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A REVIEW AND ANALYSIS OF THE HISTORICAL DEVELOPMENT OF MACHINE TOOLS INTO COMPLEX INTELLIGENT MECHATRONIC SYSTEMS

This paper presents an analytical review of the development of machine tools (MT) into complex mechatronic systems. The basic periods, inventions and achievements in their historical development are marked which are represented in seven stages depending on the most essential changes for each period. Other fundamental and important discoveries and inventions are given along with the immediate achievements and changes which have affected the development of MT. A diagram of the changes in the relationship between the MT mechanical, electronic and software components is presented depending on the rate of development of the different stages as well as an opinion is shared on the conceptual schema of the environment of a future intelligent MT.

1. INTRODUCTION

Machine tools (MT) as a main part of the production systems have a considerable influence on the level and efficiency of the entire production process. In the literature there are different viewpoints and classifications of the periods of development of the production equipment. In most cases it is difficult to answer the question of whether the production equipment creates conditions for the development of science or vice versa. However, it should be clearly stated that this interrelationship is a complex process of mutual supplementation and successive accumulation of knowledge, experience and conditions for their mutual advancement and development.

This paper presents an analytical review of the development of MT from the most primitive means of production to complex mechatronic systems. The basic and most important periods, inventions and achievements are described in their historical development represented in seven stages (Fig. 1).

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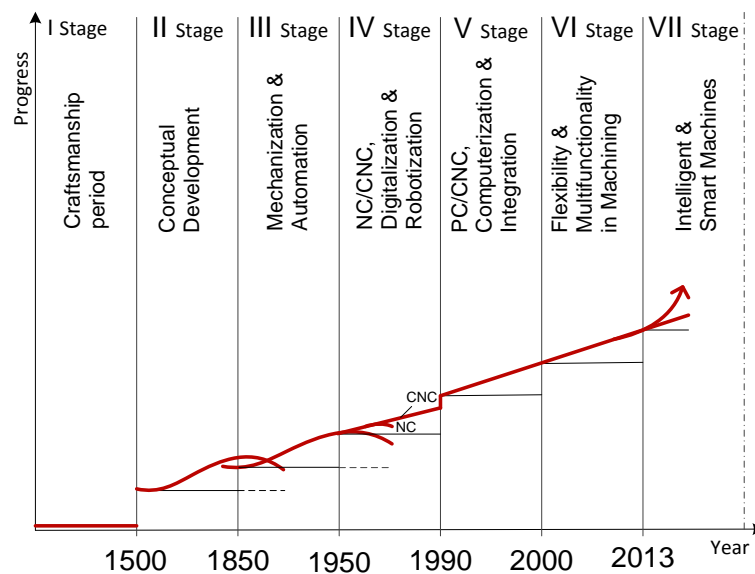


Fig. 1. Schematic representation of the advancement and use of the respective technology/characteristic

2. STAGES

2.1. FIRST STAGE (UP TO 1500 AD)

From a historical perspective the earliest data in scientific literature on a prototype of a “machine” for processing are assumed to be the drawings of tools used mostly for boring holes in bones, non-metallic or soft metal materials [1]. Thus, the picture in which the main production process is hammering and the tools are just a hammer and a chisel was not changed essentially until the 14th -15th cent.

In passing we should mention the indisputable artefacts from the Ancient Times showing definitely serious knowledge in the fields of astronomy, mechanics, mathematics and even robotics. We can provide examples with the various mechanisms mentioned in the works of Plato, Homer, the developments of gear made by Archimedes (3rd cent. BC) which made it possible to develop the Antikythera Mechanism [2] dating back to c. 100 years BC. The first modern inventor Heron of Alexandria invented an automatic device for collecting money donations in a temple (1st cent.AD), etc. Also known are a number of ancient mechanized military devices, musical and entertaining mechanisms, etc.

Water power was the only type of energy for more than 15 centuries and since the middle of the 14th century the water wheel began to be used in metal processing (hammering).

2.2. SECOND STAGE (FROM 1500 TO 1850)

The first lathes for processing screws for clockmakers appeared during the 15th century (1480) and later on lathes for boring cannon barrels (1540) were developed.

Towards the end of the 16th – 17th centuries during the Baroque period the lathes from a technical point of view stopped to develop since they were used mainly for making decorations from wood, ivory or metal for furniture and ornamentations [3].

During the following 15th, 16th and 17th centuries the impact of science increased in the fields of book printing, mathematics, physics and chemistry. The works of Leonardo da Vinci were impressive (15th cent.). He suggested the ideas about a number of innovations including a lathe foot launched by pedal, the principle of milling with a tool resembling a cylindrical file, etc.

In the late 18th century in Great Britain arose conditions favourable for the development of machine-based production of machines. Machine tools filled a need created by textile machinery during the Industrial Revolution in England in the middle to late 1700s [4]. The significant role of H. Maudslay in designing MT should be noted, especially the mechanical carriage design and developed in 1800 the first work-practical screw-cutting lathe, thus introducing the first standardized screw sizes and threads. This lathe laid the basis for machine building and we can assume that it marked the beginning of the conceptual development of machine tools. The Maudslay's screw-cutting lathe allowed the standardization and use of interchangeable parts as a prerequisite for the future mass production. And after a series of improvements Maudslay's mechanical carriage, adapted from the lathe to other types of metal-cutting machine tools, marked the beginning of machine tools with sophisticated working mechanisms [5].

It should be noted the role of other inventors contributed to the development of machine tools: G. Vaucanson (1751, France) developed a lathe having a structure, parameters and functions similar to the modern universal lathes; D. Ramey (1778, England) designed two lathes for thread cutting with constant and variable pitch; Seno (1795, France) designed a specialized lathe for thread cutting, the drive being by a lead screw and interchangeable gears; Maudslay's associate D. Clement, designed a vertical lathe for processing large-diameter workpieces; J. Whitworth (1835, England) made a fundamental improvement inventing the automatic feed in a transverse direction by connecting the transverse and longitudinal feeds; E. Whitney (in the 1820's and 1830's) developed several designs for milling machines for the Colt arms plants (USA); the patent for a milling machine issued in the name of J. Naismith (1829, England) [1,6].

A considerable breakthrough and a step forward is the copying lathe designed by Th. Blanchard (1818). That was an important step in the development of the mass production lines which would grow into a trend during the following stage. The invention of the milling machine (I. Uitni, 1818), the automatic woodworking lathe (K. Vippil, 1842), the first turret lathe (S. Fitch, 1845) followed. In summary, those designs during the first half of the 19th century can be assumed to have shaped up the ideas and conceptions of the main types of MT.

An indisputable stimulus for the development of production and, in particular, MT was the use of steam as a driving force. During that stage the beginning of another decisive power in the future development of the industrial production can be marked, and in particular, of MT, namely, the principle of conversion of electrical energy into mechanical energy (M. Faraday, 1821) as well as the DC electric motor invented by Th. Davenport (1837).

2.3. THIRD STAGE (FROM 1500 TO 1850)

The third stage in the MT development was characterized by a process of further improvement in the area of mechanization and automation. Elements for complete mechanization of processing were introduced such as automatic control along two coordinate axes; automatic adjustment of tools and processed workpieces; fast change in the cutting operation mode, etc. [7-9]. At that time the series production of lathes started introducing interchangeability of workpieces and units manufactured by one company (USA, 1850).

The efforts for improving MT were directed towards enhancing the automation of the processing cycle. In 1854 the first turret with replaceable tools was designed and Hr. Spencer invented the first versatile engine automatic lathe (1873). In the period 1870 – 1890, based on the aforementioned developments, “automatic” turret lathes (on the basis of cams) were designed and distributed which could be used to implement part-cutting cycles without human intervention. Other concepts and types of machines appeared such as the horizontal boring machine (1874) operating with natural cylindrical abrasives and after carborundum was invented, artificially synthesized discs began to be used (1893).

Along with the still missing individual stable drive, the next step in the MT development was the improvement of the component base and the connections and contact between the moving links of the machines. Thus we come to 1883 when Fr. Fischer [10] invented the technology of steel ball manufacturing and in 1898 Cleveland Machine Screw Co. published for the first time the Ball Screws [11]. These two inventions opened the way to a considerable increase in the quality and efficiency of MT.

The discovery which became the symbol and motor of that stage was the introduction of the electric drive and the design of an effective electric power transmission system by means of alternating current (N. Tesla, 1888).

A strong impact on steelmaking and, hence, on machine building and particularly on the MT development had the Bessemer converter (H. Bessemer, 1856) and the Martin process (P. Martin, 1863) for steelmaking. World depressions also played an important part by creating prerequisites for competition between companies thus practically becoming generators of the Industrial Revolution.

The discovery of tungsten carbide (A. Moissan, 1893), the scientific approach to metal cutting (Paris, 1900) and the high-speed tools (F. W. Taylor & M. White, 1906) contributed to the development of technology and the design of the first assembly line (Vicker Sons & Maxim Gun Factory, 1900), and the introduction of the production line (Ford, 1909) marked the beginning of a new organization of production.

2.4. FOURTH STAGE (FROM 1950 TO 1990)

The beginning of this stage is related to the fast development in the field of digitalization and robotization of the production processes and production in general. The first numerical control MT (NC) (MIT, USA, 1952) was created as well as the first

industrial programmable robot Unimate (G. Devol, 1954), the thyristor (General Electric, 1956), the first commercial applications of ball screws (1956), the first practically applicable machining centre Milwaukee-Matic Model II (Kearney & Trecker Corp., 1958), the integral circuit (1959), the first standard programming language G-Code (MIT, the early 1960s), the DNC systems (1960).

As a result more than 80 different NC machine tools were exhibited at the Chicago World's Fair (1960). For a period of seven years (1959 – 1965) the number of sold MTs increased by approx. 40% (from 200 to approx. 2050). That rate of MT production continued after 1965 (up to 1978) [12].

The implementation of the new type of numerical control set in the next more than fifty years three big technological innovations (NC, CNC and PC), named “waves” [12], and had a major effect on the machine tool industry. There are various classifications of the types of the machine tool's control (e.g. generations of the NC controller). But for the purpose of this study these three major innovations have been adopted. These innovations can be observed during which the new technologies experienced strong diffusion and were implemented in machine tools. The first wave obviously was the introduction of numerical controls for machine tools in the 1950s and 1960s; the second - in the 1970s and 1980s was triggered by the implementation and development of microcomputers for numerical controls and the third wave – after 90s development was triggered by the effect computers had on the entire value chain. The ultimate goal is to integrate and automate the entire production process [12].

The implementation of the numerical control set certain requirements to MT in the next years from: 1) a structural perspective (change in the architectural concept - body configuration, placement and allocation of structural units (beds guideways, ribbing, etc.) aiming to reduce the thermal deformation [13], enhancement of the flexibility, stability and reliability of the machine, improvement of the precision of mechanical parts and component base etc.); 2) a technological perspective (combination of functions and integration of mechanical operations in one machine, new instrumental and construction materials, etc.); 3) an organizational perspective (enhancement of the flexibility of machines, transfer to batch production) and 4) a scientific perspective (the use of mathematical methods of optimization, development of the research activity, etc.).

The main trends in the development were directed towards creating designs and mechanisms of high reliability, long life and high efficiency. That, in turn, required the use of standardized/unified machine components and units with high kinematic capacities which are characterized by high precision and operational reliability. A process of miniaturization and development of software industry began in the field of electronics.

The intensive development of machine building during the 1970s created prerequisites for disintegration in the competences and a change in the value chain which gave companies competitive advantage [14]. The competence of MT producing companies to manufacture precise mechanics led to creating know-how in electrical engineering and electronics (intel and Busicom designed the microprocessor in 1971) and the digital control systems allowed the production of more precise machines and specialization in different directions. Individual specialized modules and systems were bought primarily by specialized companies.

In 1973 Siemens used a computer process for the first time and in 1976 Sinumerik 7 was the first to use a microprocessor thus marking the beginning of a new development of CNC systems in the direction of microcomputers, making them reprogrammable. A process of separating hardware from software began and, hence, the possibility to personalize the control systems in the various types of MT. A series of improved versions designed by Sinumerik followed thereby turning it into a leading company in that field.

As a result of the increase in production and decrease in the price of microprocessors from 1978 to 1984, the sales of CNC machines grew by approx. 30-40% per year. The price of a microcomputer system item in 1973 went down by approx. 50% as compared to that of an NC item in 1963 [12].

Most industrially developed countries began to create national programs including universities in close cooperation with the industry and industrial organizations in order to meet those needs, accelerate and enhance the development and implementation of the CNC control. At the same time, demand for goods in society is moving toward more individualization and diversification. At the same time, demand for goods in society is moving toward more individualisation and diversification. This requires a high flexibility of machines and systems to produce in smaller batches and in a larger variety. A large Japanese R&D project FMSC (Flexible Manufacturing System Complex) provided with Laser [15,16] is one of the internationally outstanding activities in high technology for flexible manufacturing in small volume production. In the field of machining the purpose has been to develop a multi-functioned machining system (machining complex), in which the processing functions of cutting, grinding, quenching, welding, and measurement of parts are integrated. In this system, modular units can be recombined according to required machining functions. A number of different production systems (a headstock, requiring machining and assembly functions with high accuracy; a second movable spindle; a biaxial gear box, consisting of various part configurations and requiring complicated machining and assembly functions) have been developed, installed and integrated at the Tsukuba test plant.

The inventions and innovations created in the 1980s had a strong impact on the MT development. The step less spindle speed control permitted the continuation of the fundamental investigations in the area of cutting processes and allowed the transfer to simplifying and even eliminating gear boxes. Magnetic bearing was first applied in 1980 (IPEMT, Darmstadt University of Technology) and the introduction of the AC servo motors (Fanuc, 1982) improved considerably the MT feed transmission. The first personal computer IBM PC (Don Estridzh) was invented in 1981. In the same year the MAZAK Co. introduced the first dialogue programmed CNC system MAZATROL. Another important invention is stereolithography (Ch. W. Hull, 1983), later called 3D printing or additive manufacturing (AM).

At the beginning of the 1980s Computer-integrated manufacturing began to be developed and promoted by machine tool manufacturers and the Computer and Automated Systems Association and Society of Manufacturing Engineers (CASA/SME) of the USA [11]. The principal roles of the computer in the information processing cycle is to integrate the different functions (design, manufacturing, and business operations) into a unified, well-coordinated, and smooth-running system. This requires extremely high flexibility in the manufacturing system.

With increasing the degree of automation and digitalization of MT the need arose for a new generation of sensors for measuring speeds, sizes and shapes in a digital form in real time towards a digital control of the entire system. The need for a change in the concept of programming by creating hierarchically structured computer languages also arose. The demand was to express the commands in words rather than in codes and to compile automatically subprograms in an integral program system.

During that stage a value reassessment of the market image of the MT producers was made. The CNC systems forced producers to increase even more the accuracy requirements to machines, and hence, change the criteria for their assessment, making the price a quality indicator.

Another characteristic feature of the stage is the massive invasion of Japanese companies at the beginning of the 1980s on the world export market (especially the US market) and the beat-down of the prices of the western producers by more than 50%. The reason for that is the fact that in the years of the two oil crises (1973 and 1978), while most companies reduced their investments for new technologies, the Japanese companies gave priorities to the CNC technologies. The Japanese production in 1976 got ahead of the USA and has since stayed at the top becoming a catalyst for the development of the market since 1978 [12,17-19].

At that stage a fast process of software development started. This was a transition from the paper-based to CAD, CAM, the step-by-step implementation of the software systems MRP and MRPII, PPS, ERP and a number of other systems aiming at the integration and automation of the entire production process.

In 1987 the server was designed as a means of centralized data storage and in 1990 the first module open structure based on Windows was created. These innovations were symbols of the next stage in the development of MT (the CNC-PC symbiosis).

2.5. FIFTH STAGE (FROM 1990 TO 2000)

At the beginning of this stage the introduction of the PC and CNC systems in the MT control was carried out. The first PC/CNC models were still limited in terms of processor capacities and memory although they offered better alternative solutions. In 1994 those deficiencies were overcome by the producers of control systems (e.g. Siemens and Fanuc) through building PC in the CNC modules. A process began of replacing older programming languages with graphic user interface, the use of local networks for access and data transmission. In 1996 Siemens developed the first safety integrated CNC system [20].

This stage is characterized by: 1) a change in the competitive environment (the German producers regained their positions and along with the dominant role of the Japanese producers, Taiwan, Korea and China entered the market as strong competitors); 2) ultramodern technology was created (ultra-high speed, ultra-precise accuracy); 3) high production efficiency was achieved.

This stage should also be noted for the fact that on August 6th, 1991 the World Wide Web project was announced concerning the universal information system of hypertext documents enhancing the popularity of Internet.

In the period 1997–2002 large-scale activities were carried out by university research teams and leading companies directed towards the development of concepts and strategies for scientific research in the field of intelligent computer control thus giving impetus to the development of control systems and MT during the following years [4, 21-23].

There was a growing tendency towards combining the machining operations performed on one machine as well as the workpieces processed at one installation/on one machine. In 1992, INDEX presented a new generation of “Mill-turn” centres based on a modular component system. Another good example is Hardpoint concept of Erwin Junker Machinery Inc., Mori Seiki NL Series, Mazak Integrex Model 200-III ST, etc.). The machines are equipped with the respective tools suitable for machining complex workpieces by turning, drilling, threading, cutting and gear grinding. The concepts, similar to Integrex, combine information and production technologies in one machine with the view to widening the scope of the processed products.

The growing tendency towards shortening the product life-cycle and the fast technological development changed the conception of certain complex processing sectors lacking the necessary flexibility and efficiency. This called for creating concepts for module construction with possibilities for structural reconfiguration of machines in order to meet adequately the market changes and requirements for frequent change in the production program. Hence the need arose for combining more flexibility and “intelligence” in the next MT generation.

As a result, in the middle of the 1990s began a process of a series of innovations in the MT structural design. Based on the well-known HEXAPOD manipulation structure, parallel kinematic MTs as well as hybrid kinematic MTs were designed [4]. Those concepts called for the creation of a number of innovations related to the drive method: six-degree-of-freedom of the tool/workpiece; controlled balancing and dynamics of motion of the actuating device; machine flexibility, etc. The other novelties in this direction are the reconfigurable MTs allowing an increase in both flexibility and productivity. That is a machining system which can be created by incorporating basic process modules (both hardware and software) that can be rearranged or replaced quickly and reliably [24-26].

2.6. SIXTH STAGE (2000 - 2013)

The beginning of the 21st century is associated with the development of the ICT technologies. The first expectations that they could solve common problems turned into a driving force for the highly complicated economic progress. This stage is marked by the strong advancement in the field of integrated production machines and systems with extensive use of smart and sensor components, artificial neuron networks, devices using the principles of fuzzy logic, telecommunication and global production networks, internet and high-speed information systems [27-29]. “Machine simulation” and “virtual prototyping” gained a strong impetus (e.g. Siemens). The newly developed simulators allow the procedures for machine processing and the entire production process to be analysed in virtual mode whereas the virtual CNC control permits integration into commercial simulation systems. A number of tools for the end users include web-based monitoring

of the condition and platforms for online diagnostics, online maintenance as well as various online services.

Another tendency is related to the development of nanotechnologies and, hence, the need for designing super precision machines (sinking, grinding, polishing, lapping) with resolution of the order of 1-10 nm.

In 2005 Siemens put on the market a new generation of PLC Sinumerik 840D SL based on Sinamics S120 with possibilities for communication through Industrial Ethernet /Profi net. Since 2008 began a process of integrating and merging of the CNC hardware with the CAD/CAM-CNC processes which was realized by developing Sinumerik Mdynamics (2010) for Sinumerik 840Dsl and Sinumerik 828D [20]. This resulted in improving the graphic images of the new standard Sinumerik user interface and Sinumerik Operate was extended by using day-to-day practical functions through “copy” and “paste” thus helping the intuitive use of the user’s interface on the part of the operator.

In 2005 started the fourth generation of multifunctional machines (horizontal machining center) manufactured by MAZAK (Integrex®IV Series) which are designed for performing various operations such as turning, milling, drilling, thread cutting and grinding for processing rotational and prismatic workpieces. “Mill-Turn” and “Turn-grind” centres of the Index Group combine the advantages of the turning, grinding and milling processes, such as shorter cycle times, high quality and maximum process safety [28].

The next step was the use of information networks in real time for production control (e.g. MERLIN, 2013) and a machine-to-machine/M2M communication platform designed by Memex Automation. These innovations allowed the fast evaluation of the effectiveness and maximization of the production efficiency[29].

In the field of machine control a significant step forward is the new MAZATROL SmoothX CNC. It is a famous component of the Smooth Technology package of the Mazak Co. [30, 31]. According to Mazak, this CNC system has brought about a four-fold increase in the speed compared with the previous generation of machines [34]. The “smooth technology” platform is an umbrella term designating a fully integrated package involving machine design, engineering maintenance, CNC technologies and decision making.

With including more operations in one machine, adding operations such as 3D printing, welding, etc. to the mechanical processing operation, the term “hybridity” began to acquire a different meaning for multi-tasking machines (2014). Such is the case with the hybrid MTs of the Mazak Corporation Integrex i-400 AM and VTC-530/20 FSW. Integrex i-400 AM is a multifunctional machine with an integrated 3D Fiber laser printer, operating with metal dust for adding material to the workpiece including marking and subsequent full 5-axis turning and milling operations. VTC-530/20 FSW is a vertical machining centre with a highly technological head for frictional welding of metals, thermoplastics, etc. by abrasive heating followed by milling [32].

Since the beginning of the 21st century a considerable growth has been noted in the development, production and sales of 3D printers (AM machines). According to Wohler’s Associates, the sales of 3D printers and services in 2012 amounted to \$2.2 billion worldwide, a 29% increase as compared with 2011. Nowadays the AM technologies are being applied in all fields of industry [23, 36-38].

Figure 2 shows the development of MT according to the rate-of-change coefficient $\left(\frac{x-x_i}{x_i}\right)$, where: x is the period from the beginning of the available information and x_i is the duration of the i^{th} stage in years. It can be seen from this figure that the curve of the latest century acquires a strongly singular character (structural and technological singularity).

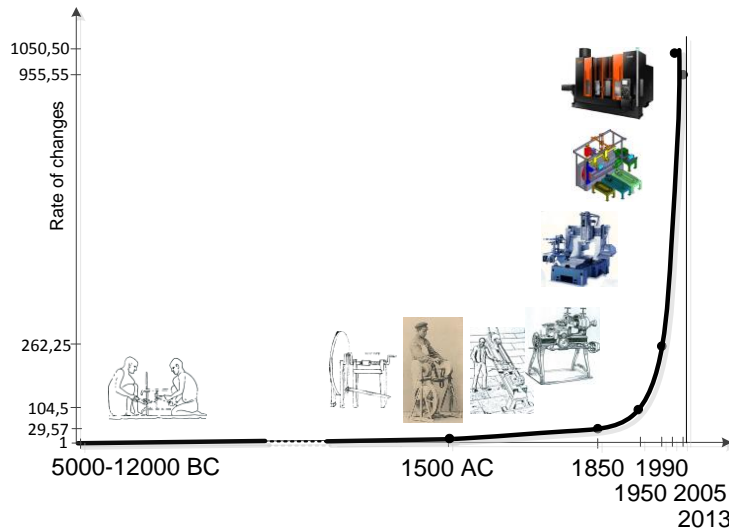


Fig. 2. MT development according to the rate of changes

The relationship between the relative weight of the mechanical, electronic and software components of machine tools has changed over the periods of historical development (Fig. 3). It can be seen from this figure that since the 1950s (stage 4) the relative weight of the programming units and software has increased at the expense of the MT mechanical, electrical and electronic system.

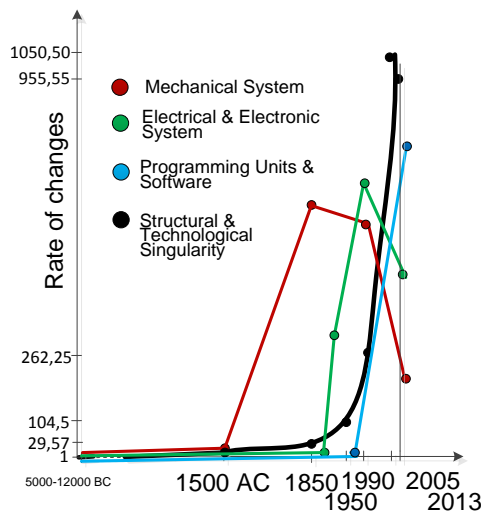


Fig. 3. Change in the relationship between the mechanical, electronic and software components of machine tools

2.7. SEVENTH STAGE (AFTER 2013)

This stage is identified by the project related to the Fourth Industrial Revolution (Industry 4.0). This term was first announced at the Hanover Fair (2011). In April 2013 a cooperation agreement was signed through association, the start of the Industry 4.0 Platform being officially announced at the Hanover Fair 2013.

The Industry 4.0 concept is based on the SIEMENS leading solutions for digital design and product manufacturing. These solutions are expected to create conditions for the automation of the entire life cycle of the products as well as integration of cyber-physical systems which design virtual copies of the physical world in order to trace the physical production processes, communicate and make decentralized decision by themselves in real time. In other words, the basic principles of the implementation of the so-called “smart factories” include: interoperability; virtualization; decentralization; possibility to operate in real time; orientation towards services and modularity [27, 39-41].

It is difficult to predict the future changes resulting from the principles underlying Industry 4.0 but they will certainly affect the development of MT, the main trends being in the direction of: the use of new materials and improvement of the component base relating to reliability, speed, metal and energy consumption, aesthetic properties, etc.; new design solutions based on self-organization; development of the principles and components of artificial intelligence and smart technologies. All that will make the machine tool a complex, smart system as is shown in the exemplary conceptual schema in Fig. 4.

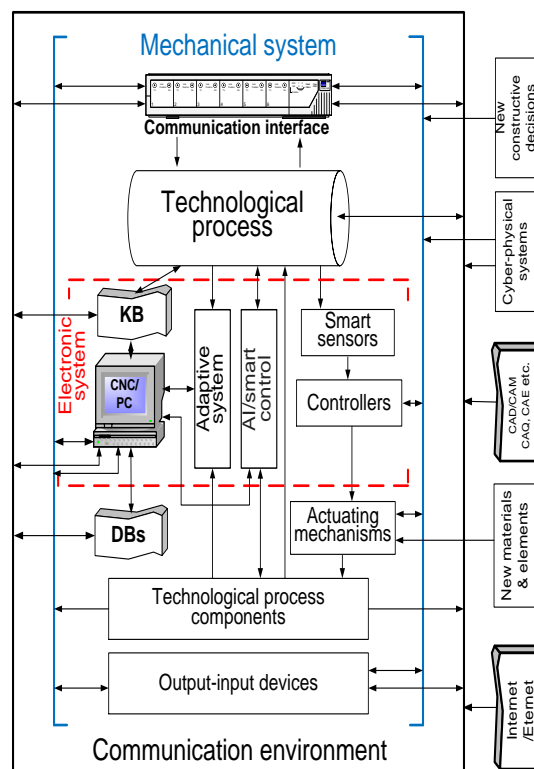


Fig. 4. Conceptual schema of a smart MT

3. CONCLUSION

The article presents in seven stages the main and significant innovations and inventions in the development of machine tools. A detailed analysis is made of the present state of production and market environment as a result of the MT development and, vice versa, the impact of the market environment on their development. From the diagram proposed concerning the MT development according to the rate of changes during each stage it can be seen that during the latest century the curve of structural and technological changes has acquired a strongly singular character. This tendency of fast intensification of the development will definitely lead, along with increasing the variety and level of production, to inevitable problems and the occurrence of various risk factors as well as the need for changes in the field of education, namely, the training of a new type of specialists with new competences and mentality. From the proposed diagram of the changes in the relationship between the mechanical, electronic and software components of machine tools it can be seen that the relative weight of the program units and software has considerably increased since the beginning of the process of digitalization in 1950s. An opinion on the conceptual schema of development of the environment for a smart MT is shared.

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