

Metrological Validation of a Sensorized Spindle Emulator for Indirect Cutting Force Measurement for Robotic Machining

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1. INTRODUCTION

The adoption of industrial robots for machining operations provides extended workspaces, operational flexibility, and cost-effectiveness compared to traditional CNC machine tools. However, their serial architecture yields low structural stiffness and highly pose-dependent dynamics, causing trajectory deviations and severe vibrations during the cutting process [1, 2].

Accurate measurement of cutting forces is crucial for process monitoring, chatter suppression, and tool wear evaluation. Commercial sensors and conventional dynamometers struggle to isolate cutting forces in robotic applications due to bandwidth limits—often failing to capture both low-frequency structural vibrations and high-frequency tool vibrations simultaneously [3]—and poor signal-to-noise ratios at typical robot resonances (10–30 Hz) [2, 4]. Indirect methods utilizing motor currents also lack cutting-zone proximity, bandwidth, and are heavily affected by joint friction [5].

A growing area of research involves integrating sensors directly into the spindle housing for force measurement, aiming at non-invasive solutions. Strain and piezoelectric sensors are commonly used to monitor cutting forces without modifying the tooling system. Another approach employs capacitive or eddy-current sensors (ECS) to detect relative displacements between the spindle shaft and the housing. However, cutting force measuring systems (CFMS) based on relative displacement sensors often suffer from low signal-to-noise ratios and limited frequency bandwidth, discouraging their adoption in industrial environments. Furthermore, these methods are heavily influenced by spindle runout, temperature variations, and rotational speeds. Thermal drift, in particular, remains one of the most critical challenges, requiring advanced compensation strategies to maintain measurement accuracy over time.

To address these metrological gaps and current technological trends—such as miniaturization, high-sensitivity multi-sensor fusion, and real-time computation—this paper introduces a Sensorized Spindle Emulator (SSE). Designed as an autonomous physical twin (and a key enabler for a Digital Twin framework), the SSE serves as a validation platform to investigate edge-computed, real-time indirect force estimation via local compliance.

2. STATE OF THE ART IN FORCE FILTERING TECHNIQUES

The reconstruction of cutting forces from measured signals (strains, displacements, or accelerations) requires the inversion of the system's structural dynamics. This is typically achieved through Transmissibility Frequency Response Functions (TFRFs). A summary of the most advanced filtering techniques developed over the past decade for CFMS applications highlights a trade-off between computational speed, accuracy, and calibration requirements.

When fast, real-time filtering of cutting forces is required, Augmented Kalman Filters (AKF) and Universal Augmented Kalman Filters (UAKF) are highly recommended. However, they demand human intervention for the preliminary parametric identification of the measured TFRFs. If a small processing delay is acceptable, non-parametric filters—such as Regularized Deconvolution Filters (RDF/URDF) or Optimal Inverse Filters (OIF/SOIF)—are generally preferred. Among these, OIF and Sub-Optimal Inverse Filters (SOIF) stand out due to their significantly lower computational cost and broader applicability. SOIF, in particular, can be effectively applied even when the measured TFRFs exhibit a wide and complex spectrum of resonances.

For simpler dynamometer configurations, where the input force is applied over a confined area, conventional approaches based on a classic 3×3 TFRF model yield satisfactory results. Conversely, when the tool-workpiece contact point varies widely—and when all internal signals of the device are

available—modern filtering methods based on the expanded transmissibility model should be preferred. A critical limitation of most aforementioned filters is the need for complete recalibration whenever the dynamometer or the sensorized spindle is mounted on a different machine tool or experimental setup. This limitation can be overcome by equipping the base of the measuring system with accelerometers and computing the Universal Inverse Filter (UIF), which actively decouples the internal dynamics from the variable external boundary conditions.

3. THE SENSORIZED SPINDLE EMULATOR AND EDGE ARCHITECTURE

The proposed SSE (Fig. 1) reproduces spindle dynamics while emulating robotic constraints, aiming for a non-invasive, highly integrated measurement ring. A rigid-body spindle is supported by elastomeric suspensions, acting as a high-frequency low-pass filter while providing the compliance needed to correlate radial deflection with cutting force. Springs, dampers, and a tilting joint replicate the manipulator's macroscopic low-frequency behavior and varying gravity effects.

Omitting bulky load cells maximizes compactness and measurement bandwidth, pushing towards a miniaturized solution. Radial displacement is measured by a custom linear Radial Displacement Sensor (RDS) based on ECS technology, capable of providing sub-micrometer accuracy [6]. To ensure rigorous metrological accuracy without relying on offline TFRF identification that would invalidate upon repositioning, the SSE explores an online, multi-sensor fusion approach.

An IMU tracks spatial orientation, while accelerometers are directly coupled to the RDS stator. Peltier cells regulate elastomer temperature, and a rotary encoder synchronizes signals with spindle rotation. Aligning with the Smart Component paradigm [7], all sensor fusion executes locally on an embedded edge node. This ensures real-time processing, minimizes latency, conserves robot controller bandwidth, and enables true 3D force reconstruction at the edge.

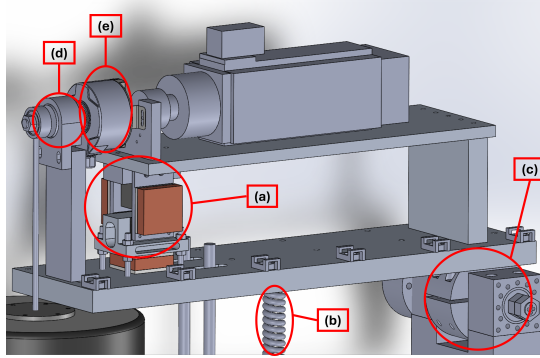


Figure 1: Representation of the SSE architecture, highlighting (a) the elastomeric suspensions with temperature conditioning, (b) the low-frequency dynamic simulation module, (c) the tilting joint, (d) the radial displacement sensor, and (e) the rotary encoder.

4. METROLOGICAL CHALLENGES AND METHODOLOGY

4.1. UNIVERSAL INVERSE FILTERING AND EXTERNAL DYNAMICS REJECTION

Robotic machining dynamics are governed by multi-source compliance that generates complex, pose-dependent FRFs highly susceptible to mode-coupling [8]. These continuous time-varying dynamics and structural non-linearities invalidate traditional static FRF models obtained via offline testing.

To counteract these low-frequency structural resonances (10–30 Hz), the SSE leverages the principles of Universal Inverse Filtering (UIF). By placing an accelerometer directly on the stator of the radial displacement sensor, the system captures the absolute motion of the spindle housing (induced by the robot's macroscopic vibrations). The localized edge-fusion algorithm synchronizes the high-bandwidth relative displacement data from the RDS with the absolute kinematic data from the housing accelerometers and the IMU.

This continuous, in-situ updating allows the algorithm to subtract the external inertial dynamics from the relative shaft-sensor displacement. As a result, the external macro-dynamics are dynamically rejected, isolating only the structural deflections strictly caused by the tool-workpiece interaction, eliminating the need for system recalibration when the spindle moves within the workspace.

4.2. ELASTOMER THERMAL COMPENSATION

As highlighted in recent literature, thermal drift is a major obstacle for displacement-based CFMS. Elastomer stiffness is highly temperature-dependent, directly altering the compliance matrix used for force reconstruction. The symmetric design of the custom radial displacement sensor intrinsically cancels out the shaft's radial thermal expansion, ensuring that the acquired signal is free from thermo-mechanical artifacts.

4.3. DYNAMIC RUN-OUT AND SPEED EFFECTS EVALUATION

Speed-dependent dynamic run-out alters instantaneous chip thickness, affects the gap measured by ECS sensors, and triggers harmonic instability [9]. By synchronizing the radial displacement readings with the rotary encoder, the edge algorithm maps this specific geometric harmonic signature in real-time. A synchronized time-domain averaging filter separates the dynamic run-out profile from the load-induced deflections, purifying the signal before it feeds into the inverse structural filter.

5. CONCLUSIONS

The Sensorized Spindle Emulator provides a rigorous, highly sensorized validation platform for indirect force estimation in robotic machining, acting as a physical precursor to a complete Digital Twin of the cutting process. By physically replicating robot dynamics and utilizing high-frequency edge sensor fusion, it addresses the historical limitations of relative displacement sensors. Specifically, the integration of stator-mounted accelerometers enables the implementation of Universal Inverse Filtering, successfully isolating localized cutting forces from low-frequency inertial disturbances without requiring pose-dependent recalibrations. This in-situ architecture offers a scalable, non-invasive Smart Spindle integration tailored for modern Industry applications.

REFERENCES

- [1] Li, Z., et al. "Research progress in the dynamics of heavy-duty robots from the perspective of machining process." *Robotics and Computer-Integrated Manufacturing*, 100 (2026).
- [2] Li, N., et al. "A review on cutting chatter detection and suppression in robotic milling," *Robotics and Computer-Integrated Manufacturing*, 100 (2026).
- [3] Shokrani, A., et al. "Sensors for in-process and on-machine monitoring of machining operations." *CIRP Journal of Manufacturing Science and Technology*, 51 (2024), 263-292.
- [4] Zhang, P., et al. "Systematic review of Cutting Force Measuring Systems in machining: Principles, design, filtering techniques and applications," *International Journal of Machine Tools and Manufacture*, 210 (2025).
- [5] Yaoguo, M., et al. "Research progress on intelligent monitoring of machining condition based on indirect method," *Advanced Engineering Informatics*, 67 (2025).
- [6] Iacono, N., et al., "Validation and Optimization of a Low-Cost Sensor for the Measurement of the Radial Displacements of a Cylindrical Conductive Target," *2025 IEEE International Workshop on Metrology for Industry 4.0 & IoT (MetroInd4.0 & IoT)*, Castelldefels, Spain, (2025).
- [7] Wojcicki, J. and Bianchi, G., "A Smart Spindle Component concept as a standalone measurement system for Industry 4.0 Machine Tools," *2020 IEEE International Workshop on Metrology for Industry 4.0 & IoT*, Roma, Italy, (2020).
- [8] Xin, S., et al. "A review of robotic machining dynamics: A new perspective based on multi-source compliance," *International Journal of Machine Tools and Manufacture*, 218 (2026).
- [9] Jing, X., et al. "A runout measuring method using modeling and simulation cutting force in micro end-milling," *The International Journal of Advanced Manufacturing Technology*, 91 (2017): 4191-4201.