Management and Production Engineering Review
Volume 10 • Number 3 • September 2019 • pp. 14–28
DOI: 10.24425/mper.2019.129595

MECHANICAL ENGINEERING IN INDUSTRY 4.0

Adam Hamrol[1], Józef Gawlik[2], Jerzy Sładek[2]

[1] *Poznan Univeristy of Technology, Poland*
[2] *Cracow University of Technology, Poland*

Corresponding author:
Adam Hamrol
Poznan Univeristy of Technology
Management and Production Engineering Department
Piotrowo 3, 61-138 Poznan, Poland
phone: (+48) 61 665 2774
e-mail: adam.hamrol@put.poznan.pl

Received: 6 April 2019
Accepted: 29 August 2019

Abstract
The article presents tools, methods and systems used in mechanical engineering that in combination with information technologies create the grounds of Industry 4.0. The authors emphasize that mechanical engineering has always been the foundation of industrial activity, while information technology, the essential part of Industry 4.0, is its main source of innovation. The article discusses issues concerning product design, machining tools, machine tools and measurement systems.

Keywords
Mechanical engineering, information technology, mass customisation, Industry 4.0.

Introduction

Manufacturing of goods on an industrial scale has been lasting for just over 200 years. During that time the industry underwent several transformations. At present it is entering the era of the fourth industrial revolution, shortly Industry 4.0 [1]. The name, Industry 4.0, is a derivative of the stages of industrial development, named respectively: the first, second and third revolution or the industry 1.0, 2.0 or 3.0. It is acknowledged that the first industrial revolution began at the turn of the 18th and 19th centuries and was associated with the introduction of a steam engine on an industrial scale. Revolution 2.0. is associated primarily with the introduction of a production line and with electric drives. The use of programmable digital controllers in technological machines initiated third industrial revolution.

The fourth industrial revolution is usually identified with broadly understood digitalisation [2, 3]. It allows, through digital integration to improve the efficiency of production processes, to use products more effectively and to make social and economic environment more human friendly. The integration takes place in a space called Cyber Physical Space – CPS [4, 5] in which systems are controlled and monitored by computer algorithms. Industry 4.0 ultimate goal is to meet the idea of so-called mass customization of products [6], i.e. meeting the needs and expectations of an individual customer on a mass scale.

Processes realized within Industry 4.0 can be considered in two dimensions. In Fig. 1 they are symbolically represented by two imaginary planes. The horizontal plane relates to the broadly understood market and the vertical one the life cycle of a product taking place in a specific production enterprise (from product design to its sale). On the horizontal plane, cooperation between enterprises is realised (e.g. within a company network or in so called cloud manufacturing), as well as communication between customers and products they use, customers with each other or with products producers (service). Forms of such cooperation are performed with the use of information technology (IT), such as Cloud Computing [3], Internet of Things [7–9], Big Data [10, 11], Artificial Intelligence [12]. They also refer to intelligent factories (Smart Factory) [13], enterprise networks or cloud manufacturing [14, 15]. They are determining the way of conducting broadly understood business activities.

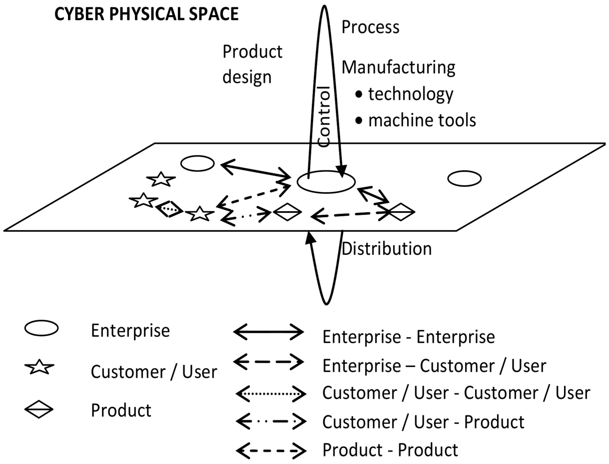

Fig. 1. Cyber Physical Space in the market and within an enterprise.

It is striking that scientific articles as well as popular studies dealing with Industry 4.0 are focused mainly on IT aspects, as mentioned above. Lesser attention is paid in literature to activities carried out in the areas of product design, manufacturing process preparation or its execution (machine tools or measurement systems), it means to areas illustrated in Fig. 1 on the vertical plane. And it is in these activities that the products acquire the properties that their future buyer and user expects. IT's are invaluable support for them, but only a support.

The idea expressed above is illustrated in Fig. 2. The product's properties are a reflection of its design (idea), the materials used and the quality of the manufacturing process. Each product, regardless of its type (e.g. cars, pieces of furniture, fabrics, food products, plastic containers, etc...) is manufactured according to a specific technology (specific for a given product) with the use of appropriate tools, machine tools, machine equipment, ie resources, that are products of specialists dealing with engineering mechanical. The development of mechanical engineering is supported by information technology, automation and robotics. Effective use of tools and machine tools is a management task.

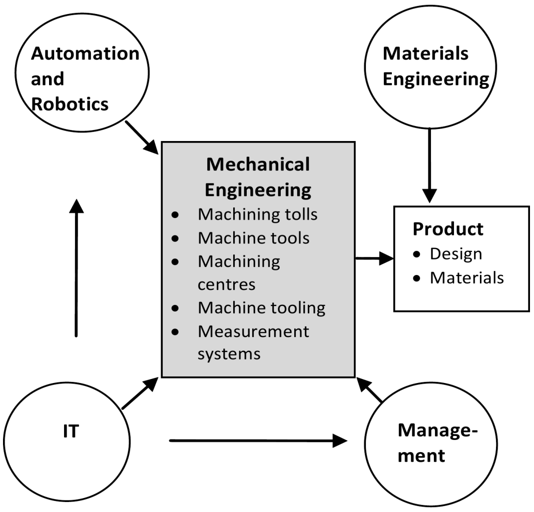

Fig. 2. Relations between mechanical engineering and other areas of engineering and business activity.

It can be concluded that the activities related to mechanical engineering transform the idea included in the product design into an added value for the customer. Their effectiveness depends on the support from IT, automation, robotics, management and others.

The subject of this article are tools and systems based on newest IT's achievements and used by mechanical engineers. In particularly the following issues are presented:

- product and processes design
  - distributed and integrated CAx,
  - Knowledge Based Engineering (KBE),
  - digital models, eg virtual reality (VR),
- manufacturing processes:
  - additive manufacturing (AM),
  - intelligent tools,
  - flexible, configurable technological machines and machining centers,
- inspection:
  - flexible, on-line-operating measuring systems.

The examples of solutions presented have been developed in majority by teams guided by the authors of the article.

Product design

Introduction

Giving each client the opportunity to purchase products that meet their individual needs and expectations is possible through the so-called mass customisation (MC). In order for customised products to be competitive, they should not be more expensive than those offered in mass production [17]. MC therefore poses a challenge for engineers and managers to ensure an economically acceptable unit cost of a product.

There is no doubt that in the near future technologies, machine tools, production systems, forms of organisation and production control will have the potential to compensate for unit costs in mass production and mass customised production. It can therefore be assumed that in the era of MC the "battle" for the client will be played in the field of product design. After all, customers' needs, expectations and requirements are difficult to predict. If they can be successfully identified and then quickly translated into a feasible product design, delivery time will be short and the customer satisfaction level will be high.

Today, designers have many IT tools at their disposal that help achieve this goal. Among those tools are: integrated CAx (CAx – Computer Aided Technologies) systems, KBE systems, systems for designing and testing digital prototypes in virtual reality.

Integrated CAx systems supported by knowledge management systems

Computer systems supporting engineering works are used at all stages of the development and production cycle of the product, from the development of the product concept, through design, prototyping and testing, and the preparation of machining programs on CNC machine tools. The manufacturers of these systems put special emphasis on their integration (Fig. 3).

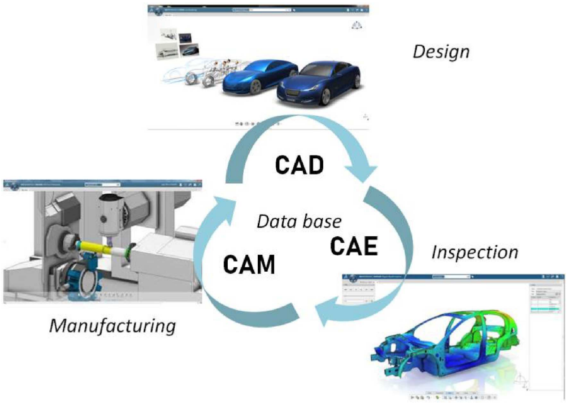

Fig. 3. Integration of CAD/CAM/CAE systems.

The integration ensures efficient data exchange between all parties involved in product development and product manufacturing launch as well as the ease to edit and make changes to the project. Thanks to working in a cloud mode (Cloud Computing) access to all resources of the systems (both data and executive applications) is possible from any device connected to the Internet, and designers have a lot of flexibility in exchanging information.

Modern CAD systems support the development of technical documentation, conceptual work related to the interpretation of expectations and customer requirements (e.g. through free-form modelling techniques or visualizations of products and processes). CAE systems allow the designed structure to be analysed in many different aspects, e.g. in terms of loads and strength conditions (e.g. MES method), flows (for example injection molding die filling), kinematic and dynamic analyses (e.g. simulation of combustion engine operation or aerodynamic evaluation of a shape of an aircraft wing) or operation and usage of the designed product (e.g. ergonomics of car cockpit operation).

An example of using CAE tools is shown in Fig. 4. The machine tool is intended for machining parts up to 500 kg by milling and drilling (holes up to 1600 mm long). When designing, minimizing the size and weight of the body was adopted as the decision criterion. The results of calculations and simulations checking the body deformations under the action of loads derived from the weight of machined elements and cutting forces were made using the Solid Works program. It was indicated that the L-shaped body shape is optimal and that in order to obtain a favourable relation between the body weight and its strength it is necessary to introduce additional ribs on the back wall.

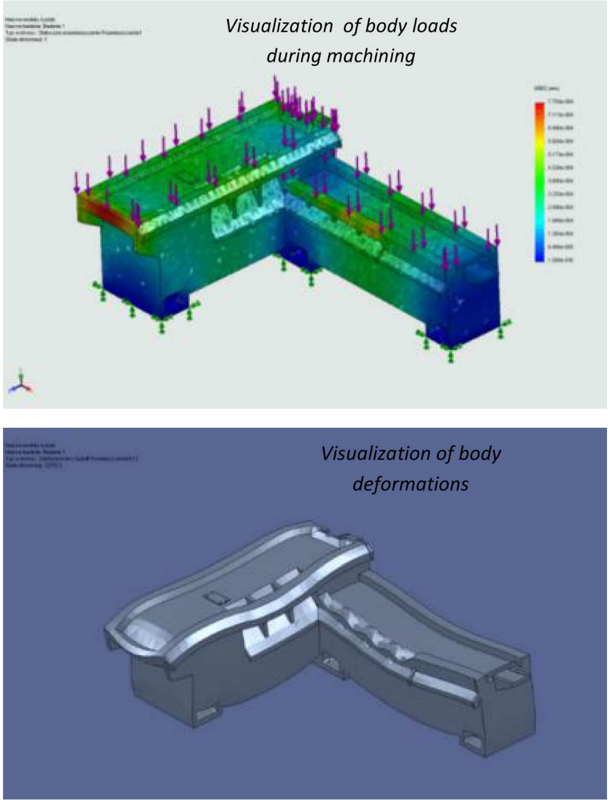

Fig. 4. Visualization of machine tool load and deformation [18].

Integrated CAD/CAM/CAE programs are of great importance in implementing the strategy of mass customisation. An example is production of parts for the automotive industry, where components having the same purpose may differ from one another due to the variety of vehicles in which they are used. Similar problems occur other industries, e.g. household appliances, sanitary or electronic. In such cases, engineers try to use systems that, on the one hand, allow for flexible response to customer requirements, and on the other, maximize the standardization of technical solutions used. An example of such approach are the KBE systems, which on the basis of collected and appropriately processed expert knowledge enable automatization of repetitive and routine tasks in CAx systems.

The basis of KBE is usually a group of software tools that allow for the representation of knowledge. Its implementation is carried out through appropriate description of facts (values of features), dependencies occurring between them (relations) and procedures referring to the activities resulting from them [19]. This allows the construction of parametric, "intelligent" 3D models, also called autogenerating models, which can quickly adapt to variable input data.

In an enterprise that produces armchairs for mass communication (buses, trains), constructors must adapt seats and fixings to customer requirements and the technical conditions of a particular vehicle. The result of their work is construction documentation, including assembly drawings and executive drawings of all seats and fixings. The solution that streamlines their work is designing using self-generating models that enrich parametric CAD models with properly registered knowledge with e.g.:

- identified functional and constructional features of the product,
- relationships between functional and constructional features of the product,
- rules describing the principles of selecting constructional features of the product, that take into account other requirements (e.g. related to manufacturing, assembly or operation).

The KBE class design system presented in Fig. 5 allows you to shorten the design time, and thus has a positive effect on the time of the customer's order.

CAD programs are also the source of data for digital or physical prototyping of products and for programming CNC machines. By constructing special CAD autogenerating models and appropriately prepared CAM machining templates, it is possible to automate the CNC programming process completely (machine tools, industrial robots). In mass personalization, this is important because the CAD/CAM system is able to offer a correct, optimal control program for the CNC machine relatively quickly and without human intervention. Such solutions are already encountered, e.g. in the automotive industry, in the area of manufacturing of special production equipment [20].

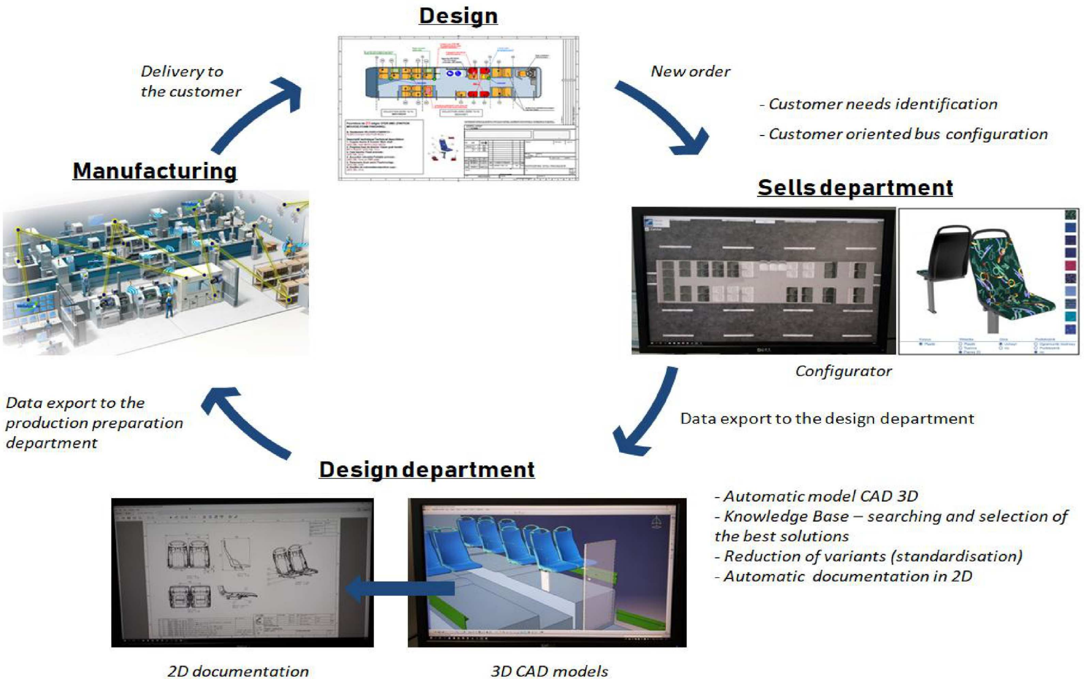

Fig. 5. Implementation of KBE in design process of a city buses (from a project implemented in the VR Laboratory at Poznan University of Technology).

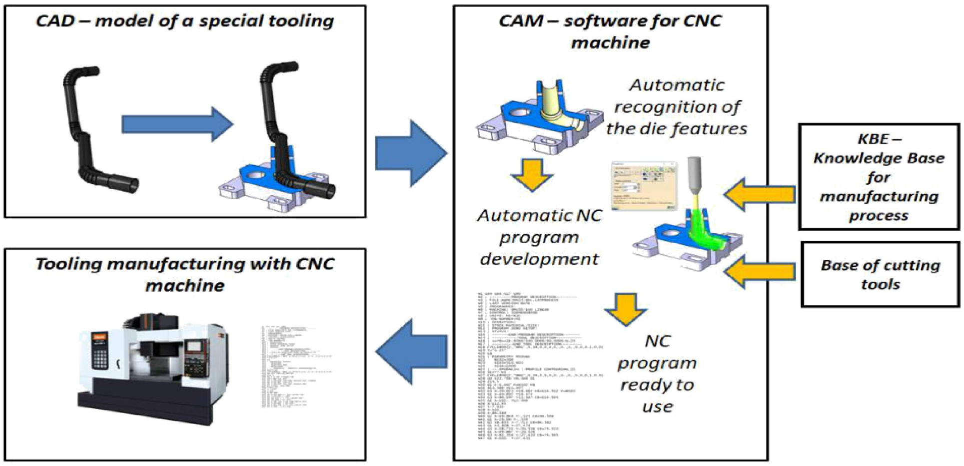

Fig. 6. Design of special tooling in CAD/CAM system with the use of auto-generative models [21].

The process of manufacturing special tooling is an example of a production made to order (“Make to Order”) in which the design of the device is based on the product model provided by the customer (digital or real). Programming of machining of special tooling on CNC machines is time-consuming, requires high qualifications and, as a result, has the greatest impact on manufacturing costs. To shorten this process, a special IT solution was developed, Fig. 6, using the capabilities of integrated CAD/CAM systems, knowledge bases, auto-generating CAD – model preparation of a special tooling *models and special machining templates. Thanks to the integration and efficient data exchange, the new system allows the programming time to be significantly shortened.*

Project activities should be integrated with other processes. Specialized IT platforms are created for this purpose. The 3D Experience platform from Dassault Systems [22] is, for example, ready to “handle” distributed projects (also globally) for various company departments (marketing, sales, technical departments) and their suppliers, where not only the company management can have insight on the progress of work on the project, but also the client.

Digital models (prototypes)

An integral part of the product design or manufacturing process preparation is the construction and testing of its prototype. This allows to check the design and construction solutions before the product is transferred to production. Designing a new casting technology, e.g., requires incurring large costs associated with preparation of instrumentation necessary to produce casting moulds. Therefore, before making the mould it is necessary to optimize the procedure of casting technology in order to obtain high quality castings at low production costs. A rational procedure of casting technology design optimization involves the use of computer systems to Subsec. 3.1) and test them. In this chapter the attention is drawn however to digital product prototypes (digital models), including those created in virtual reality.

In traditional digital modeling, there is no interaction between the model and the modeled object. The digital model is used for calculations or simulations and their results are included in the product design.

Currently, the concept of the so-called digital twin is used in digital modeling, Fig. 7. It was first defined as a simulation of an object (machine, process, system) that combines digital and physical models together and with data from the physical model obtained from sensors. This ensures that the digital model reflects perfectly its actual equivalent’s features [25]. To ensure this it is necessary to use advanced methods of artificial intelligence and analysis of large data volumes (Big Data).

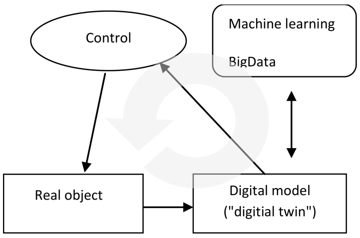

Fig. 7. Digital twin concept.

The “digital twin” concept already has practical applications. The company General Electric uses it, for example, in the design of critical elements of jet engines to predict incidents related to its operation [26].

One of the forms of the digital product model is a model developed in a virtual or augmented reality, Fig. 8. Virtual reality (VR [27]) – in other words, computer simulation with the involvement of human senses – is a technology used from the late 1990s. Augmented reality (AR [28]), which is the superimposition of 3D and 2D data on the image of the real world, has also been known since the late 1990's, however, its effective industrial applications have been known only for several years.

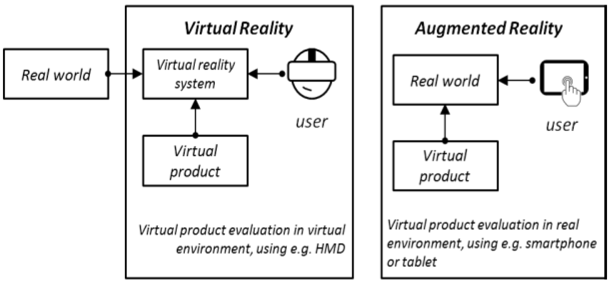

Fig. 8. Idea of Virtual Reality (VR) and Augmented Reality (AR).

Virtual prototyping allows inclusion of the end user in the design process. An example of such a solution is shown in Fig. 9.

To support design of the urban buses, VR class system, called the VDS (Virtual Design Studio) has been developed with particular emphasis on the interaction with the customer. The use of three-dimensional visualizations and immersion environment allows testing the selected design variant in a similar way to testing the actual product. A "tour" of a virtual bus displayed in high resolution, gives the opportunity to interact with objects in its interior. It allows to avoids problems and mistakes that may occur in the case of traditional design process (without the support of 3D and VR technologies).

The vehicle design/configuration process is divided into three stages. First – preparatory, so-called Preconfiguration, consists of recognizing the basic expectations of the customer and determining the characteristics of the vehicle such as its length, number of doors and coloring. The features determined this way form the basis of the proper configuration, implemented with the use of 3D projections. At the last stage, the client may, in full immersion mode (in the HMD helmet), take a virtual walk through the version of the vehicle designed with his participation.

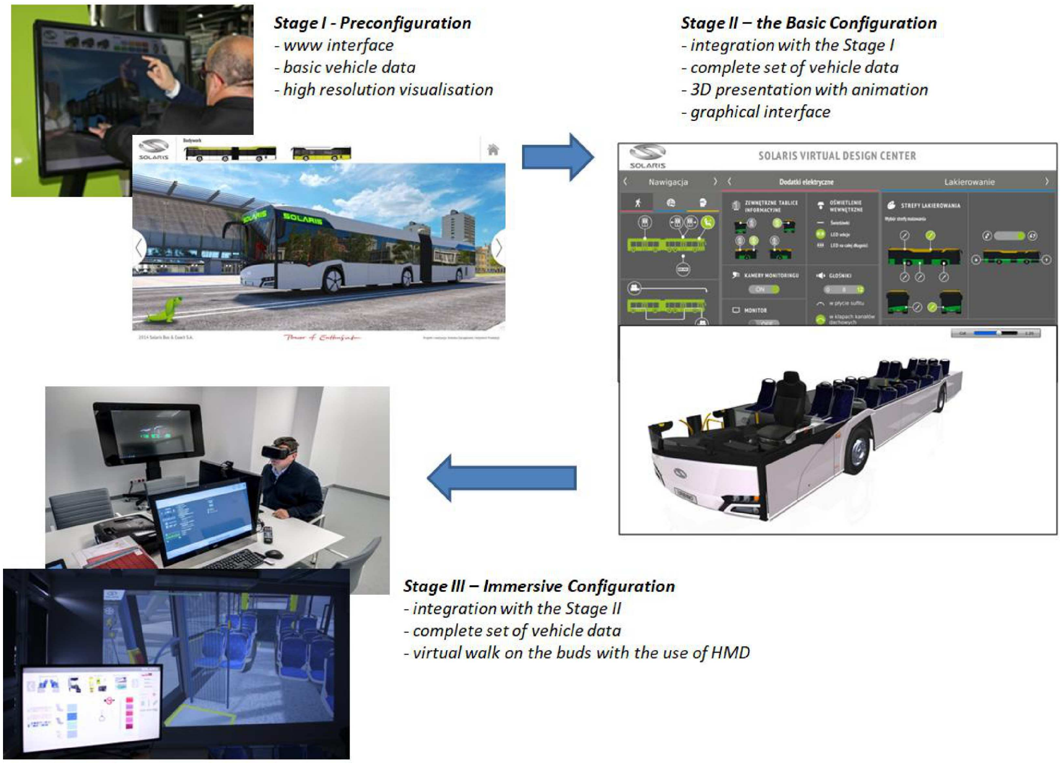

Fig. 9. Stages of designing of an urban bus in *Virtual Design Studio* system [29].

Technologies, tools and machine tools

Additive manufacturing

Additive manufacturing is the effect of combining simple techniques in the field of bonding materials, processing plastics, etc., with IT technologies. A common feature of all additive manufacturing methods is the application of layers or "portions" [30], which projects a three-dimensional digital model stored in a CAD environment. Devices for additive manufacturing are controlled numerically and the standard format for data exchange between the model and the device control system is the STL (Standard Triangulation Language) format [31].

Additive manufacturing allows to obtain products of complex geometry without the need for additional technological equipment. This is its basic advantage. In relation to technologies of traditional manufacturing technologies (casting, machining and processing of plastics), however, it has significant limitations related to the accuracy, efficiency and strength of manufactured parts or products. Additive manufacturing methods have found applications not only in the creation of prototypes and in the rapid production of technological tools (Rapid Tooling – RT). They enable production of multi-material elements [34] and short series of usable products. In practise methods such as [32]:

- stereolithography (SLA):
- 3D printing (3DP)
- selective laser sintering (SLS),
- layered laminating (Laminated Object Manufacturing, LOM),
- shaping with plasticized polymer material (FDM)
- are used.

The most popular in terms of industrial applications is the incremental shaping of plasticized polymeric material [33], called FDM (Fused Deposition Modeling). It consists in the linear application of plasticized material, extruded through a circular section nozzle moving in the X and Y axis, parallel to the work table of the device. The work table after applying the material within one layer lowers its position relative to the head according to the Z axis by the value corresponding to the defined thickness of a single layer (Fig. 10).

The materials used in the FDM method are thermoplastics such as ABS, PC, PLA and their variants. It is also possible to manufacture products made of composite materials, but those in which the carrier is always a thermoplastic material. Thermoplastic materials can be machined, covered with protective, decorative or metal coatings, which is particularly important in the case of visual prototypes. Examples of products manufactured using the FDM method are shown in Fig. 11.

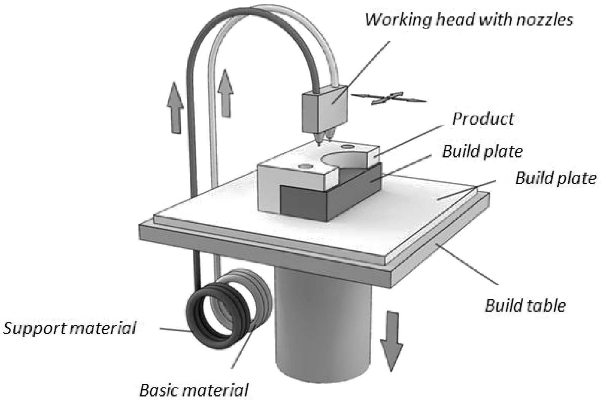

Fig. 10. The scheme of Fused Deposition Modeling [34].

Fig. 11. Examples of products printed with the use of FDM (Rapid Prototyping Laboratory at Poznan University of Technology).

Intelligent cutting tools

Cutting tools used in modern machining systems, in addition to being characterized by high durability and reliability, must be adapted to the implementation of complex machining operations, carried out in changing conditions. Mechatronic tools, sometimes called "intelligent tools", are able to meet those requirements [35, 36]. The essence of structural solutions of mechatronic tools is contained in the application of sensors and software that allows for monitoring parameters characterizing the machining process. An example of a boring head with a system for remote correction of radial settings of the tool's edge is shown in Fig. 12 [37].

Mechatronic tools can be driven by their own motor or by machine spindle, equipped with an independent control system or be connected to the CNC machine control system. The data transmission can be carried out wirelessly or via a fixed connection. An example of mechatronic tools with its own control system is the U-COMAX head (Fig. 13).

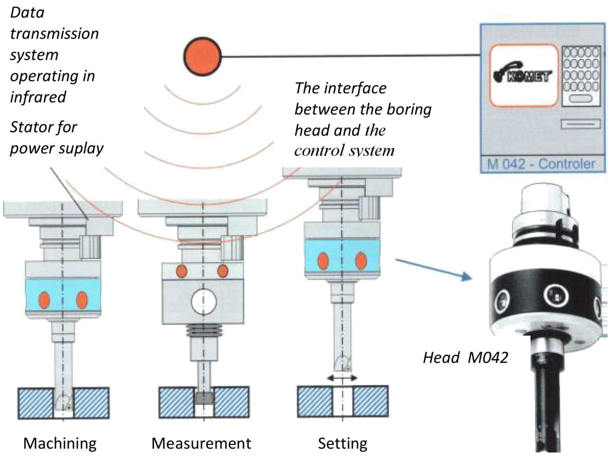

Fig. 12. Boring head system with a system for remote correction of radial settings of the tool's edge (Komet's solution [37]).

Fig. 13. U-COMAX head with independent drives (a) and examples of products made with it (b) [D'Andrea solution [37]].

The head is equipped with independent drives – one main drive motor and the other motor to drive the feeds in the U axis. Such mechatronic tool sets are mainly used on task machine tools, for example in production lines. The drive in the U axis is controlled directly from the CNC machine tool system or from an independent controller. With U-COMAX heads, internal and external surfaces, grooves, cones, concave and convex surfaces (also spherical) can be processed by interpolation with other controlled machine axes.

Inn cutting process elastic deformation of the tools is a highly undesirable phenomenon. It is the cause of machining errors (occurrence of waviness, deterioration of surface roughness, increase of the wear intensity of the blades). The effects of this adverse phenomenon can be limited by the use of mechatronic tools with deformation correction (Fig. 14).

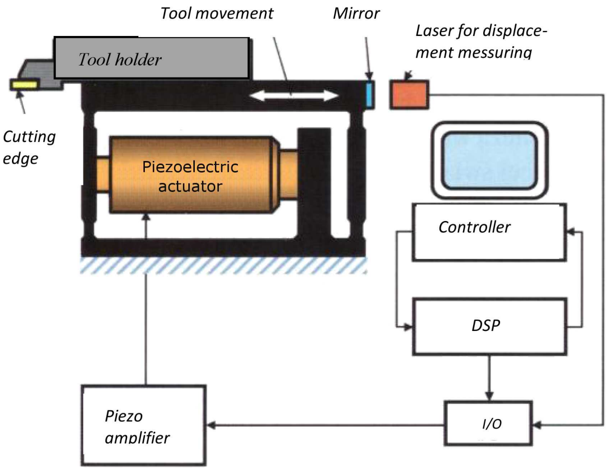

Fig. 14. Diagram of the mechatronic tool for automatic deformation correction [38].

Intelligent machine tools

The development of modern production systems is moving towards intelligent production systems (Intelligent Manufacturing System – IMS). An intelligent production system is a system in which human control is replaced by machine data processing using IT technologies of artificial intelligence [39–41]. Intelligent manufacturing systems in coincidence with information systems should be integrated into one complex hierarchical system, controlled by the central unit of a CNC. An example is the concept of an intelligent machine tool, depicted in Fig. 15.

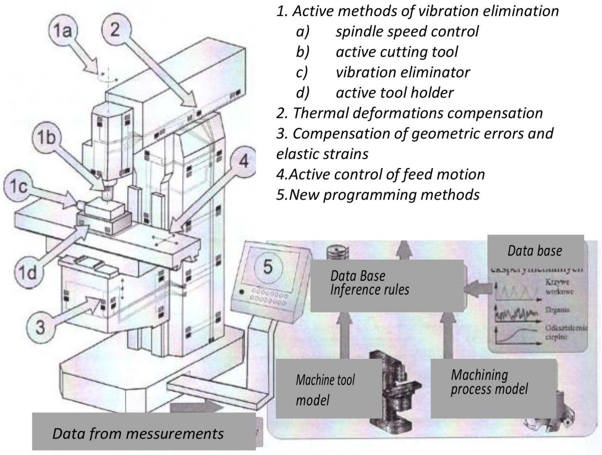

Fig. 15. Conceptual scheme of an intelligent machine tool [42].

The CNC control system, using information about the current state of the machine tool, from the knowledge base of the implemented technological process and inference rules stored in the program actively controls the tool movement path and compensates for the impact of unfavorable phenomena on the process and the technological quality of the products.

The basis for effective intelligent control of the properties of machines and technological devices is to forecast their state in real time. Modern software is based, among many, on artificial neural networks and fuzzy sets theory. These types of software have properties that enable them to function properly under conditions of some scattering of values, and thus the ambiguity of input signals. During the realization of technological process, they gather new information – new knowledge and through learning they automatically adapt their decisions to new conditions of the process implementation. Neural networks have the ability to self-organization, involving unattended learning, which enables them to use information from the process and model data. Acquiring specific knowledge during the process and transforming this knowledge to the continuation of this process is an interactive process of creating self-innovation. These types of advanced software tools used to control intelligent production systems enable, to a certain extent, to adapt functioning of the system to current external exertions. In this sense, intelligent production systems have the features of autonomy and openness.

Reconfigurable RSP production systems

The basis of production systems in industry 4.0 are Reconfigurable Manufacturing Systems [43, 44]. In such systems, thanks to the easy interchangeability of functional units, it is possible to make quick changes to their structure, and thus quickly adapt the system to the changing demand.

Reconfigured production systems should be characterised by: modularity, integrity, flexibility, scalability, convertibility and supervision.

Modularity means creating a technical solution by a combination of previously made individual parts and assemblies, which are functional modules (example – Fig. 16).

Integrity involves the design of the machining system in such a way that all its elements and modules create a hierarchical system that is supervised by the central unit of the CNC. The CNC control system uses information from the current assessment of the production system status.

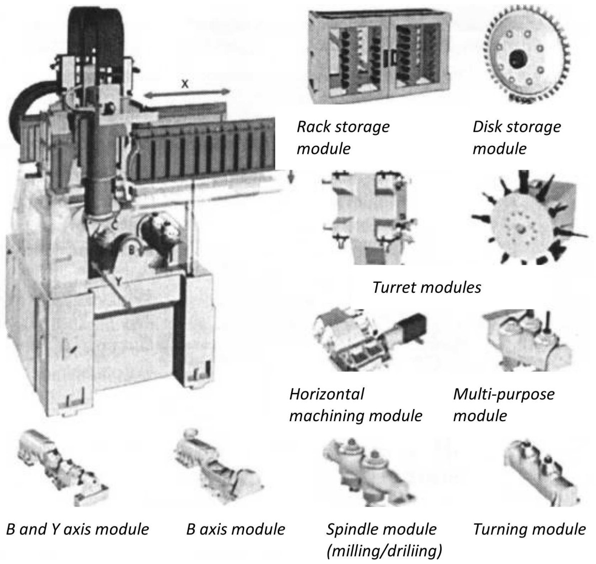

Fig. 16. Modular construction of the machining center [44].

Flexibility means the possibility of using different techniques and technologies of production (machining, plastic forming, heat treatment, measuring stations, etc.) connected with each other by automated transport devices in such a way that different workstations are able to process various objects passing through system via various technological routes.

Scalability is a feature of the production system making it possible to adapt its structure to the changing production range while meeting required criteria (eg product quality, production efficiency, production costs, etc.).

Convertibility means the possibility of exchanging information with other CAD systems thanks to the use of interfaces for loading data saved in a solid form, including the location of points, surfaces, material data, etc.

Supervision includes the measurement of the parameters of the production system status, identification and assessment of the measurement result in relation to criterion values and the current monitoring of the trend of changing the values of these parameters in order to counteract the disruption of the process.

An example of a reconfigurable machining station is the multi-task drill WCZ 140 for drilling deep holes in diameters ranging from ∅ 4 to ∅ 32 mm, depth up to 1600 mm, with the possibility of adapting it to milling operations or drilling operations using a vertical head mounted on a vertical spindle (4) (Fig. 17).

The WCZ 140 drill is equipped with digital servo drives, motors for feed movements and spindles, rolling roller guides in 4 axes. In the horizontal drilling process with a special arrangement of three sliding steadies stable barrel drill work is ensured. The SINUMERIK 840D numerical control system is integrated with the software of the cutting process control system, so that in the event of disturbances (e.g. due to inhomogeneity of the material being processed and thus accelerated wear of the blades, chip locks), the machine is automatically shut down.

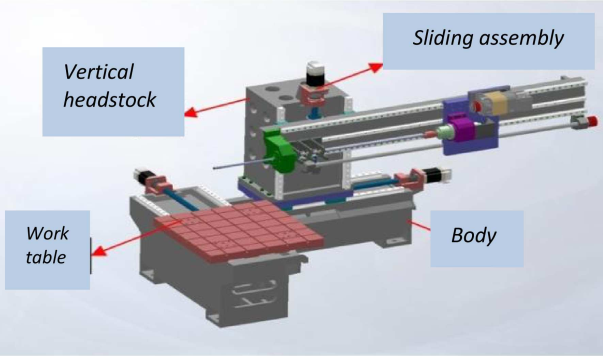

Fig. 17. Multi-purpose drilling machine WCZ 140 [18].

Measurement techniques and systems

The changes that took place in metrology in the nineteenth and early twentieth century, above all the normalization of the units of measurement system and the development of patterns and measuring tools were one of the factors enabling the introduction of mass production, which was the beginning of the second industrial revolution. However, it was the application of computer techniques that initiated a real revolution in the field of measurement systems.

The ability to carry out complicated calculations in a short time allowed in the 1950s to introduce into the industrial practice the first coordinate machines, which nowadays are a basic tool in assessing dimensional compliance of manufactured objects with their geometric specifications [46–47]. In the coordinate technology, during the measurement, the coordinates of the measuring points located on the surface of the tested object are determined, which allows to recreate the geometry of the element being inspected and to evaluate the assessed features. The most common tools of Coordinate Technology are still contact Coordinate Measuring Machines (CMM), in which measurement of coordinates of a point requires contact between the measuring head and the measured object. The changes of the position of the measuring head in the basic orthogonal machine coordinate system are measured using linear transducers. This method allows to obtain the accuracy of up to 0.1 µm. Non-contact systems are not characterized by such high accuracy but they display a number of other advantages, mainly shortening the duration of the measurement. The trend observed in recent years clearly shows that such systems operating additionally in connection with, for example, industrial robots in the future will be one of the most popular tools in advanced production processes.

From the point of view of P4.0, two key areas of the development of measurement systems can be distinguished:

- changing the emphasis of postproduction control (post-process metrology) towards control during manufacturing process (in-process metrology or in-line metrology) and
- development of methods for assessing accuracy measurements in near real time.

In-process metrology

In-process metrology allows the integration of the measurement process with the manufacturing process. It requires controlling selected parameters of the production process, as well as taking measurements during the production of objects and automatic analysis of the results obtained so that almost immediate prevention of the dysregulation of manufacturing processes is possible. Conducting measurements during the manufacturing process is a problem that may be solved by the development of contactless techniques. Already, systems using laser triangulation or structural light scanners are installed on production lines, allowing taking measurements on the production line (in-line metrology), but this type of measurement is done after the object has been processed, and the information obtained as a result can only be used to correct the manufacturing process of next objects.

In-process metrology requires a very detailed knowledge of the controlled process, in particular, information on the influence of various parameters determining its course and its impact on the properties of the manufactured element. Usually it is connected with the necessity to develop a functional model of the considered system, which allows to simulate the impact of changes of selected parameters on the result of the machining process. Compatibility of the simulation results with the operation of the actual system is checked by conducting research of creating a series of elements, using the values of process parameters included in the simulation, and then evaluating the properties of the obtained elements, e.g. using Coordinate Measuring Machines. Such approach also allows to observe possible correlations between the exchange of values of selected process parameters and the characteristics of the created element.

An example of a technological process within which in-process metrology has been successfully applied is the process of manufacturing toothed shafts [48]. The preparatory analysis allowed to select process parameters and geometrical parameters of the manufactured element which should be controlled during the process. Among them were: apical diameter, toothing depth, circumferential scale and actual axial displacement of the workpiece and information about its rotation angle. Due to the specificity of the production process discussed, the possibility of using methods requiring contact with the measured surface for measuring parameters was rejected. This would require too much interference in the machining process itself and modifications during its course. Non-contact distance sensors were recognized as the best choice, which enabled measurement of most of the mentioned parameters. The location of the sensors is shown in Fig. 18. A special software was prepared that allowed to analyse the data collected on an ongoing basis and additionally integrated all necessary information, which allowed to control the process and to prevent deviations in near real time. Additionally, an important issue in this context is the problem of assessing the accuracy of int-process measurements. The subject still expects proper development, and one of the possible directions of development in this area are so-called simulation methods for accuracy evaluation.

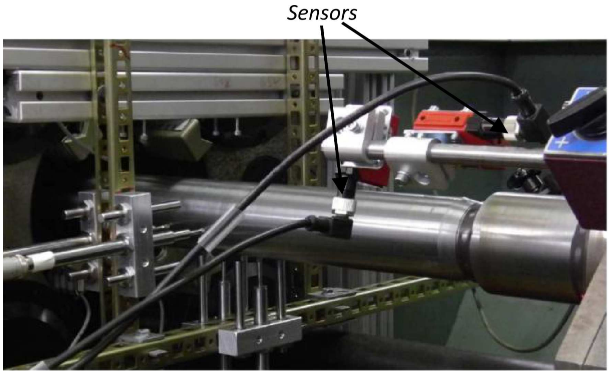

Fig. 18. Arrangement of sensors in the in-process measurement system for the process of rolling the teeth [48].

Metrological systems used on the production line (in-line/in-situ metrology)

The desire to control 100% of manufactured parts means that on the production line, after individual machining processes and assembly processes, measuring systems are installed. Their main characteristics are a high degree of automation and the shortest measurement time, as they must not slow down the tact of production. Among the systems of this type, the most common are scanning systems based on the use of a structural light scanner mounted on an industrial robot. Thanks to this system configuration, the scanner's basic measuring range is significantly increased, and the high redundancy of the industrial robot enables the scanner to reach hard-to-reach places of manufactured parts, which are often large-size parts. To achieve even greater reduction of working time, such systems are multiplied (Fig. 19).

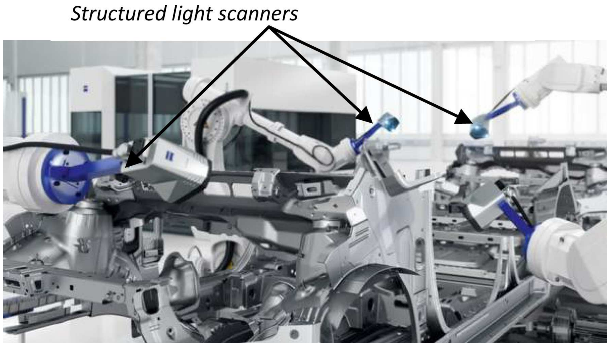

Fig. 19. Structured light scanners mounted on industrial robots used for quality control on a production line in the automotive industry [49].

Another very often used solution is robotization or automation of workstations using CMM, in which measured parts are delivered to the measuring space of the machine and positioned in it by industrial robots or by automatic feeders in the form of e.g. conveyors (Fig. 20). Robotic measuring cells are sometimes connected with vision systems that are able to recognize type of a part being picked up by the robot and, on this basis, select correct location and type of assembly in the measurement space. The cells of this type are usually controlled by PLC controllers.

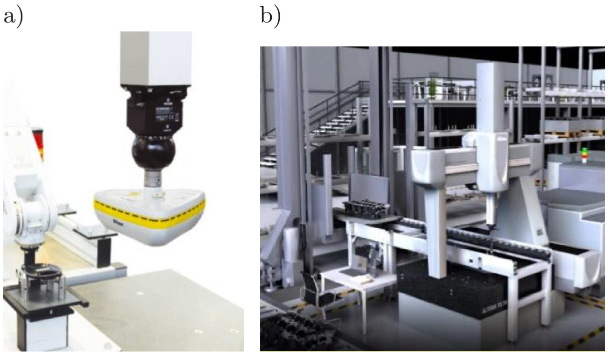

Fig. 20. Automation of measurements on a Coordinate Measuring Machine: a) CMM cooperating with an industrial robot, b) items delivered to the CMM measuring space using an automatic Fedder [50].

External influences network correction systems

The enormous bandwidth of the Internet networks and the high speed of data transfer, which is achieved today, have enabled the development of systems for remote error correction of measuring devices. One example is a system that allows external corrections of thermal influences on the measurement accuracy of any medium-sized CMM, without the need to interfere with the machine's construction. The idea of the system is to develop a model of the error field of the coordinate measuring machine in variable thermal conditions, with the use of a thermostable standard and external temperature measuring sensors. In order to build such a system, the CMM error field should first be identified and then the thermal influence on the deformation of its structure should be modeled in order to develop an effective system of its correction in operating conditions, assuming obtaining determined MPE boundary errors of a given CMM. It is also possible to use this system to reduce thermal influences – just as it was solved in the case of so-called active correction systems mounted in more accurate machines at their construction nodes.

The basis of the CMM error field model is a database based on long-term monitoring of thermal conditions, using a specially designed arrangement of a set of sensors for a given CMM and its working space. The analysis of temperature changes in the CMM environment allows to develop a model of thermal interactions on CMM and the determination of limit temperatures for which CMM accuracy tests were planned with the use of a thermostable standard. The system was designed in such a way that information about the current CMM temperature is transmitted online to the supervising laboratory server and the system installed on the server returns corrective data of the new CAA matrix to the computer controlling the accuracy of the coordinate measuring machine. The idea of a thermal impact correction system using internet data transfer is presented in Fig. 21.

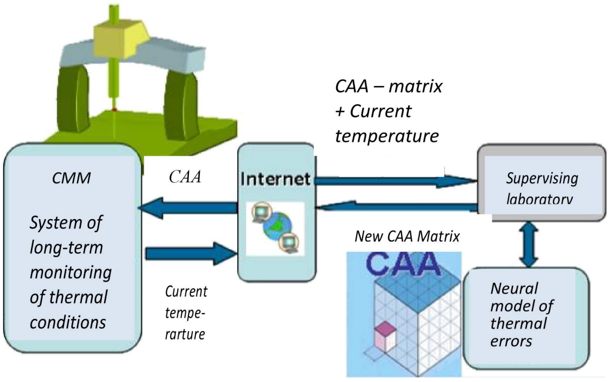

Fig. 21. The idea of the thermal interactions correction system using the Internet data transmission between the adjusted CMM and the supervising laboratory.

Simulation methods for measuring the accuracy of measurement

The measurement result without information on its accuracy is basically useless in the context of assessing the conformity of the controlled characteristics with the specification of their completion. A commonly accepted measure of measurement accuracy is its uncertainty. It is a parameter defining the range associated with the measurement result in which the real value of the measured quantity is included with a given probability. In the case of the Coordinate Technology, the basic method for determining the measurement uncertainty is the method based on multiple measurement of the measured element and the calibrated object. This method, due to the need for numerous repetitions of measurements, could hardly be used in the case of measurement tasks requiring a short duration of measurement, e.g. in in-process metrology. That is why there is a growing interest in so-called simulation methods of determining uncertainty, which allow to assess the accuracy of measurement in near real time.

One of the methods belonging to the mentioned group is a method that uses a virtual model of the measurement system. Its preparation requires a lot of analysis and research on the identification of errors in the considered system, however a virtual machine prepared in such a way can be used to estimate uncertainty for practically any measurement task. On top of that, often it will operate in incomparably shorter time than it would with other methods (as opposed to current methods that require multiple repetition of the measurement, only a single execution is required) [46]. The first model of this kind for CMMs was prepared in Germany in the last century. Since then, this method has been developed by a number of research centers around the world, including Poland, where it was also successfully adapted for other coordinate systems.

The general concept of a virtual machine using neural networks and a virtual machine prepared in the Polish Laboratory of Coordinate Metrology (LMW) is shown in Fig. 22.

The kinematics of the machine and errors related to the operation of the measuring head were considered as the most important sources of errors. Machine kinematics can be tested with the use of material patterns in the form of ball plates or hole plates,

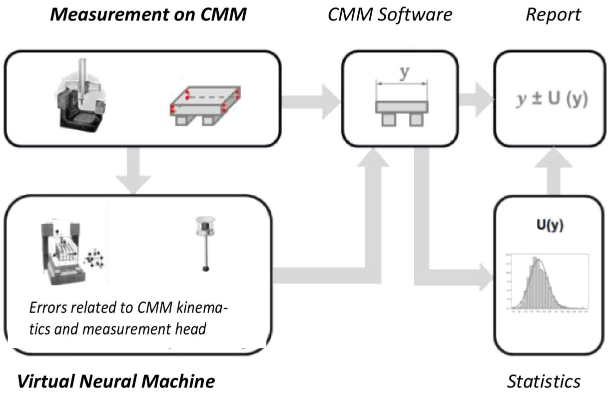

Fig. 22. General scheme of operation of a virtual machine based on the use of neural networks [45].

for which in the calibration process the position of the centers of the balls or holes is determined in advance. Then, by measuring the plate on the measuring system being tested, it is possible to determine the device errors at selected points as the difference between the value obtained from the measurement and the one obtained during the calibration process, and to obtain information on the scatter of indications. The plate is measured in a certain number of positions – which allows to identify errors in the entire working space of the tested device – and orientation to account for the impact of errors associated with machine movement along all three axes. In this way, the so-called reference grid is created. It is a set of input data for that part of the virtual machine that is responsible for modeling kinematic errors. With the use of such a model it is possible to determine the error for any position in the measuring system's workspace. This information is available directly for reference points (in which errors are determined empirically) while for other points, which is the vast majority of cases, error modeling is carried out using a neural network. Network preparation is an important stage in the creation of the final model, and its final design is the result of many attempts and the search for such network architecture that ensures receiving satisfying results.

The second source of errors included in this virtual machine is the neural model of measurement head errors. Data for its preparation is obtained by repeated measurement of a ring or a ball pattern with negligible small shape errors and adequately small diameter to limit the effect of kinematics on the accuracy of the test. The standard should be measured with the use of an even distribution of measurement points. Then, after determining the element associated with the method of least squares, it is possible to determine the error at a given measurement point and link it with the direction of the vector of approach from which the measurements were made. In the case of directions not included in the experiment, the error value is modelled using the neural network. After completing the experimental part and preparing both parts of the model, you can then simulate any measurement task.

During the simulation, the coordinate measurement result of each point included in a given measurement task is burdened with errors modelled by the appropriate virtual machine modules. The appropriate geometric elements are determined from the simulated points, which features (or relations between them) are evaluated. Next, with the use of statistics, the uncertainty of a specific measurement task is determined on the basis of results obtained through multiple simulations.

The big advantage of virtual CMM accuracy models is the ability to use them in the cloud and the ability to remotely access simulation results of virtually any measurement whose accuracy is assessed. Thanks to that, data provided by such systems can be analysed by people with specialist knowledge in the field of analysis of accuracy of coordinate measurements, while the very service of such systems can be performed by metrologists working in production plants who do not have to have specialist knowledge in this area. Similar solutions based on data processing in the cloud are used in CMM for periodically checking the accuracy of CMM indications. The company that participates in such checks purchases or lends a standardized control pattern along with a prepared measurement program that runs on a checked measuring machine. The results of these measurements are then automatically placed in the cloud, where they are analysed. Based on the conducted analysis, the user receives a report on the condition of the tested machine and its accuracy.

Conclusions

Industry 4.0 is a password, associated primarily with digitization, computerization, robotization, the Internet of Things, Big Data or virtual factories. But the basis of industry 4.0, which results from its very name, are manufacturing systems, and in them systems and methods of product design, manufacturing technologies, technological machines and measuring systems. The purpose of this article was to show that industry 4.0 is the integration of these two worlds. His goals are to best meet the individual expectations and needs of customers as well as the best use of resources, while remembering the need for sustainable development. It remains only to expect that this will happen.

References

[1] Lu Y., *Industry 4.0: A survey on technologies, applications and open research issues*, Journal of Industrial Information Integration, 6, 1–10, 2017.

[2] Alcacer V., Cruz-Machado V., *Scanning the Industry 4.0: A Literature Review on Technologies for Manufacturing Systems*, Engineering Science and Technology, an International Journal, 22, 899–919, 2019.

[3] Dostatni E. et al., *Automation of the Ecodesign Process for Industry 4.0*, In Intelligent Systems in Production Engineering and Maintenance, Springer International Publishing, pp. 533–542, 2019.

[4] Monostori L. et al., *Cyber-physical systems in manufacturing*, CIRP Annals, 65, 2, 621–641, 2016.

[5] Wang L., Törngren M., Onori M., *Current status and advancement of cyber-physical systems in manufacturing*, Journal of Manufacturing Systems, 37, 517–527, 2015.

[6] Mai J., Zhang L., Tao F., Ren L., *Customized production based on distributed 3D printing services in cloud manufacturing*, Int. J. Adv. Manufacturing Technology, 84 (1–4), 71–83, 2016.

[7] Xu D., He W., Li S., *Internet of Things in Industries: a survey*, IEEE Transactions on Industrial Informatics, 10(4), 2233–2243, 2014.

[8] Madakam S., Ramaswamy R., Tripathi S., *Internet of Things (IoT): a literature review*, Journal of Computer and Communications, 3, 164—173, 2015.

[9] Zawadzki P., Żywicki K., *Smart product design and production control for effective mass customization in the Industry 4.0 concept*, Management and Production Engineering Review, 7(3), 105–112, 2016.

[10] Gandomi A., Haider M., *Beyond the hype: big data concepts, methods, and analytics*, International Journal of Information Management, 35(2), 137–144, 2015.

[11] Mourtzis D., Vlachou E., Milas N., *Industrial big data as a result of IoT adoption in manufacturing*, Procedia CIRP, 55, 290–295, 2016.

[12] Kujawinska A. et al., *Assessment of ductile iron casting process with the use of the DRSA method*, Journal of Mining and Metallurgy, 52, 1, 25–34, 2016.

[13] Hozdić E., *Smart factory for Industry 4.0: a review*, International Journal of Modern Manufacturing Technologies, 7(1), 2015.

[14] Siderska J., Jadaan K.S., *Cloud manufacturing: a service-oriented manufacturing paradigm. A review paper*, Engineering Management in Production and Services, 10(1), 22–31, 2018.

[15] Liu Y., Xu X., *Industry 4.0 and cloud manufacturing: a comparative analysis*, ASME. J. Manuf. Sci. Eng., 139(3), 2016.

[16] MacCarthy B., Brabazon P.G., Bramham J., *Fundamental modes of operation for mass customization*, International Journal of Production Economics, 85(3), 289–304, 2003.

[17] Senyo P.K., Addae E., Boateng R., *Cloud computing research: A review of research themes, frameworks, methods and future research directions*, International Journal of Information Management, 38(1), 128-139, 2018.

[18] Gawlik J., *Development and construction of a deep hole drilling machine WCZ 140 CNC with an automatic process monitoring system and its implementation in production*, Cracov Univeristy of Technology, Projekt celowy ROW-III-0472, 2009.

[19] Zawadzki P., *Methodology of KBE System Development for Automated Design of Multivariant Products*, Advances in Manufacturing. Lecture Notes in Mechanical Engineering, Springer, pp. 239–248, 2018.

[20] Kowalski, M., Zawadzki P., *Tooling CAD models preparation process for automated technology design system*, Advances in Manufacturing II, Lecture Notes in Mechanical Engineering, Springer, pp. 36–44, 2019.

[21] Kowalski M., Zawadzki P., *Decomposition of knowledge for automatic programming of CNC machines*, Management and Production Engineering Review, 10, 1, 2019.

[22] Gomez-Jauregui et al., *Education for the Industry of the Future (IoF) with the 3D Experience Platform*, Advances on Mechanics, Design Engineering and Manufacturing, Springer, pp. 761–769, 2019.

[23] Ignaszak Z., Popielarski P., Hajkowski J., Codina E., *Methodology of comparative validation of selected foundry simulation codes*, Archives of Foundry Engineering, 15(4), 37–44, 2015.

[24] Ignaszak Z., Popielarski P., *Sensitivity tests of simulation models used in chosen calculation codes on uncertainty of thermo-mechanical parameters during virtual mechanical stress estimation for ferrous alloy castings*, Defect and Diffusion Forum, 312–315, 758–763, 2011.

[25] Tao F., Cheng J., Qi Q., Zhang M., Zhang H., Sui F., *Digital Twin-driven product design, manufacturing and service with big data*, International Journal of Advanced Manufacturing Technology, 94, 9–12, 2018.

[26] Shafto M. et al., *Modeling, simulation, information technology & processing roadmap*, National Aeronautics and Space Administration, 2012.

[27] Gorski F. et al., *Effective Design of Educational Virtual Reality Applications for Medicine using Knowledge-Engineering Techniques*, Eurasia Journal of Mathematics Science and Technology Education, 13/2, 395–416, 2017.

[28] Syberfeldt A. et al., *Support systems on the industrial shop-floor of the future – operator's perspective on augmented reality*, Procedia CIRP, 44, 108–113, 2016.

[29] Gorski F. et al., *Immersive City Bus Configuration System for Marketing and Sales Education*, Conference: International Conference on Virtual and Augmented Reality in Education (VARE), Book Series: Procedia Computer Science, 75, 137–146, 2015.

[30] Górski F., *Mechanical properties of composite parts manufactured in FDM technology*, Rapid Prototyping Journal, 24, 8, 1281–1287, 2018.

[31] Gardan J., *Additive Manufacturing Technologies: State of the Art and Trends*, International Journal of Production Research 54, 10, 3118–3132, 2016.

[32] Tofail S.A. et al. *Additive manufacturing: scientific and technological challenges, market update and opportunities*, Materials Today, 21(1) 22–37, 2018.

[33] Górski F., *Mechanical properties of parts of medical components produced using additive manufacturing technologies*, Advances in Science and Technology Research Journal, 11, 2, 166–171, 2017.

[34] Górski F., *Influence of process parameters on dimensional accuracy of parts manufactured using fused deposition modeling technology*, Advances in Science and Technology Research Journal, 7, 19, 27–35, 2013.

[35] Cichosz P., Kuzinowski M., *Controlle and mechatronics machine tools* [in Polish: *Sterowane i mechatroniczne narzędzia skrawające*, PWN, Warszawa, 2016.

[36] Min B.-K., O'Neal O., Koren Y., Pasek Z.: *A smart boring tool for proces control*, Mechatronics, 12, 2002.

[37] Information materials of D'Andrea, Komet, Mapal [from 35].

[38] Gawlik J., Plichta J., Świć A., *Production processes* [in Polish: *Procesy produkcyjne*], PWE, Warszawa, 2013.

[39] Wang L., Toerngren M., Onori M., *Current status and advancement of cyber-physical systems in manufacturing*, Journal of Manufacturing Systems, 37, 517–527, 2015.

[40] Liu C., Xu X., *Cyber-physical machine tool – the era of machine tool 4.0*, Procedia CIRP, 63, 70–75, 2017.

[41] Skoczyński W., *Sensors in CNC machine tools* [in Polish: *Sensory w obrabiarkach CNC*], PWN, Warszawa, 2018.

[42] Pajor M., Marchelek K., *Aspects of creating the concept of a smart machine tool* [in Polish: *Aspekty tworzenia koncepcji obrabiarki inteligentnej*], Inżynieria Maszyn, 16, 1–2, 7–39, 2011.

[43] Zawadzka L., *Contemporary problems and directions of development of flexible production systems* [in Polish: *Współczesne problemy i kierunki rozwoju elastycznych systemów produkcyjnych*], Gdańsk: Wydawnictwo Politechniki Gdańskiej, 2007.

[44] Honczarenko J., *Numerically controlled machine tools* [in Polish: *Obrabiarki sterowane numerycznie*], WNT, Warszawa, 2017.

[45] Sładek J., *Coordinate metrology accuracy of systems and measurements*, Springer, 2016.

[46] Hocken R., Pereira P.H., *Coordinate measuring machines and systems*, CRC Press, 2012.

[47] Ratajczyk E., Woźniak A., *Coordinate measuring systems* [in Polish: *Współrzędnościowe systemy pomiarowe*], Oficyna Wydawnicza Politechniki Warszawskiej, Polska, Warszawa, 2016.

[48] Wieczorowski M., Eichner T., Lindner I., Pereira A., *A concept of in-process measurement system for spline forming*, Management and Production Engineering Review 6, 73–81, 2015.

[49] https://www.zeiss.com/metrology/solutions/carbody/inline.html, 15.04.2019.

[50] https://www.nikonmetrology.com/images/brochures/cmm-automation-en.pdf, 15.04.2019.