

Design Optimization and Active Disturbance Rejection Control of High-Precision Lightweight Linkage Robots with Flexible Joints

Leo Liu^{*}

High School Affiliated to Renmin University, Beijing, China, 100080

^{*}Corresponding Author. Email: liujiale818@163.com

Abstract

Lightweight linkage robots can reduce inertia and energy consumption in high-speed, high-precision manipulation, but reduced mass increases structural compliance and joint flexibility. Nonlinear stiffness, hysteresis, transmission error, and residual vibration can therefore degrade end-effector accuracy. This paper treats precision as a mechanical-control co-design problem, reviewing structural optimization, flexible-joint modeling, ADRC, disturbance observation, and learning-based compensation. Automotive suspension failures and Chinese recall statistics are then used as a reliability analogue. From 2021-2025, annual recall counts were relatively stable, whereas the number of affected vehicles varied markedly; design-related defects consistently accounted for about three-fifths of recalled vehicles. The evidence supports a design principle for lightweight robots: mass reduction should be constrained by fatigue life, stress concentration, manufacturing variability, and realistic dynamic loading, while robust control is used to reject disturbances and suppress vibration. Reliable high precision therefore depends on structurally robust lightweight design supported, rather than replaced, by advanced control.

Key words

Lightweight Linkage Robots; Active Disturbance Rejection Control; Structural Optimization; Suspension Fracture; Fatigue Failure; China Automotive Recalls

1. Introduction

High-precision manipulation is increasingly re-

quired in semiconductor fabrication, aerospace assembly, and medical surgery. Lightweight robots improve dynamic response by reducing moving inertia, but

reduced mass also increases structural compliance and joint flexibility. Nonlinear stiffness, hysteresis, transmission error, and residual vibration can consequently degrade end-effector accuracy [1][2].

Precision is therefore a co-design problem. Topology and shape optimization can improve stiffness-to-mass ratio [3], while robust control methods such as sliding-mode control, disturbance observers, iterative learning control, and ADRC compensate flexible-joint nonlinearities and external disturbances more effectively than conventional PID control [4].

This paper reviews these structural and control approaches and then examines suspension fracture cases and Chinese automotive recall data as an engineering analogue for fatigue, stress-concentration, and manufacturing risks in lightweight load-bearing systems. The central argument is that high precision requires fatigue-aware structural optimization combined with disturbance-rejection control.

2. Literature Review

2.1 Structural Design and Optimization of Lightweight Linkage Robots

Lightweight manipulators reduce inertia but can increase elastic deformation and end-effector error. Structural optimization must therefore preserve adequate stiffness across the workspace rather than pursue minimum mass alone. The practical objective is a robust stiffness-to-mass ratio under configuration-dependent loading.

Wang et al. integrated part-level topology optimization with parametric system optimization for lightweight serial robots using finite-element-derived stiffness-mass metamodels [5]. Chen et al. similarly showed that optimized geometry can reduce compliance-induced error in parallel machining robots [6], while Palmieri et al. demonstrated that extreme lightweighting in a deployable soft arm increases dependence on accurate stiffness modeling and control [7]. Collectively, these studies show that control can compensate residual compliance but cannot substitute for inadequate structural stiffness or fatigue strength.

2.2 Modeling of Joint Flexibility and

Nonlinearities

High-ratio transmissions introduce joint elasticity, nonlinear torsional stiffness, hysteresis, friction, and transmission error. Kircanski and Goldenberg demonstrated load-dependent stiffness and significant hysteresis in harmonic drives [8], while Chen modeled the coupled dynamics of flexible joints and links [9]. These effects become especially important during high-speed acceleration reversals and near resonant modes.

Vakilinejad et al. further identified and compensated periodic gear transmission errors [10]. High-precision control should therefore model predictable elasticity, friction, and transmission errors where possible, while estimating unmodeled and time-varying effects online as disturbances.

2.3 Advanced Control Strategies for High-Precision Trajectory Tracking

Flexible lightweight systems require simultaneous trajectory tracking and vibration suppression. Garcia-Perez et al. combined cascaded sliding-mode control with Multiple Positive Position Feedback to separate rigid-body tracking from active damping [11]. Disturbance-observer methods offer a complementary approach by estimating aggregate uncertainty rather than requiring a perfectly identified model.

Kim and Oh developed a disturbance-observer-based dual-position controller [12], and Xu et al. showed that an extended flexible-joint model improves manipulator precision [13]. These results motivate ADRC: its Extended State Observer estimates lumped disturbances such as friction, parameter variation, and unmodeled elasticity so that the feedback loop can compensate them online.

2.4 Data-Driven and Learning-Based Compensation Techniques

Data-driven methods complement model-based control when joint stiffness, friction, payload, and transmission behavior vary with operating condition. Tayebi's adaptive iterative learning control improves repeated trajectories by learning from previous errors [14], whereas neural-network methods can approximate nonlinear dynamics in less repetitive conditions.

Aouaichia et al. integrated Neural Network Model Predictive Control with ADRC [15], while Rahmani and Redkar combined Koopman-operator modeling with robust sliding-mode control [16]. A defensible lightweight-robot architecture is therefore hybrid: physics-based models define the safety-critical baseline, learning compensates residual nonlinearities, and ADRC rejects disturbances that cannot be reliably modeled in advance.

3. Analysis of Real-World Structural Failures: Automotive Suspension Fracture Incidents in China

Automotive suspension systems provide a useful engineering analogue because, like robotic linkages, they are lightweight load-bearing assemblies exposed to repeated, multi-axial, and transient loads. The cases below are used to identify transferable mechanisms—stress concentration, fatigue, material variability, and insufficient validation—rather than to claim direct equivalence between automobiles and robots.

3.1 Case Studies of Suspension Failures in Daily Commute Scenarios

The Volkswagen Sagitar case attracted attention between 2012 and 2014 after reports of rear trailing-arm fractures associated with the coupled non-independent suspension. Similar fracture locations were repeatedly reported, consistent with a localized structural weakness or stress concentration [17]. More than 140 complaints were recorded between July 25 and August 5, 2014, representing about half of all complaints on the national defect platform during that interval [17]. The subsequent investigation and recall illustrate why structural changes must be validated against realistic cyclic and impact

loading, not static strength alone.

In the 2021 Tesla Model Y recall, 21,599 vehicles were recalled because steering knuckles might not satisfy design-strength requirements [18]. Reported heat-treatment deviations could reduce hardness in a small proportion of parts, with an estimated defect probability of 0.2%-1.0% [18]. The low probability but severe consequence highlights manufacturing-process capability and material-property variability as reliability constraints alongside optimized geometry. Neither case proves that lightweighting causes failure; both show how inadequate fatigue, stress-concentration, or process control can create safety-critical weaknesses.

3.2 Data Analysis of Automotive Suspension Defects in China

Table 1 summarizes national recall statistics from 2021-2025. Because the dataset contains only five annual aggregate observations and the design-related shares for several years are approximate, the analysis is descriptive rather than inferential. Three measures are particularly informative: the stability of annual recall counts, the volatility of vehicles affected, and the persistent share attributed to design-related defects.

Across the five years, the mean number of recall actions was 214.6, with a narrow range of 190-233 and a coefficient of variation of approximately 7.7%. By contrast, the number of vehicles involved averaged 7.61 million but ranged from 4.49 to 11.24 million, producing a much higher coefficient of variation of approximately 29.7%. This divergence indicates that recall frequency and recall scale measure different aspects of reliability: a relatively stable number of recall campaigns can still affect sharply different numbers of vehicles when a defect is embedded in a widely deployed platform or component. The 2024 total of 11.24 million vehicles was approximately 67.0% higher than in 2023, before falling by about 39.1% in 2025.

Table 1: China Automotive Recall Statistics (2021–2025)

Year	Total Recalls	Vehicles Involved (million)	Design-Related (% of vehicles)
2021	232	8.74	~60%
2022	204	4.49	~58%

Year	Total Recalls	Vehicles Involved (million)	Design-Related (% of vehicles)
2023	214	6.73	64.7%
2024	233	11.24	~62%
2025	190	6.85	61.6%

Source: State Administration for Market Regulation (SAMR), China [19][20].

Design-related defects also show strong persistence. The annual design-related share ranges from approximately 58.0% to 64.7%, with a simple five-year average of about 61.3%; weighting by the number of vehicles involved gives an approximate share of 61.5%. Thus, roughly three out of every five recalled vehicles in this series were associated with design-related causes rather than manufacturing causes. In 2025 specifically, steering-system defects affected about 2.29 million vehicles, or 33.5% of recalled vehicles, while suspension complaints represented 3.1% of consumer defect reports and body/structural issues 17.2% [20]. These indicators use different denominators and should not be added together, but they consistently show that load-bearing and motion-transmission systems remain important reliability domains.

For lightweight-robot design, the principal implication is therefore risk concentration rather than a direct statistical transfer from automobiles to robots. The high variance in vehicles affected demonstrates how a single design weakness can scale across a product population, while the persistent design-related share suggests that verification of geometry, material limits, and load cases is at least as important as manufacturing quality control. Accordingly, topology optimization for robot links should be evaluated not only by mass and static stiffness, but also by stress concentration, fatigue life, sensitivity to manufacturing tolerances, and performance under representative dynamic load spectra. These aggregate recall data cannot establish causality between lightweighting and failure, but they provide a quantitative reliability rationale for imposing such constraints.

3.3 Material Selection and Structural Design Implications for Lightweight Robots

The automotive evidence is transferable at the level

of failure mechanism. Suspension components and robotic linkages both experience repeated load reversals, local stress concentrations, and sensitivity to material and process variation; fatigue and reliability constraints should therefore be integrated into lightweight design before control compensation is considered.

3.3.1 Material Fatigue and Fracture Mechanisms

A fracture analysis of an aluminum-alloy rear suspension control arm identified microcrack initiation near coarse Al-Fe-Si-Mn inclusions, with silicon segregation accelerating crack propagation [21]. Fatigue striations and intergranular fracture features indicated progressive cyclic damage rather than a single overload. Similar concerns apply to robotic links: joint interfaces, bolt holes, section transitions, bonded regions, and machined features can concentrate stress, so material selection must be paired with manufacturing-quality control and representative fatigue testing.

3.3.2 Design Optimization with Reliability Constraints

Reliability-based design optimization extends conventional topology optimization by including uncertainty in material properties, geometry, payload, and loading together with fatigue-life constraints. FEA can identify stress concentrations and evaluate candidate geometries under representative cyclic spectra. ADRC, trajectory shaping, and vibration suppression can then reduce residual transient and oscillatory loads. The resulting principle is clear: first establish a structure that remains safe under realistic uncertainty and fatigue constraints; then use control to improve precision and reduce avoidable dynamic loading.

4. Conclusion

Lightweight robots offer lower inertia and faster response, but structural compliance, flexible joints, friction, transmission error, and fatigue constraints create a coupled precision-reliability problem. The literature supports integrating topology optimization and flexible-joint modeling with disturbance observation, ADRC, and learning-based compensation rather than treating mechanical and control design independently.

The automotive cases provide a practical reliability analogue. The Sagitar case illustrates a recurring structural weak point, whereas the Model Y recall illustrates manufacturing variability in a safety-critical load path [17][18]. SAMR data for 2021-2025 add a quantitative perspective: recall counts were comparatively stable, affected-vehicle totals were much more volatile, and design-related causes represented about 61% of recalled vehicles on average [19][20]. These data do not establish that lightweighting causes failure; they show the system-scale consequences of replicated structural or process vulnerabilities.

For robotic systems, the resulting co-design principle is to optimize mass, stiffness, fatigue reliability, and control performance together. Reliability-based optimization and FEA should establish adequate structural margins, while ADRC and learning-based compensation reject disturbances and suppress vibration. Future experimental work should measure tracking error together with strain and vibration on a flexible-joint manipulator to test whether precision gains also reduce structural loading and fatigue indicators.

Future research could further develop this framework from experimental validation toward an integrated structural-control co-design methodology. A flexible-joint manipulator test platform could first be established to compare different lightweight link geometries under controlled variations in payload, trajectory speed, joint stiffness, and external disturbances. Structural parameters such as link thickness, material distribution, and local reinforcement could then be optimized together with ADRC parameters using multi-objective criteria including mass, end-effector tracking error, vibration amplitude, peak stress, and predicted fatigue life. Rather than evaluating controller performance only through trajectory accuracy, future experiments should also investigate whether disturbance rejection and trajectory

shaping can reduce cyclic stress amplitudes at critical structural locations. In addition, uncertainty in material properties, manufacturing tolerances, joint backlash, and payload conditions could be incorporated into reliability-based optimization to examine the robustness of the proposed design across realistic operating conditions. Finally, combining physics-based flexible-joint models with data-driven residual compensation or digital-twin-based condition monitoring may enable the system to update its disturbance and fatigue estimates during operation. Such work would move lightweight robotic design beyond static mass reduction toward a closed-loop framework in which structural optimization, precision control, and long-term reliability are evaluated simultaneously.

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