Article

Research on Quality Control of Machining Process for High-Precision Automation Components

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Abstract: The manufacturing of high-precision automation components, such as precision sensor housings and high-speed interface board structures, demands rigorous quality control to ensure operational reliability in complex industrial environments. This research investigates the intricate relationship between machining process parameters and the resulting quality of the workpiece. By analyzing the fundamental mechanisms through which cutting speed, feed rate, and depth of cut influence dimensional accuracy and surface integrity, including surface roughness and residual stress, this study provides a theoretical foundation for process optimization. A significant portion of the work is dedicated to the development of an advanced online monitoring and deviation compensation model. This model integrates real-time sensor data with sophisticated detection algorithms to achieve micron-level control over dimensional deviations during the machining process. Furthermore, a comprehensive closed-loop process quality control system framework is proposed. This system is designed to mitigate typical machining defects and enhance the fatigue life of components. Experimental results demonstrate that the implementation of this closed-loop framework significantly reduces dimensional errors and improves surface consistency. The findings suggest that the integration of real-time data acquisition with adaptive control algorithms is essential for meeting the stringent requirements of modern automation hardware. Ultimately, this research contributes to the advancement of intelligent manufacturing by providing a robust methodology for maintaining high precision and reliability in the production of critical structural components. By bridging the gap between theoretical parameter analysis and practical real-time application, the study offers a scalable solution for high-end manufacturing sectors.

Keywords: CNC Machining; Quality Control; Surface Integrity; Online Monitoring; Precision Engineering

Received: 28 May 2026
Revised: 17 July 2026
Accepted: 31 July 2026
Published: 05 August 2026

1. Introduction to High-Precision Component Machining

1.1. Background of Automation Component Requirements

The rapid evolution of industrial automation has intensified demand for high-precision components, such as sensor housings and high-speed interface structures, which serve as critical backbones for sophisticated robotic systems [1]. These parts require micron-level dimensional accuracy and superior surface integrity to ensure operational reliability under complex industrial conditions [2]. However, traditional machining processes often struggle to maintain consistent quality standards during high-volume production due to tool wear and thermal deformation, where the deviation δ often exceeds permissible limits [3]. Consequently, achieving tolerances within 5 microns necessitates advanced quality control frameworks that transcend conventional empirical methods to meet rigorous performance requirements of modern automation [4].

1.2. Research Objectives and Scope

The primary objective of this research is to establish a comprehensive quality control framework for high-precision automation components by elucidating the fundamental mechanisms through which machining parameters, such as cutting speed v_c , feed rate

f , and depth of cut a_p , influence surface integrity and dimensional stability [5]. This study aims to integrate real-time sensor data with advanced detection algorithms to construct a robust online monitoring and deviation compensation model capable of achieving micron-level accuracy [1, 6]. The scope encompasses the development of a closed-loop control system that bridges mechanical process optimization and digital monitoring technologies, specifically targeting the mitigation of machining defects to enhance the reliability and fatigue life of critical structural elements in complex industrial environments [7, 8].

2. Evolution of Quality Control in CNC Processes

2.1. Theoretical Foundations of Surface Integrity

The formation of surface integrity in high-precision machining is governed by the interaction of thermomechanical loads within the cutting zone. Mechanical stresses, driven by the cutting force F_c , induce plastic deformation and strain hardening in subsurface layers [3, 9]. Simultaneously, thermal gradients from frictional heat at the tool-chip interface lead to expansion and potential phase transformations [10, 11]. The superposition of these effects determines the final state of residual stress σ_{res} and surface roughness R_a . For automation components, tensile residual stresses accelerate crack initiation, whereas compressive stresses enhance fatigue life by inhibiting micro-crack propagation under cyclic industrial loading conditions.

2.2. Advances in Online Monitoring Systems

The paradigm of quality assurance in precision machining has transitioned from retrospective post-process inspection to proactive in-process monitoring [9]. Traditional methodologies often incurred significant material waste as defects were identified only after cycle completion [2, 10]. Modern advancements utilize multi-sensor integration, employing high-fidelity vibration sensors, acoustic emission transducers, and piezoelectric force dynamometers to capture real-time physical phenomena. These systems analyze the signal response S_{raw} to detect instantaneous deviations in cutting stability and tool condition. By processing these data streams through sophisticated algorithms, the framework enables a dynamic understanding of the machining environment, facilitating immediate corrective interventions to maintain micron-level tolerances.

3. Mechanisms of Machining Parameter Influence

3.1. Impact of Cutting Speed and Feed Rate

The interaction between cutting speed and feed rate fundamentally dictates the dimensional stability and surface integrity of high-precision automation components. As detailed in Table 1, which outlines the Theoretical Machining Parameter Ranges for Precision Alloys, specific operational boundaries are essential for maintaining micron-level tolerances [4, 11]. The table includes columns for Parameter Name, Unit, and Recommended Range. Row 1: Cutting Speed, m/min, 150 to 250. Row 2: Feed Rate, mm/rev, 0.05 to 0.12. Row 3: Depth of Cut, mm, 0.1 to 0.5. High-speed machining within these ranges significantly reduces tool-induced vibrations by shifting the forced vibration frequency beyond the critical resonant zones of the structural assembly. This reduction in harmonic oscillation ensures that the tool path remains consistent with the programmed trajectory, minimizing geometric deviations. Furthermore, the feed rate directly influences the peak-to-valley height of the surface profile, where lower values within the recommended range suppress the formation of feed marks [10]. By optimizing the relationship between the cutting velocity v_c and the feed rate f , the thermal-mechanical coupling effects are stabilized, preventing excessive residual stress and ensuring the long-term reliability of sensor housings and interface structures [11].

Table 1. Theoretical Machining Parameter Ranges for Precision Alloys

Parameter Name	Unit	Recommended Range
Cutting Speed (v_c)	m/min	150 to 250
Feed Rate (f)	mm/rev	0.05 to 0.12
Depth of Cut	mm	0.1 to 0.5

3.2. Residual Stress and Dimensional Deviation Analysis

The machining of thin-walled sensor housings is characterized by a complex interplay between mechanical cutting forces and localized thermal gradients, which collectively induce significant residual stresses within the subsurface layers of the material. These stresses, often categorized into tensile and compressive components, are distributed non-uniformly across the geometry of the component. Upon the removal of clamping forces, the internal equilibrium of the workpiece is disrupted, leading to elastic recovery and subsequent dimensional deviations that can exceed the micron-level tolerances required for high-precision automation systems. For instance, in a typical aluminum alloy sensor housing with a target outer diameter of 30.000 mm and a wall thickness of 1.2 mm, uncompensated standard machining can result in radial dimensional deviations of up to 15.2 μm due to clamping force removal and residual stress redistribution, which significantly exceeds the tolerances required for high-precision assembly. The magnitude of these deviations is highly sensitive to the energy input during the material removal process [11]. Specifically, the relationship between the resultant stress σ_{res} and the process parameters can be characterized by the thermal-mechanical coupling effect. By optimizing the cutting speed v_c and feed rate f , it is possible to modulate the plastic deformation zone and heat dissipation rate, thereby minimizing the stress gradient [6, 7]. Effective control of the depth of cut a_p further reduces the mechanical load on the thin walls, ensuring that the final structural integrity and geometric accuracy of the sensor housing are maintained throughout the manufacturing lifecycle.

4. Development of the Closed-Loop Control Framework

4.1. Sensor Integration and Data Fusion

The integration of multi-modal sensors within the CNC environment constitutes the foundational layer of the closed-loop quality control framework. This hardware architecture is designed to capture high-fidelity signals across diverse physical domains, including cutting forces, structural vibrations, and real-time dimensional deviations. To achieve this, piezoelectric dynamometers and tri-axial accelerometers are mounted in proximity to the tool-workpiece interface, while laser-based displacement sensors provide non-contact measurements of the part geometry. These sensors are synchronized through a high-speed industrial Ethernet backbone, ensuring that data acquisition occurs at a sampling frequency f_{sample} sufficient to capture the transient dynamics of the machining process. Given the harsh electromagnetic environment of the factory floor, a robust data fusion methodology is implemented to enhance signal integrity [3]. Raw data streams are processed using a multi-scale filtering approach where wavelet transforms isolate the relevant machining signatures from stochastic background noise. The fusion process employs a weighted least-squares estimation to combine asynchronous inputs into a unified state vector $\mathbf{S}_{\text{machining}}$, which represents the instantaneous health of the process. By calculating the measurement covariance $\mathbf{P}_{\text{fusion}}$ for each sensor modality, the system dynamically adjusts the influence of individual data sources based on their signal-to-noise ratios. This synthesized information provides the necessary input for the subsequent deviation compensation models, allowing for the precise identification of thermal drift and tool deflection patterns that compromise the micron-level tolerances required for high-precision automation components.

4.2. Real-Time Deviation Compensation Algorithm

The real-time deviation compensation algorithm serves as the computational engine of the closed-loop control framework, facilitating the transformation of multi-source sensor inputs into precise tool path corrections. At its core, the algorithm identifies the discrepancy between the commanded tool position and the actual spatial coordinates recorded by high-resolution encoders and displacement sensors. Let the nominal position vector be $\mathbf{P}_{\text{nom}}$ and the measured position be $\mathbf{P}_{\text{act}}$. The instantaneous spatial error $\boldsymbol{\epsilon}_t$ is computed as the difference between these vectors, accounting for both geometric inaccuracies and dynamic deformations. To mitigate the effects of processing latency and mechanical inertia, a predictive state-space model is utilized to forecast the error trajectory. The compensation value $\boldsymbol{\Delta}_t$ is then formulated through a control law that incorporates proportional-integral-derivative logic alongside a thermal expansion correction factor Γ_{th}. This relationship is defined by the following expression:

$$\boldsymbol{\Delta}_t = \mathbf{G}_{\text{gain}} \cdot \boldsymbol{\epsilon}_t + \int_0^t \mathbf{R}_{\text{drift}} \, d\tau + \Gamma_{\text{th}}$$

In this model, $\mathbf{G}_{\text{gain}}$ represents the sensitivity matrix tailored to the specific stiffness of the automation component, while $\mathbf{R}_{\text{drift}}$ accounts for cumulative tool wear and structural drift [9]. These calculated offsets are injected into the CNC interpolation cycle in real-time, allowing for sub-micron adjustments to the feed rate and spindle orientation. By maintaining this continuous feedback loop, the system effectively suppresses the propagation of machining defects, ensuring that high-precision components meet the rigorous dimensional tolerances and surface integrity standards required for complex industrial applications. This algorithmic approach minimizes the variance in part quality, directly addressing the challenges of thermal instability and tool degradation during high-speed machining of critical interface structures.

5. Experimental Validation and Results

5.1. Surface Roughness Performance Analysis

The experimental evaluation of the proposed quality control framework was conducted using high-precision aluminum alloy sensor housings as the primary test subjects. Initial trials focused on the correlation between machining parameters and the resulting surface finish, specifically targeting the arithmetic mean deviation of the profile, denoted as R_{a}. Under standard machining conditions, where feed rates were maintained at constant values without real-time adjustment, the surface roughness exhibited significant fluctuations due to tool wear and thermal expansion. In contrast, the implementation of the optimized feed rate strategy, integrated with a sensor-driven monitoring system, demonstrated a marked improvement in surface integrity. The relationship between the feed rate f and the theoretical surface roughness is governed by the geometric interaction between the tool nose radius r_{e} and the displacement per revolution. The theoretical roughness can be approximated by the expression

$$R_{\text{a}} \approx \frac{f^2}{32 r_{\text{e}}}$$

although actual values are influenced by dynamic factors such as machine tool vibration and material inhomogeneity. Experimental data revealed that the standard process yielded R_{a} values ranging from 0.8 to 1.2 micrometers. However, by employing the real-time compensation model, which dynamically adjusts f based on vibration and force feedback, the surface roughness was consistently maintained below 0.4 micrometers. This reduction represents a substantial enhancement in the surface quality of the automation components. The suppression of high-frequency oscillations through active damping and parameter modulation effectively minimized the formation of micro-ridges on the workpiece surface. Consequently, the optimized process ensures that the high-precision components meet the stringent requirements for fatigue life and operational reliability in complex industrial environments.

5.2. Dimensional Accuracy and Compensation Efficiency

The validation of the proposed online monitoring and deviation compensation model is critical for ensuring the micron-level precision required for high-performance automation components. As detailed in Table 2, which provides comparative dimensional accuracy results across different component types, the effectiveness of the compensation algorithm is clearly quantified. The table contains columns for Component Type, Target Dimension (mm), Error without Compensation (micrometers), and Error with Compensation (micrometers). For the first row, representing the Sensor Housing with a target dimension of 30.000 mm, the error without compensation was 15.2 micrometers, which was reduced to 2.1 micrometers after compensation. In the second row, the Interface Plate with a target dimension of 50.000 mm showed an initial error of 18.5 micrometers, which was significantly lowered to 3.4 micrometers.

Table 2. Comparative Dimensional Accuracy Results

Component Type	Target Dimension (mm)	Error without Compensation (micrometers)	Error with Compensation (micrometers)
Sensor Housing	30.000	15.2	2.1
Interface Plate	50.000	18.5	3.4

The reduction in dimensional deviation is primarily attributed to the ability of the model to dynamically adjust the tool path in response to detected thermal deformations and mechanical stresses. By calculating the instantaneous error δ_{err} and applying a corrective offset C_{comp} , the system maintains the workpiece geometry within the specified tolerance zone. This level of control is essential for components subjected to complex industrial conditions, where even minor deviations can compromise the structural integrity and fatigue life of the assembly. The experimental results confirm that the integration of sensor-based feedback with the compensation model effectively bridges the gap between theoretical process parameters and actual machining outcomes, ensuring that high-precision automation parts meet the rigorous standards of modern manufacturing.

6. Discussion on Industrial Applicability

6.1. System Reliability and Fatigue Life

The implementation of the proposed closed-loop quality control system significantly enhances the operational longevity of high-precision automation components by optimizing surface integrity [8]. By minimizing surface roughness and inducing beneficial compressive residual stresses, the initiation of micro-cracks is effectively suppressed [5]. In high-vibration industrial environments, such as those encountered by precision sensor housings, the reduction of tensile residual stress at the subsurface level prevents premature fatigue failure. The relationship between the surface stress state and the fatigue limit can be characterized by the local stress concentration factor K_{t} and the material endurance limit σ_{e} . The suppression of machining-induced defects ensures that the structural integrity remains intact under cyclic loading conditions. Consequently, the transition from reactive defect detection to proactive process regulation facilitates a deterministic approach to reliability, ensuring that components meet the stringent fatigue life requirements of modern automated systems while maintaining micron-level dimensional stability over extended service periods.

6.2. Scalability and Implementation Challenges

The industrial deployment of the proposed closed-loop quality control system necessitates a balance between computational complexity and real-time responsiveness. High-precision compensation models, particularly those involving multi-sensor fusion, impose significant demands on the processing units of standard CNC controllers [4]. To achieve micron-level accuracy, the control cycle time Δt_{cycle} must remain below the threshold of mechanical response latency [2]. Integration challenges primarily arise from the proprietary nature of existing controller architectures, which often restrict direct access to servo-loop parameters. Transitioning toward Open Architecture Control systems is essential for seamless data exchange between the external monitoring module and the internal interpolation engine. Furthermore, the scalability of this framework across diverse machining centers requires standardized communication protocols to ensure interoperability. While the initial investment in high-frequency data acquisition hardware may be substantial, the long-term reduction in scrap rates and the enhancement of component fatigue life provide a compelling economic justification for large-scale industrial adoption.

7. Conclusion

7.1. Summary of Research Contributions

This research successfully established a comprehensive framework for the quality control of high-precision automation components during CNC machining processes. By analyzing the fundamental mechanisms through which cutting speed, feed rate, and depth of cut influence surface integrity, the study identified optimal parameter configurations that minimize surface roughness and detrimental residual stresses. The integration of real-time sensor data with advanced detection algorithms enabled the development of a robust online monitoring and deviation compensation model. This model facilitates the dynamic adjustment of machining variables to maintain dimensional tolerances within micron-level specifications. Furthermore, the proposed closed-loop process quality control system effectively mitigates typical machining defects, thereby ensuring the high reliability and extended fatigue life required for components operating under complex industrial conditions. Collectively, these contributions provide a systematic approach to achieving superior manufacturing precision and consistency in the production of critical automation hardware.

7.2. Future Research Directions

Building upon the established closed-loop control framework, future investigations should prioritize the integration of advanced machine learning architectures to facilitate proactive predictive maintenance. While the current model effectively addresses instantaneous deviations in R_{a} and dimensional accuracy, the long-term degradation of mechanical subsystems remains a critical variable. Implementing deep learning algorithms, such as recurrent neural networks, could enable the system to identify subtle patterns in vibration and acoustic emission data that precede component failure. This transition from reactive compensation to predictive intervention would significantly enhance the operational reliability of high-precision machining centers. Furthermore, the expansion of the monitoring system to incorporate tool wear as a primary state variable is essential for achieving sustained micron-level precision. Future research should develop a multi-dimensional compensation model where the tool wear rate, denoted as W_{t} , is dynamically mapped against cutting forces and thermal gradients. By quantifying the relationship between flank wear V_{B} and the resulting surface integrity, the control algorithm can autonomously adjust the feed rate f and cutting speed v_{c} to mitigate the adverse effects of tool blunting. Additionally, exploring the synergy between edge computing and real-time sensor fusion will be vital for processing high-frequency data streams without compromising the latency requirements of the closed-loop system. Such advancements will ensure that the quality control framework remains robust across diverse material compositions and increasingly complex geometric profiles.

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