DIAGNOSTICS AND MAINTENANCE OF MACHINE TOOL SPINDLES-NEW VIEWS

ONDREJ HOLUB, MILOS HAMMER

Brno University of Technology
Faculty of Mechanical Engineering
Brno, Czech Republic

This paper discusses changes in the field of maintenance brought by the Fourth Industrial Revolution - Industry 4.0. Main pillars of the Industry 4.0 are as follows: digitization, interconnection, linking and visualization of all corporate parts, starting from production, through maintenance, and ending by logistics.

Maintenance is one of the areas affected most by these changes. It is not enough to monitor only certain machine parameters and assess their status –the offline diagnostics. Monitoring of all machines and measurable parameters is requested and, in addition to it, it is advisable to ensure visualizationfor the users –the online diagnostics.

Technical diagnostics belongs to important aspects for ensuring maintenance, mainlythe preventive, predictive and proactive maintenance. Vibrodiagnostics is one of the most widespread diagnostics in the field of mechanical engineering, where the signal from the source of vibrations carries the information concerning the cause of vibrations, and its analysis can establish, even well in advance, the emerging or developing defect or damage.

This article describes the differences between the online and the offline vibrodiagnostics and analyzes the results of specific measurements. Online diagnostics visualization with the possibility of its use in the maintenance sector is demonstrated here as well.

KEYWORDS

industry 4.0, maintenance, technical diagnostics, offline- online diagnostics, vibrodiagnostics, visualization

1 INTRODUCTION

Industry 4.0, the Internet of Things – this way the fourth stage of industry development is named abroad (Fig.1). In this period the world around us is changing materially, and industrial companies are no exception. Machines, devices, products and communication technologies and their electronics, sensors, software can be interconnected with people gradually through Internet. They will thus create a production network, where thereal-time information will be shared. This will allow for a better collaboration and provide an opportunity to improve quality and decision-making of process management, optimize coordination of activities and increase efficiency throughout the whole value creation process. Therefore the cyber-physical systems, able to communicate with each other, will be faced more and more in the future.

Thanks to such complex systems, the maintenance system will be further developed. Maintenance will include inspections and checks of machine components through remote access and automatic start-up of service and maintenance, if necessary.
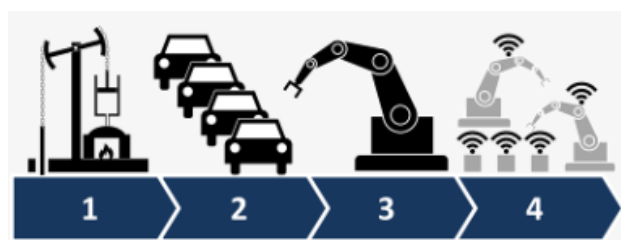

Figure1. Stages of industrial development[Brdicka 2016]

The recorded data will be analyzed to identify possible wear or danger of impending machine failure. This way set systems will lead to the continuous expansion of predictive and proactive maintenance,which not only provides an overview of the impaired status and possible failure, but the gathered data will allow to draw conclusions about condition and status of the machine and to take the required measures or maintenance, incl. the corrective actions and the cause of occurrence. [Legat 2013].

As already mentioned above, technical diagnosis is important throughout the process. Technical diagnostics is a separate discipline dealing with non-disassembly and non-destructive methods and means focused on determining technical condition of the object [Helebrant 2014]. Nowadays it is not enough to choose a suitable diagnostic method and select the optimum types of sensors and diagnostic tools. The diagnostician is nomore satisfied with mere detection and localization of the existing failure, but requires precise fault specification. Much more higher demandsare raised on creation of an appropriate diagnostic system, it means the system based on the object and means of diagnostics, operation and methodology, i.e. the methods, procedures, etc.

The diagnostic methods are usually broken down by the diagnostic variable. Therefore for instance the electrodiagnostics, tribodiagnostics, thermodiagnostics, noise and defectoscopic diagnostics, etc, are thus differentiated. All those mentioned above are used widely in technical practice. Vibrodiagnostics undoubtedly belongs among them, it is nowadays elaborated in greater details, and its deployment in the industry is extensive. Vibrodiagnostics has been discussed very much and therefore this paper will not explore it any further. With respect to the fact that this method is promising for development of Industry 4.0, this fact will also be applied in the presented paper.

Use of vibrodiagnostics in the offline and online mode is the issue discussed frequently these days. More knowledge is so far known and practically verified from the offline vibrodiagnostics sector. There has been little known yet about the possibilities of using the online vibrodiagnostics in terms of methodology, used diagnostic tools, e.g. sensors and devices, etc. Therefore this paper is also devoted to comparison ofthe offline and online vibrodiagnostics.

2 ONLINE AND OFFLINE DIAGNOSTIC SYSTEM

This chapter introduces two major diagnostic systems that are used in industrial practice – the online and offline one. Diagnostic system evaluates the technical state of objects. It consists of diagnostic means (devices, methods), diagnostic (monitored) objects and the operator who performs and evaluates the measurement[CSN 2010]. Diagnostic object - the object being monitored - is in this case the machine tool spindle. In the following Experiment chapter, the data obtained from both systems will become subject to statistical analysis.

This will show whether the systems differ from each other in the evaluation[Helebrant 2014], [Kutalek 2015].

2.1 Online diagnostic system

Measurement using the online diagnostic system is aimed at continuous monitoring of selected parameters and their limit values. If the limit values are exceeded, a predetermined sequence of activities follows that help to identify the specific cause of the exceedance.

Diagnostic means includes all devices, procedures, methods, and programs that are necessary for the analysis and evaluation of the technical state of the object under investigation - the spindle. In this case, these are mainly sensors, control units, and evaluation software.

Diagnostic means used for online measurement:

- **Vibration sensor VSA005** - for vibration measurement, vibration sensor VSA005 from IFM was selected(Fig. 2). It is an accelerometer that is being connected to an external VSE diagnostic unit. The sensor meets the EN61000-6-2 / 3 and EN 50178 Electromagnetic Compatibility requirements. The vibration sensor is located on the machine cover as close as possible to the spindle. Important specifications for vibration measurement:
  - Measuring principle: Capacitive
  - Measuring range: ± 25 g
  - Frequency range: 0 - 10k Hz
  - Sensitivity: 0.2 mg / √Hz
- **Evaluation unit VSE100** - in order to evaluate VSA005 vibration sensor data, it is necessary to have a VSE100 evaluation unit (Fig.2). To ensure compatibility, this unit also comes from IFM. Several vibration sensors can be connected to the unit. The unit records these data and then processes them. The evaluation unit has internal memory that allows to store the data in real time but it is necessary to select the appropriate recording interval. The unit has several inputs and outputs that can be combined. In this case, the most important is the data interface option. This allows the unit to connect to the production network and to evaluate the data using a suitable program.
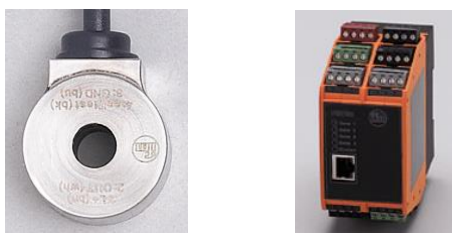

Figure 2. Sensor VSA005, evaluation unit VSE100

- **Software Efector Octavis** - the Efector Octavis was used to evaluate the vibration parameters which is supplied by the IFM along with the sensors. The software is used to control and adjust the monitored parameters for the vibro-diagnostics of the technical system objects and for the evaluation.

2.2 Offline diagnostic system

Offline diagnostic system measurement is most frequently used in regular - preventive maintenance. The operator has a portable measurement system that measures the object directly on the site. In industrial practice, this system is often used to detect the exact cause of exceeding limit values that have been traced from online tracking. This is primarily because

of the enhanced analysis options that the online monitoring system does not allow.

The diagnostics was performed on the same object again – the spindle – to be able to compare the results. However, the sensor for offline measurement was located directly on the spindle body (Fig. 4).

In this case, the offline diagnostic system consists of:

- **VIBXPERT II**(Fig.3) is a high performance, full-featured FFT data collector and signal analyzer which allows easy condition monitoring of equipment found in many industries. VIBXPERT II collects field data including vibration information, bearing condition, inspection, and process data. Extensive analysis functions facilitate data analysis and condition diagnostics on site.
- **VIB 6.142 R** – mobile industrial accelerometr, M5 thread flat, electrically insulated. Vibration and shock pulse measurement with data collectors on standard machines. Electrically insulated accelerometers prevent leakage currents during 2-channel measurement on machines of different potential. Important specifications for vibration measurement:
  - Measuring principle: Capacitive
  - Measuring range: ± 98 g
  - Frequency range: 0 - 20k Hz
  - Sensitivity: 0.2 mg / √Hz
- **VIB 3**.420 – Magnet holder. If the best available measurement location has a flat or curved ferromagnetic surface, then the magnetic holders provide good signal transmission to flat-bottomed accelerometers with M5 thread e.g. VIB 6.142R. The holders mount quickly and easily onto a wide range of curved or flat surfaces.

Figure 3. VIBXPERT pack

3 EXPERIMENT

The purpose of this experiment is to compare the two most common machine monitoring systems - online measurements, which are ongoing and which are most commonly used today to track time changes and offline measurements that often come in just after the notification from the online measurement system where the limit values have been exceeded.

Measurements were made at the machine tool spindle. The online sensor is located on the machine frame but as close as possible to the spindle. This is due to the handling of products or the replacement of spindle where the sensor can not be placed directly on the spindle. The sensor for offline measurement can be placed as desired but it is advisable to place it as close as possible to the bearings and for the sake of

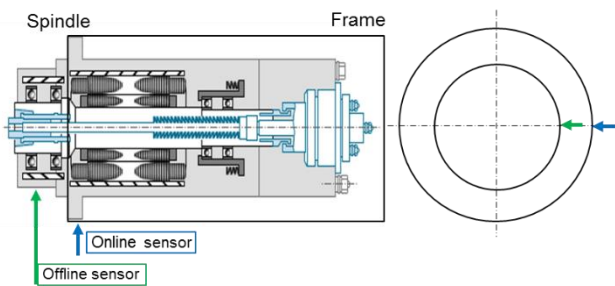comparison in the same direction as the online sensor. The whole layout shown inFig. 4.

Figure 4. Measurement layout

The vibration parameter RMS was selected for the measurement. The RMS value is one of the most important parameters in evaluation of the amplitude because it takes both the time history of the wave into account and gives us an amplitude value which is directly related to the energy content, and therefore it shows the destructive abilities of the vibration. The Efector Octavis program directly enables the setting and evaluation of this parameter according to ISO 10816-1[CSN 1998].

3.1   Statistical analysis

The measured data is recorded in Table 1. 15 values were measured within a few weeks. Therefore, it is necessary to consider the wear of the spindle itself.

Measurement no.	RMS – offline [mm/s]	RMS – online [mm/s]
1	0,71	0,65
2	0,58	0,45
3	0,32	0,21
4	0,6	0,5
5	0,7	0,62
6	0,66	0,55
7	0,47	0,33
8	0,36	0,27
9	0,36	0,28
10	0,43	0,47
11	0,39	0,31
12	0,48	0,25
13	0,55	0,37
14	0,65	0,5
15	0,4	0,2
Mean	0,51	0,40
Median	0,48	0,37
StDev	0,129	0,142
Min	0,32	0,2
Max	0,71	0,65

Table 1. Statistical data

Some basic statistical parameters were calculated such as mean, standard deviation, and others. The biggest difference is in average values, and it is obvious that for online measurements they are on average almost always 20% lower than in case of offline measurements. Offline measurements thus appear as a more stringent ones and shows higher values

of RMS parameters. This difference needs to be statistically evaluated to see if the difference between the measurement systems is significant.

For illustration, the data was graphically processed using the Time Series Plot tool which shows the differences between the online vs. offline measurement. It can be observed that both time series almost copied themselves with the already mentioned difference of 20% (Fig. 5).

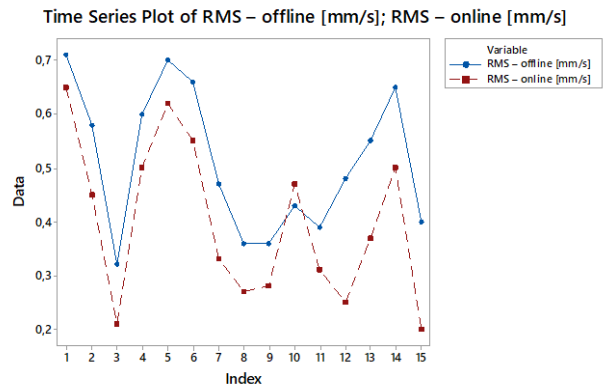Statistic software Minitab 17 was used for statistical evaluation.

Figure 5. Time Series Plot of RMS offline and online

3.1.1   Requirements for 2-Sample t test.

To compare whether the diameters of the two independent sets are different, a 2-Sample t test was selected.To perform this test, you must meet certain requirements. The data must have a normal distribution and must meet the test for equal variences.
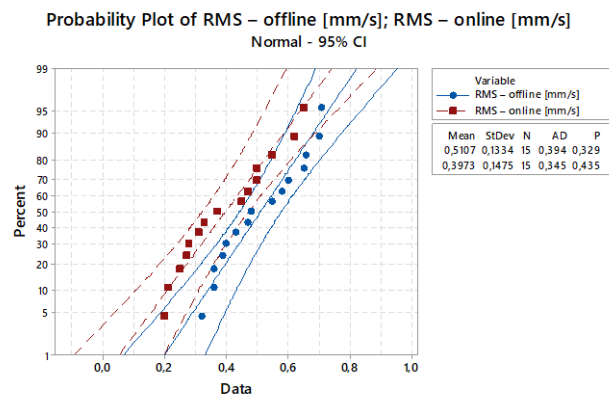

Figure 6. Probability Plot of RMS offline and online

Using the Anderson-Darling test, it was confirmed that the data come from a set that has a normal distribution. P value for both sets is more than 0.05 so it can be said that at the significance level of 5%, the data originates from a set with a normal distribution(Fig. 6).

As a further requirement which must be met before performing the 2-Sample t test, it is necessary to test that both sets have equal variance.

The Bonett's method and Levene's method, or the F-test for normal distribution data are generally used to test for equal variances. Minitab17 often uses Welch's method, which does not assume that the two samples have equal variances. Research shows that the test performs well with unequal variations even when the sample sizes are not equal. However, despite these information, Bonett's method and Levene's

method were used. P values for both methods were greater than the zero hypothesis rejection criterion. It can therefore be assumed that the sets have equal variances[Team 2016].

3.1.2   2-Sample t test

All the requirements before comparing the average values of the two sets were met. Therefore, the 2-Sample t test can be performed.

Hypotheses were determined as:

- H0 - The first data set (results from offline measurements), has no average values greater than the second data set (results from online measurements)

- HA - The first set of data (results from offline measurements) has average values greater than the second set of data (results from online measurements)

Two-Sample T-Test and CI: RMS – offline [mm/s]; RMS – online [mm/s]

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Two-sample T for RMS - offline [mm/s] vs RMS - online [mm/s]

                    N   Mean  StDev  SE Mean
RMS - offline [mm/s]  15  0,511  0,133   0,034
RMS - online [mm/s]   15  0,397  0,147   0,038


Difference = µ (RMS - offline [mm/s]) - µ (RMS - online [mm/s])
Estimate for difference:  0,1133
95% lower bound for difference:  0,0260
T-Test of difference = 0 (vs >): T-Value = 2,21  P-Value = 0,018  DF = 28
Both use Pooled StDev = 0,1406
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Figure 7. Two-Sample T-test and CI for RMS

According to the P values of 0.018, we reject the zero hypothesis in favor of an alternative hypothesis. The first set of data has mean values significantly higher than the second set of data (results from online measurements) (Fig. 7)[Team 2016].

4   VISUALIZATION OF RESULTS

The ability to interpret results correctly is undoubtedly the most important phase of monitoring and diagnosing the condition and status. However, it is often necessary to hand over results of the project even to the people who do not have any deeper knowledge in this issue. This fact can be facilitated by a number of monitoring and visualization systems. Visualization must be simple and well arranged and at the same time it must have a high information capability(value)[Team 2016].

Our spindle is driven by a three-phase asynchronous engine that is also subject to monitoring. The monitored spindle will be connected to this design afterwards. This whole design has beenelaborated for several machines at the same time.

The whole process of visualization was running mainly in the Reliance 4 Design programme and can be described in several steps:

4.1   Design of template - overview

A new project has beenestablished in the programme, where the created template will be stored. At first it was necessary to upload scheme of the enginehaving the programme in the preset component database. A propeller, created in the Blender programme, was attached to this scheme. These two parts were assembled in the Gimp graphics program afterwards. The whole scheme was then uploaded into the Reliance 4 Design programme, using the "Component Palette" menu bar. Further on, the graphical elements, such as display, progress indicators, etc., were created using this palette (Fig. 8).The photos below are in the language that is used in the company for the application.

4.2   Design of the template– in greater details

Design of detailed displaying of one engine was created by applying the same procedure. The engine parameters, such as power, revolutions, etc., were added, as well as the floating graph that will display effective value of vibration velocity as the main parameter. The whole branch for monitoring electrical variables, like current, voltage, THD and others, is the integral part of engine detail. The complete design is shown inFig. 9.
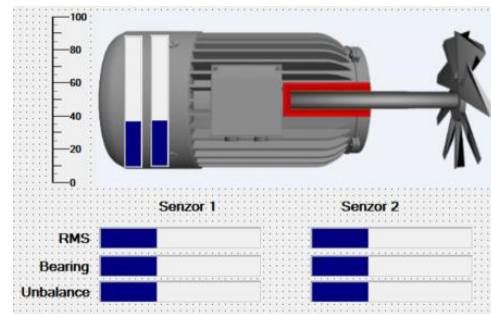

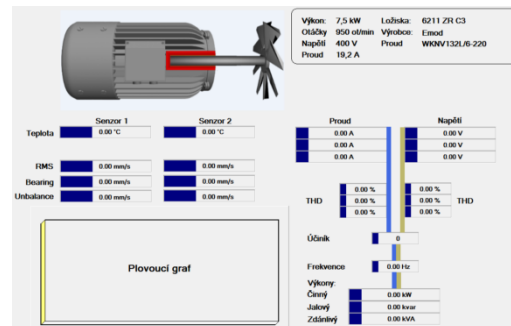**Figure8**. Design of template visualisation - overview

Figure9. Design of template visualisation – detail

4.3   Date structure

When the graphical form of our templates is created, all monitored parameters have to be linked with their variables. The overall issue of interconnection and linking is rather complex, and therefore a simplified link system is illustrated here.

- The IFM company sensors are connected to the OPC server. The OPC server can be understood as an intermediary - a service that can view the network addresses of the sensors and units and read the measured values. Using the OPC server, the Reliance 4 programme is able to communicate, and - using its data structure - to record the real values coming from the sensors for individual visual elements.

- The SOCOMEC system for measuring electrical variables works on a similar principle. The current and voltage modules are coupled in the Diris Digiware D-50 imaging unit; the data are then transferred to Modbus tcp, where the variables, interconnected and linked with the SOCOMEC system addresses, are defined. The Reliance 4 is able to be combined with these variables and to display them as the visual design.

All downloaded data can also be stored in the MySQL database, where the historical data are stored; they can also be used for graph loading, reading and displaying, if necessary. This is a

very complex solution for data storing and required data displaying finally. The Figure 10 shows the entire route of assigning particular objects directly in the EO programme for individual monitored parameters from the OPC server data structure till incorporation of variables into the visualization parameters. This process is very lengthy, and it is necessary to identify a clear and well-arranged system and adhere to its rules to avoid unwanted changing or overwriting the monitored variables (Fig. 10).
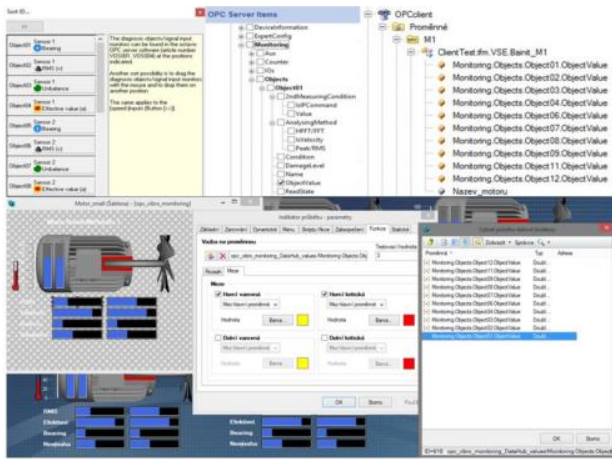

Figure 10. Data structure

This way all the variables requested by the visualisation - both the vibration, temperature and electrical values, and the limit values for preset parameters - were connected. All data are displayed at the current time. It is also possible to consult history, to find development of trends and to show charts and graphsby the desired time period.

4.4 Final displaying
All modifications were made in the design environment; after project start-up it is possible to see the final appearance for multiple engines, in the next phase extended by the spindles of the monitored machines.
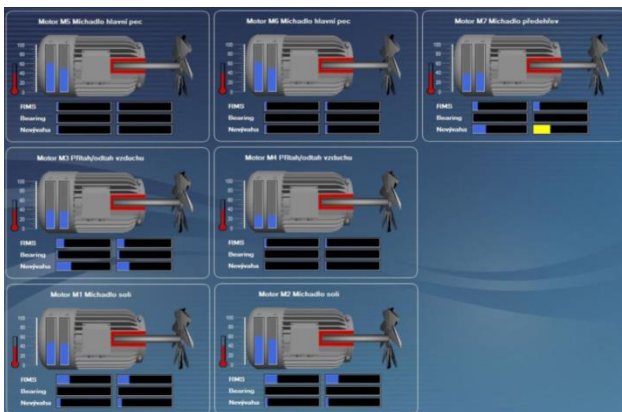

Figure 11. Final displaying - overview

When selecting the first motor, a detailed view of the engine will be opened with the complete information and possible options, incl. monitoring individual parameters (Fig. 11, Fig. 12).
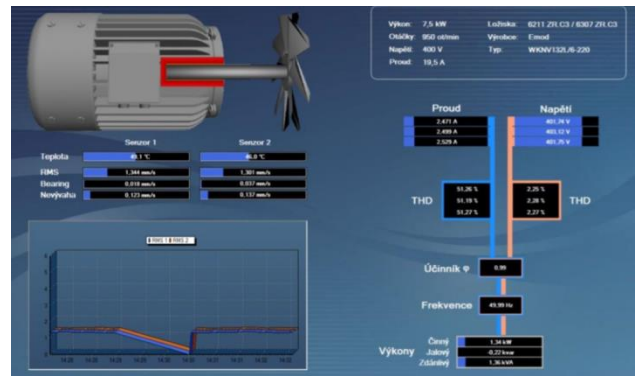

Figure 12. Final displaying - detail

All data are recorded in the corporate database and can be accessed at any time, if data traceability is necessary. All displayed parameters can be accessed by a right mouse click to view the chart and trend development. Exceeded limit values will be shown as the red or yellow column of the relevant parameter instead of the blue one.

5 CONCLUSION

The measurement showed that the difference between the average RMS value measured by the offline diagnostic system is by 20% higher than the value measured with the online diagnostic system.

Using the statistical analysis that included a 2-Sample t test, it was confirmed that the average RMS value measured by the offline system is indeed significantly higher than the RMS measured by the online system.

It can be said that the offline diagnostic system is more stringent when evaluating the RMS parameter. This is mainly due to better device parameters and more accurate analysis that VIBXPERT contains. The location of the sensor also has a great effect on the resulting values. While offline measurements are performed directly on the spindle, the online measurement sensor is located on the machine cover. The data collection, which has taken place throughout the whole life of the spindle, also has a major role to play. For more accurate results, it would be necessary to track multiple spindles throughout their lifetime.

It should be noted that the RMS parameter in an industrial enterprise serves exclusively to monitor the vibration trend. When the limit values are exceeded, it is the trigger for additional actions which aim to find the exact cause. These other actions are the use of vibrodiagnostics directly on the machine (offline) and the use of frequency spectra and other analyzes to determine the exact cause.

The paper presents the visualization system, where the technician responsible for monitoring and assessing condition and state will have a better overview of the state of the machines - engine and spindles. It is also applicable in the field of maintenance in the company and facilitates better decision-making and planning of maintenance interventions [Legat 2013]. Everything is also associated with better planning of financial resources and funds for diagnostics and maintenance[Sherwin 2000].

6 DISCUSSION

Machine maintenance and diagnostics are very closely related to Industry 4.0 which is increasingly changing the world around us and industrial companies are no exception. Machines, devices, products, and communication technologies and their electronics, sensors, and software can be connected with people through Iinternet. All this together will create a

production network in which the real-time information will be shared. This will allow for a better collaboration and provide an opportunity to improve quality and decision-making in process management, optimize coordination of activities, and increase efficiency throughout the whole value creation process. Therefore the cyber-physical systems, able to communicate with each other, will be faced more and more in the future.

Thanks to such complex systems, the maintenance system will be further developed, too. Maintenance will include inspections and checks of machine components through remote access and automatic start-up of service and maintenance if necessary. The recorded data will be analyzed to identify possible wear or danger of machine failure. This way set systems will lead to continuous expansion of proactive and predictive maintenance, which not only provides an overview of the impaired status and possible failure, but the data gathered will allow you to draw conclusions about condition and statusof the machine. This will

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CONTACTS:

Ondrej Holub, Ing.
Milos Hammer, Doc. Ing. CSc.
Brno University of Technology
Faculty of Mechanical Engineering
Institute of Production Machines, Systems and Robotics
Department of Quality, Reliability and Safety

Technicka 2896/2, Brno, 616 69, Czech Republic
+ 420 541 142 194, holub@fme.vutbr.cz
+ 420 541 142 194, hammer@fme.vutbr.cz