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Evolutionary neuro-fuzzy system for surface roughness evaluation

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ABSTRACT

The paper presents a system that, according to the requirements referring to the product quality given in surface roughness, with minimum machining time and maximum metal removal rate, recommends optimal cutting parameters with the possibility of surface roughness control during the machining process. The suggested evolutionary neuro-fuzzy system for evaluation of surface roughness is composed of three units: surface roughness prediction by cutting parameters, multi-objective optimization of cutting parameters aimed at minimum machining time and maximum metal removal rate and control of obtained or required surface roughness by means of the features quantified from digital image of the observed machined surface. The paper outlines the idea and architecture of the system as well as the possibilities of implementation. The obtained results, illustrated by experimental research, justify the application and further development of the suggested evolutionary neuro-fuzzy system for evaluation of surface roughness within the given constraints.

1. Introduction

A production process is aimed at achieving, based on technical documentation, predetermined product quality using available production equipment at reasonable costs and time limits dependent on terms of delivery. Surface roughness is often used as an index of the product quality, but it is usually considered as a technical requirement that the product must meet so as to completely fulfil its function. If chip forming machining is considered, depending on the type of operation, by using an adequate parameter selection it is possible to achieve required surface roughness by an adequate choice of machining parameters. A production process or parts of a production process can be systematically controlled by offering variance of manufacturing processes in accordance with the required product quality, imposed constraints and objectives. Production conditions, parameters and constraints of production processes affect production results and characteristics of a product. It is possible to keep achieving better results by generating knowledge base on input and output variables of the studied processes.

As the suggested system integrates surface roughness prediction by means of cutting parameters, cutting parameters optimization in view of the set objectives within the set constraints, and the surface roughness evaluation of the observed machined part surface based on the features of digital image, the review of the research so far has been conducted in three directions. The advantage is given to the most often investigated operations: turning and milling.

Papers [1,2] analyse approaches and methods used for predicting surface roughness. Thus paper [1] classifies the methods into four main groups: (i) approaches that are based on machining theory to develop analytical models and/or computer algorithms to represent the machined surface; (ii) approaches that examine the effects of various factors through the execution of experiments and the analysis of the results; (iii) approaches that use designed experiments; and (iv) artificial intelligence (AI) approaches. Paper [2] classifies the methods into three main groups: (i) pure modelling-based approach; (ii) signals-based approach; (iii) artificial intelligence based approach. The evolutionary neuro-fuzzy system for evaluation of surface roughness covers almost all of the mentioned approaches. What it does not cover is the approach that is based on machining theory to develop analytical models and/or computer algorithms to represent the machined surface, the example of which is given in paper [3] and which could eventually be used to expand it. When machining parameters are used to predict surface roughness, the following three input variables are most often used: spindle speed or cutting speed, feed rate and cutting depth, either for turning [4] or milling [5]. In addition to the given, the following variables are also often used as input variables: nose radius, cutting force [6], vibrations [7] or amplitude of vibrations, tool stepover between two adjacent passes, cutter axis inclination angle [8] or workpiece inclination angle [9]. Among the methods used for prediction the most frequently used ones are: regression

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methods [10], artificial intelligence methods [11], response surface methodology [8] and various hybrid methods [12–14] that show improvements with regard to individual methods. Surface roughness prediction by machining parameters has been investigated on various materials: structural steels, corrosion resistant steels, cast steels, titanium alloys, aluminium alloys and other metals. Errors in surface roughness prediction based on machining parameters are below 5% [15] while the artificial intelligence methods are shown as the most effective methods [16–18].

In a number of cases surface roughness prediction using cutting parameters does not meet the demands of the current production so optimization of cutting parameters is performed. It is necessary to determine the cutting parameters whose application will enable the realization of one or more objectives considering the known constraints. The objectives of parameter optimization in machining most often are the following: minimum surface roughness [19], maximum surface roughness [20], minimum unit costs [21], minimum machining time [22] and minimum production costs [21]. In addition to the single objective optimization a multi-objective optimization is often applied [24]. The optimization process requires the definition of fitness function and constraints if they exist in the observed problem. The fitness functions and constraints of optimization problems can be given as mathematical formulae, however, the models obtained by regression methods or methods of artificial intelligence can also be used. The derived mathematical formulae are most often based on theory and experience while the models obtained by statistic, regression or artificial intelligence methods in most cases include experimentally or arbitrarily taken data of investigation process. Similar to predicting, the following variables are most often optimized in the process of machining: cutting speed, feed rate and cutting depth. The most frequently used optimization method in optimizing cutting parameters is genetic algorithm [25,26] which often results in improvements higher than 10% considering the objectives of optimization [27]. In addition to genetic algorithm the following optimization methods are also used: the Taguchi method [28,29], Ant Colony Optimization [30], Simulated Annealing, Memetic algorithm, Tabu research and Particle Swarm Optimization. Almost all of them are applied and compared in paper [31] for the purpose of minimizing unit production cost. So as to obtain better results, using the same optimization model the authors often examine the fitness functions obtained by various techniques such as neural networks and response surface methodology [32] or they try to improve the optimization method by applying different hybrid methods [23,33,34].

To complete the circle of surface roughness evaluation, after prediction and optimization it is of the essence to check whether the desired or demanded quality of the product, i.e. surface roughness, can be repeatedly obtained. The most frequently applied method to control the machined part surface roughness is the use of the features of the machined surface digital image as input variables for prediction model [35,36]. Firstly the machined surface digital images acquisition will be performed. Acquisition of machined surface digital images is performed first of all, then the images are converted into matrixes, after that, using different approaches, various features, usually scalers, are quantified out of the matrices that mathematically describe the digital images. The obtained scalars are used as input variables in the creation of models for control (evaluation) of surface roughness. The features of a digital image are often represented by statistical values such as arithmetic mean and standard deviation [37], various kinds of norms such as the Euclidean and Hamming norms [38], various wavelet transforms such as the Harr wavelet transform [39], and the two-dimensional Fourier transform [40]. Difference between prediction and control of surface roughness refers among others to time phase of machining; prediction is possible previous to the beginning of machining while control i.e. evaluation can start only following the observed surface machining. The models used for control (evaluation) of surface roughness on average have a higher degree of error than the models used for predicting surface roughness; however, time phase of control gives the possibility to also use cutting parameters along the features of digital image while evaluating the given surface roughness [41,42]. Combination of cutting parameters and digital image features as input variables can considerably reduce error in evaluating the machined part surface roughness [40,41,43]. For surface roughness control (evaluation) artificial intelligence methods are used more often than regression methods due to their robustness and somewhat better approximation [44] to the trend of acquisition of digital images in a dynamic surrounding [45].

The main motivation for developing the evolutionary fuzzy inference system for surface evaluation came after reviewing available references and noticing the lack of papers that unite these units into an interrelated system. In order to create such a system in a quality way, basic restrictions need to be set. The idea of using the proposed system was developed from the need to define optimal cutting parameters. These cutting parameters should enable realization of the set objectives with a possibility of varying the constraints imposed if the required product quality is to be met.

The present paper is aimed at creating and presenting a system that connects prediction, optimization and control in the process of machining with the emphasis on surface roughness. As the methods used in creating the suggested system include the elements of neural networks, fuzzy logic and evolutionary computing, the system is named: "Evolutionary neuro-fuzzy system for surface roughness evaluation".

2. Description of evolutionary neuro-fuzzy system for evaluation of surface roughness

Evolutionary neuro-fuzzy system consists of three units [46]: prediction of surface roughness based on cutting parameters, multi-objective optimization of cutting parameters and evaluation of surface roughness based on the features of digital image. Fig. 1 displays a schematic description of the evolutionary neuro-fuzzy system for evaluation of surface roughness whose functionality is shown by the example of face milling.

The use of the system is schematically shown for the three units together with their connections and training phases for those units where training is indispensable.

The function of the system first unit is to connect cutting parameters: spindle speed, feed per tooth and cutting depth with mean roughness *Ra*, i.e. to predict the mean roughness *Ra* by means of the cutting parameters. Mean roughness *Ra* is selected for the output as it is the most frequently used indicator of the surface roughness quality. Fig. 1 bottom left part shows the usage of the first unit of the system along with the training and checking phase. Fuzzy inference system (FIS) for surface roughness Ra prediction by means of cutting parameters is generated by the ANFIS method using the data experimentally obtained in the training and the checking phase. The ANFIS method is a programmed procedure for defining all the fuzzy inference system (FIS) parameters by using the available or measured data which describe the target system. In this unit the target system is composed of the cutting parameters and the mean roughness Ra. Fig. 2 displays general architecture of the applied ANFIS method for acquiring the fuzzy inference system (FIS) composed of three inputs and one output.

The ANFIS architecture is most often presented by 5 layers. The layers consist of a number of nodes described by node functions. If there are three inputs in the system, each input being described with three different categories (fuzzy sets), then the fuzzy rules

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