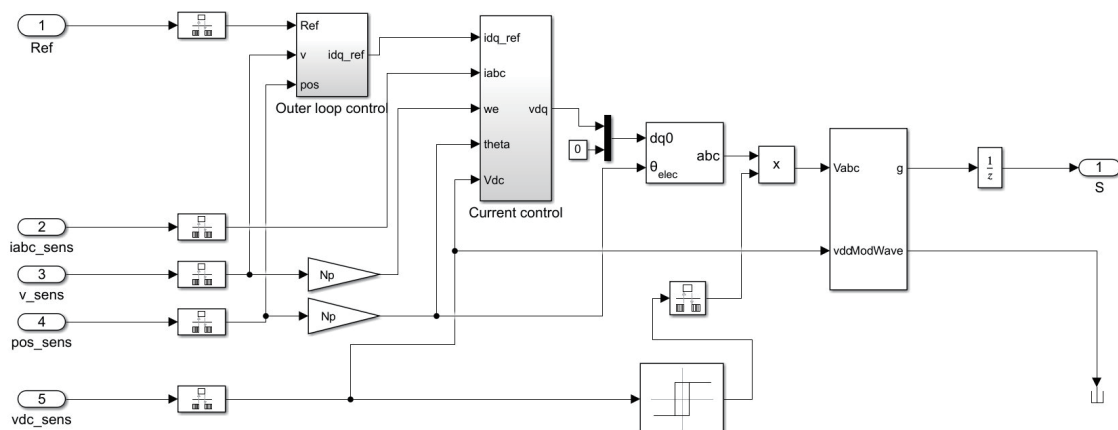


Fig. 5. (Color online) MATLAB/Simulink closed-loop block diagram of the PID-controlled single-axis air-bearing PMLSM positioning platform.

displacement. This sensing-in-the-loop simulation architecture ensures that the quantization effects and signal bandwidth limitations of the physical encoder are accounted for in the controller evaluation, rather than assuming ideal continuous feedback.

Figure 6 presents the simulated closed-loop bidirectional step response of the single-axis air-bearing PMLSM positioning platform under PID control, comprising a forward step command from 0 to 0.1 m followed by a return step from 0.1 to 0 m. Both the motor position and motor velocity responses are displayed. For the forward step, the encoder-in-the-loop simulation exhibits an initial response delay of approximately 0.40 s, after which the carriage accelerates rapidly to a peak traversal speed of approximately 1.2 m/s, yielding a rise time of approximately 0.07 s after motion onset and a settling time of approximately 0.40 s from command onset. The return step exhibits symmetric dynamic behavior, with a comparable response delay and a peak reverse speed of approximately -1.2 m/s, confirming consistent bidirectional tracking performance. The motor velocity profile in both directions decays rapidly to near zero following the transient phase, indicating effective closed-loop velocity damping under the current PID parameterization.

3.3 Simulation of the disturbance rejection control

Figure 7 presents the MATLAB/Simulink block diagram of the ADRC scheme implemented for the single-axis air-bearing PMLSM positioning platform. The ADRC architecture comprises three functionally distinct modules: the tracking differentiator, the extended state observer, and the nonlinear state error feedback law.

The tracking differentiator processes the reference position command $r(t)$ to generate a smoothed trajectory profile and its derivative approximation, effectively suppressing the

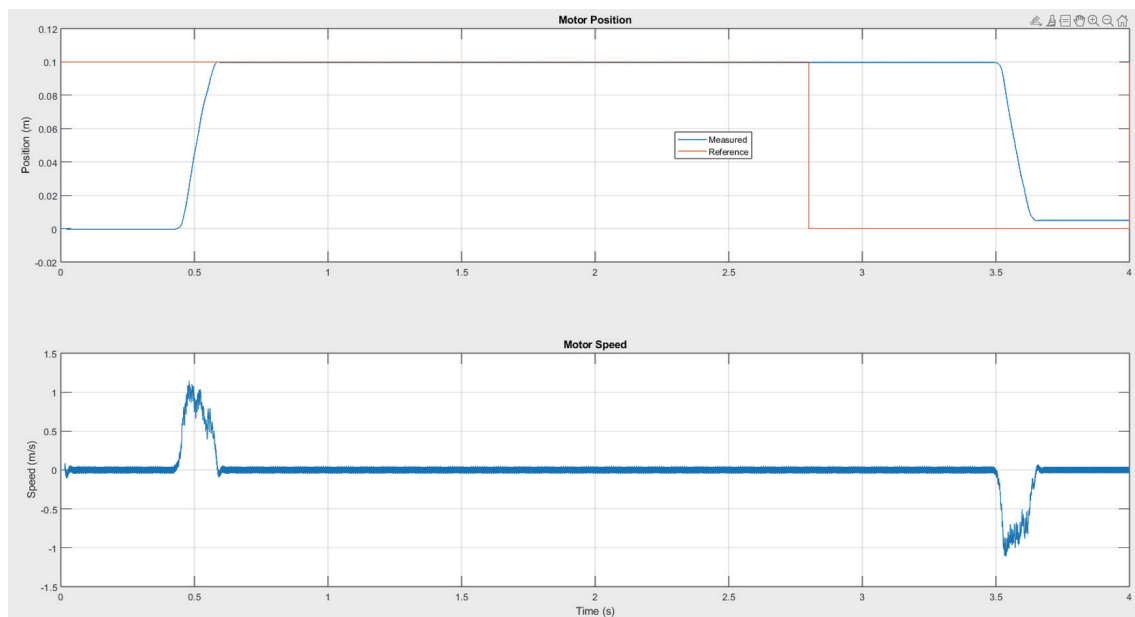


Fig. 6. (Color online) Closed-loop bidirectional step response of the single-axis air-bearing PMLSM positioning platform under PID control.

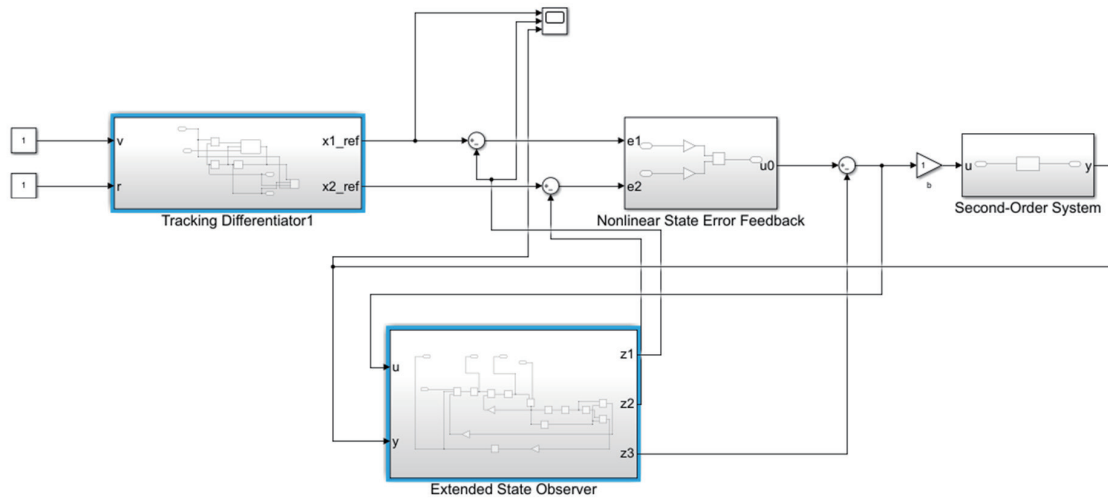


Fig. 7. (Color online) MATLAB/Simulink block diagram of ADRC scheme for the single-axis air-bearing PMLSM positioning platform.

amplification of high-frequency noise that would otherwise be introduced by the direct numerical differentiation of the reference signal. The extended state observer constitutes the core sensing-and-estimation module of the ADRC architecture. It receives the displacement feedback signal $y(t)$ acquired from the Renishaw TONiC™ T3031-15A encoder (resolution: 1 nm) and continuously estimates the full system state vector $\hat{x} = [x_1, x_2, \hat{x}_3]^T$, as defined in Eqs. (7) and (8). Critically, the third extended state $\hat{x}_3$ provides a real-time estimate of the total disturbance $w(t)$ —encompassing thrust ripple, air-bearing pressure fluctuations, payload variations, and unmodeled nonlinear dynamics—without requiring an explicit disturbance model. The accuracy of this disturbance estimation is directly dependent on the fidelity of the encoder feedback signal; the sub-nanometer resolution and low signal jitter ($< \pm 0.5$ nm *RMS*) of the TONiC™ encoder therefore play a critical role in enabling reliable extended state observer convergence under high-speed operating conditions. The nonlinear state error feedback module then combines the tracking differentiator-generated reference derivatives with the extended state observer state estimates to compute the disturbance-compensated control output $u(t)$, as expressed in the control law derived, effectively reducing the plant to a double-integrator and enabling precise trajectory tracking.

In contrast to the fixed-gain PID controller, the ADRC architecture does not rely on an accurate plant model and maintains closed-loop stability and dynamic performance even under significant modeling uncertainties or time-varying external disturbances.

Figure 8 presents the simulated closed-loop bidirectional step response of the single-axis air-bearing PMLSM positioning platform under ADRC, comprising a forward step command from 0 to 0.1 m followed by a return step from 0.1 to 0 m. Both motor position and motor velocity responses are displayed. In contrast to the PID response, the ADRC-controlled platform exhibits

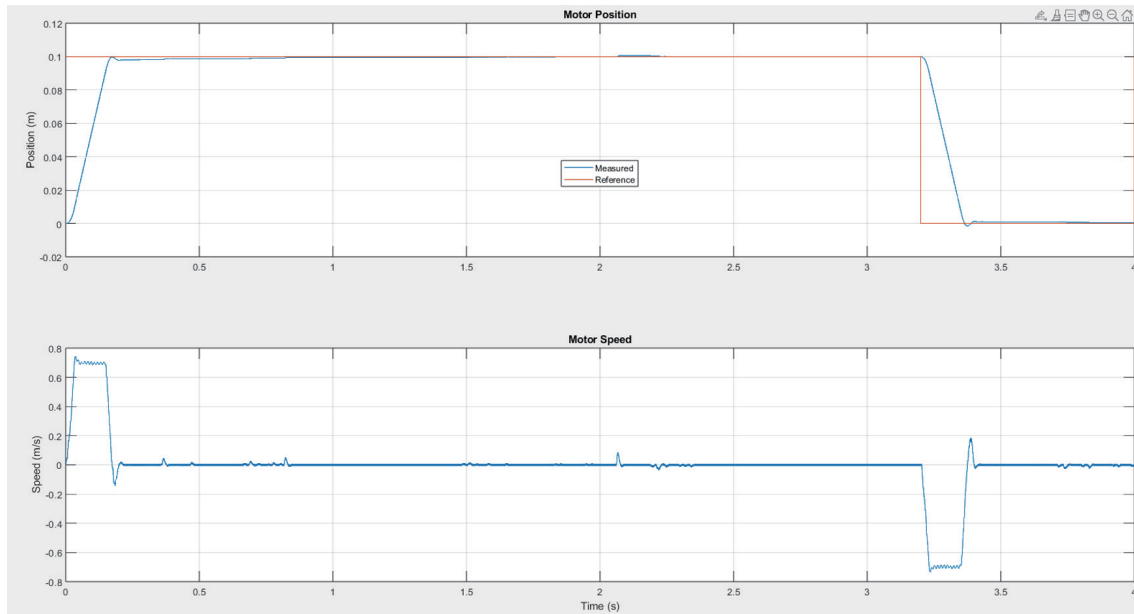


Fig. 8. (Color online) Closed-loop bidirectional step response of the single-axis air-bearing PMLSM positioning platform under the active disturbance rejection control.

no discernible initial response delay: the carriage begins moving immediately upon command onset, reflecting the extended state observer's ability to generate an instantaneous disturbance-compensating control action without requiring integral term accumulation. For the forward step, the system achieves a rise time of approximately 0.12 s and a settling time of approximately 0.20 s, with a minor overshoot of approximately 1–2%, reaching a peak displacement of approximately 0.101–0.102 m before converging to the 0.1 m target with negligible steady-state error. The peak traversal speed of approximately 0.75 m/s is notably lower than the PID counterpart (~1.2 m/s), indicating a smoother, more controlled acceleration profile under ADRC. The return step exhibits symmetric dynamic behavior with a comparable response delay and peak reverse speed of approximately -0.75 m/s, confirming consistent bidirectional tracking performance. The high-fidelity displacement feedback provided by the Renishaw TONiC™ T3031-15A encoder (resolution: 1 nm; jitter: $<\pm 0.5$ nm *RMS*) enables the extended state observer to continuously reconstruct the velocity state $\hat{x}_2$ and total disturbance estimate $\hat{x}_3$ in real time, directly underpinning the observed improvements in response speed and disturbance attenuation relative to the PID baseline.

3.4 Measured current-loop step response under PID and ADRC control

Under PID control, the measured phase-q current exhibits a peak overshoot of approximately 20% (0.060 against the 0.05 command) on the rising edge and a comparable ~20% undershoot on the falling edge. Under ADRC, the same test shows a reduced overshoot of approximately 16%

(0.058) and an undershoot of approximately 14%, indicating smoother current tracking and reduced transient ringing relative to the PID baseline, consistent with the improved disturbance-rejection behavior predicted from the ADRC simulation results. Both controllers converge to the commanded ± 0.05 level with negligible steady-state error, as shown in Figs. 9 and 10 and Table 1.

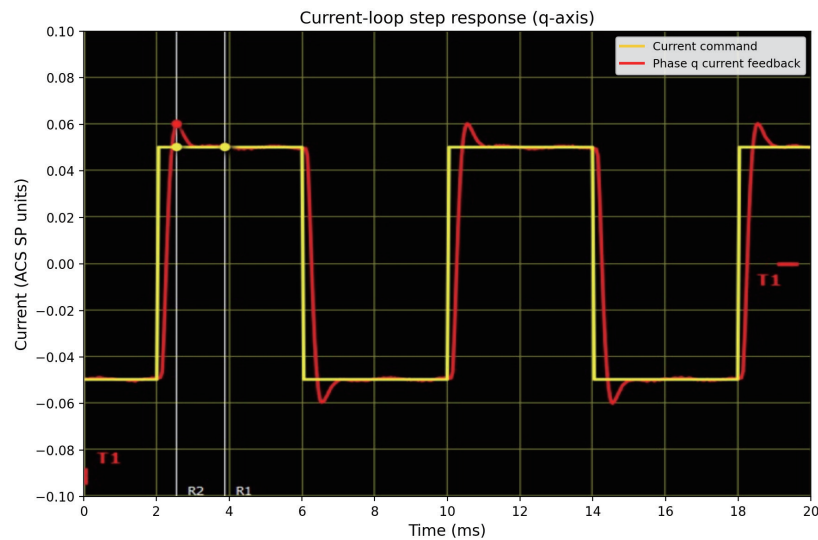


Fig. 9. (Color online) Measured current-loop (q -axis) step response of the physical platform under PID control.

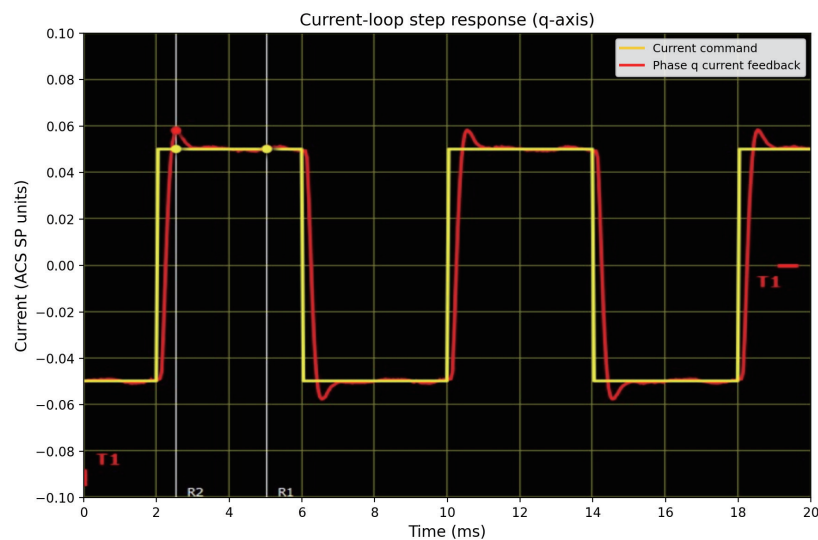


Fig. 10. (Color online) Measured current-loop (q -axis) step response of the physical platform under ADRC.

Table 1

Measured current-loop step-response comparison.

Metric	PID	ADRC
Command amplitude	± 0.05 (ACS SP units)	± 0.05 (ACS SP units)
Peak current, rising step	0.060	0.058
Overshoot, rising step	20%	16%
Peak current, falling step	-0.060	-0.057
Undershoot, falling step	20%	14%
Steady-state tracking	Converges to ± 0.05 , negligible steady-state error	Converges to ± 0.05 , negligible steady-state error
Qualitative transient behavior	Larger overshoot/undershoot, more pronounced ringing before settling	Reduced overshoot/undershoot, smoother convergence

Reliance on a single optical incremental encoder introduces several limitations: the RTLC20-S tape scale is susceptible to thermal expansion and contamination-induced signal dropout, and any single-point failure of the readhead or scale interrupts the entire closed-loop feedback path with no independent cross-check. A laser interferometer, such as the unit available in our laboratory's precision-positioning setup, can serve as a redundant or reference-grade sensing channel, offering sub-nanometer resolution and direct traceability to the optical wavelength standard, at the cost of higher sensitivity to air turbulence and optical alignment drift over long travel ranges. Capacitive displacement sensors offer an alternative that is largely immune to the optical contamination and thermal expansion of a graduated scale, but their practical range is typically limited to sub-millimeter gaps, making them more suitable as a local, high-bandwidth redundancy check near specific target positions than as the primary long-stroke feedback sensor. A practical redundancy strategy for this platform would therefore pair the TONiC™ encoder as the primary long-stroke feedback sensor with a laser interferometer or capacitive sensor used intermittently for calibration and cross-validation, and with a plausibility check implemented in the ACSPL+ control program to flag disagreement between channels.

Extending the present single-axis architecture to a multi-axis (e.g., planar X-Y or gantry) configuration introduces three principal challenges. First, synchronization: when two parallel PMLSM forcers drive a common gantry beam (a dual-linear-motor configuration), any transient mismatch between their individual closed-loop responses induces yaw error across the beam; this can be mitigated by a master–slave synchronization scheme in which the slave axis's ESO-based disturbance estimate is corrected using the measured position difference between the two axes. Second, cross-axis coupling: motion along one axis can mechanically or electromagnetically perturb the orthogonal axis through carriage inertia and air-bearing pressure redistribution; within the ADRC framework, such coupling can be treated as an additional component of the lumped “total disturbance” term $w(t)$ estimated by each axis's own extended state observer, avoiding the need for an explicit coupled dynamic model. Third, controller scalability: the ACS SPiiPlus CMhp controller used in this study supports coordination of up to 32 EtherCAT axes, so the ACSPL+ multitasking framework already provides the computational and communication bandwidth required to extend from one to several ESO-based control loops running in parallel, although the real-time task scheduling and inter-axis communication latency would need to be re-verified as axis count increases.

4. Conclusions

In this study, we presented the design, dynamic modeling, sensing integration, and simulation-based control evaluation of a single-axis air-bearing PMLSM positioning platform. The Renishaw TONiC™ T3031-15A optical incremental linear encoder (resolution: 1 nm, jitter: $<\pm 0.5$ nm *RMS*, *SDE*: $<\pm 30$ nm) served as the primary sensing element, providing the high-fidelity displacement feedback essential for closed-loop PID control and state reconstruction in the ADRC framework—directly linking sensing performance to disturbance rejection capability. Both control strategies were evaluated under identical simulated closed-loop bidirectional step commands in MATLAB/Simulink. Under PID control, the platform exhibited an initial response delay of approximately 0.40 s, a rise time of approximately 0.07 s after motion onset, a settling time of approximately 0.40 s, and a peak traversal speed of approximately ± 1.2 m/s, with negligible steady-state error and symmetric bidirectional behavior. Under ADRC, the initial response delay was completely eliminated—the carriage responded immediately upon command onset owing to the extended state observer’s instantaneous disturbance compensation—yielding a rise time of approximately 0.12 s and a settling time of approximately 0.20 s, with a smoother peak traversal speed of approximately ± 0.75 m/s and negligible steady-state error. Relative to the PID baseline, ADRC achieved a 50% reduction in settling time, while the nanometer encoder feedback enabled the continuous real-time reconstruction of the velocity state and total disturbance estimate. These results validate the proposed sensing–actuation–estimation architecture as a foundation for future multi-axis extension and sub-nanometer contouring in precision manufacturing and semiconductor metrology applications.

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