Smart Quality in CNC Machining

Angelo Rizzi [1], Spyridon Paraschos [2], Miguel Á. Mateo-Casalí [3] and Diego Silveira [4]

[1] *Fidia S.p.A, Corso Lombardia, 11, 10099, San Mauro Torinese, Italy*
[2] *Centre for Research and Technology Hellas (CERTH), Information Technologies Institute (ITI), 6th km Charilaou-Thermi Rd, 57001, Thermi, Thessaloniki, Greece*
[3] *Research Centre on Production Management and Engineering (CIGIP), Universitat Politècnica de València, Camino de Vera s/n Ed. 8B, Acceso L, Planta 2a, Ciudad Politécnica de la Innovación, 46022, Valencia, Spain*
[4] *Instituto Tecnológico de Informática (ITI), Calle Nicolás Copérnico, 7, 46980, Paterna, Valencia, Spain*

Abstract

In the mold and die industry, goods are produced by milling, a machining process that involves removing material from a workpiece using a rotating cutter to produce complex components. This removal process is semi-automatic and controlled by a computer (CNC) whose actions are controlled by settings chosen by human operator. A wrong parameter selection will result in the bad behavior of a machine, causing vibrations and bad quality of the produced part, requiring manual finishing operations to achieve the required surface roughness.

This paper describes the conception, implementation and usage of AI solutions provided by European Project i4Q (Grant Agreement number: 958205 — H2020-NMBP-TR-IND-2018-2020 / H2020-NMBP-TR-IND-2020) to control and optimize the machining process.

Keywords

Industry 4.0, Machine tools, Artificial Intelligence, Manufacturing, CNC, Surface roughness, Chatter detection

1. Introduction

The growing manufacturing demand for higher machining productivity, enhanced surface quality, and better tool life requires an online monitoring system to diagnose tool conditions and product quality control. Fidia recognizes the unwavering pursuit of enhanced machining quality as necessary for market longevity. This pursuit demands a dual approach, encompassing both mechanical refinement and sophisticated software compensation, to meet the ever-increasing demands of high product quality, machining productivity, high-speed performance, and unwavering precision. In the realm of quality, two paramount characteristics emerge – dimensional accuracy and surface roughness – meticulously evaluated through offline measurements of processed components. However, machine vibrations, arising from the intricate dance between the workpiece and the cutting tool, pose a formidable threat to these quality metrics. These vibrations disrupt the workpiece's surface smoothness, erode its dimensional precision, generate noise, and accelerate the tool, requiring manual finishing operations to achieve the desired surface quality. These operations have been estimated to be around 15% of the total processing cost. Therefore, shopfloor operators tend to select conservative combinations of cutting parameters, diminishing productivity to ensure the desired quality.

Fidia, in its commitment to excellence, remains steadfast in its dedication to mitigating these vibrations through a combination of mechanical innovations and advanced software calibrations, ensuring that its products consistently deliver the highest standards of machining expertise.

12th International Conference on Interoperability for Enterprise Systems and Applications (I-ESA24), April 10th -12th, 2024, Chania, Crete, Greece
a.rizzi@fidia.it (A. Rizzi); sparaschos@iti.gr (S. Paraschos); mmateo@cigip.upv.es (M.Á. Mateo-Casalí); dsilveira@iti.es (D. Silveira); 0000-0001-6445-5723 (S. Paraschos); 0000-0001-5086-9378 (M.Á. Mateo-Casalí);
0009-0008-8180-0531 (D. Silveira)

Vibrations are well-known issues in the machining and metal cutting sector, where the spindle vibration is primarily responsible for poor surface quality in workpieces. The consequences range from the need to finish manually the metal surfaces, resulting in time consuming and costly operations, to high scrap rates, with the corresponding waste of time and resources.

The main problem of conventional solutions is that they address the suppression of machine vibrations separately from the quality control process, but also solutions aimed individually at each of these problems suffer from serious drawbacks. Vibration suppression is usually based on passive custom-made solutions that are effective only at specific frequencies (narrow band) and broadband active vibrations control is still uncommon. In addition, product quality (e.g. in terms of surface roughness and geometrical accuracy) is currently assessed only off-line and by adequate measurements. In this scenario, if deviations with respect to reference values are detected, it is not possible to automatically adjust the CNC process parameters to reduce/compensate for such errors. Thus, adjustment procedures rely on machine operator skills, and it is usually time-consuming to identify the appropriate corrective solutions.

2. Fidia

At the heart of Fidia's expertise lies the design, manufacture, and sale of specialized Numerical Controls, High Speed Milling Systems, and Flexible Manufacturing Systems, empowering the production of intricate components and shapes primarily for the automotive, aerospace, and energy realms (**Figure 1**). While a dedicated CNC may be more costly than a generic one, its precision-driven capabilities offer unparalleled control over the machine, unlocking a vast expanse of manufacturing prowess and granting unfettered access to critical data. The primary objectives of FIDIA's participation in the i4Q Project revolve around monitoring and adapting processing conditions to ensure that the workpiece quality aligns with customer requirements.

Figure 1. Fidia's expertise

2.1. Estimation of Final Surface Quality

Evaluating the final surface quality involves analysing roughness, also known as surface texture. Traditionally, this process relied on manual operations, introducing subjectivity and errors. Automated roughness measurement techniques have been developed to address this, including profilometers, stylus instruments, and optical profilometers. However, these methods remain time-consuming. Predicting surface roughness requires an Artificial Intelligence (AI)-based tool capable of correlating processing conditions (axial and radial depths of cut, axes feed, spindle rotation speed, workpiece material, tool geometry). Algorithms are trained during testing sessions, where quality measurements are taken using a Mitutoyo rugosimeter after the machining process.

2.2. Chatter Detection and Removal Algorithm

Chatter during the machining process can result in undesirable marks on the final workpiece surface (see **Figure 2**). Utilizing Fast Fourier Transformation (FFT) analysis of vibrations and correlating them with current processing conditions (spindle speed rotation, number of tool flutes) enables the identification of chatter occurrences. This algorithm aims to detect and eliminate chatter during the process.

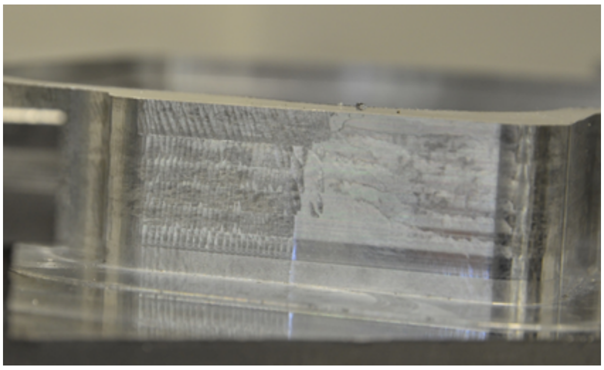

Figure 2. Chatter marks (left part of workpiece)

2.3. Trend-Based Evaluation of Machine Tool Conditions

Analysing the trends of processing signals (positions, speeds, currents, and torques) collected during the periodic execution of dedicated reference tests requires Big Data solutions. Variations in these parameters during identical tests help identify degradation patterns and possible faulty components (failure modes) compared to nominal conditions. New processing constraints will be imposed on the equipment to mitigate the impact of failures on the process while awaiting maintenance intervention.

2.4. Fidia Infrastructure

The previously defined objectives require the following challenges to be met at Fidia. On the one hand, the collection and synchronisation of data from different sources via the CNC machine setting as well as accelerometer/temperature sensors. All this data is accessible through a REST API via a Fidia component that hides all the interconnection details of the different sources. On the other hand, it will be necessary to secure the transfer and storage of the factory data to a remote repository where analysis can be performed with more powerful systems than those available in the factory.

i4Q solutions addresses desired goals by combining advanced vibration monitoring methods with AI-driven prediction of quality indicators. First, an add-on kit to monitor the behaviour of the cutting process has been developed and integrated. This kit integrates accelerometer and temperature sensors with other CNC data, used to feed AI-driven (Machine Learning) trained algorithms that predict in-process that could impair quality such as the occurrence of vibrations that could impair part quality or surface roughness of machined parts. The process is complemented in the training phase, with data from the inspection of already machined workpieces to refine the Al models and algorithms. As a result, implemented solutions react in advance to deviations that could cause undesired defects on the surface, producing workpieces with smoother surfaces. By using the i4Q solutions, the quality, productivity, and efficiency of the machining process are increased, with a lower number of rejected parts and less time devoted to reworking and manual finishing.

3. Solutions Implementation and Algorithms

In the context of the i4Q Project, Thessaloniki Centre for Research & Technology (CERTH) and University Polytechnic of Valencia (UPV) have implemented a set of individual solutions to address the key objectives set by Fidia. The introduced solutions are standalone microservice applications capable of effectively handling, processing, and analysing real-time manufacturing data to offer insights into machine condition monitoring and product quality control processes. Additionally, the i4Q solution suite's idea is to offer tools applicable to different manufacturing scenarios and work in conjunction with legacy data acquisition and infrastructure analytics systems. Therefore, the REST

API provided by FIDIA was utilised to ingest real-time sensor data into the i4Q analytics pipeline, starting with the i4Q “Data Integration and Transformation Services” (i4Q^{DIT}) solution.

The i4Q^{DIT} solution offers a platform for the efficient processing of manufacturing data, and encompasses essential functionalities for managing manufacturing data streams, such as reading, cleaning, storing, indexing, enriching, and ensuring compatibility with APIs. The solution provides a range of pre-processing functions that convert intricate raw data from manufacturing processes into formats suitable for subsequent analysis. In the context of the FIDIA pilot implementation, the i4Q^{DIT} solution receives real-time tool position, vibration and motor current data from the aforementioned REST API and applies a set of feature extraction techniques, to enrich the useful information data payload. These techniques include primarily the utilization of Fast Fourier Transformations and Butterworth filtering. The FFT allows the conversion of signals from time to frequency domain, thus enabling a more efficient examination of the eigen frequencies that are innate to the machine, which cause the occurrence of undesired oscillations during the manufacturing process [1]. To complement the utilization of FFT, Butterworth filtering is used to eliminate unwanted high-frequency noise, artifacts and fluctuations present in the sensor signals, resulting in a smoother representation of the underlying data [2]. To enhance the available data even further during the pre-processing pipeline, additional features based on rolling window mean and median values have also been calculated and added for each signal. After the data have been properly prepared, they are accessible via a Kafka Message Broker for real-time data consumption, or through a MongoDB database for long-term storage and analysis of historical records.

Figure 3. Vibration FFT feature extraction through i4Q^{DIT}

The pre-processed data resulting from the i4Q^{DIT} are then being exploited by the i4Q “Infrastructure Monitoring” (i4Q^{IM}) solution, which is responsible for providing proactive alerts to the machine operators upon the detection of machine malfunctions or the degradation of specific components, such as the wear of the CNC tool. This is achieved through the employment of an AI predictive condition monitoring algorithm, capable of correlating the occurrence of such machine problems to the data produced by the installed sensors. The implemented algorithm is a Light Gradient Boosting Machine (LGBM), which is efficient and scalable framework built around an ensemble of tree-based classifiers [3]. The tool allows the user to consume historical or real-time sensor data from various sources (Local directories, MongoDB, Kafka) and evaluated the presence of component degradation based on their values, with the option to use either the pre-trained LGBM model or by training a new one, if the manufacturing conditions have changed and necessitate adjustments. The machine status predictions along with the importance of each sensor’s signal towards the predictions of the model are being presented to the user via an intuitive interface that facilitate the machine condition monitoring process.

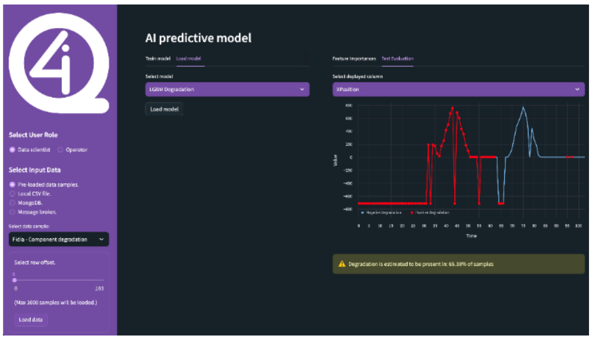

Figure 4. Component degradation detection through i4Q^{IM}

Connected to i4Q^{DIT}, we also find the i4Q “Rapid Quality Diagnosis” (i4Q^{QD}) solution, which is a microservice whose objective is to provide a quick and efficient diagnosis of failures regarding the quality of the manufactured products and the conditions of the overall manufacturing process. Specifically, i4Q^{QD} incorporates intelligent techniques to predict machine chatter, which refers to undesirable vibrations occurring during the machine operation, that can negatively impact the quality of the machined product and machining efficiency. The employed techniques are based on state-of-the-art Machine Learning (ML) algorithms, and specifically on the LGBM framework, which can efficiently detect suboptimal machine operation conditions after its training on the pre-processed industrial vibration sensor signals provided by i4Q^{DIT}. Once it detects the possible error, it will interact directly with the "i4Q Manufacturing Line Reconfiguration Toolkit" (i4Q^{LRT}) solution. This will oversee the analysis of the state of the machine at that moment and provide possible reconfiguration values to avoid possible errors.

In conclusion, the i4Q Project leverages FIDIA's REST API to integrate sensor data into the i4Q analytics pipeline, enabling efficient processing and extracting valuable information. The i4Q^{DIT} ensures the appropriate preparation of the industrial manufacturing data by applying several preprocessing techniques. The i4Q^{IM} solution incorporates AI techniques to facilitates the condition monitoring procedures through the efficient detection of component degradation instances. Finaly, the i4Q^{QD} microservice uses advanced Machine Learning techniques for rapid quality diagnostics of the manufacturing process, while the i4Q^{LRT} solution ensures proactive reconfiguration of the manufacturing line based on detected errors. Together, the i4Q suite offers tools applicable in various manufacturing scenarios, improving machine health monitoring and product quality control.

4. Solutions Integration

At the beginning of the project, i4Q solutions were developed independently by the different partners involved (also known as solution providers) in the form of Docker containers, which facilitated their later integration. Afterwards, Fidia provided a machine in their facilities and a remote connection mechanism so that the solution providers could connect to the machine and deploy the developed solutions there.

Once the deployment of the different i4Q solutions using Docker containers was completed, the integration phase began, which has been carried out over the last few months. During this phase, the quality of the developed solutions, and their adjustment to the requirements were analysed with the collaboration of solution providers and the company. This has helped to detect some problems that had not been considered during the development of the solutions, leading to some modifications and improvements. These changes have allowed the integration between the deployed solutions to be completed correctly, as shown in **Figure 5**.

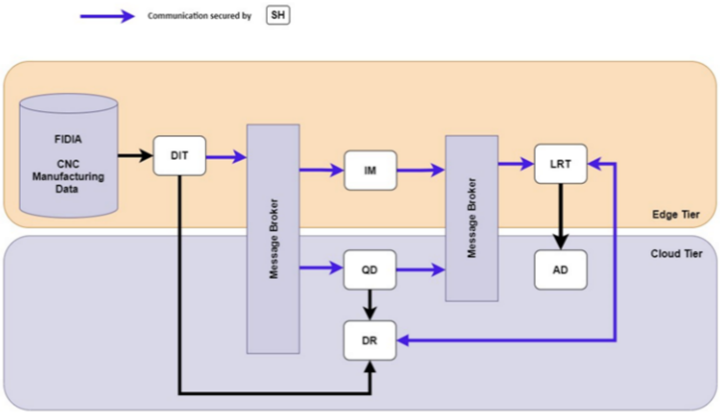

Figure 5. i4Q solutions Integration Diagram in Fidia's infrastructure

Three types of interactions can be identified in this infrastructure: (i) **direct interaction** – when one solution sends data to another directly (e.g. to store data produced in a database, the interaction between $i4Q^{DIT}$ and $i4Q^{DR}$ or $i4Q^{QD}$ and $i4Q^{DR}$ solutions); (ii) **secured direct interaction** – these are solutions that interact directly using SSL certificates (e.g. the interaction between $i4Q^{LRT}$ and $i4Q^{DR}$ solutions, however, all other solutions connected by purple arrows also use SSL certificates to secure the communication between them); (iii) **indirect interaction** – occurs when a solution uses an API or communication mechanism to send/receive data to/from another data source (e.g. the $i4Q^{DIT}$ solution obtains data from Fidia machines by making requests to a REST API and sends the data processed via the Message Broker so that other solutions, such as the $i4Q^{QD}$, can consume it in real time).

5. Results

At the time of writing, the ongoing evaluation sessions are providing first data on the performance of the implemented solutions. The first results are promising, especially around vibration detection. In 92% of cases, vibration has been successfully detected without causing damage to the machine or the cutting tool. The implementation of these solutions on production lines is expected to provide more information on the effectiveness of vibration detection in real operating environments.

As for the assessment of surface roughness, the process is still a manual and time-consuming operation. Efforts are underway to collect a substantial data set for training AI solutions. Data collection is still ongoing at the time of writing, highlighting the continued dedication to building a comprehensive dataset that enhances the capabilities of AI models in surface roughness assessment.

In the field of trend-based evaluation of machine tool conditions, the evaluation period spans several years. The designed solutions show potential effectiveness, and their evaluation is expected to extend well beyond the conclusion of the i4Q Project. This extended evaluation will provide a comprehensive understanding of the performance of the solutions over an extended span of time, offering valuable insights for the optimisation of machining processes. These first results lay the foundation for further exploration and refinement of the proposed solutions.

6. Conclusions

In conclusion, the i4Q project showcases a well-integrated suite of microservices designed to empower mould manufacturers. This project goes beyond simply collecting sensor data; it leverages AI and Machine Learning algorithms to transform the data into actionable insights for real-time monitoring, proactive fault detection, and enhanced quality control. The i4Q suite has several key strengths:

- **Modular Design**: Developed as independent microservices, the i4Q solutions offer flexibility and scalability, allowing for easy integration with existing manufacturing infrastructure.

- **Advanced Analytics**: By utilising Machine Learning algorithms like Light Gradient Boosting Machines (LGBM), the i4Q suite facilitates proactive detection of component degradation and potential quality issues like machine chatter.
- **Real-time Data Processing**: The i4Q^{DIT} solution ensures efficient data pre-processing, enabling real-time analysis of sensor readings for faster decision-making.
- **Improved Machine Health**: The i4Q suite empowers operators to monitor machine health and prevent failures before they occur, minimising downtime and production disruptions.
- **Enhanced Quality Control**: By rapidly diagnosing potential quality issues, the i4Q^{QD} solution, helps manufacturers maintain consistent product quality.

While some functionalities, like surface roughness assessment using AI, are still under development, the initial results regarding vibration detection are promising. The ongoing evaluation process focused on trend-based machine condition assessment holds the potential to yield valuable insights for long-term machining process optimisation.

Overall, the i4Q project paves the way for significant advancements in AI-powered manufacturing solutions, empowering companies to achieve greater efficiency, improved product quality, and a stronger competitive edge.

Acknowledgements

This paper is supported by European Union's Horizon 2020 research and innovation programme under grant agreement No 958205, project i4Q (Industrial Data Services for Quality Control in Smart Manufacturing).

Declaration on Generative AI

The author(s) have not employed any Generative AI tools.

References

[1] Shrivastava, Y., & Singh, B. (2019). A comparative study of EMD and EEMD approaches for identifying chatter frequency in CNC turning. *European Journal of Mechanics-A/Solids*, 73, 381-393

[2] Selesnick, I. W., & Burrus, C. S. (1998). Generalized digital Butterworth filter design. *IEEE Transactions on signal processing*, 46(6), 1688-1694.

[3] Ke, G., Meng, Q., Finley, T., Wang, T., Chen, W., Ma, W., ... & Liu, T. Y. (2017). Lightgbm: A highly efficient gradient boosting decision tree. Advances in neural information processing systems, 30.