Development of methods for analyzing patterns of current consumption in a system for wireless monitoring the effectiveness of metalworking production

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Annotation. Now the world is actively developing a trend of digitization of production enterprises. However, not all existing enterprises are equipped with a proper system for collecting and displaying information. Hence, the task of simple and fast integration of the monitoring system for the technological process produced by Metalworking equipment is quite relevant. To solve this problem, the article presents algorithms for accounting for the number and type of manufactured parts on Metalworking machines, as well as diagnosing the quality of the technological operation, based on temporary patterns of electric current consumed by the machine. This information, collected from the entire production cycle, will allow you to plan production more effectively.

1. Introduction

Monitoring of the production process is one of the essential components of successful and effective production management [11, 12]. Modern CNC machines are usually equipped with built-in monitoring systems that provide comprehensive information about the processing process via a digital channel. However, in the absence of such a built-in service, the problem arises of equipping the equipment with a third-party, independent device that allows you to provide data for the monitoring system of the workshop/enterprise level.

Currently, there are quite a lot of such systems on the market, but almost all of them require some degree of integration with the monitored equipment and / or continuous interaction with the operator.

2. Setting the monitoring task

The aim of monitoring the processing process on CNC machine tools can be divided into three levels (both in terms of the degree of detail of monitoring and the complexity of its implementation).

- the first level of monitoring is the monitoring of the actual operating time of the machine in the part processing mode, in the idle mode, as well as (and) the idle time of the metal cutting machine;
- the second level of monitoring, including the previous one, adds accounting for the type and quantity of parts manufactured on the machine;
- the third level of monitoring, including the previous two, adds diagnostic capability processing, evaluating, changing current magnitude and the duration of individual operations, the correct modes of operation, the consistency of the parameters and properties of specified items, quality and tool wear.
3. Analysis of methods for monitoring the operation of machine tools

The first level of monitoring is implemented by simple means of analyzing the intervals of finding the current value between certain levels, using the simplest methods of filtering and / or statistical data processing, such as digital filtering, time window averaging, median filters, etc. This level is implemented in most existing systems for monitoring the operating time of industrial equipment, for example, counters of operating time. Our method of calculating time allows you to divide the total time of equipment operation by the time of idling and the time of work during the processing of the part. This information allows you to more accurately predict the remaining resource until the next maintenance service, as well as improve the efficiency of production planning.

The implementation of the second level of monitoring requires the use of methods for selecting and recognizing patterns in time series, for which correlation methods [3], synchronous filtering methods [4], methods for analyzing statistical characteristics on the time window, OLS, etc. can be used. A review of the most promising methods that are used to detect and isolate patterns in time series can be found in [13, 14].

The third level of monitoring, in addition to using the methods of the two previous ones, requires taking into account the features of the processing process, namely: physical processes occurring during cutting [18], properties of the processed material, characteristics and wear of the processing tool [15], properties of the coolant, etc. For example, we can use the simple formula of cutting force [19]:

\[ F_0 = \rho (S_p - X_1) \]

where \( \rho \) - is the stiffness coefficient of cutting, included all characteristics of material and cutter, and \( S_p \) - is a feed per rotation. An increase in the hardness of the material or wear of the cutter will cause an increase in cutting force and, as a result, an increase in the current consumed by the machine tool, which will lead to an increase in the amplitude of the pattern as a whole (in the first case), or only in the processing interval with a worn tool (in the second case) [20].

The full use of this direction of monitoring and diagnostics should be accompanied by the construction of a mathematical model of the processing process [16, 17], taking into account the cutting, friction and dynamics of the machine drives, and its verification using standard workpieces and tools. The recording of the current pattern of the reference processing process in the future should serve as a reference for assessing the status of the processing of subsequent workpieces. In the study, we considered 3 methods of work control of machine tools: identification of the main actuator by means of rotation sensors; identification of the main actuator by measuring the magnetic field around the main drive; measuring the current consumption of the entire machine by means of a current transformer. The first two methods are applicable for tasks that correspond to the first level of monitoring.

Tracking the rotation of the main drive is as follows: on the rotating shaft of the engine, a "mark" is installed, which is either a reflective pad (for optical or infrared sensors), a magnet (for sensors based on a reed switch or a Hall sensor), a metal curtain (for inductive sensors or Hall sensors with a built-in magnet), and so on. A sensor corresponding to the label is installed on the stationary part of the engine, which provides an indication of the fact of rotation of the main drive. The disadvantage of this method is the complexity of mounting this measuring system, and sometimes it is impossible.

Experimental studies on measuring the rotating magnetic field around the main drive stator have shown their good magnetic shielding and the futility of this method of measurement.

The analysis of options for solving the problem showed that the only method that meets the requirements of all three stages of monitoring is to control the electric current consumed by the equipment under study. This method provides the simplest integration into existing systems with no structural changes.
4. Methods of conducting experiments and data analysis

Experiments on measuring the current consumed by industrial equipment were conducted at a Metalworking site equipped with multi-spindle machines and processing centers. The VTL-600 type machine was used as the main one (Fig. 1).

![Figure 1. Vertical lathe VTL-600, used for research](image1)

An inductive current sensor of the SCT-013-000 type [1] was connected to one of the phases of the input feeder of the machine. The induced current was rectified and averaged using a bridge diode scheme on Schottky diodes, filtered by a second-order passive low-pass filter, and connected to the input of an 10-bit ADC wavgat D1 mini microcontroller [2] based on ESP-8266 (fig. 2). Current values were read every 100 ms, averaged over 1 second, and sent to the cloud server using the MQTT Protocol. Data was stored on the server and then analyzed on the local computer.

![Figure 2. Components used in the design of the measuring system.](image2)

a - current sensor, b - microcontroller board
During three months of experiments, more than 850 MB of data was accumulated, in particular, from the machine in question – more than 4 million current counts, which corresponds to ~1200 working hours. In fig. 3 you can see the developed web-interface to data, collected in cloud. It realize 1st level of monitoring – demonstrate the curve of current consumption, mean current, and intervals between patterns.

![Web-interface to data, collected in clouds](image)

**Figure 3.** Web – interface to data, collected in clouds

A typical graph of the current consumed by the machine in the process is shown in fig. 4. the graph shows a period of time that is 120,000 seconds away from the beginning of measurements (one frame is 10,000 seconds). In the drawing, you can see the sections of idling (minimum current values in the region of zero and after 5000 seconds), and fluctuations in current consumption that occur during various processing operations.
Figure 4. Typical view of the current consumed by the machine during operation, frame No 12

Figure 5 shows, for example, another section of current recording for frame 57. In this case, the part manufacturing operation is shorter, and more of them get into the frame. Areas of downtime are more noticeable.

By analyzing the data obtained, you can divide the task of diagnostics and monitoring of industrial equipment into three hierarchical levels, determined by both the complexity of the analysis [3, 4] and the information received by the end user:

Level 1. Calculating engine hours and analyzing equipment downtime. The problem can be solved almost immediately after the sensors are installed and data accumulation begins by determining the idling level of the machine, and dividing the diagram into sections "work" - "simple". This service is provided by almost all software products on the market, and does not require significant costs when configuring the customer.

Level 2. Counting the parts produced on the machine and sorting them by type. This service requires more in-depth data analysis, associated with the preliminary accumulation of information about the types of manufactured parts and further classification of patterns during the recording of the current
value. Correlation analysis methods, synchronous filtering methods, and others are used to find and classify patterns. However, the time distortion of the pattern can be a significant complication when it is stretched, compressed or torn for technological reasons, for example, when a modifier or program stop is introduced into the CNC program. However [5], this task can be successfully solved, but it will require time-consuming initial configuration and further support from the customer. As a rule, common programs for recording the operating time of industrial equipment do not offer such a service.

Level 3 includes a full-fledged diagnostics of the process of Metalworking (or other) production due to an in-depth analysis of the current amplitude in the pattern itself and its comparison with the standard. The idea of the analysis is that the current consumed in the production process depends on both the properties of the processed material and the state of the cutting tool. That is, as a deviation of phys.- mech. both the billet properties from the standard and the tool wear will be displayed in the value of the current consumed [6, 7]. However, such diagnostics are currently not implemented by any of the known commercial software products, because it is labor-and knowledge-intensive, and, in fact, requires disclosure of the cutting dynamics for each individual part being processed.

Analysis of the accumulated experimental material [8] has shown that the above hypothesis is true, and, moreover, tool wear can be detected even for consecutive patterns (fig. 6, 7). Figure 5 shows quite clearly the increase in the amount of current consumed from 1 to 3 pattern, most likely associated with the gradual wear of the tool performing the same type of operation (turning) [9,10]. Figure 6 shows the same increase in the current level from the 1st pattern to the 4th.

![Figure 6. Overlapping sequential patterns, see figure 3](image-url)
Figure 7. Overlapping sequential patterns, corresponding to Fig. 4.5. callout-an enlarged area in the region of 0-100 seconds

5. Discussion of results
The research presented in this paper is, in fact, an assessment of the feasibility of implementing a system for monitoring power consumption by production equipment, monitoring services, evaluating the effectiveness and diagnostics of the equipment used. The accumulated experimental data allow us to say that with proper analysis (perhaps using machine learning methods and pattern recognition methods), it is possible to create a monitoring and diagnostics system that corresponds to the concepts of "digital production".

Potentially, the current monitoring system of metalworking equipment can serve as the basis for creating a "digital passport" of the manufactured part, since the current pattern corresponding to the manufacturing process reflects the characteristics and parameters of all operations performed on the machine.

Conclusions
According to the results of the research, it can be argued that the approach to creating a system for monitoring and diagnosing the operation of industrial equipment, based on measuring the current consumed by the equipment, and its further analysis and processing, will allow you to implement all three proposed diagnostic levels, bringing this area as close as possible to «digital production».

Gratitudes
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