Industry 4.0 and Technological Evolution in CNC Machines

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Abstract: This work, entirely based on a documental research strategy, consists of an analysis of the technological evolution of the machining processes with Computer Numerical Control machines regarding the new concept of Industry 4.0. This concept involves integration of cyber-physical systems with the manufacturing processes, the use of the Internet of Things in industrial processes and the development of complex virtual systems. An attempt was made to understand how current processes can be adapted or changed to the concept under study when analyzing the evolution of machining tools for CNC machines. A thorough study was done to adopt the distinguishing features of the Industry 4.0 concept, applying it to machining processes in CNC machines. The use of virtual technology in machining tools is still a subject in development, and it was one of the main focus of this work. The main factors that can influence directly or indirectly the production processes of a factory with CNC machines were analyzed. The types of machining processes for CNC machines and the types of machining tools developed with virtual technology possibilities were studied and explored. Following the analysis, suggestions for future applications and for improvements in production structures are proposed.

Keywords: CNC tools; computer numerical control; computer aided manufacturing; cyber-physical systems; internet of things; virtual technology; industry 4.0

1. Introduction

The work related to this research consisted of an analysis of the technological evolution of the machining processes with CNC (Computer Numerical Control) machines regarding the new concept of Industry 4.0. The concept fits into the current transformation process for the so-called fourth industrial revolution, which involves the integration of cyber-physical systems (CPS) with the manufacturing processes and the use of the Internet of Things (IoT) in industrial processes, among other characteristics (Kagermann et al, 2013). The main objectives of this work were:

1. To adopt the distinguishing features of Industry 4.0 by applying it to the machining processes in CNC Machines.
2. To study the issues related to the technological evolution of the tools used in CNC machines with virtual technology.
3. To study and analyse the integration factors for production systems that include a CAM (Computer Aided Manufacturing) software, a tool with virtual technology and a CNC machine.
4. To develop proposals for future applications and enhancements on the studied topics.

In order to carry out this project, a detailed analysis of numerous primary, secondary and tertiary literary sources was carried out in relation to the proposed topic of Industry 4.0 and to the principles it approaches, correlating it with the machining processes in CNC machines and with production tools with virtual technology possibilities, which are currently under development. All the relevant information was synthesised so that it was possible to develop a complete and detailed knowledge and understanding regarding the proposed research.

Simultaneously and in parallel, and in order to reach the first objective of this work, a thorough study was done in an attempt to adopt the features of Industry 4.0 by applying them to the machining processes in CNC Machines. With the knowledge acquired, a framework was established relating the features of Industry 4.0 and the machining processes, in order to present suggestions for an improved operational condition for machining processes with CNC machines.

One of the main factors that influences the development of machining processes in CNC machines are the tools used in CNC machining processes for the production of parts, components or similar artefacts (Fountas et al, 2016). Therefore, for the development of the second objective, it was necessary a thorough study of the issues related to the technological evolution of the tools used in CNC machines with virtual technology. The use of virtual technology possibilities in machining tools is still a subject in development (Chen et al, 2015). It was analysed the main factors that can influence directly or indirectly the production processes of a factory with CNC machines (Shneor, 2018).

When virtual technology is considered, the need for software is inevitably addressed. In CNC machining operations, a CAM software performs machining simulations for CNC machines. Often, it is made in a not very efficient way, because there is a considerable need for the programmer's knowledge, because it depends on the type of CNC machine, on the tools that are used, on the kind of workpiece material and on production data (cutting speed, RPM, cutting feed, etc.)(Liu et at, 2007). The programmer transmits all this information to the software. If there is any incorrect information, or if it is not according to the type of material, or if there is non-ideal machining data, there will be a direct impact on the execution of the machining process. The third objective of this work is related to this situation. As such, it was studied and analysed the information flows of a production system that includes a CAM software, a tool with virtual technology possibilities and a CNC machine. The aim was to verify how this set can jointly work, and what changes are necessary to improve this production process, so that the communication system can work more efficiently without being so dependent on the need of the programmer's knowledge. That objective was integrated with the concept of Industry 4.0 to achieve the main objective, as mentioned above. In the sequence of this work, a framework for an improved production model will be proposed, which involves an alternative architecture for the structure of the model. It will also provide the basis for better understanding the possibilities for application in the future, having in mind the concept of Industry 4.0 (Deng et al, 2018). The last objective of this work is to propose future applications concerning the mentioned topics.

2. Methodology

The methodology used during the development of this work was based on a documental research strategy. The bibliographic research was based in scientific publications and on searches made on several databases, including SCOPUS, Web of Science and Science Direct. The search strings were related to the machining area, and included machining processes, CNC machines, CAM and CAD software, machine tools, Industry 4.0, cyber-physical technology, Internet of Things, smart factory, social networks. The criteria for article selection was based on the direct relevance to the main research object of the study, which was CNC machines, CNC machine tools and industry 4.0 concept. The methodology of this work also has been based on one of the author´s experience of programming and operation of CNC machines with machining processes engineering, and from data derived from direct observation and experimentation with these production processes.

3. Exploring the literature and articulating new possibilities

3.1 The Concept of Industry 4.0

The definition of the term Industry 4.0 was first presented in 2011 in an edition of the Hannover Fair as a project in the High-Tech Strategy of German Industry (Hermann et al, 2015). Shortly thereafter, in the year 2013, the German working group presented a report about Industry 4.0 (Hermann et al, 2015). The report defined the environment for Industry 4.0, which included a strong customization of the products obtained with high flexibility of mass production, presenting an introduction of systems with own organization (own automation, own configuration, own diagnosis, etc.) to obtain an adequate connection between the real world (people and machines) and the virtual world (Devezas et al, 2017). This new approach to industrial processes is centered on the intensive use of advanced Information and Communication Technology (ICT) resources in order to ensure greater flexibility in production systems and processes, as a consequence of the increasing complexity of products and supply chains (Faller et al, 2015). The concept has been caught up by many stakeholders and currently many agents around the world are initiating projects and programs to ensure competitive enhancement through adaptation to digital transformation (Kagermann et al, 2013).

The main purpose of Industry 4.0, enabled by the convergence and integration of existing, emergent and new technologies, is the creation of smart factories. These are capable of managing process complexity, operate with less disruption, and more efficiently. The interaction between humans, machines and resources resembles a social network (Kagermann et al, 2013). In these installations, cyber-physical systems monitor physical plant processes and make decentralized decisions. Physical systems are converted into objects of the Internet of things, communicating and collaborating with each other and with humans in real time through wired and wireless networks connected to the Web (Marr, 2016).

3.2 CNC tools with CPS capabilities and CNC machines

A new tool with cyber-physical technology potential has emerged in the CNC machining area. The technology is a combination of sensors, algorithms, the cloud, data analysis, and connectivity with Internet of Things (Sandvik-Coromant, 2018). The traditional tools do not have the capacity to collect and transmit in real time operational information during the process execution. The new tool raises up the opportunity to analyze the implications for future production when used on CNC machines, and in this research it will be used as a way to do that. Digitalization of manufacturing opens new opportunities to improve productivity and effectiveness (Botkina et al, 2018)

This new tool provides cyber-physical technological potential. Cyber-physical systems correspond to the physical and the virtual systems integrated in a network that brings together physical resources and processes (Gorecky et al, 2014). In these networks, multiple information circulates from different sources, which is monitored and synchronized between the factory and the cyberspace (Lee et al, 2015). The tool with CPS potential has two main dimensions or implications, one regarding the CPS and the other IoT, both related to the concept of Industry 4.0.

3.3 Cyber-Physical Systems and CNC Tools

The emerging concept\approach of cyber-physical systems focus on the integration of computational applications with physical devices and it is designed as a network of interactive physical and cybernetic elements (Leitão et al, 2016) The CPS controls and monitors real-world physical infrastructures and have a high impact on industrial automation.

On CNC machine tools, the manufacturing resources are the parts of the physical system which are required in order to perform machining tasks. Manufacturing resources are the tools and materials, such as cutting tools, machine tools, fixture and parts, and also the machining environment, like vibration and temperature. The CNC machine tool makes a specific work task with given manufacturing resources. Through the operation status data, the resulting work, quality and productivity of the CNC machine can be expressed by the characteristic parameters in the work process (Sandvik-Coromant, 2018).

The CPS model of a CNC machine tool work process includes a model input, which consists of two parts, the work task and the manufacturing resources, while the output is the corresponding operation status data when the machine tool performs a task (Chen et al, 2015). The CPS model of a CNC machine tool work process can be defined in association with the work task, manufacturing resources and operation in the cyber system in parallel with the physical system.

In CNC tools, the cyber-physical system works by taking the application data through connected software and hardware, with sensor-equipped tools that are adjusted to control and monitor machining performance in real time (Villalba-Diez et al, 2021). The CNC machine is controlled via accurate on-site data dashboards, through the cloud and via integration with the user's software and machine environment. The tool with CPS potential connects into existing software, offering two-way connectivity and accurate data quality. In these networks, multiple information circulates from different sources that is monitored and synchronized between the factory and cyber space (Lee et al, 2015)

The information captured by the tool is informed to the CNC machine and manager\operator through CPS connected software and hardware, where the data could be managed and monitored to get a better precision and quality on production in real time. The tool gives the information in real time execution, and if some problem happens, the tool can detect it and a reliable solution can help avoid or minimize machine tool and workpiece damage. The operator can monitor the machining process in real-time and interact with the machine tool when the tool detects, e.g., overload forces. These can help the operator on time execution, where other actions are programmed if some problem occurs.

3.4 Internet of Things and CNC Tools

The Internet of Things is an extension of the current Internet, which provides to the objects the possibility to connect to the Internet, but with computing and communication capabilities (Jang et al, 2018). CNC tools connected via Internet of Things can monitor the machining performance and make decisions about how to optimize the processes based on accurate information. Cloud-based analytics and local systems enable the use of all the data collected on machining operations.

The design of cyber-physical systems and the implementation of their applications need to rely on IoT enabled architecture and protocols, to be able to manage and process large datasets, and to support complex processes to manage and control those systems at different scales. The large-scale nature of IoT based CPS can be effectively and efficiently supported by cloud computing infrastructures and platforms, which can provide flexible computing power, resource virtualization and high-capacity storage for data flows and ensure security, protection and privacy. The IoT is a key domain in which data streams are generated, and the volume of this data is expected to increase (Jang et al, 2018).

The Internet of Things is responsible for sensing the physical world, and for networked and interconnected objects that are exclusively addressable, like the sensors on a CNC tool. So, they take the information flow of the abstraction process through sensors and transfer it to the Internet with world connectivity, where it is transferred to the cloud computing infrastructures and platforms, which can provide flexible computing power, resource virtualization and high-capacity storage for data flows and ensure security, protection and privacy.

3.5 Communication between CAM software, tools with cyber physical capabilities and CNC machines

New tools with cyber physical systems potential in CNC machining raise the opportunity to know how it could work integrated with a CAM software and a CNC machine (Moor et al, 2021). The main aim of this chapter is to study how a CAM software works in communication between a tool with CPS capabilities and a CNC machine.

The introduction of computer graphics allows the creation of virtual workpieces on the computer, and to handle and study them. The universal application of computer aided systems brings substantial benefits to the manufacturing area. CAM involves a software associated with functions in manufacturing engineering, process planning and CNC programming (Dubovska et al, 2014).

We could say that for most of the steps from the manufacturing model (CAM) to the CNC program creation, the work is being executed in the cyber world. There is the possibility that the CAM software does the simulation in the cyber world and then, if the process has no problems there, it could be executed in the real world, following two procedures: first, the simulation on CAM is done, and then it follows the process execution on the CNC machine. The two procedures are not simultaneous.

With CNC tools with CPS, complemented with software packages, it will be pertinent to know what the implications of this procedure and what changes could be done on CAM. In the case of the tool developed by Sandvik Coromant (2018), which is mentioned in this work as a mean to explore the concepts mentioned before, the tool with CPS potential provides a Toolguide software that communicates with CAM software, and there is a facility to choose the ideal tool and parameters to do the simulation on CAM before going to the machine. This facility uses an open API (Application Programming Interface) and the possibility to connect with the tool library and tool management systems on CAM. While programming on CAM, the programmer does not create a tool to execute the simulation on software, because it is already provided by the Toolguide. So, the communication between the CAM software, the CNC machine and the software of the CNC tool are still not working in an integrated way and on real time when machining the physical workpiece. It nevertheless contributes to decrease the time on process simulation on CAM software, giving the information about the process executed from the data and suggesting parameters to use in certain materials. The information executed in real time could then be transferred to the software for future applications on CAM simulation. As the data could be saved on the Cloud during the process execution, the software with API connected with CAM could help the programmer when he is programming, facilitating with information about what is the ideal tool to be used in the process and the right parameters that could be used for specific materials.

3.6 Integrated production involving tools with CPS capabilities, CNC machines and CAM software within the concept of Industry 4.0

This section aims to show how a tool with CPS and the CNC machines communicating with CAM could work integrated through a communication architecture.The technology combination of CNC tool with CPS capabilities, CNC machine and CAM software helps to transform the actual production processes on Industry 4.0 environment through the IoT and CPS, the interface of the physical world and cyber world (Trstenjak et al, 2017).

This combination of the technology with a CNC tool with CPS capabilities, CNC machine and CAM software, could transform the actual production processes on Industry 4.0 environment. With the CNC tool there is the capacity to transfer the information in real-time to the cyber world, and the process, the human and the machine could have a virtual and real interaction, helping to increase the productivity and reduce the waste time (Siddharta et al, 2021).

The main purpose of Industry 4.0 is the creation of the so-called smart factory, which is capable of managing process complexity, operate with less disruption, and more efficiently, through the interaction between humans, machines and resources, resembling a social network (Kagermann et al, 2013). The smart factory environment consists of a new integrative real-time intercommunication between every manufacturing resource that could help increase the manufacturing efficiency (Pereira et al, 2017). The smart factory environment of the Industry 4.0 concept, the CNC machine and CAM software, and the sensors and software combination provided by the CNC tool with CPS potential allow an intercommunication between the real world and the cyber world, giving the information to the operator\manager about what is happening in real time manufacturing. Thereby, this change could improve the traditional manufacturing process, upscaling to a smart manufacturing process the machining area. The main adaptations\transformations are:

1. CNC tool with CPS capability gives the information on process execution in real-time: On traditional processes execution using the traditional CNC tools, there is no capacity to give information about what is going on during the machining execution (cutting temperature, roughness, vibration, etc.). A CNC tool

with CPS enables the capacity to transfer this information and transmit it to the software through the sensors, and the operator\manager has the possibility to verify the crucial points to manage or alter if necessary. Thereby, it creates an Industry 4.0 cyber virtual and real interaction (Villalba-Diez et al, 2021).

2. CNC tool with CPS capability gives the information about CNC machine: Similarly, to the previous point, in the traditional process execution using the traditional CNC tools, there is no capacity to give information about machine health. Although other ancillary technologies may provide this information, they will not do it through the CNC tool. The CNC tool with CPS capability creates the ability to transfer the information about the machine health, enabling the detection of some problem during the process execution on CNC machines, and triggering alterations or maintenance. This is another aspect of the concept of Industry 4.0, where multiple information from different sources that are monitored and synchronized between the factory and cyberspace (Lee et al, 2015; Ahmad et al, 2020).
3. Human interaction on the process in real-time: In the traditional process execution on CNC machine: There is no human interaction when the machine is working during the machining process. If some problem occurs on the machine or in the tool during the process execution, the implementation of a CNC tool with CPS potential enables the possibility for the software to give information to the operator and machine about what it is happening in real-time and changes to correct the problem can be made.
4. Cutting tool information saved on a cloud: In traditional mechanical CNC tools, there is no capacity to save the cutting information on the cloud. By using the CNC tool with CPS capability during the process execution, it is possible to save the information on the cloud in real-time, and there is the possibility to save the actual information of the process and to use it later in future production processes with similar characteristics. Intelligent processing will support IoT applications by collecting data from databases and Network service providers can process a large volume of messages instantly through cloud computing.
5. CAM Software supported by CNC tool software on virtual world: The software from the tool with CPS capability could connected to the CAM with the API (Application Programming Interface), giving the possibility to use the virtual library of tools with CPS on virtual process execution for simulation. All information filed by the operator on CAM is transferred to the program when generated on a post-processor. The interaction between systems based on high-performance software and dedicated user interfaces, integrated with digital networks, create a new universe of functionalities for systems on Industry 4.0 (Longo et al, 2017).

4. Proposals for future process applications

4.1 Real time measurement

As it follows from the topics that were addressed in this study, CNC machines are working centred on a three-dimensional space (X, Y and Z axes)(de Souza et al, 2020). The feed movement is realized by individual or simultaneous axes movement (Bosetti et al, 2014). Thereby, the three-dimensional machines (machines for measurement) are based on a three-dimensional space as well. Some of them are called CNC Coordinate Measuring Machine, and are specifically designed for measuring components on the production line while keeping pace with modern machine tools.

The software from the tool with CPS capability could provide in the future similar information about measurement, just like the measurement machines provide nowadays (Koleva et al, 2015). The most common process to make a measurement on a workpiece on a three-dimensional machine is collecting the point through the sensors by the probe.

We suggest that the measurement will not be based on point collection using a probe as a sensor to collect the dimensions but, alternatively, it will be done by the CNC tool with CPS during the process execution. Following the path of the axes previously programmed, the CNC tool could collect measurement information and transfer it to the CNC machine. The process measurement is a very sensitive process, and it needs a sensor (probe or CNC tool with CPS capability) to collect the information. We suggest that the measurement with the CNC tool is done by using the tool for finishing on process machining (tool used to remove small material and give the finishing on the surface). As the tool follows its path, the information is transferred to the CNC machine. If the CNC software has the capacity to do an automatic correction, the movements of the machine could compensate the variations of measurements transferred by the tool. In consequence, there will be no human intervention to make the measurement and no waste with machine stoppages.

Until nowadays, the measurement on CNC machines was not done because there were no CNC tools with capacity to transfer the measurement information during the process execution. The measurement information is done only by probe (sensor measurement) on physical contact. Since the new CNC tool with CPS capability has been implemented in the machining area with capacity to transfer the information during the process execution, this procedure could be now done.

4.2 Flow information model

In the process execution of CNC machines using a CNC tool with CPS capability, the tool has the capacity to send the information about roughness, vibration, cutting and temperature. Thus, we suggest that the improvements to process architecture implies the implementation of two main dimensions, the tool enabled measurement and the communication with social networks through the tool with CPS capability (Figure 1).

The proposal for tool measurement on CNC machines is to use the CNC tool with CPS capability giving the information about the measurement on process execution through the sensors, where the workpiece could be measured during the process execution and, when the process is done, the workpiece would be already measured, and no time would be lost with machine interruptions. The tool would follow the programmed axes path during the measurement, collecting measurement information and transferring it to the CNC machine through the software and hardware.

The process measurement is a sensitive process that needs a sensor to collect the information. The idea is to do the measurement with the CNC tool using the tool for finishing operation. This option implies less removal of material on process machining. The tool software will send the information collected by the tool sensors to the software and hardware of the CNC machine as shown in Figure 1. Thereby, the software of the CNC machine has to be modified compared to the actual software on CNC machines. The machine software has to be able to collect the information on real-time and make the changes automatically. This is one of the most important steps for the development of this proposal. The software will communicate with the tool making the automatic compensation. CNC machines are working centred on a three-dimensional space (X, Y and Z axes) and the three-dimensional machines work in three-dimensional space as well to make the measurements. This possibility is viable for development, it will be a technology combination between the software from CNC machines and three-dimensional machines. The software from the tool and the machine will work in articulation with each other, exchanging information about measurement during the process execution. We know that during the process execution there are numerous parameters to be considered, such as material, RPM, speed, insert, among other aspects that could influence the process execution. Thereby, the initial step to implement the proposal is to do the measurement of the basic process execution on CNC lathe machines for finishing surfaces, as a first implementation, test and analysis of the proposed idea.

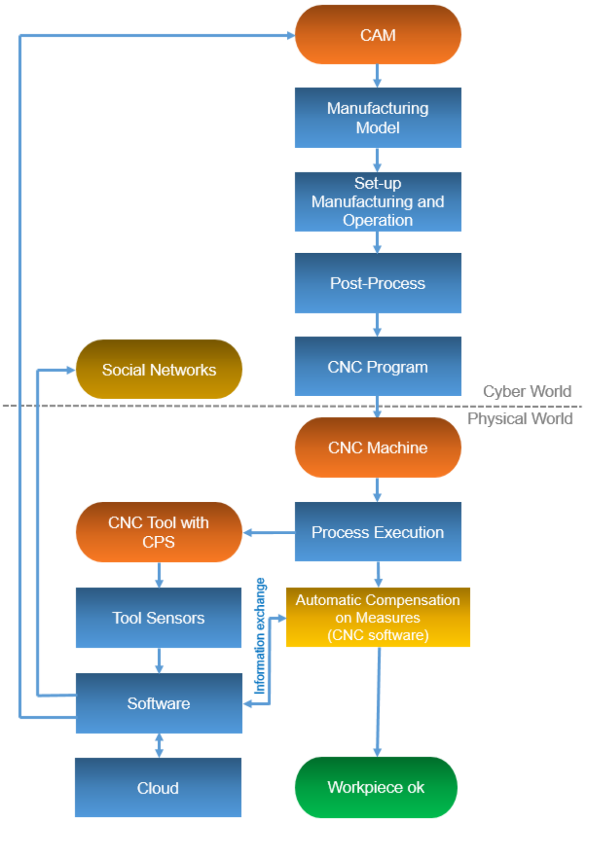

Figure 1: An information flow model between CNC tool with CPS capability, CNC machine and CAM

The software of the CNC machine will have the capacity to interpret the measurement as the three-dimensional machine works, answering automatically to the changes during the process execution (finishing with measurement).This process will consist on the adaptation of the actual software on CNC machine software, because the actual software is not able to do the automatic corrections, because there is not a CNC tool with the capacity to do the measurement during the process execution. Thereby, on the process simulation using a CAM software in the cyber world, it could be created a new operation function, the operation of measurement, where the programmer could select this function to do the simulation on the virtual world.

In general terms, the information flow proposed in the model of Figure 1 is as follows. First, it starts with the communication flow with the CAM on the cyber world, and the process simulation using the CNC tool with CPS capability is keeping the same steps of the currently used processes, until the creation of a CNC program. However, there are some new possibilities. The information processed in real time (by the CNC tool with CPS capability) could be transferred to the software for future applications on CAM simulation. As the data could be saved on the cloud during the process execution, the software with API (Application Programming Interface) connected with CAM could help the programmer when he is programming, facilitating and providing information about what is the ideal tool to be used in the process and the right parameters to be used for specific materials.

Then, the CNC program is received by the CNC machine for process execution in the physical world. New possibilities also emerged at this stage. As the machine is already prepared for process execution, the CNC tool with CPS capability and the CNC machine start to work together. The sensors from the CNC tool collect the information during the process execution, keeping it on the cloud and then, through the software, the information is transferred to CAM for future simulations, and to the social network, and is keeping the communication integrated with the CNC machine for information exchange.

The new feature of communication with a social network embodies communication possibilities of a CNC tool with CPS capability with the Internet of Things. The CNC tool could communicate with social networks (e.g. dedicated, professional, social networks), where groups can discuss the problem in real time or post as a discussion. The yellowish brown fields in Figure 1 show the main differences of the process compared to actual ones

5. Conclusions

The work related to this research consisted of an analysis of the technological evolution of the machining processes with CNC machines, having in mind the new concept of Industry 4.0. In order to reach it, a thorough study has been done to adopt the features of Industry 4.0 applying it to the machining processes in CNC Machines.

One of the main factors that influence the development of machining processes in CNC machines are the tools used in CNC machining processes for production. Issues related to the technological evolution of the tools used in CNC machines with virtual technology capability were considered. A better understanding of how the virtual technology works with machining tools on CNC machines was done. It was possible to analyse the main factors that can influence directly or indirectly the production processes of a factory with CNC machines.

This study enabled a better understanding about virtual technology addressed by software on machinability. We used a new tool with cyber-physical capability that has emerged in the CNC machining area as way to demonstrate how this kind of tool technology could work on CNC machines. It provided the opportunity to study how a CAM software works in communication between the tool with CPS capability and the CNC machine, presenting the CAM connection possibilities and its implications. A study and analysis of how a production system can work in an integrated way between the tool with CPS capability, the CNC machine and the CAM software within the concept of Industry 4.0 has been done, providing a better understanding of how this recent technology implementation of machining processes could be adapted under the concept of Industry 4.0.

Finally, following the original proposals presented regarding the integration of CNC tools and machines, a general proposal for an improved production system in the machining area was made. This proposal showed how this new production model could work, integrating a tool with CPS capability, the CNC machine and the CAM software, giving a new idea of communication and interaction between them.

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References

Ahmad, M. I., Yusof, Y., Daud, M. E., Latiff, K., Kadir, A. Z. A., & Sair, Y. (2020). Machine monitoring system: a decade in review [Review]. *International Journal of Advanced Manufacturing Technology*, *108*(11-12), 3645-3659. https://doi.org/10.1007/s00170-020-05620-3

Bosetti, P., & Bertolazzi, E. (2014). Feed-rate and trajectory optimization for CNC machine tools. *Robotics and Computer-Integrated Manufacturing*, 30(6), 667-677. doi: 10.1016/j.rcim.2014.03.009

Botkina, D., Hedlind, M., Olsson, B., Henser, J., & Lundholm, T. (2018). Digital Twin of a Cutting Tool. *Procedia CIRP*, 72, 215-218. doi: 10.1016/j.procir.2018.03.178

Chen, J., Yang, J., Zhou, H., Xiang, H., Zhu, Z., Li, Y., & Xu, G. (2015). CPS Modeling of CNC Machine Tool Work Processes Using an Instruction-Domain Based Approach. *Engineering*, 1(2), 247-260. doi: 10.15302/J-ENG-2015054

Deng, C., Guo, R., Zheng, P., Liu, C., Xu, X., & Zhong, R. Y. (2018). From Open CNC Systems to Cyber-Physical Machine Tools: A Case Study. *Procedia CIRP*, 72, 1270-1276. doi: 10.1016/j.procir.2018.03.110

de Souza, A. F., Martins, J., Maiochi, H., Juliani, A. D. P., & Jaskowiak, P. A. (2020). Development of a mobile application for monitoring and controlling a CNC machine using Industry 4.0 concepts [Article]. *International Journal of Advanced Manufacturing Technology*, *111*(9-10), 2545-2552. https://doi.org/10.1007/s00170-020-06245-2

Devezas, T., Leitão, J., & Sarygulov, A. (2017). *Industry 4.0: Entrepreneurship and Structural Change in the New Digital Landscape*. Switzerland: Springer International Publishing AG.

Dubovska, R., Jambor, J., & Majerik, J. (2014). Implementation of CAD/CAM system CATIA V5 in simulation of CNC machining process. Procedia Engineering, 69, 638-645. doi: 10.1016/j.proeng.2014.03.037

Faller, C., & Feldmüller, D. (2015). Industry 4.0 Learning Factory for regional SMEs. *Procedia CIRP*, 32, 88-91. doi: https://doi.org/10.1016/j.procir.2015.02.117

Fountas, N. A., Stergiou, C. I., Majstorović, V. D., & Vaxevanidis, N. M. (2016). Intelligent Optimization for Sculptured Surface CNC Tool-paths. *Procedia CIRP*, 55, 140-145. doi: 10.1016/j.procir.2016.08.033

Gorecky, D., Schmitt, M., Loskyll, M., & Zühlke, D. (2014). Human-machine-interaction in the industry 4.0 era. *12th IEEE International Conference on Industrial Informatics (INDIN)*, 27-30 July.

Hermann, M., Pentek, T., & Otto, B. (2015). Design Principles for Industrie 4.0 Scenarios: A Literature Review. *Working Paper No. 01 / 2015*. Technische Universität Dortmund, Fakultät Maschinenbau.

Jang, J., Jung, I. Y., & Park, J. H. (2018). An effective handling of secure data stream in IoT. *Applied Soft Computing Journal*, 68, 811-820. doi: 10.1016/j.asoc.2017.05.020

Kagermann, H., Wahlster, W., & Helbig, J. (2013). *Recommendations for implementing the strategic initiative Industrie 4.0: Final report of the Industrie 4.0 Working Group*. Frankfurt, Germany: Acatech - National Academy of Science and Engineering.

Koleva, S., Enchev, M., & Szecsi, T. (2015). Automatic dimension measurement on CNC lathes using the cutting tool. *Procedia CIRP*, 33, 568-575. doi: 10.1016/j.procir.2015.06.080

Lee, J., Bagheri, B., & Kao, H.-A. (2015). A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems. *Manufacturing Letters*, 3, 18-23. doi: https://doi.org/10.1016/j.mfglet.2014.12.001

Leitão, P., Colombo, A. W., & Karnouskos, S. (2016). Industrial automation based on cyber-physical systems technologies: Prototype implementations and challenges. *Computers in Industry*, 81, 11-25. doi: 10.1016/j.compind.2015.08.004

Liu, Y., Guo, X., Li, W., Yamazaki, K., Kashihara, K., & Fujishima, M. (2007). An intelligent NC program processor for CNC system of machine tool. *Robotics and Computer-Integrated Manufacturing*, 23(2), 160-169. doi: 10.1016/j.rcim.2006.04.003

Longo, F., Nicoletti, L., & Padovano, A. (2017). Smart operators in industry 4.0: A human-centered approach to enhance operators' capabilities and competencies within the new smart factory context. *Computers and Industrial Engineering*, 113, 144-159. doi: 10.1016/j.cie.2017.09.016

Marr, B. (2016). *What everyone must know about industry 4.0*. Tech. Forbes Contributors,. from http://www.forbes.com/sites/bernardmarr/2016/06/20/what-everyone-must-know-about-industry-4-0/#327956184e3b

Moor, M., Vaher, K., Riives, J., Kangru, T., & Otto, T. (2021). Modern robot-integrated manufacturing cell according to the needs of Industry 4.0 [Article]. *Proceedings of the Estonian Academy of Sciences*, *70*(4), 407-412. https://doi.org/10.3176/proc.2021.4.06

Pereira, A. C., & Romero, F. (2017). A review of the meanings and the implications of the Industry 4.0 concept. *Procedia Manufacturing*, 13, 1206-1214. doi: 10.1016/j.promfg.2017.09.032

Sandvik-Coromant. (2017). *Metal Cutting Knowledge*. from https://www.sandvik.coromant.com/en-gb/knowledge/Pages/default.aspx?Country=pt

Sandvik-Coromant. (2018). We're ready for Industry 4.0. Are you? , from https://www.sandvik.coromant.com/en-us/campaigns/pages/coroplus.aspx?Country=pt

Shneor, Y. (2018). Reconfigurable machine tool: CNC machine for milling, grinding and polishing. *Procedia Manufacturing*, 21(2017), 221-227. doi: 10.1016/j.promfg.2018.02.114

Siddhartha, B., Chavan, A. P., Hd, G. K., Subramanya, K. N., & Ieee. (2021, Jan 27-28). IoT Enabled Real-Time Availability and Condition Monitoring of CNC Machines. *IEEE International Conference on Internet of Things and Intelligence System (IoTaIS)*, Electr Network.

Trstenjak, M., & Cosic, P. (2017). Process Planning in Industry 4.0 Environment. *Procedia Manufacturing*, 11, 1744-1750. doi: 10.1016/j.promfg.2017.07.303

Villalba-Diez, J., Gutierrez, M., Martin, M. G., Sterkenburgh, T., Losada, J. C., & Benito, R. M. (2021). Quantum JIDOKA. Integration of Quantum Simulation on a CNC Machine for In-Process Control Visualization [Article]. *Sensors*, *21*(15), 14, Article 5031. https://doi.org/10.3390/s21155031