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ARCHITECTURE OF SUPERVISORY SYSTEMS FOR SUBTRACTIVE MANUFACTURING PROCESSES IN INDUSTRY 4.0 BASED MANUFACTURING

Key words: Subtractive processes, supervision, Industry 4.0, cyber-physical systems, artificial intelligence shell systems.

Abstract: General design rules and algorithms for supervisory systems of subtractive manufacturing processes in INDUSTRY 4.0- based manufacturing are presented in the paper. They are formulated based on the analysis of the communication standards for manufacturing integration, the idea of cyber-physical systems, and the architecture of supervisory systems operating locally. It is assumed that the monitoring and signal conditioning functions can be performed locally by a given production site, whereas the measurement signals processing aiming at signal features extraction, features selection and integration as well as a diagnostic decision making can be performed in the cyber space of the whole production system. Therefore, in accordance with the CPS idea, they will be available for its each element. In consequence, the separation of monitoring and signal conditioning functions from signal processing and decision-making functions creates the possibility to base the development of the proposed systems for collaborative supervision of subtractive manufacturing processes on the methodology of shell artificial intelligence systems development.

Architektura systemów nadzorowania procesów obróbki ubytkowej w wytwarzaniu według koncepcji Industry 4.0

Słowa kluczowe: obróbka ubytkowa, nadzorowanie, Industry 4.0, systemy cybernetyczno-fizyczne, szkieletowe systemy sztucznej inteligencji.

Streszczenie: W artykule zaproponowano zasady budowy i algorytmy działania szkieletowych systemów nadzorowania dyskretnych procesów obróbkowych opartych na idei systemów cybernetyczno-fizycznych będących elementem koncepcji wytwarzania INDUSTRY 4.0. Założono, że funkcje monitorowania i wstępnego przetworzenia sygnałów pomiarowych mogą być realizowane lokalnie przez dane stanowisko pracy, natomiast funkcje związane z przetwarzaniem sygnałów mającym na celu wyznaczenie symptomów stanu obiektu nadzorowanego, selekcję i integrację tych symptomów oraz podejmowanie decyzji mogą być realizowane w przestrzeni cybernetycznej całego systemu produkcyjnego i w związku z tym, zgodnie z ideą CPS, będą dostępne dla każdego jego elementu. Rozdzielenie funkcji monitorowania od funkcji przetwarzania sygnałów pomiarowych i podejmowania decyzji powoduje, że budowa proponowanego systemu może być oparta na metodyce budowy szkieletowych systemów sztucznej inteligencji oferujących uniwersalny, w ramach określonej metody, wielowariantowy mechanizm przetwarzania i integracji danych, który jest zdolny do modelowania stanu obiektu w oparciu o dostarczone dane bieżące. Tak skonstruowany system, po dostarczeniu odpowiednio sformalizowanej wiedzy dziedzinowej i danych, będzie mógł obsługiwać różne rodzaje produkcji.

Introduction

One of the basic factors influencing the development of manufacturing technologies is the automation of machining processes. It is motivated by economic considerations, very high requirements for products quality and safety, and the comfort of work conditions. The development of mechanical design, drives, electronic devices, information technologies, as well as the achievements of control theory and mechanical technologies results in the increase of the autonomy of automated machining systems. It means that the necessity of the supervision of machining processes by human being operators can be significantly reduced.

The automatic supervision of production processes belongs to the most advanced features of the autonomy of every machining system. Such a supervision takes into its operation scope not only the course of the a priori established program of machining but also responds to different disturbances including slowly-changing and rare occurrences such as a tool wear or cooling system failure.

Possibilities of the contemporary microprocessors, the development of the data transmission standards and the Internet offer new prospects for linking single production sites into integrated, computer-controlled systems to build systems like Flexible Manufacturing Systems (FMS). These systems, using Local Area Networks (LAN) and standard industrial communication networks (e.g., Ethernet, Profibus, or Fieldbus) can collaborate with business and operations management sections as well as, through the Internet, with a group of cooperating companies. The automated supervision of such machining systems has become a necessity, but new capabilities in this field have been simultaneously created. It has aroused an increased interest of the industry in trustworthy, reliable, and easily operated automated supervision systems for manufacturing operations. This interest has found a reflection in many research works in this field around the world [1, 2, 8–11, 15–17, 21–23]. Although results of these works enable more advanced supervisory systems to be built, no specific solutions are available in the field of such systems integration with other systems of this type (horizontal integration) and with other components of the factory communication structure (vertical integration). Such an integration would improve the efficiency and the area of the application of supervisory systems in manufacturing.

1. Communication standards in manufacturing integration

The ISA-95 standard is now a basic international standard for models of information exchange in factory floor integration. It shows management and production control in a factory as a multilevel hierarchical structure [13]. Figure 1 illustrates this structure showing the functions of its individual levels and types of software for their execution.

The ISA-95 standard was mainly developed to unify data exchange between MES and ERP class systems [12]. Communication information model between these systems is implemented with the Business to Manufacturing Markup Language (B2MML), which is a functional implementation of eXtensible Markup Language (XML) developed just for the ISA-95 standard [12]. However, communication of the MES class systems with components of the lower levels as well as data exchange between the levels 1, 2, and 3 is not subjected to such homogeneous standards. Only the newest versions of MES allow the open standards to be used for such aims [22]. The OPC-UA standard (OLE for Process Control – Unified Architecture) especially offers a broad scope for data processing and exchange between the lower levels of the factory communication structure [19]. Among others, the data format in OLE-UA can be also based on XML. However, the open standards require standardization already on the stage of system design, which limits its elasticity in terms of measurement, diagnostic, and optimization procedures integration with the standard CNC procedures [7]. Another drawback of the ISA-95 standard is the lack of capacity for direct information exchange between individual production system physical components and their software, which is the lack of interoperability between them, and it is very important for their horizontal integration. These problems can be solved with the aid of the MTConnect protocol implemented recently by the Association for Manufacturing Technology (USA). This is an open source, royalty free standard for information exchange and utilization by different components of the machining systems [4, 13, 19]. It is based on the interoperability idea in relation to software and hardware, which enables the information exchange regardless of the standard used for this formerly. Figure 2 shows an overview of the MTConnect architecture.

The "MTConnect Device" is an element of equipment (machine tool, control unit, sensor, etc.) which is a source of data. A specific data going from

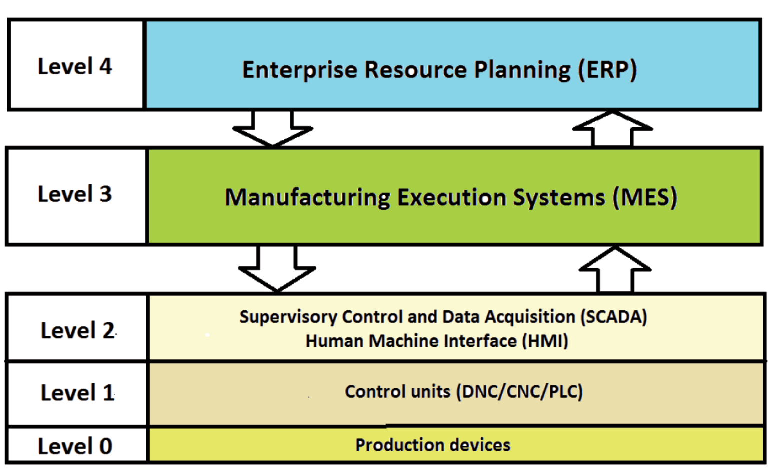

Fig. 1. Hierarchical structure of ISA-95 industrial communication standard

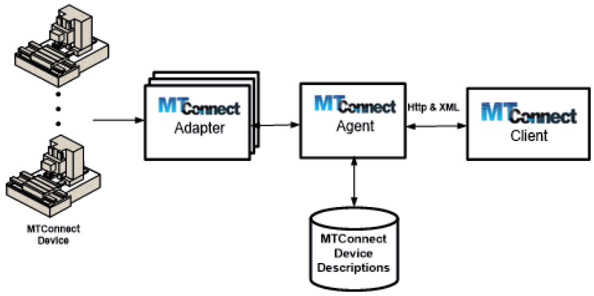

Fig. 2. MTConnect architecture [19]

a device is converted into the format accepted by the remaining elements of the system by the "Adapter." The "Agent" is a server working as a bridge between one or more devices and the "Client," which is an application requiring a specific functionality from the agent. The web based client applications use http and XML to access the agent, requiring from it such services as data processing for process state assessment or other types of process knowledge. The functionalities provided by the server collaborate with "Devise Descriptions" which are a set of device data models. In this way, MTConnect offers an information model enabling the development of current real-time models of different production system elements providing the highest level of interoperability [19].

Originally, MTConnect was developed as a standard for data exchange between physical devices of machining systems to support their maintenance and management. However, in the case of supervisory systems for subtractive processes, the nature of the data requires processing is different, because they usually are a time series of signals characterizing the supervised process course. Thus, MTConnect procedures will have to be adapted to such signals processing.

2. Cyber-Physical Systems

The newest approach to the problem of information exchange between executive components of production systems (levels 0, 1, 2) are the cyber-physical systems (CPS) [14]. They are elements of the conception of the fourth industrial revolution frequently named "Industry 4.0" [6]. This conception assumes that machines and production devices will be able to identify their own current state as well as the state of the process performed by them. They also will be able to communicate with each other using an advanced network. It will allow manufacturing to be based on the collaboration of the all participants of the production process (Collaborative Manufacturing) [3], so a decentralized, more intelligent and flexible production control based on information coming from monitoring systems of individual production sites will be possible.

To be implemented, such a conception requires present, local monitoring and production control systems to be replaced with the cyber-physical systems that link cyber space of the Internet with the material space of production. Information obtained from CPS can be utilized locally (as happens currently), or/and it can be sent to the network called Internet of Things where, after some processing, can be made available for and utilized by all elements of the production system to optimize its performance. Because integration of control and diagnostic systems acting on the lowest levels of production still is in an initial stage of development, there is a need to develop design rules and algorithms for collaborative supervisory systems capable of exchanging information with each other as well as with higher levels of production.

Figure 3 presents the 5-level architecture of CPS, which clearly defines how to implement CPS, beginning

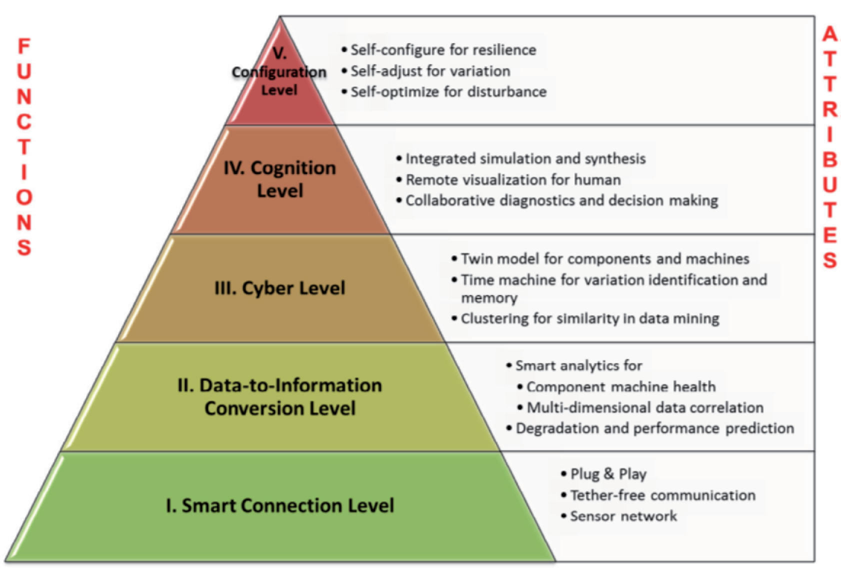

Fig. 3. 5-level architecture for implementation of Cyber-Physical System [14]

from the level of an object data acquisition to the level of a reliable knowledge about the object state [14].

The guidelines for manufacturing CPS results from the ISA-95 standard and are related to different time-based demands and computational requirements of a given manufacturing system [18].

3. Architecture of supervisory systems for subtractive processes in Industry 4.0.

One or more sensors generating analogue signals characterizing the state of supervised process are the basis of each automatic supervisory system for production processes. The measured analogue signals have to be conditioned to adapt them to the requirements of next stages of their processing. The final stage of signal conditioning is the conversion of the signals into a digital form. All the conditioning procedures are performed by hardware. Next, the digital signals can be processed only by software procedures. These procedures include feature extraction and selection to find such signal features that allow different models of the process outputs to be developed, and then they can be used in the application of these models for fault detection and the process state classification. The flow chart of the described supervisory functions is illustrated in Fig. 4.

Information processing technology offered by CPS allows the following innovative approach to be adopted. In supervisory systems for subtractive processes working according to Industry 4.0 conception, the monitoring and signal conditioning functions can be performed locally by a given production site, whereas the measurement signals processing aiming at signal features extraction, features selection, and integration as well as diagnostic decision making can be performed in the cyber space of the whole production system; so that, in accordance with the CPS idea, they would be available for each of its elements.

Formulation of the above approach results from the fact that signal features extraction, features selection and integration, as well as a diagnostic decision making are the function performed by a software regardless of the symptom type and the object type. Furthermore, execution of these functions in the shared cyber space will make possible the utilization of "historical" and comparative data simultaneously for the all objects collaborating with each other in the production system. In contrast, the monitoring functions are performed by hardware, so they have to be assigned to the individual production sites.

Taking into account the proposed approach, the new architecture of the supervisory system for subtractive manufacturing processes can be illustrated by the structure presented in Fig. 5.

The separation of monitoring and signal conditioning functions from signal processing and decision-making functions creates the possibility to base the development of the proposed systems for the collaborative supervision of subtractive manufacturing processes on the methodology of artificial intelligence shell systems development. Such systems offer a universal, in the framework of a given artificial intelligence method, multi-option data processing and an integration engine that is able to model the object state based on the provided data.

The development of methods of reliable data acquisition from different sources (sensors, controllers, MES and ERP systems) should be a starting point of the CPS based supervisory system for subtractive processes. The MTConnect protocol should be used with this aim in view.

Establishing of a set of data processing algorithms available in the system would be the next stage. These algorithms should offer a broad spectrum of signal features that are useful for the implementation of diagnostics of the system components. The algorithms of the frequency analysis (FFT), time time-frequency analysis (wavelet transform), as well as the algorithms of signal analysis in the time domain, especially the principal component and the independent component analysis, should be used [12].

Diagnostic methods, including prognostics and health management procedures should be based on the statistical and artificial intelligence techniques [12, 16, 17, 21]. All diagnostic procedures have to work in the

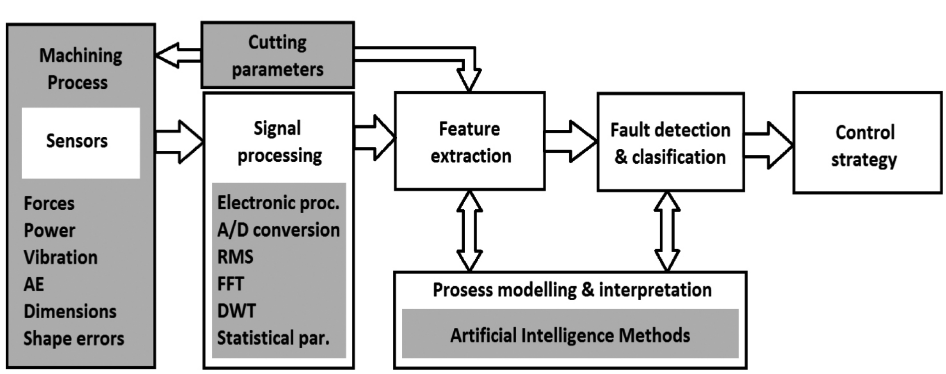

Fig. 4. Functional units of the supervisory system working locally

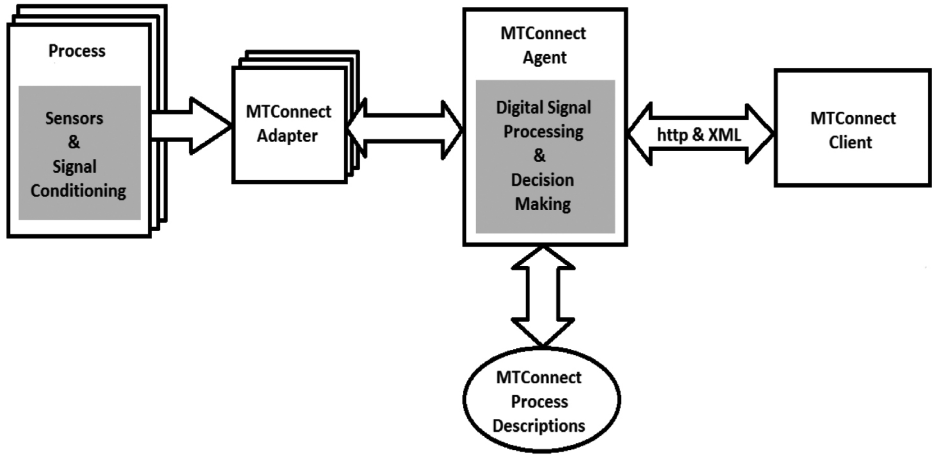

Fig. 5. New architecture of the supervisory system for subtractive manufacturing processes

CPS framework. Thus, a peer-to-peer network model of the CPS has be developed. This model will utilize the "time machine" idea, which is a method allowing a historical data to be taken into account for a typical malfunction pattern recognition [14].

Conclusions

The creation of a unified communication platform securing the standardization of the direct exchange of information in the production system is the main task for the CPS. Thus, the development of general design rules and algorithms of them for use in the collaborative supervision of subtractive manufacturing processes of machines will have a significant contribution in the transformation of today's factories into Industry 4.0 factories with higher technical and economic potential. The development of the proposed diagnostic system with the aid of the artificial intelligence shell system building methodology will result in the availability of the system to serve different types of the subtractive manufacturing processes and work with all types of data.

Cloud computing is the next step in the development of the proposed system [5, 18]. All the diagnostic procedures carried out in the CPS framework require a huge amount of data to be processed. Thus, the utilization of cloud computing as a communication network delivering different computational services carries new opportunities in this area and accelerates the introduction of such advanced manufacturing technologies into practice. By utilizing data from all manufacturing hierarchy levels, cloud computing increases the efficiency of data processing and integration. It forms a practical tool for the realization of the Internet of Things and cyber-physical systems.

Cloud computing also gives new opportunities for bringing into practice prognosis-centred technologies in processes and equipment supervision. There are many prognosis methods, but their applications are specific. Application of crowdsourcing is an opportunity (as well as a challenge) to solve the main problem in this area, because it is the means of fusing a variety of data [5]. Generally, the opportunity and challenge in cloud-based manufacturing supervision is the efficient allocation of a huge amount of different data and the results of their processing in on-line mode.

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