A lightweight asymmetric compensation framework for continuous MWIR zoom control under direction-dependent load variations

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ABSTRACT

Continuous zoom mechanisms in mid-wave infrared (MWIR) imaging systems often employ nonlinear cam profiles and preload springs to achieve precise lens-group motion and backlash reduction. However, these mechanical structures introduce significant position-dependent and direction-dependent load variations, resulting in asymmetric dynamic behavior. Such nonlinearities make it difficult for a single globally tuned PID controller to satisfy tracking requirements. This paper presents an experimental investigation of load asymmetry in an MWIR zoom mechanism driven by a DC coreless motor with incremental encoder feedback. Based on these observations, a lightweight asymmetric compensation framework rooted in local feedforward linearization is proposed. To replace manual heuristic tuning and improve system adaptability, the method introduces an automated calibration procedure combined with polynomial curve fitting to systematically generate continuous directional bias profiles. This is integrated with direction-dependent PID parameter selection and startup torque injection without requiring additional sensors or complex observers. Experimental validation demonstrates that the proposed method improves the startup success rate from 85% to 100%, reduces the mean overshoot from 10.3 to 3.4 counts, and decreases the mean settling time from 3078 ms to 330 ms. The results demonstrate that the automated characterization and continuous compensation of directional load asymmetry significantly improve the control performance of MWIR zoom systems while maintaining low implementation complexity.

Keywords: MWIR zoom lens; DC coreless motor; Asymmetric load compensation; PID control; Preload spring; Nonlinear cam mechanism; Zoom control.

1. INTRODUCTION

Continuous zoom mechanisms in MWIR imaging systems play a critical role in long-range surveillance, border security, and target tracking applications [1, 2]. To accommodate high magnification ratios within compact form factors, modern optical systems require the precise synchronization of heavy lens groups [3, 4]. In physical implementations, this synchronization is achieved using nonlinear cam grooves, while high-stiffness preload springs are typically integrated to strictly eliminate mechanical backlash and ensure optical axis stability [5, 6].

In the broader context of optoelectronic observation systems, advanced servo techniques, such as adaptive PID control, have been successfully implemented to manage operational load variations in conventional gear-driven mechanisms [7]. However, for compact MWIR modules specifically, the combination of nonlinear cams and preload springs introduces fundamentally different, highly nonlinear actuation characteristics. The driving load varies dynamically with both the zoom position (due to the variable pitch angle of the cam) and the motion direction (due to the assisting or resisting nature of the spring force). Furthermore, compact MWIR zoom actuators typically rely on DC coreless motors equipped only with incremental encoders, lacking direct torque or current sensors due to strict space and cost constraints [8, 9].

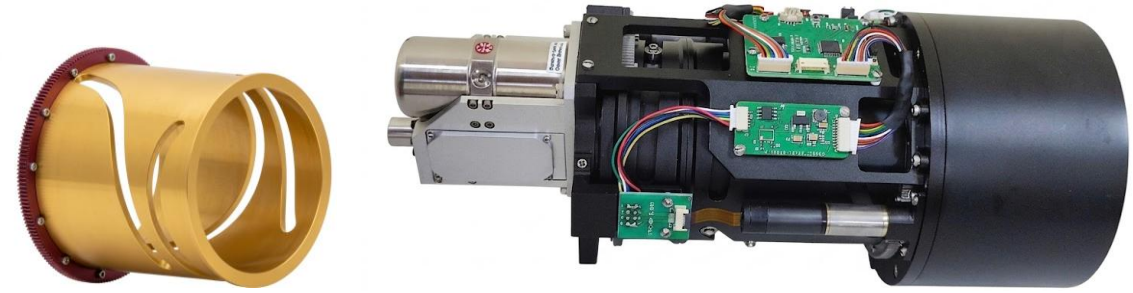
Under these conditions, conventional position control utilizing a globally tuned PID controller struggles to simultaneously satisfy startup reliability, low overshoot, and fast settling time across the entire asymmetric load field [10-12]. While optical designs and general servo mechanisms are well-documented, quantitative experimental studies addressing directional load asymmetry directly rooted in MWIR mechanical structures remain limited.

To address this practical gap, we propose a lightweight asymmetric compensation framework based on local feedforward linearization. Moving beyond heuristic parameter tuning, the framework incorporates an automated calibration procedure featuring polynomial curve fitting to systematically generate continuous directional compensation profiles. The main contributions of this work are: (1) Experimental characterization of position- and direction-dependent load asymmetry in MWIR zoom systems; (2) Formulation of a lightweight asymmetric control framework utilizing only standard encoder feedback; (3) Development of an automated calibration and curve-fitting procedure; and (4) Quantitative validation demonstrating significant performance gains in startup reliability and transient response.

2. PROBLEM

2.1. System description and problem formulation

The investigated MWIR zoom mechanism comprises a DC motor, a nonlinear cam transmission (Figure 1a), moving lens groups, and a preload spring.



a) *b)*

Figure 1. *Hardware configuration of the continuous MWIR zoom mechanism: (a) Nonlinear cam groove profile; (b) Physical structure of the 25-360 mm objective lens.*

To satisfy complex optical magnification requirements, the cam grooves are inherently designed with continuously varying pitch angles, $\alpha(\theta)$. Consequently, the mechanical transmission ratio between the motor's rotation and the axial translation of the heavy lens groups fluctuates significantly across the zoom stroke. Furthermore, to eliminate mechanical backlash and ensure optical axis stability, a high-stiffness preload spring is integrated into the moving carriage. This specific mechanical configuration fundamentally introduces severe position- and direction-dependent load asymmetry. From a physical perspective, the total equivalent load torque τ_{load} is a superposition of the variable cam transmission load, Coulomb friction, and the spring elastic force. During forward motion (e.g., wide-to-tele, $d = +1$), the compressed preload spring releases potential energy, effectively pushing the lens carriage and assisting the motor actuation. Conversely, during reverse motion (tele-to-wide, $d = -1$), the motor must actively work against the increasing restoring force of the spring to pull the carriage back. This directional spring interaction, heavily coupled with the position-dependent nonlinear cam pitch $\alpha(\theta)$, creates a highly complex dynamic load field. Under such conditions, the system relies solely on an incremental encoder for position feedback, lacking any direct torque or force sensors.

The rotational dynamics are expressed as:

$$J(\theta)\ddot{\theta} + K_{\omega}\dot{\theta} = K_u u(t) - \tau_{\text{load}}(\theta, d) \tag{1}$$

where $J(\theta)$ is the equivalent inertia, K_ω is the viscous damping coefficient, K_u is the torque constant, $u(t)$ is the control input, and τ_{load} is the total load torque comprising cam mechanics, spring preload, and friction. Crucially, τ_{load} depends on both the zoom position θ and motion direction d ($d \in \{+1, -1\}$ for forward/reverse).

Conventional control utilizes a fixed-gain PID controller:

$$u_{\text{PID}} = K_p e + K_i \int e\, dt + K_d \dot{e} \tag{2}$$

where the tracking error is $e = \theta_{\text{ref}} - \theta$. Preliminary experiments indicate that due to severe position- and direction-dependent load variations, a single globally tuned PID controller fails to ensure reliable breakaway, minimal overshoot, and rapid settling time across the zoom travel. This necessitates an asymmetric compensation strategy.

2.2. Proposed asymmetric compensation framework

To address the position- and direction-dependent nonlinearities, we propose an asymmetric compensation framework rooted in local feedforward linearization (Figure 2).

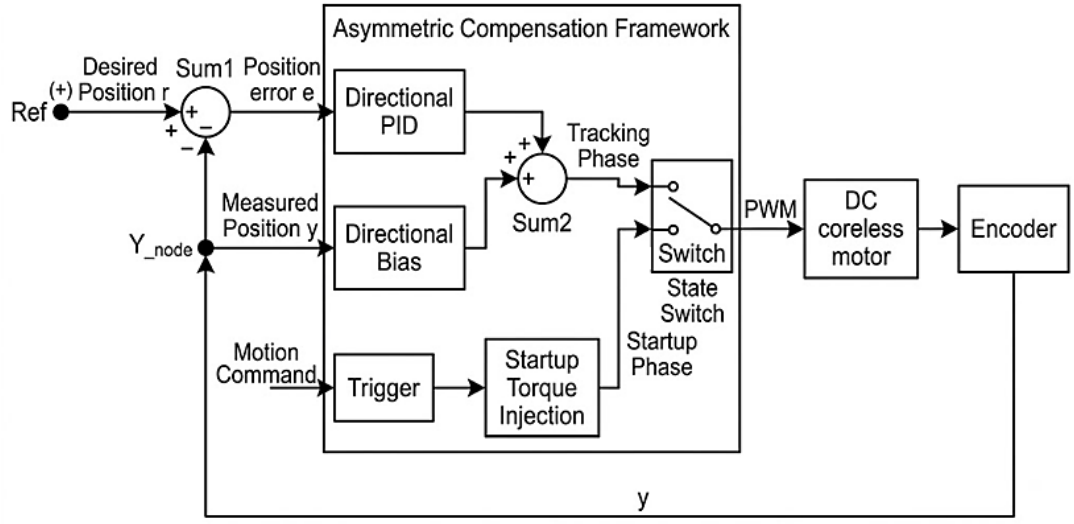


Figure 2. *Proposed asymmetric compensation framework.*

Ignoring the negligible inductance of the DC coreless motor, the active tracking dynamics yield:

$$J(\theta)\ddot{\theta} + K_\omega \dot{\theta} = K_u u_{\text{PID}} + [K_u u_{\text{bd}} - \tau_{\text{load}}(\theta, d)] \quad (3) \tag{3}$$

The directional bias u_{bd} acts as a feedforward linearizer. By calibrating $K_u u_{\text{bd}} \approx \tau_{\text{load}}(\theta, d)$, the nonlinear load is cancelled, simplifying the residual dynamics to a nominal linear second-order system:

$$\frac{\theta(s)}{U_{\text{PID}}(s)} \approx \frac{K}{s(\tau s + 1)} \tag{4}$$

For this localized type-1 second-order plant, a standard PID controller $C(s) = K_p + K_i/s + K_d s$ provides the theoretically optimal closed-loop position tracking. Specifically, the integral action (K_i) guarantees zero steady-state error, which is an absolute requirement for precise optical focusing. Simultaneously, the proportional (K_p) and derivative (K_d) terms allow for direct root locus shaping, enabling the designer to place the closed-loop poles to achieve a desired damping ratio and natural frequency, thereby suppressing overshoot and minimizing settling time. However,

because the effective inertia $J(\theta)$ and unmodeled frictions differ under spring-assisted ($d = +1$) versus spring-resisted ($d = -1$) motions, the PID parameters must be selected asymmetrically to maintain these optimal closed-loop poles: (K_p, K_i, K_d) equals (K_{pf}, K_{if}, K_{df}) for forward motion, and (K_{pr}, K_{ir}, K_{dr}) for reverse motion.

To systematically eliminate heuristic tuning and generalize the framework for various mechanical setups, an automated calibration procedure is proposed to determine the compensation parameters. This procedure can be executed dynamically during the system's initialization phase and consists of four sequential steps:

- **Step 1:** Stroke discretization.
- **Step 2:** Automated breakaway profiling.
- **Step 3:** Directional bias extraction.
- **Step 4:** Least-squares curve fitting. To avoid the interpolation discontinuities and memory overhead associated with rigid look-up tables, a least-squares curve fitting algorithm is applied. The discrete empirical offsets are approximated into continuous polynomial functions of degree n:

$$u_{\mathrm{bd}}(\theta) = \sum_{i=0}^{n} a_i \, \theta^i \tag{5}$$

where a_i represents the optimized polynomial coefficients. For the nonlinear cam profiles typical in MWIR systems, a third-order polynomial ($n = 3$) provides sufficient fidelity without overfitting. This continuous mathematical formulation ensures smooth feedforward control effort transitions across the entire zoom stroke.

Additionally, a startup torque injection $u_s = U_{\mathrm{start}}$ is applied during a brief interval to overcome static friction reliably. The final control law is:

$$u(t) = u_{\mathrm{PID}} + u_{\mathrm{bd}}(\theta) + u_s \tag{6}$$

To strictly prevent integral windup and ensure bumpless transfer during directional switching, a deadband-based state reset mechanism is implemented alongside this control law. Unlike continuous tracking servos, this system operates on a point-to-point basis. When the tracking error enters the predefined tolerance deadband, the active output is disabled ($u(t) = 0$) and the integral accumulator is explicitly reset to zero. The lens position is inherently maintained by static friction. Any transition between the forward and reverse PID parameter sets strictly occurs during this zero-state holding phase, eliminating discontinuous PWM spikes.

Furthermore, the stability of this direction-dependent switched scheme is mathematically guaranteed through a Bounded-Input Bounded-Output (BIBO) analysis based on physical constraints. From the system dynamics (Equation 1), the absolute bounds of all contributing elements are evaluated:

First, the control input $u(t)$ is physically saturated by the 100% PWM limit, strictly bounding the active motor torque:

$$|K_u u(t)| \leq \tau_{\max} \tag{7}$$

Second, because the mechanical stroke is finite ($\theta \in [\theta_{\min}, \theta_{\max}]$), the maximum spring compression is strictly constrained. Thus, the total nonlinear load is inherently bounded by a structural limit:

$$|\tau_{\mathrm{load}}(\theta, d)| \leq \tau_{\mathrm{L,max}} \tag{8}$$

Third, rearranging the dynamic equation for the maximum absolute acceleration yields:

$$J(\theta)|\ddot{\theta}| \leq \tau_{\max} + \tau_{\mathrm{L,max}} - K_{\omega}|\dot{\theta}| \tag{9}$$

This inequality demonstrates that as the angular velocity $|\dot{\theta}|$ increases, the viscous damping term $K_{\omega}|\dot{\theta}|$ grows. The velocity can only increase until the damping term cancels the bounded driving forces. Consequently, the system velocity is strictly bounded ($|\dot{\theta}| \leq \dot{\theta}_{\max}$).

Finally, the system switches between the forward and reverse PID parameter sets strictly upon motion reversal, which necessitates crossing zero velocity ($\dot{\theta} = 0$). At this exact switching instant, the kinetic energy is absolute zero:

$$E_k = \frac{1}{2}J(\theta)\dot{\theta}^2 = 0 \tag{10}$$

Since the switching transitions occur exclusively at zero kinetic energy states and all actuating inputs are bounded, the switched closed-loop system cannot accumulate divergent energy and is inherently BIBO stable.

3. RESULTS AND DISCUSSION

3.1. Experimental setup

The core system (Figure 1b) is a continuous MWIR zoom objective lens with a focal length of 25 - 360 mm (F/4.0). The actuation module features a FAULHABER 1224 SR DC coreless motor coupled with a 64:1 reduction gearhead. Real-time position feedback is provided by an integrated PA2-100 incremental encoder. Throughout the experiments, zoom positions and transient responses are quantified in encoder counts.

3.2. Results and discussion

a) Load asymmetry and conventional PID limitations

As illustrated in Figure 3 and Figure 4, both the breakaway PWM and velocity responses exhibit severe variations depending on the zoom position and motion direction, experimentally confirming the nonlinear load field.

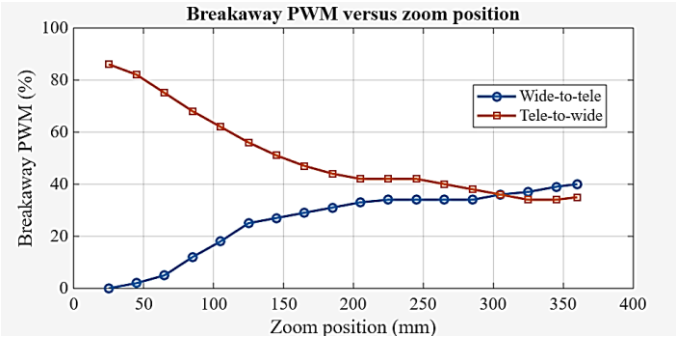


Figure 3. *Breakaway PWM versus zoom position.*

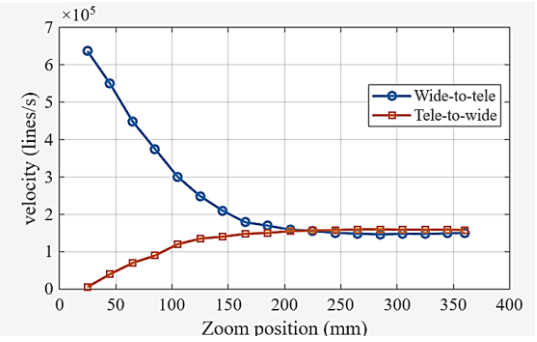


Figure 4. *Velocity distribution along zoom travel.*

Consequently, applying a globally tuned PID controller results in highly inconsistent performance. As shown in Figure 5 and Figure 6, conservative PID gains fail to overcome heavy loads (resulting in startup failures or >6000 ms settling times), whereas aggressive gains cause unacceptable overshoot (up to 30 counts) in lightly loaded regions. These results demonstrate that the performance limitations originate from the strong directional variation of load characteristics rather than insufficient PID tuning effort.

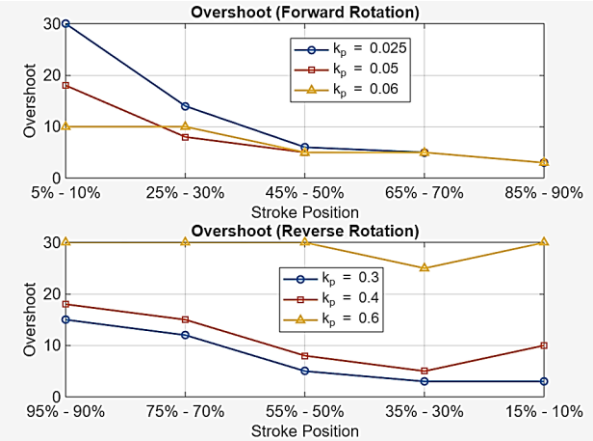


Figure 5. *Overshoot.*

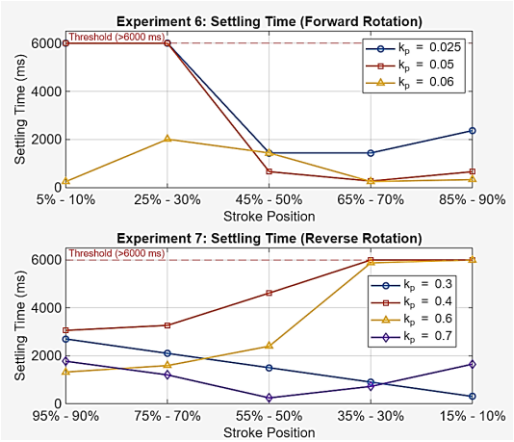


Figure 6. *Settling-time.*

b) Performance of the proposed method

Due to the direction-dependent spring forces and cam kinematics, control parameters must be optimized asymmetrically. Instead of manual tuning, the automated calibration procedure (Section 2.2) was executed to extract the compensation parameters across the zoom range. Table 1 presents the sampled discrete outputs from this automated process. For the forward direction (spring-assisted), the baseline PID parameters were systematically determined as $K_{pf} = 0.05, K_{if} = 0.05, K_{df} = 0.003$, coupled with negative duty-cycle offsets. Conversely, the reverse direction (spring-resisted) required higher actuation ($K_{pr} = 0.6, K_{ir} = 0.005, K_{dr} = 0.005$) and positive offsets to overcome spring tension. Crucially, in real-time operation, the discrete offset values in Table 1 are not used as a rigid look-up table; rather, they are fitted into a continuous polynomial function $u_{bd}(\theta)$ to ensure seamless feedforward compensation.

The proposed asymmetric compensation framework was evaluated using the same experimental platform and operating conditions. Figure 7 and Figure 8 summarize the overall performance comparison between the conventional PID controller and the proposed method:

- Mean settling time decreased from 3078 ms to 330 ms, representing an improvement of nearly one order of magnitude.

- Overshoot reduction and worst-case performance: The mean overshoot was significantly reduced from 10.3 to 3.4 counts. Correspondingly, the maximum overshoot was suppressed from 20 to 4.6 encoder counts, while the worst-case settling time decreased from more than 6000 ms to 360 ms.

Table 1. *Load compensation parameters and overshoot across focal lengths.*

Focal length (mm)	Forward duty cycle offset	Reverse duty cycle offset	Avg. forward overshoot (counts)	Avg. reverse overshoot (counts)
25	-10	+22	4.2	4.3
65	-8	+19	3.5	3.3
125	-2	+14	4.0	4.1
185	0	+12	3.2	3.2
245	0	+13	3.2	3.0
305	0	+16	2.4	2.3
360	0	+14	3.7	3.6

These results demonstrate that the proposed controller successfully compensates for the dominant asymmetry of the load field while maintaining a simple implementation structure.

Furthermore, to evaluate startup reliability, a series of micro-step tracking tests were conducted across the entire zoom range. During these short-stroke adjustments, the initial position error is extremely small. The conventional globally tuned PID controller frequently failed to generate sufficient initial torque to overcome the mechanical static friction, resulting in deadband stalling in approximately 15% of the trials (yielding an 85% success rate). By integrating the brief 100% PWM startup injection, the proposed framework reliably broke the static friction in all trials, successfully increasing the startup success rate to absolute 100% without inducing additional overshoot.

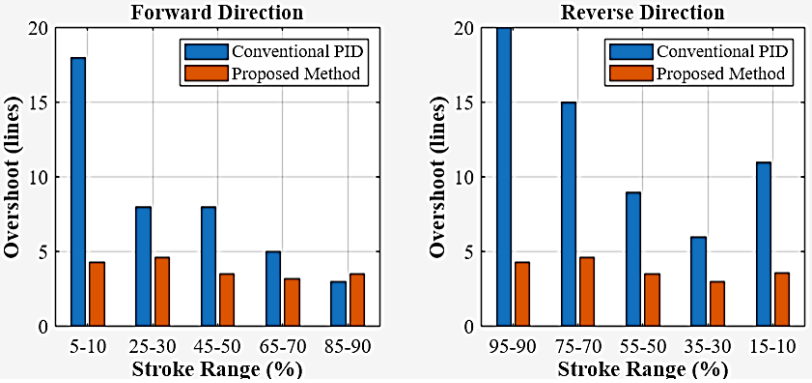


Figure 7. *Overshoot comparison.*

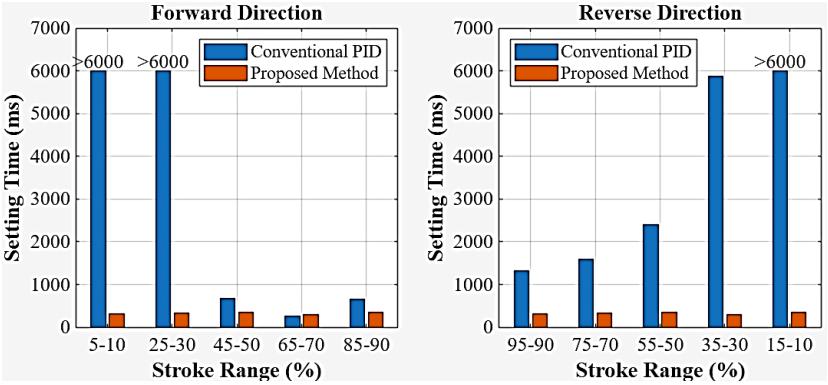


Figure 8. *Settling time comparison.*

c) Discussion

The significant performance improvements observed in the proposed framework stem from the synergistic operation of its three control components, each resolving a specific physical limitation of the MWIR zoom mechanism. First, the direction-dependent PID establishes a stable control baseline by counteracting the macroscopic asymmetry of the preload spring. This prevents severe oscillations during spring-assisted motion, primarily contributing to the reduction in mean overshoot from 10.3 to 3.4 counts. Second, the continuous polynomial bias (u_{bd}) proactively flattens the localized load variations along the nonlinear cam grooves. By mitigating mid-stroke friction gradients and local jitter, this feedforward term is directly responsible for the drastic decrease in mean settling time from 3078 ms to 330 ms. Finally, during short-stroke tracking where the initial position error is too small to generate sufficient PID torque, the brief 100% PWM startup injection effectively breaks the static friction. This targeted pulse strictly prevents deadband stalling, thereby raising the overall startup success rate to 100%.

Collectively, these results demonstrate that the primary challenge in continuous MWIR zoom control is not the lack of sophisticated mathematical observers, but rather the highly nonlinear load

characteristics introduced by the cam and spring mechanics. The proposed lightweight architecture proves that characterizing and directly compensating for this physical load field provides a highly effective alternative to complex adaptive algorithms.

4. CONCLUSIONS

This paper investigated the control challenges of a continuous MWIR zoom mechanism driven by a DC coreless motor and incremental encoder. Experimental characterization revealed significant position-dependent and direction-dependent load asymmetry caused by the nonlinear cam profile and preload spring. Results demonstrated that a single globally tuned PID controller fails to simultaneously satisfy startup, overshoot, and settling-time requirements over the entire operating range. To address this, a lightweight asymmetric compensation framework based on local feedforward linearization was proposed. Overcoming the reliance on heuristic tuning and rigid look-up tables, the framework integrates an automated calibration procedure with polynomial curve fitting to systematically generate continuous directional compensation profiles. The method requires only standard encoder feedback without additional sensors or complex observers. Experimental validation showed that the startup success rate increased from 85% to 100%, mean overshoot was reduced from 10.3 to 3.4 counts, and mean settling time decreased dramatically from 3078 ms to 330 ms. These results confirm that the automated characterization and continuous compensation of directional load asymmetry significantly enhance MWIR zoom control performance while maintaining low implementation complexity. Future work will focus on validating the system's adaptability and robustness under extreme thermal variations and multi-axis dynamic loads.

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TÓM TẮT

Khung điều khiển bù bất đối xứng tinh gọn cho hệ zoom liên tục MWIR dưới tác động của tải phụ thuộc chiều chuyển động

Các cơ cấu zoom liên tục trong hệ thống ảnh hồng ngoại sóng trung (MWIR) thường sử dụng rãnh cam phi tuyến và lò xo tiền tải để đảm bảo độ chính xác và giảm độ rơ cơ khí. Tuy nhiên, các đặc điểm này làm xuất hiện sự biến thiên tải đáng kể theo vị trí và chiều chuyển động, gây ra đặc tính động học bất đối xứng. Bài báo trình bày nghiên cứu thực nghiệm hiện tượng tải bất đối xứng trong cơ cấu zoom MWIR sử dụng động cơ một chiều không lõi từ và encoder gia tăng. Dựa trên các quan sát này, một khung điều khiển bù bất đối xứng tinh gọn dựa trên cơ sở tuyến tính hóa bù thuận cục bộ được đề xuất. Nhằm loại bỏ việc tinh chỉnh cảm tính và sự phụ thuộc vào hệ cơ khí, phương pháp giới thiệu một quy trình hiệu chuẩn tự động kết hợp với nội suy đường cong đa thức để tạo ra đặc tính bù tải liên tục theo chiều. Giải pháp này được tích hợp với việc chọn tham số PID theo chiều và tăng cường mô-men khởi động mà không cần thêm cảm biến hay bộ quan sát phức tạp. Kết quả thực nghiệm cho thấy phương pháp đề xuất nâng tỷ lệ khởi động thành công từ 85% lên 100%, giảm độ quá điều chỉnh trung bình từ 10,3 xuống 3,8 xung và giảm thời gian xác lập trung bình từ 3078 ms xuống 330 ms. Kết quả chứng minh rằng việc đặc trưng hóa tự động và bù tải liên tục giúp nâng cao đáng kể chất lượng điều khiển hệ zoom MWIR trong khi vẫn duy trì độ phức tạp triển khai thấp.

Từ khoá: MWIR; Zoom liên tục; Động cơ một chiều không lõi từ; Điều khiển PID; Tải bất đối xứng; Rãnh cam phi tuyến.