Technical Diagnostics at the Department of Automation and Production Systems

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Abstract. The article contains a summary of recent development in field of technical diagnostics at the Department of Automation and Production Systems, Faculty of Mechanical Engineering, University of Zilina. It covers diagnostics and monitoring of CNC machine tools, industrial robots, and production lines. Each part contains a description of basic approaches, methods, measurement tools and their implementation. In case of machine tool and industrial robot diagnostics, it is mainly laser interferometry and double Ballbar method. It also describes usage of the internet of things and machine learning as a tools to implement multiparametric diagnostics and monitoring on production lines.

Keywords: Technical diagnostics · CNC machine tool · Industrial robot Production line · Machine learning

1 Introduction

Every technical object, including basic tools of automation, has its own lifespan, in which it is capable of proper functionality, which can be extended to a certain extent by proper maintenance. The maintenance should be focused not only on repairs of devices, as it still usually is, but it also should prevent occurrence of unexpected downtimes and resulting financial losses. Such maintenance requires certain amount of information about machinery, production processes, mechanisms of faults, and impact on the environment. Therefore, correct maintenance requires implementing of technical diagnostics and condition monitoring at some extent. It should be clear that, in order to improve competitiveness of the business, it is desirable to increase machinery reliability to reduce its necessary downtime, and to predict development of its future condition. These reasons, together with the necessity to save resources, should be the main reasons for implementation of predictive maintenance and technical diagnostics in industry [1].

The importance of development in the field of technical diagnostics is undeniable, therefore it is one of the most researched topics at the Department of Automation and Production Systems, Faculty of Mechanical Engineering, University of Zilina. As the name suggests, the main interest of our department is industrial automation and its

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practical implementation in industry. The development of technical diagnostics in our department can be divided into three main groups: machine tool diagnostics and monitoring, diagnostics of industrial robots, and diagnostics of production lines.

2 Diagnostics of Machine Tools

CNC machine tools are complex mechatronic devices which are often mistakenly considered to be absolutely accurate. In reality it always inherits various errors and inaccuracies that affect the quality of the produced parts. Therefore, machine tool precision is considered to be one of the most important diagnostic parameters, by which it is possible to evaluate its overall technical condition.

Machine tool precision is defined as the ability to produce parts of the required shape and dimensions keeping the required tolerances, and to achieve the desired surface roughness. Geometric accuracy of a machine tool is determined by actual shape and position of its individual parts, joints, and their mutual movements. The desired geometric accuracy of a machine tool can be achieved by respecting the required accuracy of production of individual machine tool parts, nodes, and its assembly. Furthermore, most of CNC machine tools are capable of compensating geometric errors resulting from inaccuracies and wear of a construction part [2].

However, geometric accuracy of a machine tool is not sufficient to ensure precise production, as it depends on the accuracy of the path shape between a work-piece and a tool, which can be affected by various additional factors. Machine tool condition on its built in state, but also on its usage and maintenance. For further improvement of machine tool reliability and safety throughout all lifetime, early detection, prediction and location of inaccuracies, faults, and errors are of high interest. Not only critical situations and collisions, but also normal everyday use causes wear that leads to decreasing accuracy of positioning, and furthermore to production of scrap [3].

Development in this area in our department is focused mainly on improving the existing procedures of machine tool precision measurement in terms of time efficiency and implementing long-term machine tools monitoring.

2.1 Measurement of Machine Tools with a Laser Interferometer

In the field of implementing laser interferometry, much effort was devoted to design devices that help to train routines necessary to effectively perform measurement in any given condition or situation. Such devices replace machine tools during training and simulate various faults and positioning errors to provide real life experience with setting up measurement and aligning the laser, which require the most time and skill of all measurement process stages [3].

Such devices are necessary, as standard training CNC machine tools commonly used in educational process in our laboratories lack the ability to set compensation tables, and thus it is impossible to present the effect of compensation to machine tool performance in laboratory conditions.

2.2 Measurement of Machine Tools with Ballbar

Ballbar type devices are probably one of the most effective tools in terms of predictive maintenance. Normally, it is implemented according to standard ISO 230-4 that describes measurement, environmental conditions and evaluation of measurement. The Ballbar system, in our case Renishaw Ballbar QC20-W, is essentially a highly accurate linear displacement sensor which measures deviations of distance between two balls that fit into magnetic bowls connected to the moving parts of the examined device. The measurement with this device is based on measurement of radius deviations during circular movement [4, 5].

Most of research at our department regarding measurements of CNC machine tool performance with Ballbar was focused on software development. For example, the B5R2SIG software can be used to export data from measurement to be analyzed in external software, and then furthermore to compare data measured by Ballbar device with profile measured on machined parts by a roundness measuring device, such as Talyrond 73. Our research confirmed that the most of the machine tool errors, measurable by Ballbar, can be at least partially diagnosed by measuring of circularity of profile machined in a controlled environment.

2.3 Machine Tool Monitoring

The laboratory of CNC programing at our department is, similarly to other educational institutions, equipped with a training machine tool from the Emco Concept series. These machine tools are characterized by a control system which is realized as a computer software with interface and behavior simulating various commercial control systems.

The fact that the control system is running on a PC as standard software offers an opportunity to access its data in various ways. Based on this, we designed software (MT Monitor) capable of reading variables that stores information from control system, such as tool position, technological parameters, or filenames of NC programs.

Such data can be filtered and analyzed in various software. For example, the analysis of workspace usage can be very valuable. Such analysis can prevent excessive usage of specific subspaces of the machine tool workspace, and thus local wear resulting to maintenance cycle shortening.

3 Diagnostics of Industrial Robots

The main focus in this field at our department is to evaluate, analyze, and improve the existing methods, or to develop new methods if it is necessary. Most of our experiments are performed on Fanuc robots, as the department is Fanuc authorized system integrator. However, the results are still applicable for any industrial robot of common construction.

Selecting of an industrial robot for individual application requires considering some basic criteria, such as payload, workspace shape and size, number of degrees of freedom, and also other characteristics. The analysis of the performance criteria offers a detailed view of the industrial robot properties that affect its performance in a given application. The importance of individual performance criteria, together with the recommended test conditions, measurement and evaluation methods are defined in international standard ISO 9283. This standard divides the performance criteria of industrial robots into four groups:

- positioning performance,
- path performance,
- minimum positioning time,
- static compliance.

The International Organization for Standardization published technical report ISO/TR 13309 to provide an overview of metrological methods and measurement methods applicable for measuring performance criteria of industrial robots. There are also a lot of various scientific publications dedicated to such topics. The most frequently measured criteria are single directional precision and repeatability. In most cases, these measurements are carried out using indicators or a laser interferometer. Other approaches implement camera systems or devices designed primarily to evaluate CNC machine tool condition. Most of the mentioned methods are highly time and skill demanding, while in other cases the biggest problem is price and availability of measuring devices [6].

Laser tracker is considered to be one of the most common measurement devices for evaluation of industrial robots performance used by most of robot manufacturers. The main benefit of implementing laser interferometers is simplicity of measurement and ability to meet almost all conditions required by ISO 9283. On the other hand, problems appear with robots with repeatability in hundredths of millimeters [6, 7].

Implementing indicators for measuring performance criteria is a simple and relatively cheap solution. Most publications dedicated to one-directional precision and accuracy of industrial robots list indicators as the most commonly used measuring device. However, without other tools for designation absolute position of robot end point, it is possible to evaluate only relative repeatability of an industrial robot.

In case of CNC machine tools, besides laser interferometer, ballbar type devices are commonly used. The Ballbar type devices are great tools for quick and easy evaluation of Cartesian kinematics, but their usefulness for alternative kinematics is quite limited. The main limitation is the lack of methodologies and compatible software. Therefore, our research is mainly focused on implementing these two measuring devices and developing appropriate methods and software [8, 9].

3.1 Industrial Robot Measurements with a Laser Interferometer

Experimental verification was performed on industrial robot Fanuc LR mate 200iC, available in the Laboratory of robotization of production processes at our department, with the laser interferometer Renishaw XL-80. This laser system allows for multiple measurement, mainly linear, angular, and straightness measurement. In case of measurement repeatability, linear measurement was used. The accuracy of linear measurement is ±0.5 μm, and resolution is 1 nm. This type of measurement is based on relative movement of the reflector and the interferometer, which is usually static, along the laser beam emitted by the laser measuring unit XL-80. The principle of measurement limits its application to movement along the line parallel to the laser beam [6, 10].

We designed a measuring procedure based on ISO 9283 which is based on an imaginary cube (Fig. 1) that has to be placed in workspace of the examined robot. Such a cube should be as big as possible and should be placed in the most used part of robot workspace. In our case the cube edge is 470 mm long and the edges are parallel to the axes of the world coordinate system of robot (WCS). As the measurement is possible only along the line, three individual measurements are necessary, each parallel with a different axis (X, Y, Z). All measurements have a common point (P0) located in the corner of the cube. This arrangement allows for one-directional, and bi-directional measurement method.

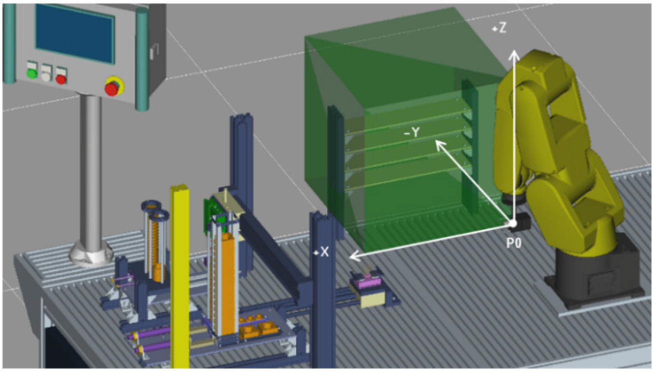

Fig. 1. A model of Fanuc LR mate 200iC workplace with position and orientation of an imaginary cube and measured axes

Measurements of industrial robots with a laser interferometer are time and skill demanding, and in comparison with measurements on CNC machines bring fewer benefits, as it is not possible to directly use a compensation table.

3.2 Industrial Robot Measurements with a Ballbar

Current trends of increasing production flexibility and shortening the time of creating a solution and its implementation to production creates more and more pressure to deploy industrial robots in applications that used to be the domain of other devices, such as machine tools or single purpose devices. Such applications require high accuracy and precision and, most importantly, performance stability over time. The most common applications include highly accurate assembly, measurement, testing, and machining. During the lifecycle, a robot's performance is changing as a result of various factors, the most important of which can be divided into the following five groups:

- environmental factors (temperature, humidity),
- parametric factors – result of production and assembly errors, impact of dynamic parameters, such as friction, hysteresis and loosen fits,

- factors related to measurement (resolution and nonlinearities of sensors),
- factors related to calculations (e.g. rounding),
- factors related to application (e.g. installation errors).

Regular diagnostic measurement, necessary to check performance criteria meeting requirements of the mentioned applications, exert pressure to develop measurement methods which would take as little time as possible. Such measurements should be performable in real industrial conditions in which the robots are deployed [5, 6].

Regular data collection is a necessary condition to implement progressive maintenance methods that allow to predict and prevent robot or production faults due to decreased performance criteria. In case of CNC machine tools, a commonly used device is Ballbar, which allows to check quickly its performance and also to evaluate errors and their sources. Results of such measurements provide a strong information base for targeting and planning maintenance [4, 5].

Measurement with Ballbar type device is not part of ISO 9283 standard, nor the technical report ISO/TR 13309. During measurement, it is not possible to fulfill measurement conditions required by the mentioned standards. The circular path on the machine tool is done as the synchronous relative motion of two perpendicular axes. Contrary, the simple circular path on industrial robot with serial kinematics requires movements in multiple joints. Therefore, measurement and result analysis also requires special approach. On the machine tool, the software for Renishaw Ballbar is capable of identifying 21 different errors describing its condition. Still, it is possible to use this device for simple check of robot condition, and with regular measurement to monitor its changes. Some errors identified by this software, such as vibrations or reversal spikes, are related to robot kinematics as well but most of them do not [6].

The basic output of this measurement is polar plot of deviations of the measured circle from the programmed ideal one. Analysis of such a plot allows to identify errors e.g. perpendicularity of both axes that manifests as an extension along 45° or 135° (Fig. 2). In case of the industrial robot, it is most probably caused by incorrect conversion of Cartesian coordinates into the angular coordinates of robot joints. The next typical error is occurrence of vibrations (Fig. 2b).

To fully understand the origin and causes of errors, it is necessary to perform tests on multiple places in the workspace, or even to use different measuring devices and methods and their combinations. It also requires detailed information about robot kinematics, exact position and orientation of tested circular path relative to the robot, and exact influence of individual drives in overall movement. Such information can be obtained by using the suitable CAE system to plan and prepare experimental verification. In our case, the Creo Parametric 2.0 was used to create a positional analysis, as shown on a model of our robot and its workplace (Fig. 3). The positional analysis can help us to plan locations and orientations of measurement in order to get different ranges of individual joint coordinates for each position, and thus to identify possible source of error in that particular joint.

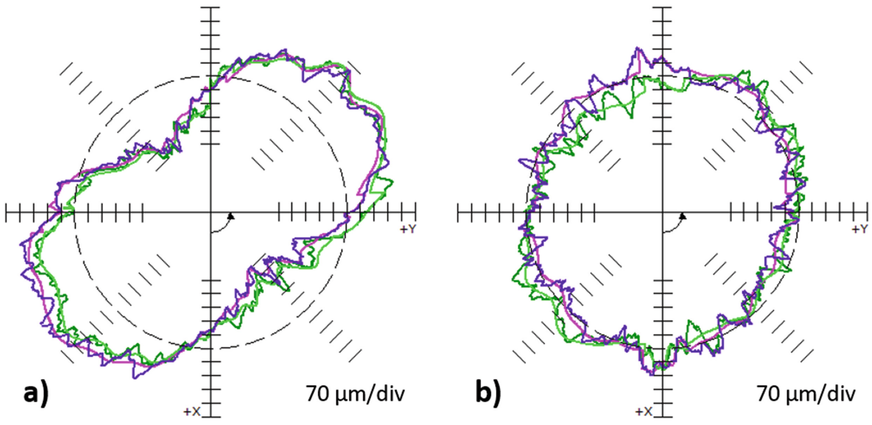

Fig. 2. An example of polar plot from measurement of industrial robot by Renishaw Ballbar QC20-W showing error in perpendicularity (a) and vibrations (b)

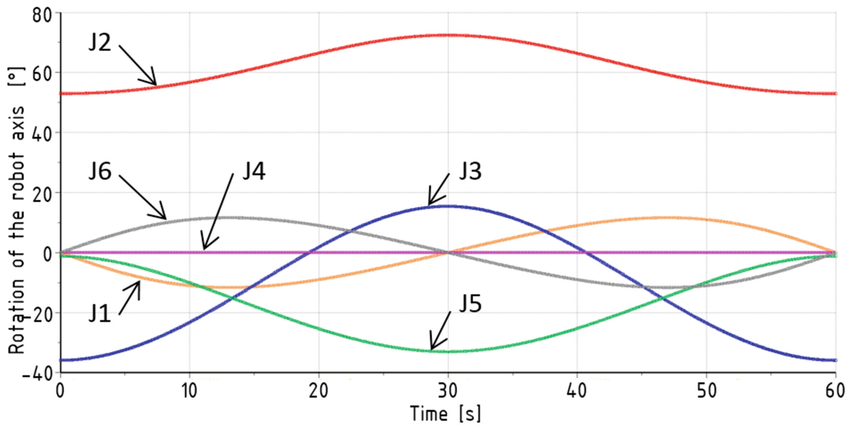

Fig. 3. Positional analysis of joints of an industrial robot during circular motion

4 Diagnostics of Production Lines

There are a lot of various elements used in general industrial automation. One of the most common types of production facilities that implements automation in engineering industry are production lines. As everything in industry, even production lines should be seen not only as tools that create products, but also as products themselves. Currently, our department cooperates with numerous companies dealing with design and manufacturing of production lines. The purpose of this cooperation is to implement modern methods of diagnostics, such as remote diagnostics and condition monitoring into newly developed production lines or to add them to the existing ones during their regular maintenance. There are a lot of various methods that can be implemented in order to increase the amount of information describing the current and future conditions of a production line and its individual parts. It is necessary to understand that a production line itself is not always simply a sum of its individual parts, and thus it requires more sophisticated and complex or even holistic approach [11].

The implementation of diagnostics into complex systems, such as production lines usually requires the following steps:

- analysis of individual production processes,
- division of the examined device into the key nodes,
- selecting appropriate diagnostic methods (physical principles, sensors, and their location),
- selecting suitable method for data acquisition (from sensors and from control system of production line),
- test run,
- analysis of data acquired in test run,
- verification or optimization of the original solution,
- deploying the final solution.

The development process usually requires several iterations and fine tuning to achieve appropriate solution that meets customer expectations. Modern technologies allow shortening of development cycles by implementing ready-to-use solutions and tools designed for rapid development [11].

One of the latest trends is to decentralize data collection by implementing a so-called intelligent industrial sensor that is meant to be connected to the Internet of Things (IoT). IoT can be used in various ways. Currently we are using Kepware KEPServerEX as a data concentrator, and PTC ThingWorx as platform to collect, process, and visualize data [8].

The collected data originates not only from sensors, that were added as diagnostic tools, but also from control system itself. The control system of any production line usually uses huge amount of variables. Therefore, it is necessary to carefully select the variables which would be reasonable to collect important data, in order to reduce traffic necessary to transmit diagnostic data. The selection and filtration can be done in one iteration of the whole optimization process. The platform used for data collection allows us to export data and process them in any other external software. We can use it to create and enhance algorithms of data processing and analysis as well. This is described in the following chapter.

4.1 Machine Learning in Technical Diagnostics

Contemporary methods of technical diagnostics commonly use state-of-the-art devices and technologies in order to ensure quality, reliability and value of data acquired by diagnostic procedures. In some cases, information of the same or even higher value can be gained by using multiple diagnostic methods, where synergic effect can take place. Simultaneous usage of multiple diagnostic method is known as multiparametric diagnostics. However, implementation of multiparametric diagnostics requires perfect knowledge of relations between the values of diagnostic parameters and condition of the examined subject. Identification of such relations is usually a complex task that requires processing of significant amount of data. Therefore, machine learning seems like an ideal tool for such kind of tasks.

It is beneficial to use machine learning and deep neural networks` algorithms in the area of multiparametric diagnostics and predictive maintenance when analyzing high volumes of data is required. It is important mainly when the dependence between measured data points and their effect on the quality of the manufacturing process is complex and non-obvious.

A typically exercised workflow when using machine learning and deep neural networks methods is the following:

- filtering and synchronizing the data,
- using simple machine learning algorithms to preliminary data analysis,
- using deep neural networks to develop a model that detects changes in condition and arising machine failures,
- implementing the model on PCs.

Filtering the data is necessary step, as the data collected from the manufacturing process can exhibit errors due environmental factors, such as interference. The most common type of error that can be easily filtered out is such a measurement error where the value is out of the physically possible range. Another frequently occurring error is missing data when, measurement was not performed or the data was not collected for any reason. If only small group of values in short time span is missing or if they are obviously incorrect, then their value can be approximated from the neighboring values. If there are more missing records, then all the values in that time span should be dropped. Then data are synchronized and resampled according to use the same time span and sampling period. Failure causes can be encoded numerically and added to the data [12, 13].

The data is then analyzed by using common regression and clustering machine learning tools to find nonobvious relationships between measurements and failure states. This step does not detect all causes of failure, but it helps to better recognize deeper relations between the measured data, collected technological parameters, and condition of the examined device acknowledged by conventional approaches. Regression and clustering results can be directly used to develop software modules for failure prediction. Sometimes it is beneficial to use some of the results of regression and clustering as additional input for deep neural networks [13, 14].

For most tasks, when it is necessary to analyze significant amount of data collected over a long time period, stamp and classical methods cannot predict all failures, but we can successfully use recurrent neural networks. The recurrent neural networks have loops that pass information from one step of the network to another and back. These loops act as memory that can store internal state and allows them to process sequential data.

The most universal recurrent neural networks that we use in monitoring, diagnostics, and predictive maintenance is the Long Short-Term Memory (LSTM) network. LSTM is a neural network capable of learning long term dependencies between input data. We use the Keras library in conjunction with TensorFlow. This approach allows us to easily test several neural network topologies and fast iteration times [13].

After the model is successfully developed and tested, it can be exported and used directly in the manufacturing process as an essential part of a control system. However, most models are too complicated and computing power demanding to run on PLCs which control the manufacturing line. In such cases, it is necessary to use either conventional computers, or dedicated industrial PCs built into the production line to collect and process data from PLCs. Running the predictive maintenance model on conventional computers has the benefit of easier monitoring and ability to update the model. This allows us to use simultaneously different models and compare their performance.

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