Doctoral (PhD) Thesis

University of Sopron

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IT-BASED INTEGRATION OF INDUSTRIAL SYSTEMS

Thesis booklet of the PhD dissertation

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1. Timeliness of the research topic, objectives

In modern countries, the third industrial revolution took place essentially smoothly, as new technologies and methodologies could be easily integrated into existing processes. The advantages of applying new solutions created tangible and significant development opportunities.

As time passed by and computer technology continued to develop, new perspectives opened up regarding data processing. The advantages thus achieved, although published in numerous specialist literature, are still much more difficult to interpret and integrate. This is especially true in the case of small and medium-sized enterprises, which constitute an important pillar of the economy. Due to the fundamental public nature of the thesis, my doctoral dissertation provides such companies with insight into the appropriate interpretation of the term I4.0 and its formulation according to a given set of conditions. The processes presented in the thesis are suitable for understanding the possibilities of IT integration of data obtained and analyzed with the help of measuring instruments.

These research areas and topics fit perfectly with general mechanical and wood engineering sciences. The thesis focuses on the planning of preventive maintenance necessary for the measurement accuracy and supervision of measurement processes, solutions, machine tools, and their long-term sustainable operation.

The presented and well-matched examinations, data collection, and their processing with an appropriate method mean process safety in the medium term, while in the longer term, the development of processes using mathematical decision-making support. My personal opinion and motivation is that we should not ignore the term I4.0 as an overused marketing slogan or campaign phrase, but rather use the opportunities it offers! It is important to emphasize that it should not be viewed as an opaque, complicated system, but as a standard development option based on technical solutions and experience; the predecessor of which, computer-aided manufacturing, has already proven itself over the past 40-50 years.

During preparing my thesis, my primary goal was to make the basic concepts of I4.0 understandable, to support the use, utilize new measurement and evaluation procedures, focusing on the situation of small and medium-sized enterprises.

My thesis introduces to the reader the topicality and importance of the topic - by presenting the different maturity levels and solution options. My research initially relates to the analysis of data obtained by measuring and modeling the background environment of the deformations caused by vice jaws on various workpieces. During the measurements, the focus of the investigation was on the mutual deformation arising from the interaction of the workpiece and vice jaws.

As a continuation, modern machining centers were brought into focus due to their universal applicability and prevalence. The study aims to verify the accuracy of wireless, optical data transmission touch probe systems integrated into CNC controlled machining centers and to push the limits of their use.

When examining the modern manufacturing environment, 3D scanning and printing cannot be ignored. The next stage of the research focuses on the geometric measurement of 3D printed workpieces. Cluster analysis was used to evaluate the data from the 3D scanner used, while traditional measuring tools were used for countermeasurement. The comparison provides an exciting and useful picture for understanding the interoperability between advanced technologies and traditional processes.

Thanks to the development of computer technology, an extensive toolkit is available for data evaluation. In this section of the thesis, the performance and accuracy of different measuring devices and procedures were compared, and the possibility of applying data fusion was examined. Data fusion provides an excellent basis for modeling tool wear, which method provides an increasingly accurate picture due to the continuous development and growth of the data package.

Nowadays, there are several options for examining the accuracy and condition of machine tools. In my thesis, I focused on developing the application of Ballbar

measurement, as it is a very accurate, yet easy and universally applicable method. The extracted data provide an opportunity to understand the errors of the machine tool, but the data packages, when evaluated using modern statistical methods, provide a more complex picture of both the current and time-varying condition of the machine.

Real-time monitoring and optimization of data sets contributes to increasing production efficiency and reducing errors.

2. Instruments used in the study

2.1 **Used tools**

Machining machine: AKIRA SEIKI Performa V2.5
positioning precision: ±0.01 mm
repetition precision: ±0.003 mm
Measuring head: Renishaw OPM40-2
direction-independent accuracy: 0.001 mm
Coordinate measuring machine: COORD3 Universal 10/7/7 measuring head: Renishaw PH20SP25M cal. ISO 10360-2
Vise: Gerardi StandardFLEX D24 mm

Torque wrench 40-250 Nm ISO: DIN EN ISO 6789-1:2017

3D printer Prusa MK4S

3D scanner: HP 3D Structured Light Scanner Pro S3

Thermometer sensor: PC21MT-0 Calex

Precision ±1% leolvasási vagy ±1ºC

Repeatability ± 0.5% of leolvasási vagy ± 0.5ºC

Round test: Renishaw Ballbar QC 20

2.2. Brief presentation of applied methods:

Stress-strain model:

$$\bar{\bar{\sigma}} = \begin{bmatrix} \sigma_x & \tau_{yx} & \tau_{zx} \\ \tau_{xy} & \sigma_y & \tau_{zy} \\ \tau_{xz} & \tau_{yz} & \sigma_z \end{bmatrix},$$

Calculating the root mean square error

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}$$

where:

y_i: the real value (the true data),

$\widehat{y_i}$: the estimated or predicted value (the value given by the model)

n: the number of data points (samples).

Fisher's F test: Then the following empirical value should be used as the test statistic

$$F_{emp} = \frac{S_X^2}{S_Y^2}$$

T probe:

$$= \frac{\bar{x} - \bar{y}}{\sqrt{(n-1)S_x^{*2} + (m-1)S_Y^{*2}}} \cdot \sqrt{\frac{nm(n+m-2)}{n+m}}$$

Where members mean:

$\bar{x}$ the mean of one of the random variables in the sample

$\bar{y}$ the mean of the other random variable in the sample

S_x^{*2} adjusted standard deviation of one of the random variables

S_Y^{*2} adjusted standard deviation of the other of the random variables

and n and m are the number of elements in one and the other sample.

3. Summary of new scientific results

3.1. Examination of deformation in a machine vice

As the first step of my thesis, I examined the important, but unfortunately often less controlled, step prior to machining. I examined the mutual deformation between the workpiece and the vice under different geometries and tightening torques.

Thesis 1. Based on the measurements and simulations carried out during my research, I have established that when clamping a workpiece in a machine vice, it is not enough to consider only the deformation of the workpiece; the elastic deformation and position change of the vice jaws also have a significant impact on the quality of the clamping. In the case of simple, cuboid workpieces of different lengths, the deformations occurring can be modeled accurately and realistically using the finite element method. The comparison of the simulation results and the measurement data allows the development of an applicable knowledge base that determines the machine vice tightening torque values that ensure optimal, safe clamping based on individual

geometric and material characteristics, as well as technological parameters (e.g. cutting forces).

3.2. Testing the measuring capability of CNC machining centers

The values provided by the Renishaw optical data transmission probe integrated into the Akira Seiki machining center can be used once for a given process, but by analyzing the data in accordance with the I4.0 concept, we get a complex picture of our device. After proper calibration and verification, the manufacturer's accuracy can Thesis 2. The experiments have shown that the accuracy of geometric measurements made with a touch probe measuring system integrated into a CNC machining machine based on the wireless optical data transmission principle is equivalent to the accuracy of a coordinate measuring machine after appropriate calibration. Unfortunately, due to the structure of companies, this data evaluation is often not performed. The touch probe measuring system, operating on the integrated wireless optical data transmission principle, records the position data available on the machining machine at a given

moment, thus burdening the measurements with positioning errors. By comparing external measurements made on the coordinate measuring machine with the data measured in the machining machine with appropriate periodicity, it is possible to conclude that the machining machine has lost accuracy or failed.

3.3. Evaluation of measurements supporting 3D technologies

Nowadays, 3D technologies have become an unavoidable part of technical life. Rapid prototyping and almost complete geometric independence have a huge impact on both product design and manufacturing processes. In my thesis, I examined the applicability and accuracy of modern 3D scanners and traditional measurement technologies for 3D printed workpieces.

Thesis 3. Using inspection measurements made with a coordinate measuring machine, I determined that based on the results from the 3D surface measurement environment of a 3D printed component, the procedure meets the accuracy class c of the MSZ ISO 2768-1:1991 standard, thus it is suitable for the automated inspection of components. The point clouds available from the surface measurements are easy-to-handle data packages, which can be used to examine the condition of the machine and to increase the accuracy of subsequent production. For the sake of practical applicability, I also performed measurements with a caliper and a micrometer. Using statistical-based tests, I determined that the caliper is also a suitable alternative for this accuracy class of the 3D printed component, however, the use of the two measuring instruments cannot replace each other, but only complements each other.

3.4. Evaluation of measurements supporting machine learning processes

Perhaps the most exciting part of my research is the investigation of the possibility of implementing data fusion. Regardless of size and series size, one of the most common reasons for unexpected machine downtime is tool breakage. Unfortunately, in extreme cases, not only the tool or workpiece is damaged, but also the machining machine can be damaged. In my research, I used geometric measurements, independent temperature measurements and values estimated based on expected tool wear. When evaluating the data package, machine learning methods are suitable for estimating future data. The larger the data package and the more times it is corrected, the more accurately the estimate can be made.

Thesis 4. The results of measurements with a measuring probe fixed to the spindle of a CNC machining center and a temperature sensor operating on the infrared measurement principle - after appropriate statistical processing - are suitable for predicting geometric deviations due to tool wear. Using the obtained values, the

number of tool correction measurements on the required workpiece can be minimized.

3.5. Introduction to ballbar measurements

The ballbar is a measuring device developed by Renishaw that obtains data from the circular movement of the machining machine. From the values obtained, we can conclude about the condition of the machining machine and the causes of its errors. In my research work, I developed the usability of the data obtained in this way.

Thesis 5. The data obtained by ballbar measurement are suitable for the analysis methods developed by me for the examination of long-term trends, or for use as correction data when transformed from a polar coordinate system to a Cartesian system. Based on the data obtained in this way, the wear of the machine tool or the change in deviations due to faulty installation or manufacturing problems can be monitored in the long term.

4. Publications related to the topic of the thesis:

1. Ledenyák, Daniel; Rosta, Tamás ; Andó, Mátyás
Improve the Practical Usability of Ballbar Machine Tool Verification In: Csüllög, Mihály; Mankovits, Tamás (szerk.) 10th International Scientific Conference on Advances in Mechanical Engineering : Selected peer-reviewed full text papers from the 10th International Scientific Conference on Advances in Mechanical Engineering (ISCAME 2024) Bäch, Svájc : Trans Tech Publications (2025) pp. 189-198. , 10 p.DOI Scopus Egyéb URL Konferenciaközlemény (Könyvrészlet) | Tudományos [36230906]

2. Ledenyák, D. ; Rosta, T. ; Hargitai, H. Novel Technique for Reducing Geometrical Inaccuracies of Clamped Workpiece During Machining: A Hybrid Method In: Khotsianovsky, Alexander; Chen, Yuan (szerk.) Material Strength and Applied Mechanics : Proceedings of the 7th International Conference (MSAM 2024) Amsterdam, Hollandia : IOS Press (2024) 554 p. pp. 269-276. , 8 p. DOI SOE Publicatio repozitórium Scopus Konferenciaközlemény (Könyvrészlet) | Tudományos [35677826] [Egyeztetett]

3. Ledenyák, Dániel ; Rosta, Tamás
Investigation The Milling Accuracy With I4.0 Compatible Processes And Method In: Dániel, Molnár; Dóra, Molnár (szerk.) XXVI. Tavaszi Szél Konferencia 2023 : Tanulmánykötet I. Budapest, Magyarország : Doktoranduszok Országos Szövetsége (DOSZ) (2023) 572 p. pp. 488-493. , 6 p.
Teljes dokumentum Konferenciaközlemény (Könyvrészlet) | Tudományos[36268612] [Nyilvános]

4. Birosz, Márton Tamás ; Ledenyák, Dániel ; Andó, Mátyás Effect of FDM infill patterns on mechanical properties POLYMER TESTING 113 Paper: 107654 (2022) DOI WoS EDIT Szakcikk (Folyóiratcikk) | Tudományos [32869201] [Admin láttamozott] Nyilvános idéző összesen: 78, Független: 76, Függő: 2, Nem jelölt:

5. Ledenyak, Daniel ; Rosta, Tamás Modern Measurement Methods Introduced in I4.0 Manufacturing Systems Műszaki Tudományos Közlemények (EN) 17 : 1 pp. 42-45. , 4 p. (2022) DOI Szakcikk (Folyóiratcikk) | Tudományos [33573978] [Admin láttamozott]

6. Ledenyak, Daniel ; Rosta, Tamás Az I4.0 gyártási rendszerekben alkalmazott modern mérési módszerek MŰSZAKI TUDOMÁNYOS KÖZLEMÉNYEK (HU) 17 : 17 pp. 42-45. , 4 p. (2022) DOI EDIT Utánközlés (Folyóiratcikk) | Tudományos [33590919] [Admin láttamozott]

7. Ledenyák, Dániel

Investigate And Improve The Accuracy Of 3d Printing In I4.0 Environment In: Molnár, Dániel; Molnár, Dóra; Nagy, Adrián Szilárd (szerk.) Tavaszi Szél 2022 / Spring Wind 2022 Tanulmánykötet II. Budapest, Magyarország : Doktoranduszok Országos Szövetsége (DOSZ) (2022) 584 p. pp. 351-358. , 8 p. Teljes dokumentum Konferenciaközlemény (Könyvrészlet) | Tudományos[36268636] [Nyilvános]

8. Kovács, Zsolt ; Ledenyák, Dániel CBN esztergaszerszámok összehasonlító vizsgálata In: Johanyák, Zsolt Csaba; Kovács, Lóránt; Pásztor, Attila; Ferenczy, Tibor; Weltsch, Zoltán; Tóth, Ákos; Dobjánné, Antal Elvira (szerk.) Kutatás és innováció 2021 : GAMF Közlemények tanulmánykötete Kecskemét, Magyarország : Neumann János Egyetem GAMF Műszaki és Informatikai Kar (2021) 477 p. pp. 13-21. , 9 p. Szaktanulmány (Könyvrészlet) | Tudományos [32600185] [Nyilvános]

9. Ledenyák, Dániel ; Kovács, Zsolt ; Rosta, Tamás Modern gyártókörnyezet adatkezelési koncepciója In: Johanyák, Zsolt Csaba; Kovács, Lóránt; Pásztor, Attila; Ferenczy, Tibor; Weltsch, Zoltán; Tóth, Ákos; Dobjánné, Antal Elvira (szerk.) Kutatás és innováció 2021 : GAMF Közlemények tanulmánykötete Kecskemét, Magyarország : Neumann János Egyetem GAMF Műszaki és Informatikai Kar (2021) 477 p. pp. 72-80. , 9 p. Szaktanulmány (Könyvrészlet) | Tudományos [32600389] [Nyilvános]

10. Ledenyák, Dániel ; Kovács, Zsolt ; Rosta, Tamás Hagyományos és modern mérőeszközök összehasonlítása pontosság és alkalmazhatóság szerint In: Johanyák, Zsolt Csaba; Kovács, Lóránt; Pásztor, Attila; Ferenczy, Tibor; Weltsch, Zoltán; Tóth, Ákos; Dobjánné, Antal Elvira (szerk.) Kutatás és innováció 2021 : GAMF Közlemények tanulmánykötete Kecskemét, Magyarország : Neumann János Egyetem GAMF Műszaki és Informatikai Kar (2021) 477 p. pp. 64-71. , 8 p. Szaktanulmány (Könyvrészlet) | Tudományos [32657277] [Nyilvános]