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CLOUD-BASED SYSTEM FOR SURFACE ROUGHNESS CONTROL IN END-MILLING

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Abstract: *The main purpose of this article is to present the structure of the cloud-based platform for controlling the roughness of the machined surface. The developed system connects computing and service resources in the cloud with physical resources in the tool shop. The connection of cloud resources and physical elements was the basis for the formation of the two-stage cyber-physical roughness control system (CPrCS) for end-milling. The two-stage CPrCS with its ability to connect sensors and actuators to the cyber world is designed to maintain a constant roughness of the treated surface by digitally adjusting the cutting conditions. CPrCS with surface roughness control via cloud technologies provides a new way to identify and eliminate defects on the machined surface during the machining process. The physical part of the CPrCS system combines a machine tool, piezoelectric sensor, and industrial computer to capture and transfer obtained data to the IoT router in the cloud. The cloud system receives information from the sensor, processes the information, performs edge computing operations, analyses, and models surface roughness data, monitors the process, visualizes the data and finally makes decisions about the necessary correction of machining parameters. An artificial neural network (ANN) is used to model and predict the surface roughness accurately. The ratios between the measured cutting forces, the cutting conditions and the actual surface roughness of the machined surface were determined using ANN. In the future, the feasibility of the in-process surface quality control through cloud technologies will be tested with additional experiments.*

Key words: *machining, end milling, cloud technologies, surface roughness, control.*

1. INTRODUCTION

The controls of modern machine tools and the smart sensors on these machines are today intelligent enough to communicate with each other and independently transfer data from the process to the cloud big databases. Cloud manufacturing technologies provide an effective environment for connecting machine tools, measuring devices, data, knowledge, software and computing resources [1]. Such new technologies enable the implementation of closed-loop control functions, where the process can be analysed and adaptive process corrections can be made based on the obtained process data.

Applications based on cloud technologies have already been implemented in the field of manufacturing [2, 3].

In manufacturing, cloud computing enables the development of new methods for effective monitoring of processes through the transfer and control of data to remote servers with computing resources, where extensive analyses are carried out and decisions are made [4, 5].

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Cloud manufacturing can significantly improve the efficiency of modelling, optimization [6] and processes control in manufacturing.

Cloud manufacturing is a manufacturing version of cloud computing [7]. It is accomplished by binding and dividing distributed manufacturing resources including software, knowledge and physical resources through internet infrastructure in the form of internet services [7].

Recently, cloud technologies have been used to create applications for machine tool monitoring, process monitoring and process control.

A particular focus of research has been on the development of smart monitoring platforms [8, 9].

The quantities obtained during the machining process, such as cutting force, temperature, tool wear and surface roughness, were stored in cloud databases.

With the help of data mining and analytical tools, analyses were carried out and models were created, which are the basis for further decision-making for process corrections.

Recently, some cloud processing monitoring applications have been designed [10].

Teti [11] developed a cloud-based application for monitoring the status of cutting tools during turning.

Tapoglou [12] developed a cloud-based control platform for monitoring and optimal selection of cutting parameters based on function blocks.

The control of surface roughness in the machining of modern difficult-to-machine materials is becoming more and more important for the smooth operation of machining systems.

Research efforts to improve the quality of the machined surface are invested in the development of advanced surface roughness control systems with integrated predictive models that effectively predict the surface roughness in real time, during the execution of the machining process.

For this purpose, the researchers created statistical and fuzzy models for predicting the surface roughness based on the measured cutting forces, vibrations and AE signals.

Due to the challenges of indirectly measuring and controlling the roughness of the machined surface during the machining process, a new cyber-physical system was developed for monitoring cutting forces and controlling surface roughness.

The system includes a new paradigm of pooling computer resources and providing remote services via the Internet. It performs detection, access, information processing, data exchange, Internet services and security and privacy operations. The system connects the cybernetic world (cloud tools) with the physical world (machine tool, sensors) via a cloud gateway. Cloud platforms with Internet applications have formed an effective ecosystem for the exchange of data, software, and computing capabilities [1].

This paper presents a cloud-based system for controlling the roughness of the machined surface. The control of surface roughness in the machining of modern difficult-to-machine materials is becoming more and more important for the smooth operation of machining systems. Heavily loaded tools are subjected to extreme forces and elevated temperatures, which causes increased tool wear and frequent damage to the cutting edge. Wear and damage of the tool is then reflected in the poor quality of the machined surface.

The goal of the research is to create a system that will detect damage and wear of the cutting edge in time and, with appropriate process corrections, and obtain the desired quality of the machined surface. By adjusting the feed rate, the system maintains a constant surface roughness and extends the tool life. The main feature of the system presented here is that it connects physical assets with computing resources on the cloud and thus forms a cyber-physical processing system (CPrCS). It transports the signals of the measured cutting forces via a cloud gateway to cloud applications, where enormous amounts of data are archived, processed and prepared for further analysis.

The paper is organized as follows: In section 2, a cloud based surface roughness control system is outlined. Section 3 describes the basic structure of cloud based control platform with detail explanations of included IoT applications. Section 4 presents physical part of cloud-based control system. Finally, section 5 concludes the paper.

2. CLOUD-BASED SURFACE ROUGNESS CONTROL SYSTEM

The structure of the cloud surface roughness control system is shown in Fig. 1.

The system is made up of two parts that are connected via a cloud gateway.

The bottom physical part of the system is at the factory level and consists of physical devices. The main element of the lower part of the system is a machining system with measuring equipment and a system for capturing and processing data. This is where the machining process is carried out, the signals from the sensors are pre-processed, filtered and transformed into a data format suitable for transfer to a cloud platform for process control. The communication junction between the CNC machine control, machine operator, and cloud gateway is represented by a PC terminal with appropriate communication software. The cloud gateway acts as a router and takes care of the two-way flow of data from the factory part of the system to the cloud platform and for the transfer of process control commands from the cloud control application to the CNC control of the machine tool.

The upper, cloud-based part of the system represents the control cloud platform of the process, which collects sensor signals, processes them, filters them, and archives them in a database.

The cloud platform consists of IoT applications for identifying characteristics of sensor signals, modelling surface roughness R_a, optimizing the process, analysing data, generating corrective measures, controlling and monitoring the process, and for visualizing the controlled process.

The platform monitors the roughness of the machined surface by measuring the cutting forces and corrects the machining process in case of deviations from the desired surface quality via the feed rate override function.

The cloud platform therefore generates process corrections and sends commands via the cloud gateway to the PC terminal, where the commands are converted into a telegram form that can be received and processed by the CNC machine control. The information flow of the signals is thus completed, forming a closed-loop control of the surface roughness during the milling process. All implemented process corrections are visualized on the control application of the system, which is accessible via the Internet as well as on the local PC terminal of the system.

3. CLOUD BASED SURFACE ROUGHNES CONTROL PLATFORM

The platform performs the function of controlling the milling process via cloud technologies. In doing so, it takes advantage of cloud tools such as decentralized data analysis and storage, data mining, modelling, process optimization, visualization of obtained solutions, remote access, large computing performance, control applications, and use of smart devices. The structure of the platform is shown in Fig. 1. The platform connects physical devices such as machine tool , measuring sensors, controllers and computers with computing resources on the cloud.

3.1. Cloud gateway

The part of the system located on the cloud platform consists of six IoT applications.

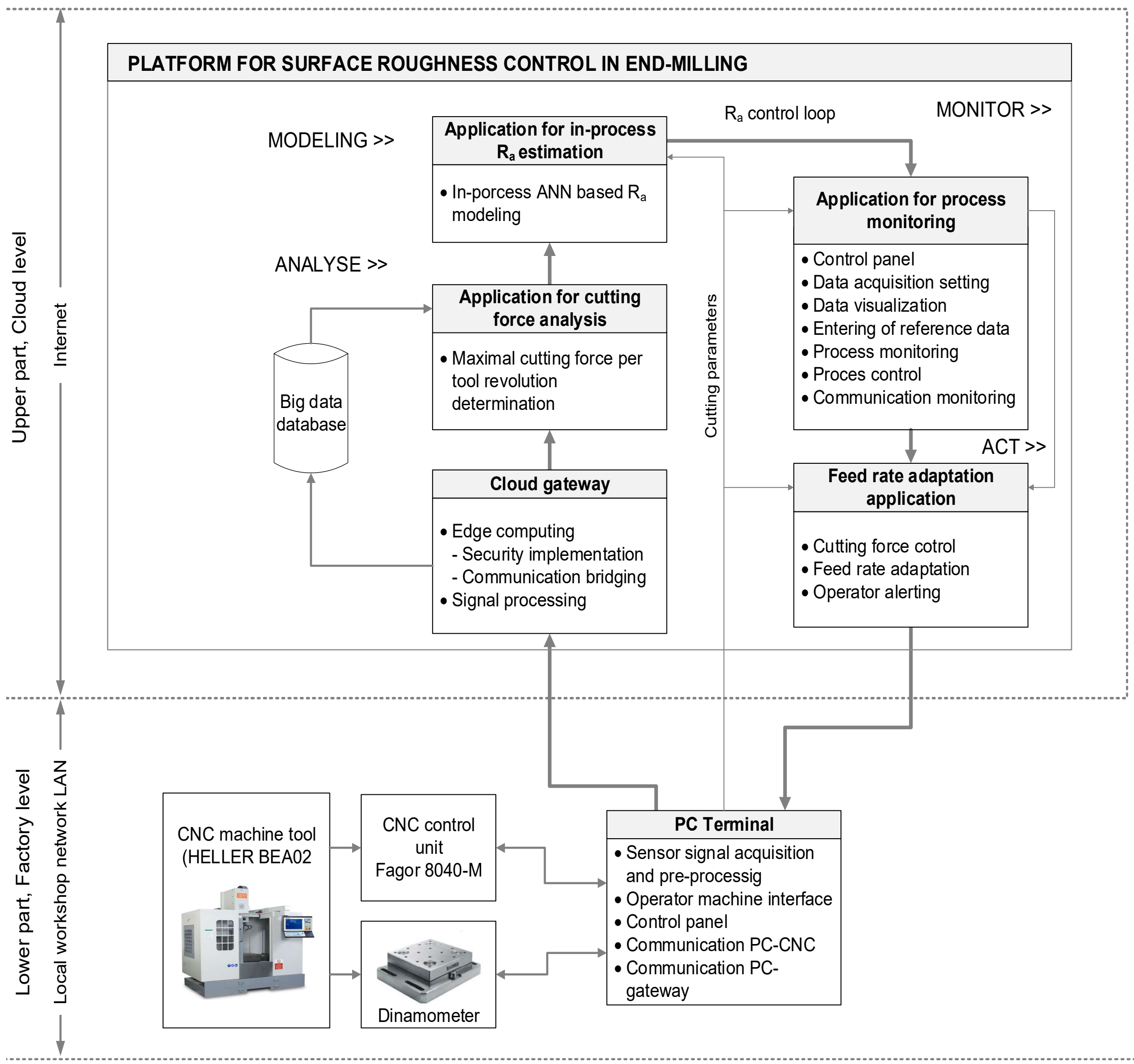

Fig. 1. The basic structure of the cloud-based surface roughness control system in end-milling.

The first application is a cloud gateway that connects the physical part of the system with the cloud part. The primary task of the gateway is to safely transfer pre-processed signals from sensors to the big database on the cloud and vice versa to transfer commands from control cloud applications to the machine tool.

An important task of the gateway is establishing communication and ensuring the security of transferred data, which is called edge computing. Typically, the cloud gateway processes, filters and timestamps the signals.

The data from the sensors is stored in the big data base, from where the application for analysing the measured cutting forces calls them. Here, the maximum cutting forces are determined, which correlate well with the roughness of the machined surface R_a.

3.2. Application for cutting force analysis

This application enters information about the current measured cutting forces for any angle of rotation of the cutting tool.

The application determines the maximum and average cutting force at full rotation of the tool.

The resulting maximum cutting force F_m is then determined.

The F_m values are then forwarded to the Application for in-process surface roughness estimation. The data is sent to the cutting force analysis application via a cloud gateway.

The Kistler dynamometer transmits the analogue values of the measured forces to the NI 950 card, which is supported by Labview software.

Labview software is installed on the local terminal, which then forwards the data to the cloud gateway.

3.3. Application for in-process surface roughness estimation

The application is intended for predicting surface roughness R_a during machining.

The core of the application is an artificial neural network with the popular back propagation learning rule, which automatically finds connections between the

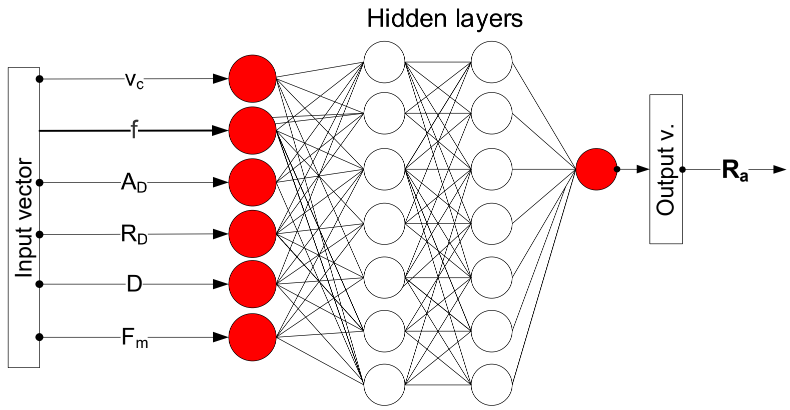

Fig. 2. Architecture of ANN based in-line surface roughness estimator.

cutting parameters, cutting tool diameter *D*, maximum cutting force F_m and R_a.

The experiments confirm that the artificial neural network independently developed the Ra model directly from the machining data that was stored in the big database.

The input vector of the neural network consists of 5 variables: feed rate (*f*), cutting speed (v_c), axial depth of cut (A_D), radial depth of cut (R_D), tool diameter (*D*) and the corresponding measured maximal cutting force.

The output vector of the neural network consists of only one neuron for the R_a variable. The output from the neural network is the roughness of the machined surface Ra in micrometres.

Figure 2 shows the topology of the constructed neural network, which contains 2 hidden layers. There are 7 neurons in each hidden layer.

The results of neural network testing showed that two hidden levels are enough to make connections between cutting parameters, cutting forces and the associated *Ra*.

For training the neural network, the learning rate was set to 0.21 and for the momentum rate the value was 0.5.

The training stop rule turned on when the network testing error was less than 4 %.

The neural network had to perform an average of 120 learning iterations, which means 6 minutes of training, to reach this condition.

Arctan activation feature has been selected in all hidden levels. A Sigmoid activation function was used in all neurons of the input and output levels.

One third of the database was intended for model verification.

The trained model sends the estimated *Ra* value to the process monitoring application. If the estimated roughness value R_a exceeds the reference desired value $R_{a\ ref}$, the feed rate adaptation process is activated in the Feed rate adaptation application.

The application transmits the command to the CNC machine control with a feed change telegram and informs the machine operator about the exceeded upper roughness limit with warning indicators.

3.4. Application for process monitoring

The application serves as a system control panel and as a user interface.

It enables remote control and management of the process. It shows the user the results of the analyses, the measured values of the cutting forces, the predicted roughness of the machined surface, the adopted process corrections and the communication status between the cloud platform and the CNC machine control.

Based on the input data (measured cutting forces, cutting parameters, tool diameter), the application predicts in real time the achieved roughness of the machined surface and the implemented process corrections to achieve the desired roughness.

The process control application is shown in Fig. 3. On top of the control application, the measured values of the cutting forces are plotted.

Here are the switches for setting the measurement chart and acquisition parameters. In the middle part of the control panel, the value of the predicted roughness of the treated surface is displayed.

The reference value *Ra* ref is set here. Next to the *Ra* display, there are switches for managing the milling process.

The operator communicates with the machine via switches, choosing between a fully automatic roughness control mode and a manual control mode. In the manual mode, the machine operator changes the value of the feed rate and the rotation frequency of the tool via the sliders.

The control panel is accessible via the password system online or on the PC terminal of the system.

3.5. Feed rate adaptation application

The application described below works as a cutting force regulator.

By adjusting the feed rate f, the application maintains the measured cutting forces at the reference values. Deviation between the measured and the reference cutting force is eliminated within 9 ms. An adjustable PI controller was used.

The controller adjusts the controller gain in response to changes in the process gain.

The regulator has three parameters that must be determined through simulations.

These parameters are: the controller sample period, the controller open loop zero K_o, and the constant *C*.

The operation of the adjustable PI is described by the following equation:

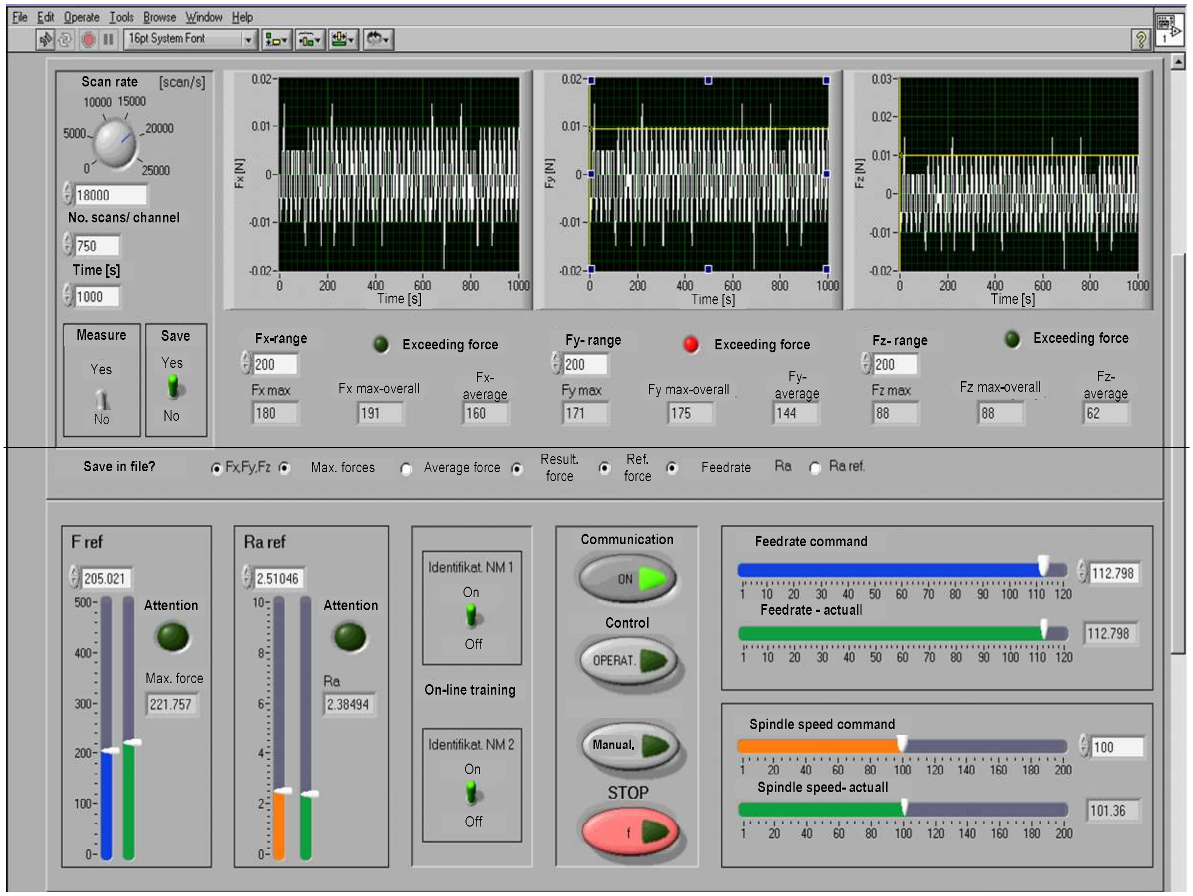

Fig. 3. Process control application.

$$f_{\%}(k) = C \cdot f_{\%}(k-1) \cdot \left(1 - \left\{\frac{f_{\%}(k-2)}{f_{\%}(k-1)}\right\} + \left[\left\{\frac{f_{\%}(k-2)}{f_{\%}(k-1)}\right\}\left\{\frac{F_m(k)}{F_{ref}}\right\}\right] + K_o \cdot T_s - [1 + K_o \cdot T_s] \cdot \frac{F_m(k)}{F_{ref}} + \frac{1}{C} \right. \quad (1)$$

where C is the control parameter to be set, $f_{\%}(k-1)$ is the percent override command at the previous sample time, F_{ref} is the reference peak force, K_o is the controller open loop zero, and T_s is the controller sample time.

Sample time was selected based on machine response and *cutting* tool speed.

When the sample time was determined, simulations were carried out at different values of C and K_o in order to analyse the responses to a step change of cutting parameters. When the value K_o is 30 and C is 0.029, a step response was achieved with a settling time of under 10 s and no overshoot.

The stability analysis of the controller showed that the system was stable in all tests.

The controller has a fast response and is easy to implement.

Finally, the application transmits the new feed *rate* command to the local terminal, where the command telegram is assembled and forwarded via DNC function to the CNC machine control.

4. EQUIPEMENT IN THE MACHINE TOOL PART

Heller Bea01 machine tool with CNC control Fagor, Kistler cutting force sensor 9257, dual-mode charge amplifier 5001 with low-pass 2 kHz limit frequency filter and industrial computer are located in the lower physical level of the control system.

An essential part of the lower part of the control system is the industrial computer, which allows the acquisition, pre-processing and transmission of signals from the force sensor to the IoT gateway in the cloud.

An algorithm for data acquisition and signal pre-processing is implemented on an industrial computer. Another algorithm implemented on an industrial computer is an algorithm to provide two-way communication between the CNC machine tool controls and the cloud-based control platform.

After surface roughness monitoring and feed rate corrections are performed, corrective feed commands are transmitted back from the cloud application to the industrial computer.

The industrial computer acknowledges receipt of commands from the cloud, then composes and sends a communication telegram via the DNC function directly to the CNC controls of the machine tool.

Accepted and applied feed rate corrections are displayed on the control panel of the industrial computer.

The operator of the machine tool is thus informed of the feed rate corrections by visual and audio signals.

5. CONCLUSIONS

The article presents a cloud-based platform for controlling the roughness of machined surface in ball-end milling. The platform ensures constant quality of the machined surface by adjusting the cutting parameters in real time, with the maximum possible level of material removal rate (MRR). To implement the control platform, it was necessary to integrate the system for measuring cutting forces into the surface roughness monitoring system. The core of the platform is the ANN surface roughness prediction model, which is described in detail in the paper. The developed ANN forecasting model predicts surface roughness with 98% accuracy. The accuracy of the model was determined based on the measurement of surface roughness after each cutting test with a surface roughness tester. The ANN model, made with this precision, shows the surface roughness to the machine operator on the system control panel. After each cutting test, the surface roughness was measured with a surface roughness tester. The efficiency of the cloud system for surface roughness control with the included ANN model is reflected in the improved surface quality.

Based on the experiment performed, it is determined;

- The IoT control platform improves the effectiveness of surface roughness monitoring and allows for faster determination of corrective control measures.
- The cloud-based system performs feed rate corrections within 12 ms, allowing the system to respond quickly to feed rate adjustments.
- ANN method with a 2% error predicts the roughness of the treated surface.
- The controller in the cutting parameter correction application is efficient and stable in controlling surface roughness under variable cutting conditions typical of end-milling.

The system created in this way enables a completely new way of controlling the quality of the machined surface and, consequently, tool wear. The developed control system is built in two stages. The lower physical stage connects the machine tool, cutting force sensor and industrial computer. The upper cloud stage connects cloud IoT applications for surface roughness control. Computational, modelling and control algorithms are implemented in this stage. The two stages are connected via internet and IoT gateway. The main feature of the developed monitoring system is that it takes advantage of cloud technologies. Outsourcing of information processing, large capacity of decentralized data storage, large information exchange, edge computing, analysis and modelling of surface roughness data, central surface quality control, data visualization and cutting conditions correction are the most important advantages of cloud services incorporated in this system. The monitoring system corrects the process by adapting the cutting parameters based on the measured cutting forces in the lower physical stage of the system. Cloud-adopted commands for correction of cutting parameters are transmitted to the CNC control of the machine via IoT gateway, industrial computer and DNC functions.

Future research will focus on the implementation of machining experiments to test the feasibility of the proposed cloud-based surface roughness control in end milling. Further research will address security and privacy issues, increase data transfer speeds, eliminate IoT gateway bottlenecks, select a cheaper and faster balanced resolution sensor, enable large amounts of data to be processed while performing control functions, and limit the amount of modelling data.

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