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CLOUD BASED CUTTING TOOL LOAD MONITORING AND CONTROL SYSTEM

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Abstract: *This paper presents a cloud based cutting tool load monitoring and control system for machining of functionally graded metal materials. This is a cutting tool load control system which connects the computing and service resources in the cloud with the physical resources in the factory level and thus forming a cyber-physical monitoring system (CPMoS) for milling. The two level CPMoS with the ability to connect the cyber world with the physical world via sensors and actuators is realized in order to maintain the cutting tool load constant by digital adaptation of machining parameters. The CPMoS provides a novel way to compensate all disturbances during the cutting process by controlling the cutting tool loads through cloud technologies. The cloud part of the CPMoS performs seven actions: sensing, information processing, edge computing, tool load data analysis and modeling, supervised monitoring, data visualization and process correction. An artificial neural network is applied to precisely model and in-process estimate the maximal and average tool loads. The physical layer consist of a CNC machine tool, piezoelectric dynamometer and local terminal which acquire, pre-process and transmit the signals from the dynamometer to the IoT gateway in the cloud platform. The special interest of future activities is to perform machining experiments in order to test the feasibility of the CPMoS for tool load monitoring in end-milling.*

Key words: *machining, end milling, cloud technologies, cutting tool load, control, monitoring.*

1. INTRODUCTION

Cloud computing is a new paradigm for pooling the computing resources and performing services over the Internet. Internet of Things (IoT) with a cloud computing is an efficient environment for sharing data, software and computing capabilities [1].

IoT performs four actions: sensing, access, information processing, applications and services and security and privacy implementation.

The cyber-physical system (CPS) is a special example of IoT with the ability to connect the cyber word (information, intelligence, communication) with the physical word via sensors and actuators.

Cloud computing has already presented application form manufacturing [2, 3].

In manufacturing the cloud computing has a potential to introduce new techniques for more efficient process monitoring, by transferring the monitoring data via servers to remote analytical resources performing advanced analysis and decision making [4, 5]. Cloud computing can significantly improve the efficiency of optimization [6], control and modeling procedures in manufacturing where especially huge computational resources are needed. Cloud manufacturing is a manufacturing version of cloud computing [7]. It is performed by connecting and sharing distributed manufacturing resources including software tools, knowledge and physical resources via internet infrastructure in the form of internet services.

In recent years, cloud manufacturing has been employed for machine tool monitoring, process monitoring and process control applications. It is especially suitable for developing of smart monitoring platforms [8, 9]. Data obtained during a machining process, such as cutting force, temperature, tool wear, surface roughness are uploaded via IoT gateway to cloud data storage. Next, the analysis are performed, providing the basis for decision making, monitoring or process corrections. A few cloud based machining monitoring application have been designed recently [10].

Teti [11] has developed a cloud framework of cutting tool condition monitoring in turning. Tapoglou [12] has developed a cloud-Based Platform for real time monitoring and for Optimal Machining Parameter Selection Based on Function Blocks.

In this paper, a cloud based cutting tool load monitoring and control system for milling is presented. The tool load monitoring in machining difficult to cut materials is essential due to frequent heavy tool wear and numerous tool breakage. The implementation of cloud based cutting tool load monitoring and control system connects the computing and service resources in the cloud with the physical assets and thus forming a cyber-physical machining system (CPMS).

The two levels CPMS adjusts the feed rate in order to maintain the cutting tool load constant and thus prologs the tool life.

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The signals from the piezo-electric dynamometer are transmitted through the internet to a cloud-based application where the process is corrected based on large amount of information and knowledge deposited in the cloud.

The paper is organized as follows: In section 2, a cloud based cutting tool load monitoring and control system is presented. Section 3 describes architecture of cloud based monitoring and control platform with detail descriptions of included IoT applications.

Section 4 presents physical assets of cyber –physical machining system. Finally, section 5 concludes the paper.

2. CLOUD BASED CUTTING TOOL LOAD MONITORING AND CONTROL SYSTEM

The developed machining system for cutting tool load monitoring and control is realized in two layers, physical and cloud layer. By connecting these two layers, a complex cyber-physical machining system is obtained. Its structure is presented in Fig. 1.

The lower level is a factory or machine tool level incorporating physical resources (machine tool, piezo-electric dynamometer, local terminal, CNC control unit) and software resources (data acquisition).

In this level the sensor signal acquiring, pre-processing, transforming into data packages and transferring to the IoT platform for machining monitoring and control over the LAN is executed.

The local terminal in lower level works as communication link between CNC unit, machining IoT platform and machine tool operator.

The cloud platform for machining monitoring and control accepts the signal packages, processes the signals, saves the data in big data base, extracts the sensor signal features providing adequate information about the cutting tool loads, models the cutting tool loads, visualizes the obtained data and corrects the machining process via control commands in order to maintain constant loads on cutting tool.

The platform for machining monitoring and control transfers back the control commands to the local terminal in the lower machine level, where the control actions are executed in connection with the Fagor CNC control unit via DNC protocol. Thus, the closed-loop control of cutting tool loads is accomplished.

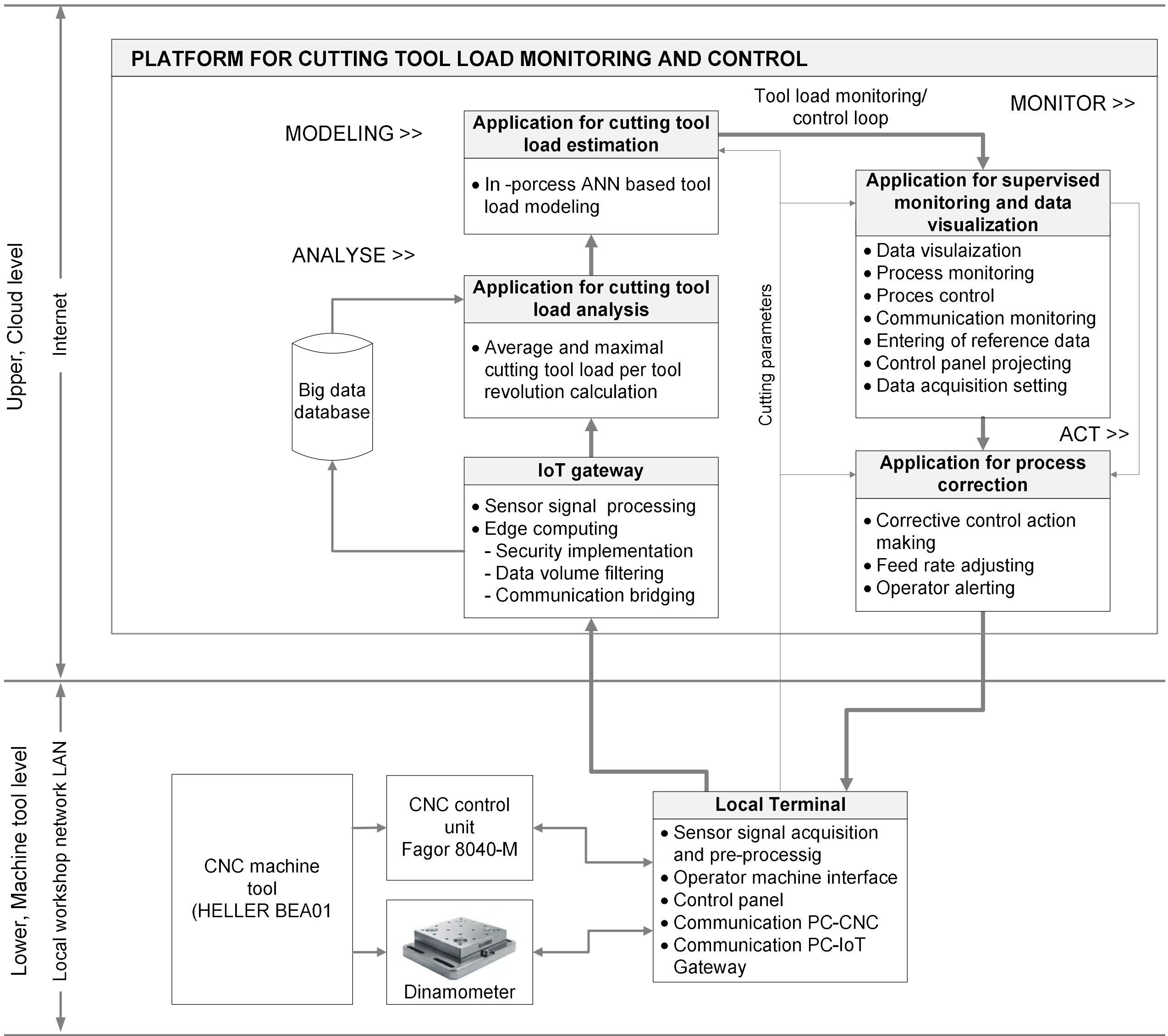

Fig. 1. The basic architecture of the cloud based cutting tool load monitoring and control system.

The executed control actions with alerts are visualized for remote user in the application for supervised monitoring and data visualization and projected for machine tool operator on the control panel of the local terminal.

3. PLATFORM FOR CUTTING TOOL LOAD MONITORING AND CONTROL

The cloud based machining platform is realized to. monitor and control the milling process during milling of multi-layered functionally graded metal materials. It is developed according to the architecture shown in Fig. 1 by connecting the physical assets (machine tool, measuring equipment, local terminal) in the physical layer with computing resources in the cloud.

The machining platform works as a process monitoring platform by taking the advantages of cloud based service recourses such as signal processing, graphical data visualisation, process value predicting, intelligent modelling and control decision making.

3.1. IoT gateway

The cloud based part of the cyber-physical system is divided into seven modules-applications according to the performed services. The first module is an Internet of things (IoT) gateway. It collects the sensorial signals from the measurement system and pre-processes them. These signals are filtered and reduced in order to perform the efficient process monitoring.

A time unit is assigned to the each sample signal and the data is sent and stored in the big manufacturing data database.

The further signal processing is carried out in an Application for cutting force data analysis, where the relevant features for cutting tool load monitoring process are extracted.

The main purpose of the gateway is to perform Edge computing activities consisting of data transfer security implementation and communication bridging.

3.2. Application for cutting tool load analysis

In this second application, the sensor signal features providing adequate information about the cutting tool load are extracted from the pre-processed sensorial data.

The pre-processed data from the piezoelectric cutting force sensor Kistler is obtained from the local terminal via IoT gateway.

The analogue force signal form the cutting force sensor is outputted to an NI 925A board controlled by the Labview software.

The Labwiew software consisting of the main algorithm for data acquisition and sensor signal processing is installed on the local PC terminal. The application acquires the components of average and maximal cutting force per tool revolution.

The values of cutting force components are forward to the application of cutting tool load estimation.

3.3. Application for in-process cutting tool load estimation

The third application is employed to realize the modeling of cutting tool loads during the machining process.

A standard artificial neural network based on the popular back propagation learning rule is used to predict the cutting tool loads on-line.

During experiments it proved to be sufficiently capable of extracting the force model directly from experimental machining data stored in the machining big data base. It is used to in-process model and estimate the cutting tool loads in few minutes. It is able to automatically connect the inputs (cutting conditions) with the components of cutting force.

The artificial neural network for modeling requires five input neurons: for feed rate (f), cutting speed (v_c), axial depth of cut (A_D), radial depth of cut (R_D), type of machined material and tool diameter (D).

The output from the artificial neural network are maximal cutting force components, therefore three output neurons are necessary.

The detailed topology of the employed neural network with optimal training parameters is shown in Fig. 2.

The topology of neural network is detained by a five-layer network with three hidden layers.

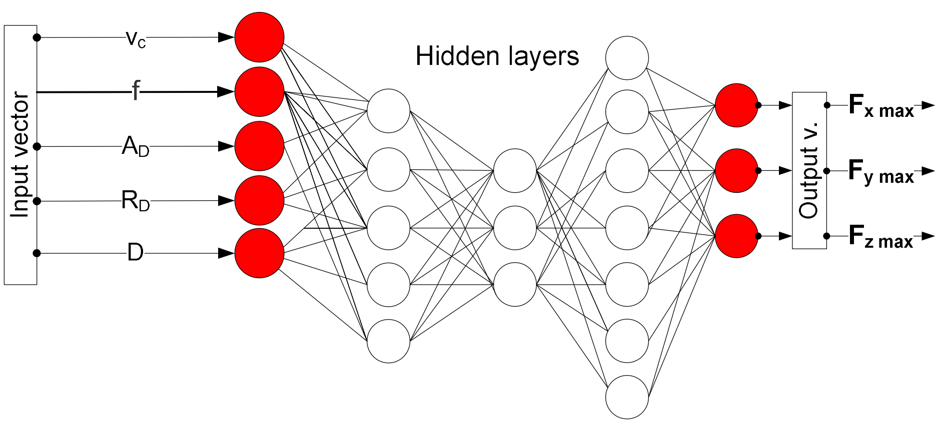

Fig. 2. Architecture of ANN based cutting tool load model.

It was found, that three hidden layers were enough to realize the usual mapping functions between cutting parameters and cutting forces. The learning rate and the momentum factor were estimated to be 0.19 and 0.78.

On-line training of the neural network is stopped when the testing error is less than the tolerance limit (5%). The Arctan function is set as an activation function in all hidden layers, while the activation function for the input and output layers is the Sigmoid function.

During the training process, 30% of the initial samples are preserved for model verification. A new sample is first checked. If it is abnormal or lies outside the norms, it is discarded; otherwise, it is used for testing.

On average, the networks needed 160 iterations to achieve this goal. Approximately 4 minutes of on-line training are needed to achieve the prediction performance of 5%. The output from the tool load model is send to the application for supervised monitoring and data visualization. This application can be accessed by the machine tool operator via the cloud or locally on the local terminal.

3.4. Application for supervised monitoring and data visualization.

The fourth application serves as a human machine interface (HMI) for the remote user to monitor and control the milling process.

The application displays and visualizes the cloud analysis results, the adopted control actions, the predicted cutting tool loads, measured cutting forces with the corresponding machining parameters. The application serves as a control panel for process monitoring and adaptive cutting tool load control.

The reference cutting tool load, measured tool loads, corresponding machining parameters and the adjusted feed rate are inputs to the application.

Figure 3 shows the developed application. It consists of three main parts.

Upper part of the application window is a monitoring part. Monitoring part has switches which enable user to define scanning parameters, measuring ranges, and accuracy of measuring. In this part the user can also visualize the predicted cutting force data.

Middle part is a control part. It consists of four buttons for controlling the milling process. Communication button enables user to establish or break communication with local PC terminal and consequently with CNC controls.

Stop button is an emergency button. In case of tool failure it stops the process by assigning the value 0 to the federate parameter.

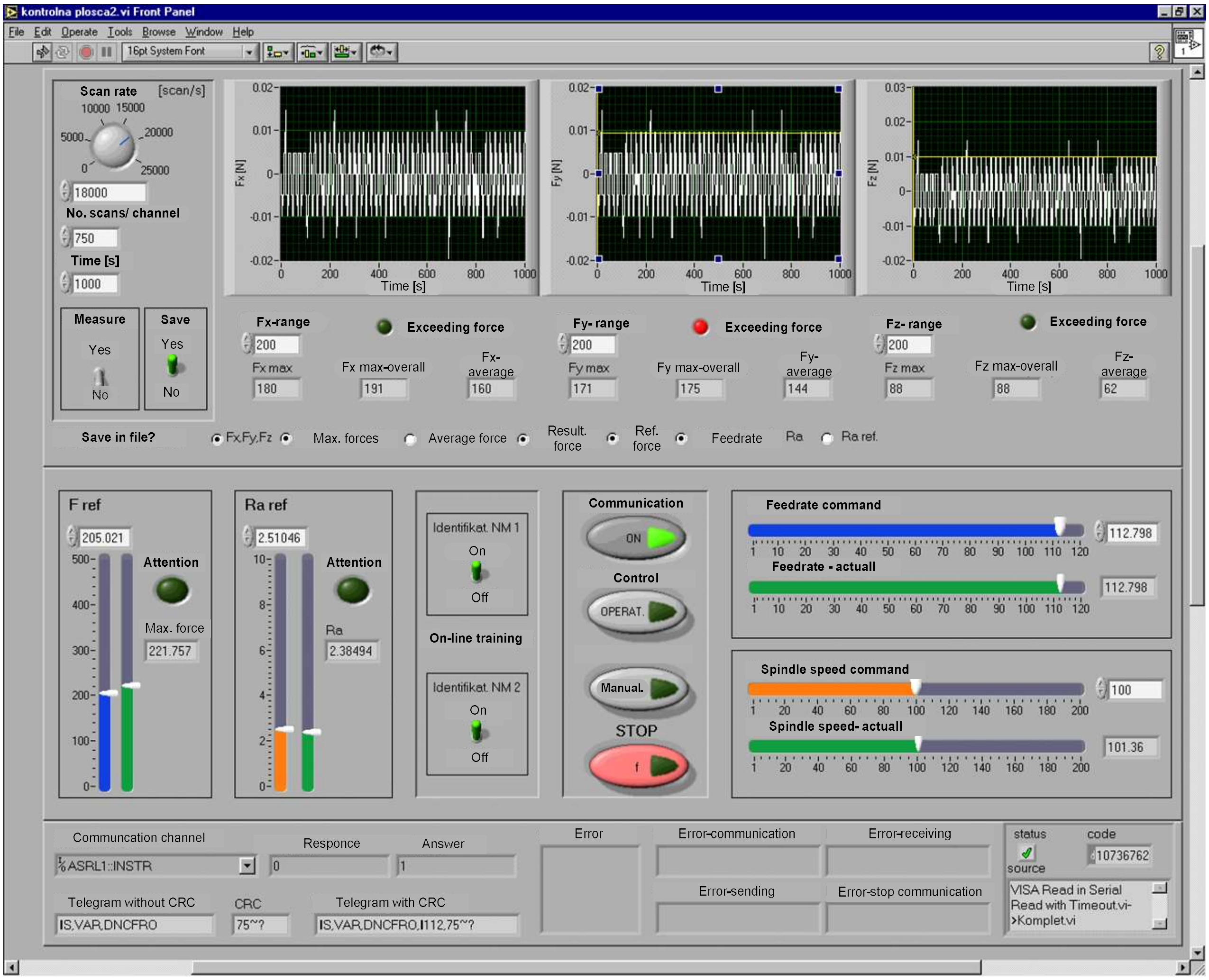

Fig. 3. Human machine interface (HMI) to monitor and control the cutting tool loads.

The third button switches between manual and automatic mode of working. Reference cutting force is set into the system by graphical slide or input window.

All important information about communication state is displayed at the bottom of monitoring window.

The monitoring panel displayed in Fig. 3 is also projected on local terminal providing a control panel for the tool user.

3.5. Application for process correction

The fifth application serves as a process control system and has process parameter adjusting capability. It monitors the maximum cutting force signals for each cutting tool revolution and compares them with the reference cutting force value. If the significant difference is identified, the control actions are executed within 10 ms after the occurrence.

The control actions are performed as feed rate adaptation and machine tool user alerting.

During process corrections, the control algorithm adjusts the feed rate values in order to minimize the difference between measured and maximal allowed cutting loads.

In this application, two controllers are available. Their block diagram is presented in Fig. 4.

A step controller in 10% increments decreases or increases the feed rate override percentage until the measured cutting force signal is below the maximal allowable cutting force. The step controller has a rapid response, and it is very easy to implement.

The second used controller is the division controller. Its structure is more complicated, but still provides fast response times. When adjusting the feed rate it considers a linear correlation between the measured cutting tool load and the f_c%. The new command of feed rate override percentage $f_c\%(t)$ is calculated according to equation 1:

$$f_{c\%}(t) = f_{c\%}(t-1) \cdot \frac{maximal\ alowable\ tool\ load}{measured\ tool\ load(t)}\ . \qquad (1)$$

The new commanded feed rate override percentage is calculated based on the previous command of feed rate and the ratio between the measured cutting tool load and the maximal allowable cutting force.

The stability analysis of the both controllers revealed that the system was stable in all the tests, except in cases where the measured cutting force approached to zero.

By limiting the controller commands the problem of the unacceptably large feed rate corrections for very small tool loads is eliminated.

Finally the application transfers the adjusted feed rate value to the application for supervised monitoring and data visualization and to the local terminal where the feed rate command telegram is constituted and forwarded to the CNC control unit.

Figure 4 shows the block diagram of the control algorithms.

4. PHYSICAL ASSETS OF CYBER –PHYSICAL MACHINING SYSTEM

The physical layer consist of a CNC machine tool (HELLER BEA01) with Fagor CNC control unit, Kistler (Type 9257) piezoelectric dynamometer, a dual mode charge amplifier (Type 5001) with a low pass filter of 1 kHz cut-off frequency and local terminal.

The fundamental part of the physical or workshop layer is the local terminal, which is used to acquire, pre-process and transmit the signals from the dynamometer to the IoT gateway in the cloud platform.

The main algorithm for data acquisition and signal

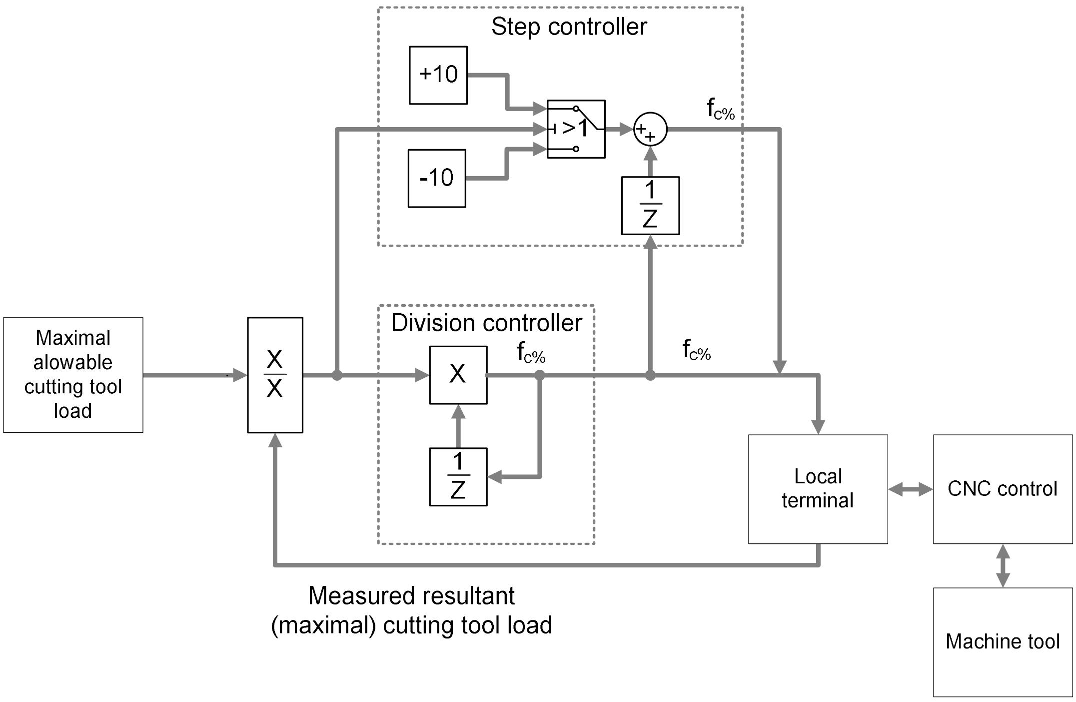

Fig. 4. General block diagram of the two employed control algorithms.

preprocessing is installed on the local terminal.

The second main function of the local terminal is to establish a communication link in both directions between machine tool CNC control unit and cloud based machining platform.

When the cutting tool load monitoring is performed and the process corrections are taken, the control commands are forward back from the cloud application to the local terminal. The local terminal accepts the control commands, constructs and sends a communication telegram with the adequate control command directly to CNC control unit.

The executed corrective control actions is confirmed and visualized on the local PC-terminal.

The machine tool user is therefore informed about the automatically executed control action with the corresponding warnings (visual and sound signals in case of cutting tool overloading) and further control suggestions.

5. CONCLUSIONS

The purpose of this contribution is to present a cloud based cutting tool load monitoring and control system aimed at on-line adjusting feedrate to prevent excessive tool wear, tool breakage and maintain the highest metal removal rate. Presented system represents a novel way for controlling the cutting tool loads in milling processes through IoT technologies. The two level monitoring and control system consists of machine tool, piezzo-electric dynamometer, resources for signal acquiring and data acquisition and four cloud IoT applications for tool load monitoring.

The lower, workshop level includes physical resources and software resources installed on the local terminal.

The physical resources are connected via internet to the cloud based tool monitoring and control platform, where computational, modeling and control resources are installed. The platform exploits the advantages of the cloud technologies such as outsourcing information processing activities, increased data storage capability, large information sharing, edge computing, tool load data analysis and modeling, supervised monitoring, data visualization and process correction.These actions are performed as cloud services.

The platform enables instant corrective process control actions based on sensorial data from the lower, physical layer.

Then, the local terminal in connection with the machine tool CNC controls executes the accepted cloud based corrective control actions.

The study's main findings are summarized below:

- IoT monitoring and control platform improves the process monitoring efficiency and enables faster determining of corrective control actions.
- Cloud based system executes the corrective process control actions every 18 ms, which allows a fast system response to adapt the feed rate.
- Time required to eliminate the excessive cutting tool load is estimated to be 64 ms.
- Artificial neural network method is efficiently employed to in-process estimate cutting *tool load* with the maximal 5 % prediction error.
- Applied two controllers in application for process correction are efficient and stable at controlling the tool load under variable cutting conditions typical for end milling.

Future work will be directed to perform machining experiments in order to test the feasibility of the proposed cloud based tool load monitoring and control in end-milling and to address the following challenges:

- security and privacy issues,
- limited data transfer speed,
- network bottleneck,
- optimal sensor type selection to balance between data resolution and data processing quality,
- massive amount of data to be processed for control operations,
- amount of data for modeling.

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