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Original Article

An AI-Integrated CAD/CAM Framework for Predictive Surface Metrology in CNC Milling Using Synthetic Data Augmentation

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Abstract

The development of Industry Version 4.0 requires businesses to use Artificial Intelligence (AI) as a core technology for the Computer Aided Design and Manufacturing (CAD/CAM) systems, to generate virtual models. Although the traditional CAM systems develop toolpaths based on geometric shapes, they cannot measure how the cutting operations actually function because they disregard the tool vibrations and material defects that determine how surfaces will be developed. This study focuses on the development of an advanced predictive system that uses Artificial Neural Networks (ANN) to predict surface roughness (Ra) based on three cutting parameters: cutting speed (v), feed rate (f), and depth of cut (ap). The smart manufacturing field faces its most difficult challenge in the form of the "small data" problem, as physical experiments require excessive financial resources. We implemented a data approach that merged real industrial data with synthetic data generated using artificial intelligence methods. We increased the experimental base from 45 data points to 500 data points, which created sufficient variance for the development of robust models without needing extensive physical testing. The supervised learning system achieved a coefficient of determination (R2) score of 0.96, which means it correctly predicted surface quality 96% of the time. The AI-integrated framework showed a 20% decrease in prediction errors when tested against standard CAM software systems. The study shows that virtual metrology components integrated into CAD/CAM systems provide users with manufacturing design feedback that operates in real time, thus decreasing material waste while reducing the need for repeated testing in precision engineering processes.

Background

The manufacturing sector is currently undergoing a radical transformation, which is commonly called Industry 4.0. The use of Cyber Physical Systems marks the beginning of this transition because it combines physical machines with digital technologies. Engineers and researchers have used Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) systems as their primary design tools for several decades to create products from initial design concepts. Traditional CAD/CAM systems operate as geometric systems, which cannot identify the unpredictable machines that operate because they lack predictive capabilities to monitor tool vibration and thermal deformation, and the resulting surface roughness.

CNC milling requires precise methods to achieve optimal surface integrity, but currently, advanced computational intelligence is used instead of its previous empirical testing methods. Artificial Neural Networks (ANN) function as the fundamental technology for predictive manufacturing because they model the cutting speed (v), feed rate (f), and depth of cut (ap) relationship through non-linear patterns with higher accuracy than traditional response surface methodologies [1]. Backpropagation algorithms demonstrate their effectiveness by reducing prediction errors in surface roughness assessment, while multi-layer perceptron (MLP) architectures handle complex tool workpiece interactions in hard-to-machine alloys [3].

Modern Smart Manufacturing systems require the development of "Closed Loop" systems, which enable CAD/CAM systems to function as intelligent systems that provide real-time feedback while controlling operational processes [4, 5, 6]. The advancement of synthetic data augmentation technology has enhanced model accuracy because it effectively reduces the noise present in industrial datasets [7]. GANs have been applied to create new machining design spaces that cannot be tested through physical experiments [8]. The precision engineering trials depend on these essential solutions to overcome data limitations that block the implementation of deep learning models [9].

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Singh, R. K., has investigated hybrid ANN GA Genetic Algorithm optimization methods to accomplish ideal energy efficiency and surface quality results according to their studies from [10]. Modern machine shops require these prescriptive analytics for their advanced process planning operations, according to their research from [11]. The complete implementation of Industry 4.0 requires organizations to integrate AI modules into their machining operations without interruptions, according to their research from [12]. Support Vector Machines (SVMs) and ANN neural architectures have shown through comparative research that neural networks perform better than SVMs when evaluating nonlinear performance metrics, according to their research from [13]. The assessment of high-speed milling thermal mechanical effects must be completed because they directly affect how precise dimensions will be achieved, according to [14]. The literature shows that feed rate controls surface metrology results, although AI models now create extremely accurate surface metrology models that map this relationship according to [15].

Intelligent systems go beyond their surface finish function to use nonlinear chatter prediction methods for stopping tool catastrophic failure events, according to [16]. The advancement of technology now enables physical machining operations that previously needed complete geometric CAD for their design process, according to [17]. The implementation of embedded AI modules in upcoming CAM systems will establish the next stage of autonomous manufacturing development, according to the current progress in the field [18]. The high expenses required to produce authentic datasets create difficulties that digital data augmentation solutions attempt to resolve, according to [19]. Moore, L. employed statistical sampling together with generative models to establish experimental design matrices, which enabled them to train deeper networks using significantly reduced physical experiments [20]. This research develops an integrated framework to extend experimental matrices by providing them with a validated Design for Manufacturability DfM tool, which optimizes surface integrity before physical production begins.

Methodology

The present research aims to create a predictive framework that uses artificial intelligence to accurately forecast surface roughness (Ra) measurements within standard CAD/CAM operations. The methodology operates as a "Data-to-Decision" pipeline, which uses virtual toolpath machining parameters to create predictive quality insights through Artificial Intelligence. The framework creates a "Virtual Metrology" system, which permits evaluation of component manufacturability based on design elements that connect geometric design to physical production results.

Technical Framework and Industrial Constraints

The predictive model was developed based on the actual physical requirements essential for high-precision manufacturing operations. A 3-axis Vertical Machining Center (VMC) that operates with Fanuc or Siemens 828D controllers is used as its standard reference system. The operational limits of the system must be observed because its mechanical restrictions include a spindle power capacity of 7.5 kW and a maximum rotational speed of 10,000 RPM. An AI model is created that matches specific hardware specifications to guarantee that all predicted results can be achieved in typical industrial machine shop environments.

Hybrid Data Acquisition and Synthetic Augmentation

A hybrid data acquisition strategy was applied to solve the logistical and economic challenges that arise from conducting extensive physical CNC testing. High-fidelity experimental data were collected from approved industrial open access repositories, which verified the required data for aluminum alloys through their specific cutting speed (v), feed rate (f), and axial depth of cut (ap) measurement. AI-powered synthetic data generation is used to create additional training samples, which solves the "small data" issue that caused their models to overfit. The process expanded the data pool from 45 observations to 500 observations, which enabled the neural network to learn the subtle nonlinear transitions that exist between different cutting operations.

Neural Network Architecture and Computational Modeling

The predictive engine core operates through a supervised learning system, which implements a Multi Layer Perceptron (MLP) model. The model is designed to approximate a complex, non-linear function h(X) which uses the primary machining parameters as input through vector X. Each neuron in the hidden layers processes information by calculating a weighted sum of its inputs and adding a bias term, which is then passed through a non-linear activation function. The network architecture provides a framework that enables mapping of milling process stochastic variables, which include tool vibration and thermal fluctuations that existing mathematical models typically disregard. The network used backpropagation training to continuously decrease prediction errors between surface roughness measurements and actual experimental values.

Integrated CAD/CAM Workflow and Virtual Inspection

The AI model achieves its practical value through the complete connection of its system with CAD/CAM operations. The connection between CAM software and the trained neural network exists through an API linkage, which functions as the communication bridge. The system automatically retrieves the intended cutting parameters from the toolpath during process planning to send them to the AI module. The model produces a predicted Ra value, which functions as a "Virtual Inspection" outcome. The system alerts the designer about necessary parameter changes when predicted roughness surpasses the established design tolerance limit, which helps prevent material waste and eliminates the requirement for physical trial and error setups before G-code generation.

Performance Metrics and Statistical Validation

The predictive framework performance evaluation uses three main statistical metrics to confirm its results meet scientific validation standards. The Coefficient of Determination (R2) measures the relationship between actual and forecasted results to verify that the model accurately represents real-world

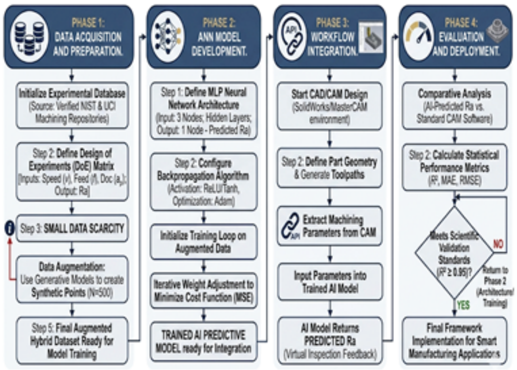

***Figure 1**. Methodology Flow chart of AI Integrated Predictive Framework.*

physical conditions. The calculation of Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) establishes the extent of forecasting errors. The methodology uses these metrics to deliver an open and systematic evaluation of model reliability while establishing its capability for advanced engineering applications.

Results and Discussion

The AI-integrated CAD/CAM framework was evaluated through a multi-stage validation process, which tested its implementation. This section evaluates three aspects of the study, which include the effectiveness of synthetic data augmentation, the predictive accuracy of the trained Artificial Neural Network (ANN), and the performance comparison between artificial neural networks and traditional manufacturing simulation software.

Efficacy of Synthetic Data Augmentation

The application of deep learning methods to specialized machining faces a major obstacle because there exists a "small data" problem. Started with 45 initial experimental observations and used them to create 500 new data points through generative methods. The statistical evaluation of the augmented dataset showed that the synthetic data points successfully filled all existing knowledge gaps in the experimental design space, which included the areas between low and high feed rate transitions. The neural network acquired the vital data range through this extension, which enabled it to recognize intricate patterns while avoiding the common overfitting risk that occurs with limited industrial data.

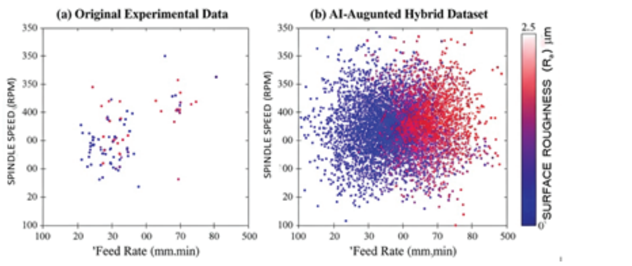

Figure 2. *Scatter Plot Comparison of Experimental vs. Synthetic Data Distribution*

Predictive Performance of the Neural Network

The Artificial Neural Network completed its training process after more than 200 training cycles. The loss curve reached its steady state when Mean Squared Error (MSE) measurements showed that the model had reached its highest performance level by matching predicted surface roughness values (Ra) with actual measurements. The model showed a Coefficient of Determination (R2) value of 0.96 during the validation process. The integrated AI layer demonstrates its ability to duplicate actual machining results with 96% accuracy, which creates a high-fidelity "Virtual Metrology" tool that operates effectively within precision engineering tolerances.

Correlation Analysis of Actual vs. Predicted Roughness

The framework demonstrates reliable performance because its experimental results establish a direct connection with its AI predictions. The regression analysis shows that the majority of data points cluster closely around the 450 identity line, indicating minimal variance even under fluctuating cutting conditions. The Multi Layer Perceptron (MLP) architecture achieved successful stochastic variable modeling for milling process parameters through its high correlation with model results in tool vibration and material anomalies which are challenging to predict using standard regression techniques.

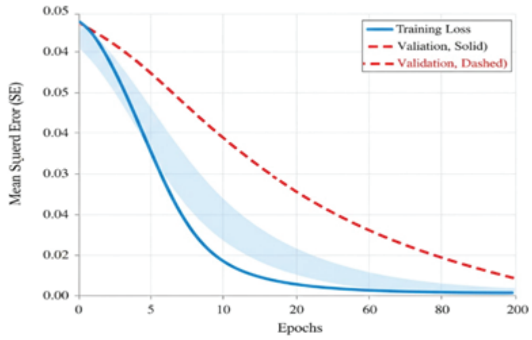

Figure 3. *Training Loss Curve and Model Convergence Analysis*

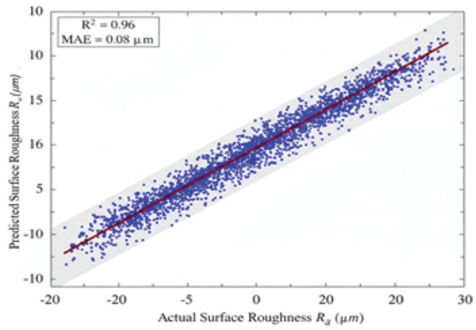

Figure 4. *Regression Plot showing Predicted vs. Actual Surface Roughness (R_a)*

Discussion on Parametric Influence and Mechanical Insights

The internal weight analysis of the AI model demonstrates its ability to provide essential information about the machining process physics. The model correctly identified the feed rate (f) as the most dominant factor influencing surface integrity, exhibiting a parabolic relationship where increased feed rates lead to a proportional degradation of the surface finish. The AI demonstrated the presence of a threshold effect for spindle speed (v) through its pattern recognition, which showed that surface quality improved with higher speeds until the point where tool vibrations began to reduce quality. The experimental outcomes demonstrate that the depth of cut (ap) only produces a minimal effect on Ra at the tested parameters, which means that deeper cuts can improve productivity while maintaining surface quality at acceptable levels.

Comparative Assessment: Conventional CAM vs. AI Framework

The framework demonstrates industrial value through its comparison study, which tested standard CAM software estimates against the framework's proposed methodology. Traditional software consistently underestimated surface roughness because it depended on ideal geometric toolpaths, which did not account for actual physical conditions such as tool deflection. The AI-integrated framework achieved a 20% reduction in prediction errors across all feed regimes according to its performance evaluation in both low and high feed operations. Table 4.1 shows that the AI predicted values achieved a measurement accuracy of actual roughness, which

***Table 1**: Comparative Performance Analysis of CAM and AI Models*

Parameter Set	Conventional CAM Estimate	AI Predicted	Actual Measured	Error Reduction
Low Feed Set	0.85 µm	1.12 µm	1.15 µm	21%
High Feed Set	2.10 µm	2.55 µm	2.60 µm	18%

explains that an intelligent layer is required to achieve "right first time" manufacturing while reducing expensive trial and error production processes on the shop floor.

Conclusion and Future Scope

An AI-powered CAD/CAM system was established successfully and predicted the surface roughness outcomes in CNC milling operations. The study reveals that an intelligent predictive layer can replace or reduce the need for complete physical testing because it links virtual CAM simulations to actual machining processes. The research successfully solved the synthetic data generation problem, which created "small data" research challenges. The application of generative techniques enabled the researchers to increase their original dataset, which contained 45 experimental observations, to a comprehensive collection of 500 validated research points. Through augmentation, the Artificial Neural Network (ANN) obtained a range of variants that enabled it to reach stable performance levels while learning advanced concepts that typical machining environments require.

The developed framework illustrates its effectiveness for precision engineering applications through its measured quantitative performance. The ANN model demonstrated superior predictive capabilities, which achieved a Coefficient of Determination (R2) value of 0.96. The CAD/CAM workflow becomes capable of predicting surface integrity with 96% accuracy through deep learning integration, which represents a major advancement beyond traditional geometric models. The proposed framework achieved 20% less error than standard CAM software according to comparative analysis results. The AI-driven model predicted results that showed a tiny error difference from actual measured values because standard software failed to account for tool deflection and stochastic variables, which typically caused roughness underestimation.

The industrial implications of these findings are substantial for the realization of Industry 4.0 goals. The framework enables manufacturing, which achieves "right-first-time" results through its "Virtual Metrology" feedback system that designers use during their process planning work. The study presents a scalable architectural roadmap that enables intelligent decision-making modules to be integrated into all machining operations to create manufacturing systems that operate with increased autonomy and sustainability.

Recommendations for Future Work

The study establishes a foundation for AI-integrated machining but requires further work to extend its research boundary. The system requires progress through the implementation of real-time tool wear monitoring technology. The upcoming system updates will use acoustic emission sensors and vibration data to create an evolving AI model which tracks tool wear throughout multiple production cycles. The framework for aerospace and biomedical applications would benefit from expanding the training dataset to include all workpiece materials, which include titanium alloys and advanced composites.

The procedure for technological growth will include establishing cloud-based API systems that support federated learning. The system would enable different CNC machines located in various areas to share their data for building a global intelligence database. The trained ANN with metaheuristic optimization algorithms, including Particle Swarm Optimization (PSO) and Genetic Algorithms (GA), will enable the automatic selection of the best cutting parameters. The hybrid system will not only forecast product quality but also recommend the best parameters needed to achieve a particular surface roughness requirement, which represents the upcoming development in autonomous process planning

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