MECHATRONIC MONITORING TOOL (MMT) FOR MACHINED SURFACE EVALUATION DURING THE CUTTING PROCESS

Anna ZAWADA-TOMKIEWICZ, Dariusz TOMKIEWICZ

Koszalin University of Technology, 15-17 Racławicka Str., 75-620 Koszalin
anna.zawada-tomkiewicz@tu.koszalin.pl

Abstract:

The subject of the paper is to describe a mechatronic monitoring tool (MMT) used for evaluation of machined surface during the process of cutting. The integral part of mechatronic tool is a smart sensor. The principle of MMT design is a ability to be used on any lathe. The MMT is composed of several functional elements.

The core element of mechatronic monitoring tool is the smart sensor, which provides the data acquisition and integration. The basis for the sensor to operate is the surface image sequence acquired during cutting. The images are pre-processed and characterized with the number of irrelevant features. Feature vector is then used by classifier in decision making process. The smart sensor grants the essential information elaborated in data processing to be used in surface and process monitoring.

In addition, the MMT embraces the mechanical and electrical systems necessary for the tool to be fastened on the lathe and powered. The system must also be equipped with the system for cutting zone cleaning.

The paper concludes with the current research challenges required to expand the application of mechatronics in smart sensor elaboration for machined surface monitoring.

Keywords: mechatronic tool, measurements in metal cutting, machined surface, diagnostics

1. INTRODUCTION

In mechanical manufacturing systems there is recorded the constant growth of the demands for precision. It embraces the capability to produce the mechanical structures with greater precision at reasonable production costs [1]. The demands concern an increase in availability of process monitoring systems, intelligent maintenance and diagnostic functions. These demands can be achieved by applying mechatronic approach for designing the cutting process with the availability of the process and machined surface quality monitoring [2].

The MMT design combines mechanical engineering, control engineering, microelectronics and computer science for the purpose to monitor the process of cutting. The aim of mechatronic tool design is to elaborate the autonomic device, which enables the wireless data transfer and wireless transmission of energy, precision positioning of the sensor with the ability to perform measurements [3]. The mechatronic system is presented in chapter 2, where concept and requirements for mechatronic systems are shown.

The MMT is under development at Technical University of Koszalin, Poland [4, 5]. The MMT is based on surface image data from machine vision. To elaborate the complete monitoring tool on a basis of surface image data functional and spatial integration of several components must be provided.

The main element – machine vision system – can be used for image acquisition and pre–processing. The demanded quality of image data imposes a requirement for the optical system and illumination system to be controlled. So, the complexity of vision system increases and constitutes the basis for smart sensor elaboration. The functional integration of smart sensor is presented in chapter 3, where image-processing techniques for machined surface image is used to determine indexes correlated with the surface roughness parameters. Estimation of surface roughness Ra parameter based on machined image was provided on-line. The maximum estimation time not exceeded one second with the accuracy suitable for system monitoring.

The method is based on digital image of a machined surface in several magnifications. The method can be implemented on any lathe and it can be used in industrial conditions as an autonomous system or a part of a complete monitoring system.

The smart sensor is a part of the MMT, which functional integration is presented in chapter 4. The MMT consists of elements enabled the acquisition and processing of image data, control of actuators responsible for illumination and optics, data transmission between the MMT components and other elements necessary to accurate operation of the MMT.

2. MECHATRONIC MONITORING TOOL

The requirements of MMT are defined by trends in microsystems technology and nanotechnology. Contemporary manufacturing systems used for machining should fulfill following characteristics

- Ability to easily adapt to different tasks.
- Automatic adaptation (without an operator) to variable conditions.
- Easy communication with the an operator and other cooperating devices.
- High quality of operation.
- Low cost of production and operation.

Construction of manufacturing systems with such features is possible through the use in addition to mechanical parts electronics the appropriate algorithms for data processing. The system, which integrats mechanical components, electronic components and software, is called mechatronic device.

The mechatronic system’s modules can be consider in two aspects: spatial and functional [2,3]. The modularization of mechatronic system allows reducing its complexity. Due to spatial and functional integration of modules design can achieved such goals as:

- Spatial integration of sensors, actuators an intelligence and data processing component into one functional unit allow to create autonomous device with simple interface to communicate with other components of system.
- The mechatronic device can operate with smallest distance to the causal location. Due that feature it is possible to measure and to control production process without influence of deviations cause by incorporating additional elements in measurement or kinematic chain.
- Modular construction of mechatronic device and standardized interface make enable fast installation and replacing. Such construction is necessary in transformable systems able to adapt to changes in production tasks.

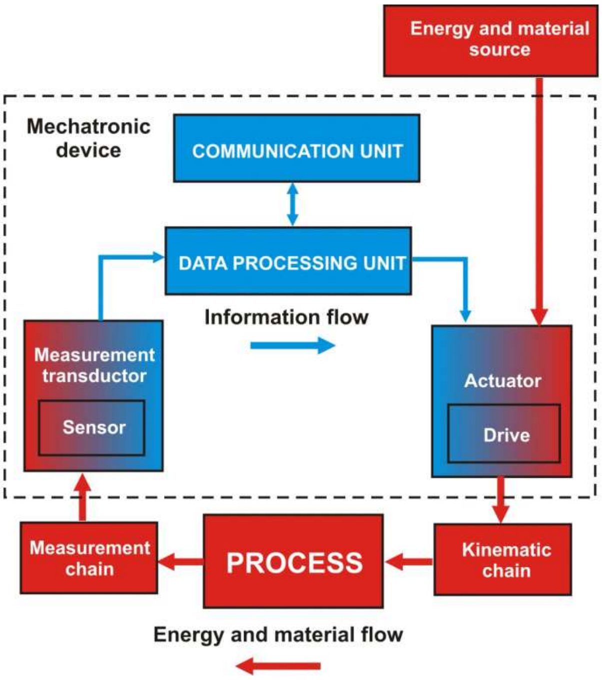

Fig. 1. The mechatronic system

Mechatronic devices typically consist of functional modules that cooperate with each other. The modules are presented in Fig. 1 and their functional role is as following:

- The measurement transducer module changes the form of a non-electrical measured signal into an electrical one. The measurement transducer also improves the quality of the measured signal by its gain, filtering, noise compensation.
- Data processing and control module, typically it can be: a microprocessor, microcontroller, signal processor or FPGA (Field Programming Gate Array). The data-processing module also consists of software responsible for accurate operation of a system (data processing and analysis, signal generation for actuators).
- Actuator module converts signal from data processing module (usually such signal has low energy) into a form that can feed a drive and force it to move to a desired position or velocity.
- The communication module is responsible for data transmission between mechatronic system modules and environment.
- Support modules are responsible for energy supply to each module, housing and other functions necessary to maintain accurate operation of mechatronic system.

In the case of the development of mechatronic monitoring tool the image acquisition and processing system is the main element. The system is equipped with elements associated with the measurement of current position of system components and their control. Because of its hardware and software complexity, this system can be called smart sensor. Smart sensor is an integral part of the MMT. The third chapter describes the functional integration of smart sensor.

3. FUNCTIONAL INTEGRATION OF SMART SENSOR

The aim of smart sensor development is elaboration of a low cost MMT of a machined surface. The system can provide the information of the quality of the surface during the process of its creation.

Features of smart sensor provide on-line monitoring of the workpiece during the cutting process. The system uses a digital image of the surface and the methods of image processing to correlate the image features with surface roughness parameters. To test and calibrate the system the experimental design is used. This method is contactless, non-destructive and non-invasive and possible to apply on-line during cutting.

After the calibration the system determines machined surface quality information for finishing machining. The system is intended to be for use in industrial environments.

Smart sensor is composed of several functional components: vision system for image acquisition, image processing system for image feature extraction and decision making system.

The first functional component, vision system, consists of surface illumination system, magnifying system, frame grabber with the image pre-processing system. The output of the first functional component is the surface image with strictly defined quality.

Surface illumination system is based on the white LEDs constituting directional lighting. The system is equipped with the actuator to change the position of light source. The input position is the elevation angle of 30°. Lighting together with optical system is centered to the axis of work.

Magnifying system is used to obtain a digital image featuring suitable field and depth of view. With the field of view of 1 mm^2 and depth of view of 100 µm the magnifying is appropriate for the surface monitoring where cut-off length is recommended 0.8 mm. The magnifying system is composed of lens and extender sets.

Frame grabber and image pre-processing are connected due to the demand of the quality of image information. First, the application of digital camera with IEEE 1394 interface for image acquisition provides the possibility to on-line control of the gathered data. Then the single frame was collected and converted it into a two-dimensional array of 8-

bit numbers. Finally, the process of image pre-processing was performed with the test of image quality. Two different image quality indexes were applied to examine if they are within certain value region. Only images of sufficient quality were used for further processing [6].

The second functional component of smart sensor, image processing system, consists of algorithms, which provide the transformation of image data into feature space. The first step embraces the set of predestined methods of image description, such as statistical space and spectrum features, wavelet features and other. All the features are then examined with the pruning method and only six normalized features are selected to be used for further processing.

The third functional component, decision making process, is strictly connected with the goal of monitoring. It consists of classifier, which is able to correlate the image features with actual process parameters [7].

For the estimation of process parameters, the recurrent neural network estimator was applied. After the initial process of preparing the structure of the network the feed-forward three-layer neural network was determined. The Extended Kalman Filter was used as the algorithm for neural network training. This algorithm enables optimal estimation of state variables in the presence of white noise. The advantage of this algorithm is its recurrent method of working.

Estimation of process parameters relays on following the changes in surface and warning when the changes are above the certain criterion. The process parameter can have different interpretation but it is good when is well known and understandable. When the criterion is correlated with surface roughness the common used parameter is Ra. In this case the estimated surface roughness Ra parameter (Ra_e) can be described with the use of a nonlinear function:

$$Ra\_e(n+1) = f\begin{pmatrix} Ra\_e(n), \\ F1(n)-F1(n-1), \\ .. \\ Fm(n)-Fm(n-1) \end{pmatrix} + w(n) \qquad (1)$$

where

$Ra\_e(n+1)$ - estimated value of surface roughness Ra parameter in the next $n+1$ step,

$Ra\_e(n)$ - estimated value of surface roughness Ra parameter in the n step,

$F1(n)-F1(n-1)$ .. $Fm(n)-Fm(n-1)$ - the difference of value for image $F1,..Fm$ features for the n and $n+1$ steps,

$w(n)$ - noise.

As is apparent from (1) the image indexes were not used in absolute way but the increments of features were applied. The neural network weight vector was adjusted after several presentations of training set so that the network error was below the threshold. The process of training was then stopped.

One of the advantages of using Kalman filter was the possibility of on-line estimation of model parameters. Such an approach enabled the surface monitoring system to be adjusted interactively by the operator during the process of cutting. When the estimation error achieved the threshold value the algorithm changed its mode from the training into the parameter estimation. The estimator parameter database was created for various cutting parameters and materials so that the time of monitoring system adjustment was as short as possible. The estimation algorithm was composed of four stages:

1. Image acquisition,
2. Image feature determination,
3. Training of recurrent neural network for new cutting parameters. It was done by the optimization of weight values in such a way that the difference between the estimated value and measured value was below the defined threshold,
4. Surface roughness Ra parameter estimation. It was done by the parameter estimation via neural network with optimized weights for defined cutting parameters.

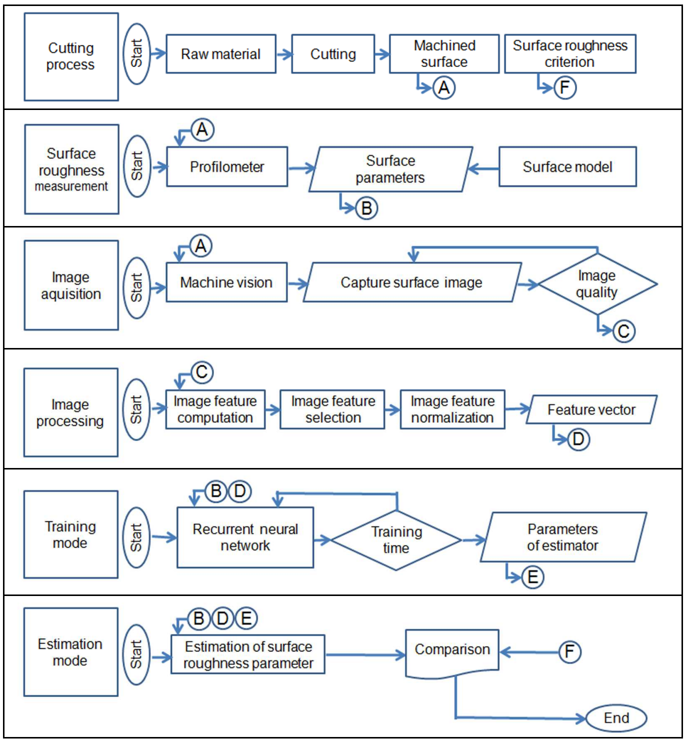

Fig. 2. The evaluation process flow for surface roughness monitoring

Smart sensor was elaborated to be a part of mechatronic monitoring tool. The communication between the smart sensor and MMT was provided through the wireless interfaces: Ethernet and ZigBee. The functional nad special integration of MMT was described in chaper 4.

4. INTEGRATION OF MECHATRONIC MONITORING TOOL

MMT was elaborated as the combination of functionally connected in one system the following subsystems: camera and sensor, data integration and image analyses, control of optics and illumination, actuators for optics and illumination. Camera and sensor unit (CSU) is responsible for gathering data from environment – especially vision data about the state of monitored surface. The data from CSU were processed in data processing unit (DPU). The DPU was divided on two functional subsystems. The first subsystem was responsible for data integration and image analyses. Together with camera the first subsystem created the smart sensor unit (SSU). The second subsystem was responsible for control of actuators. All subsystems constituting MMT exchanged data throughout data transition unit (DTU). The DTU consists of data transmission protocols such as: Ethernet, IEEE1394, RS232 and other. The DTU is also responsible for communication with additional systems, which support proper operation of the MMT system. These additional systems embrace: the camera fastening subsystem, the work zone cleaning subsystem, human machine interface (HMI) and other subsystems communicating through machine-to-machine interface (M2M) (Fig. 3).

Mechatronic monitoring tool was destined to be mounted on a CNC lathe with the SSU fastened on the lathe in such a way so that the working zone could be safely and efficiently observed. The SSU must be shied from external factors such as heat and chips.

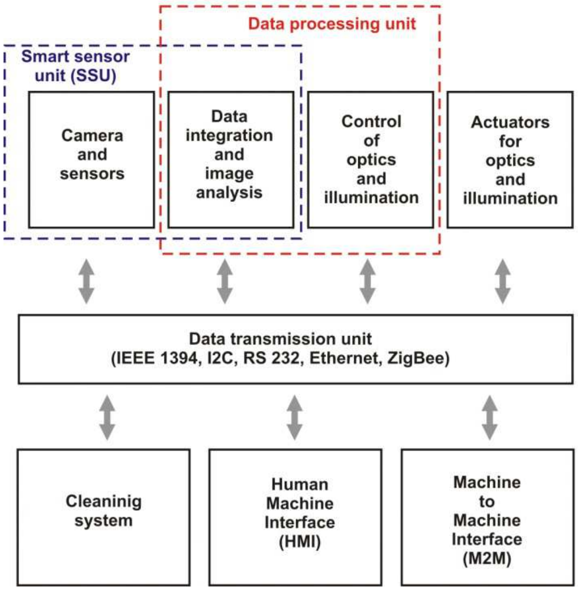

Fig. 3. The architecture of mechatronic monitoring tool

The SSU was elaborated as a monitoring system consisted of spatially integrated components. The core of the sensor is DPU, based on PC architecture with Windows environment, to control the data processing, storing and communication. Image acquisition control and other auxiliary devices are controlled with this software. The communication with lathe software for the goal of system calibration and surface roughness estimation algorithm is embedded in this system software. Ethernet network and other interfaces are applied for data transmission between the terminal and other elements of control system.

For the sake of complex and diversified tasks implemented in the system, the LabView environment was applied. The digital camera Basler A311fc was connected to DTU through the interface IEEE 1394. The shatter speed was set up in relation to rate of surface translation so that the acquired images were not blurred. The control of luminance and intensity were adjusted also to DTU. The set of functions from the IMAQ Vision library was used for the image acquisition and their further pre-processing.

The main goal of the HMI was to provide the information of the process for human operator. HMI was responsible for control of three MMT functions. One of them was oriented on the tuning of camera parameters, the second was devoted to the training of neural network estimator, the third could be described as general control of the application.

Function concerning the neural network estimator enabled the human operator the switching between the training and estimation (working) mode. This function was necessary due to the periodical calibration of the estimator and enabled the tuning of the MMT for new cutting conditions.

Human operator, who could decide if the process should be terminated, performed all the activities concerning HMI. The alarm was generated when the controlled value (counted as moving average) was higher than the defined threshold.

5. CONCLUSIONS

1. Construction of the MMT is possible thanks to the mechatronic approach. In the mechatronic system such subsystems as: smart sensor, actuator control, actuators and data transmission unit are integrated in one simple device of simplified communication with other components of manufacturing environment.
2. Development of the MMT allowed the spatial integration of diagnostic system and can be used in a vicinity of cutting zone. It was beneficial as far as reduction of measurement chain, shortening of measurement time and decreasing of measurement errors due to shortening of kinematic chain.
3. Modular construction of the MMT is beneficial for fast installation on any lathe and reconfiguration.

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