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MANUFACTURING
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Development of cyber-physical production systems based on modelling technologies

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Abstract. Internet of Things (IoT) is extending quite rapidly into the physical and virtual manufacturing worlds. IoT facilitates digitalization of manufacturing systems, which are considered vitally important to enhance the effectiveness and efficiency in the future manufacturing era. In order to compete globally and to meet the rapid market changes, manufacturing companies should consider implementation of manufacturing systems that are self-organized and decreasing constant human intervention to a minimum, still keeping the process under human control. In this paper, authors used the concept of Industry 4.0 to upgrade the manufacturing system according to the modern manufacturing needs. Manufacturing systems of Industry 4.0 are called cyber-physical production systems (CPPSs). On the other hand, modelling technologies such as process and data modelling, help to establish and understand the performance of a production system, as the evaluation of the control of an automated production system helps to make it reconfigurable and leads to grasping the idea behind the control mechanism of a CPPS. The aim of the paper is to develop a CPPS based on modelling technologies and to propose a concept of upgrading a relatively traditional production system.

Key words: CPPS, process and data modelling, manufacturing systems, IoT.

1. INTRODUCTION

Nowadays, the manufacturing industry is facing significant challenges. The ever-growing consumer market demands new, sophisticated and high-quality products while retaining their low price and short production times. Also, as compared to what the situation was twenty years ago, product lifecycles have decreased dramatically, which forces the manufacturing companies to discover new and more efficient ways of producing goods and offering services [1]. Production lines of the future would not be easily upgraded, they should rather upgrade themselves. Moreover, Industry 4.0 paradigm interconnects the parts of a production line, thanks to embedded systems, i.e. tiny computers, sensors and actuators built into the manufacturing system, forming an industrial IoT. The manufacturer is usually slow in implementing new technologies and accepting new approaches when doing ordinary tasks, which potentially results in substantial monetary losses. Already today, by implementing newer technology and techniques, production could be made faster and more efficient, resulting in savings for both – for companies and their customers, and in decreasing our impact on the environment. As humanity moves towards total reusability and environmental friendliness, our vehicles become electric, our rockets are designed to fly for dozens of times and we try to recycle materials as much as possible.

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Companies do not build different factories to produce products with different shape and size. Instead, the production line should be updated to fit new requirements. Therefore, production lines of the future should not only be easily reconfigurable but they should also update themselves. It is, therefore, logical for the manufacturing itself to become flexible and rapidly reconfigurable.

Cyber-physical systems (CPSs) are the systems of collaborating computational entities, which are interconnected with the surrounding physical world. Those on-going processes simultaneously use data acquisition and data-processing services and make it available on the Internet [2,3]. Authors suggest solving the existing problems using CPS and implementation of IoT in the manufacturing systems. Authors use a case study to develop the concept and to show its relevance.

In this study, the production system was analysed. The production system was divided into modules and analysis were performed based on the functionalities of the system's components. Therefore, the authors used modelling techniques based on Integrated Definition (IDEF) standard. Futhermore, the study describes a generic approach how to digitalize an outdated (traditional) manufacturing system. A production system was selected to grasp the relevance of the generic approach and to make the studied system rapid according to the modern manufacturing needs, i.e. a reconfigurable manufacturing system (RMS) and ultimately a cyber-physical production system (CPPS). The structure of the study can be depicted in Fig. 1, which shows the tasks and methods used for the manufacturing system.

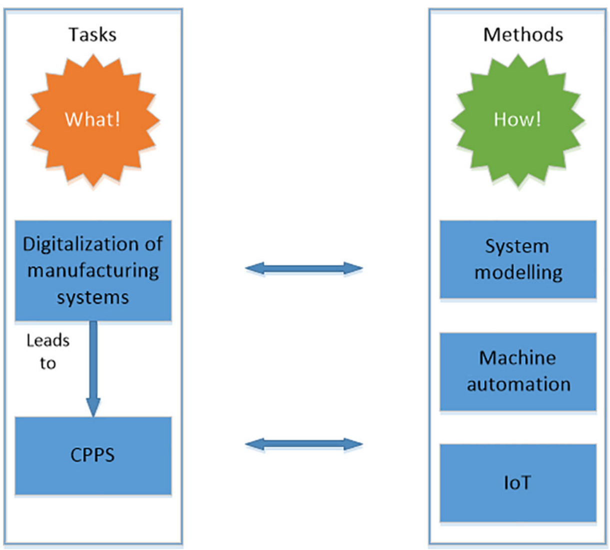

Fig. 1. Structure of the study.

2. LITERATURE REVIEW

In this section, the authors give a brief overview of the tasks and methods, such as modelling technique system, the role of automation in advancement of manufacturing system, the importance of distributed manufacturing systems, the concept of IoT and the background of CPPS. Several articles and manuscripts of the related fields are used to compile the review of the literature.

2.1. System modelling

Modelling of a system defines the process of establishing steps or workflow of a particular system that is selected for the study. Process modelling plays a significant role in identifying, establishing, analysing and extracting the activities of a system. It fulfills the requirements of transforming business process, manufacturing process, and product-development process into a process view model [4]. Massive amount of data and system complexity can lead to confusion. Therefore, a system study always requires activity modelling. It is usually challenging to recognize and remember all information, which should be known about the systems [5]. Selection of right key performance indicators (KPIs) has also an impact on a production system analysis and monitoring [6]. The authors used modelling techniques based on Integrated Definition (IDEF) standard. IDEF refers to a family of a modelling language, which covers a wide range of uses, from functional modelling to data simulation [7].

2.2. Machine automation and manufacturing systems

Automation is the use of mostly automatic equipment in a system of manufacturing or another production process [8]. There is one thing that has changed the concept of an automated machine and defined the understanding of what automation is in the modern world. That was the invention of the computer. For the first time in history, humanity has invented such a sophisticated and powerful tool, capable of performing unbelievable amounts of operations over the short periods. Over the last few decades, this technology has advanced even further. Already today, there are computers able to think, create and make decisions [9]. Moreover, as it seems to be, they are much better and faster than humans are, which brings a new understanding of automation.

A manufacturing system defines the organization to produce a product. There are many different types of manufacturing systems that came into being in the history of manufacturing due to the advancement of technologies and market fluctuation [10]. The development of manufacturing systems started from the concept of assembly line, followed by Toyota Production System (TPS), then flexible manufacturing system (FMS) and reconfigurable manufacturing system (RMS), after that web- and agent-based manufacturing system, nowadays cloud-based manufacturing system and to the recent future CPPS [11].

2.3. Concept of IoT

The exposure of the Internet has altered the daily business and personal lives during past years. It is likely to continue also in the future as it can be depicted from the current trends. IoT is an extension of the Internet. It provides instant access to the information about physical objects and leads to innovative services with high efficiency and productivity [12]. IoT adoption leads to changing old manufacturing systems into modern digitalized ones, where they are enabled to interact and communicate between themselves and with the environment by exchanging data and information "sensed" about the environment while reacting autonomously to the "real/physical world" events and influencing it by running processes that trigger actions and create services with or without direct human intervention [13]. The National Institute of Standard and Technology (NIST) describes "Cyber-physical system as the IoT, which involves connecting smart devices and systems in diverse sectors like transportation, energy, manufacturing and healthcare in fundamentally new ways. Smart cities/ communities are increasingly adopting CPS/IoT technologies to enhance the efficiency and sustainability of their operation and improve the quality of life" [14].

The Multi-Scale Systems Engineering Research Group at Georgia Institute of Technology is developing various IoT and cyber-manufacturing related technologies. For instance, big data analytics has been applied to predict manufacturing costs in cyber-manufacturing [15].

2.4. Overview of CPPS

The manufacture-orientated CPS is also called CPPS, the bases of CPS are highlighted by [16] as the representation of a physical system in the virtual world and the virtual system can be presented in the physical world. The cyber-physical systems are an expansion of embedded systems, where sensors are used to record, save and evaluate data. They interact with the physical and virtual world, communicate each other through interfaces, and use big data and human-machine interfaces [17]. CPS support real processes and provide operational control of objects – the best way to do it on a base of the process model. Process model directly manages the data and business logic of the application. The controller handles communication between users and a model. This layer accepts inputs and converts it into commands for the execution of business logic.

The components of CPPS should have their information and consist of structure information storage. The information can be exchanged between the components via communication interfaces of the CPPS and can be adopted for autonomous decisions in the production process. The communication or process control in a CPPS can be executed directly among the components as shown in Fig. 2, where the control system does not include a central or supervisory control at all. Instead, all the direct process controllers are supposed to interact with each other using standard industrial Ethernet protocols. From the software point of view, these direct process controllers should interact with each other as remote input/outputs (I/O) with no particular set up required to have everything in synchronization [18].

3. METHODOLOGY AND STEPS FOR CPPS IMPLEMENTATION

The primary method used in this paper is the case study approach to define and realize the digitalization of a manufacturing system based on the IoT concept and modelling techniques. Moreover, the literature review was carried out to describe and understand the fundamental techniques that help to build an approach of digitalization. This study defines an approach to examine and digitalize a manufacturing system based on

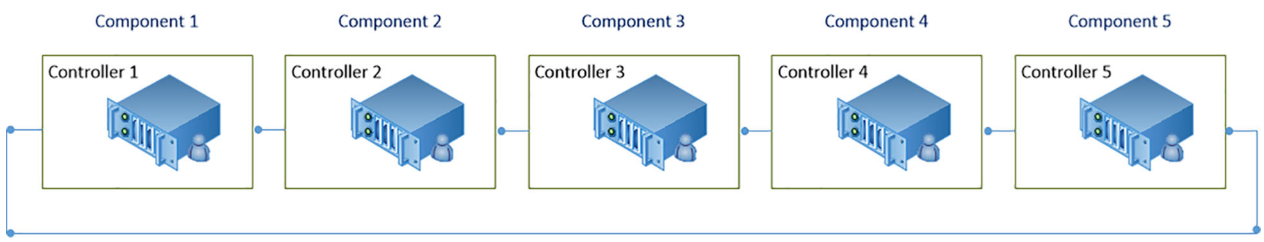

Fig. 2. Process control in a CPPS [18].

modelling technologies and CPS applications. Proposed steps are as follows:

1. Determining rationale and obstacles;
2. Designing the control system architecture;
3. Process modelling and data modelling of the system;
4. Implementation of CPS enablers;
5. Establishing communication network between all devices and components;
6. Installation of smart sensors for data collection;
7. Data processing through intelligent data analysis algorithm;
8. Visualization the status via a web browser (dashboard).

The conceptual model as shown in Fig. 3 has introduced the general approach to redesigning any existing automatic manufacturing system to CPPS. The core of this work is a process model, which directly manages the data and process logic, business rules and application data. A central element of every process model is activity or operation. Operation analysis is well-studied and widely used in industry and is connected with several types of reliability analysis, e.g., failure modes and effects analysis (FMEA), or any other, which have the similarity with process model structure, e.g., reliability block diagram (RBD) or fault tree analysis (FTA). Reliability data also may be included in the process model and used in the logical model of system controllers. In the current research, a database (DB) is used for the process time regulation, which collects process flow information and is the basis for process correction. Structure of DB is also formed by the process model. Since the process model contains the time parameter for every process activity, it is reasonable to use process simulation analysis for controlling the process changes, which significantly reduce the possibility of process errors.

4. CASE STUDY

4.1. Description of the system and obstacles

The manufacturing system was considered as a test-case to verify the proposed approach. The system is ususally used for academic research and practical purposes. The system was outdated, slow and difficult to control with the modern tools. Besides, most of the components were not working properly. The system consists of the individual components, and the layout of the system is depicted in Fig. 4.

The proposed changes in the manufacturing system were mainly related to the controllers, each component would have microcontroller. Other than those, the analogue height and width measurement gauges were replaced with time-of-flight laser sensors. It was suggested that both robotic arms of the system should be of the same model and characteristics, as well as the conveyors. The controllers' description and communication are described in the later section.

4.2. Control system architecture

Existing control system of the test manufacturing system resembled the traditional central control system.

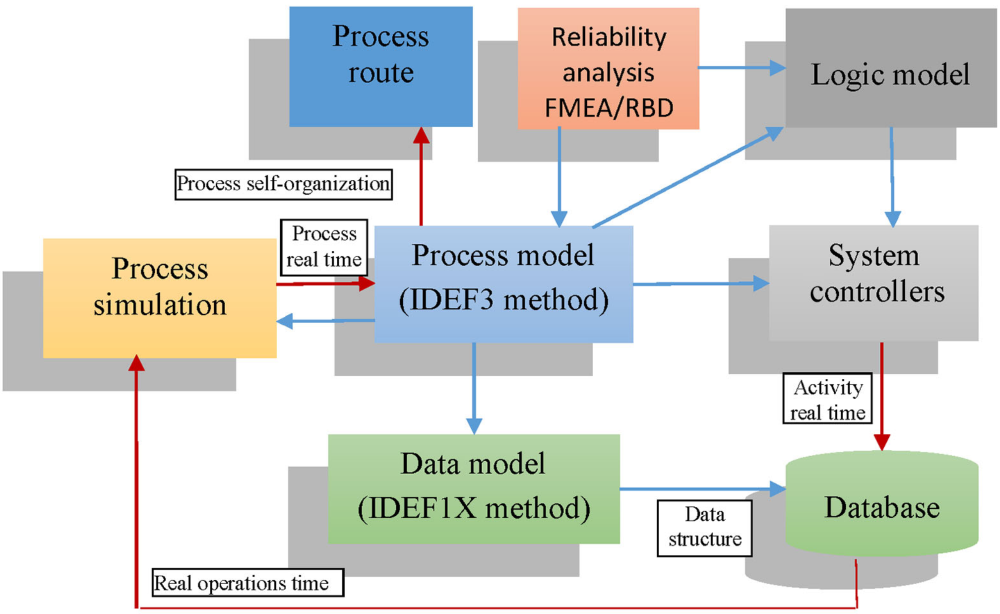

Fig. 3. Modelling centred approach for process self-organization.

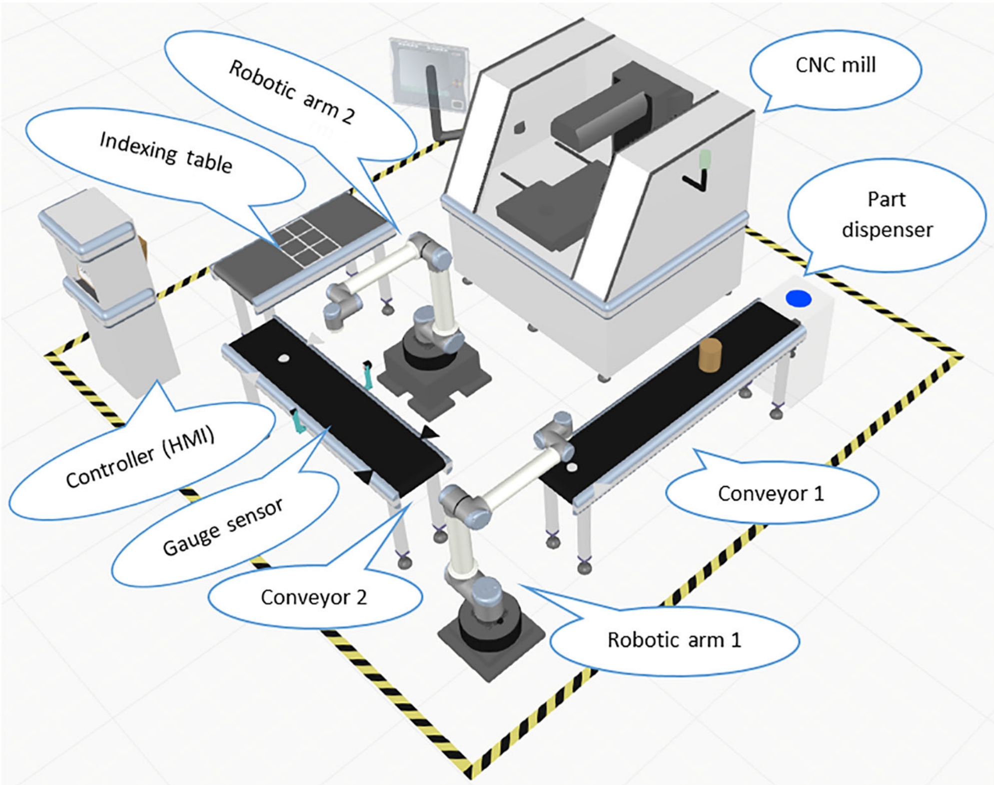

Fig. 4. Manufacturing system components and layout.

The central controller is directly or indirectly connected to the internal controller of every individual component of the system. The information flow and hierarchy can be depicted in Fig. 5.

Proposed control architecture for the test system is the combination of traditional hierarchical control with the distributed control as defined in the Industry 4.0 paradigm. The direct process controller of an individual component of the system communicates straight with controller of other components. Furthermore, the process controller of each component should also communicate with supervisory control of the system. The purpose of the supervisory control in the suggested architecture is to act as human-machine interface (HMI), data acquisition unit and data server. Therefore, it leads the system into the IoT domain and CPPS category. The distributed control and transmission of data from component to component results in faster processing speed of the system. The separate role of each component of the manufacturing test system allows reprogramming components individually. The new control system architecture can be seen in Fig. 6. Arduino microcontrollers (Nano, Uno and Mega) were used with Raspberry Pi3 as a single board computer (SBC) to collect data from microcontrollers and act as an HMI for CNC mill.

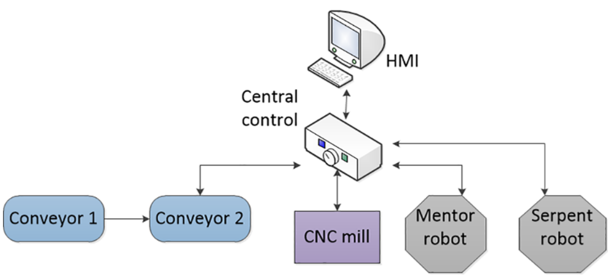

Fig. 5. The general control hierarchy of the manufacturing system (As-Is).

4.3. Modelling of the manufacturing system

The process modelling was performed by the IDEF3 method. The process model showed in Fig. 7 contains the same reference data and activity flow: arrows with double heads show the work-part movements. Arrows with single head show precedence and connections, dotted arrows show information flowing to the database (DB).

Database structure was elaborated by using the IDEF1x method as shown in Fig. 8. Every model object has a table of relation with DB and may contain many

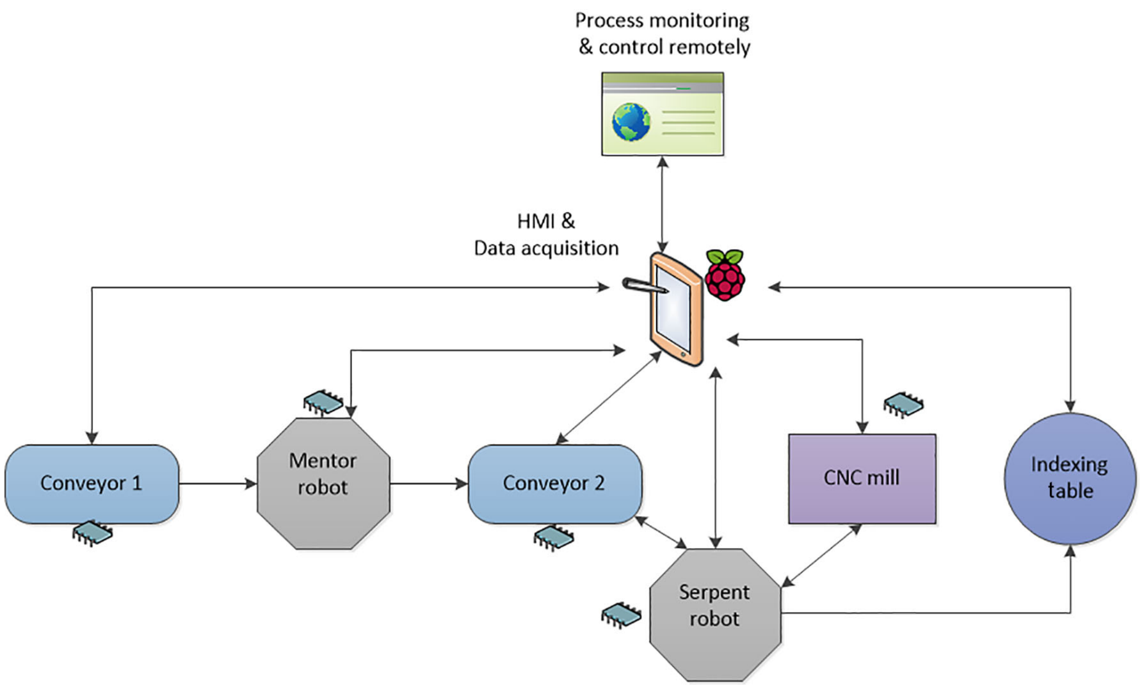

Fig. 6. The proposed control system architecture for the manufacturing test system.

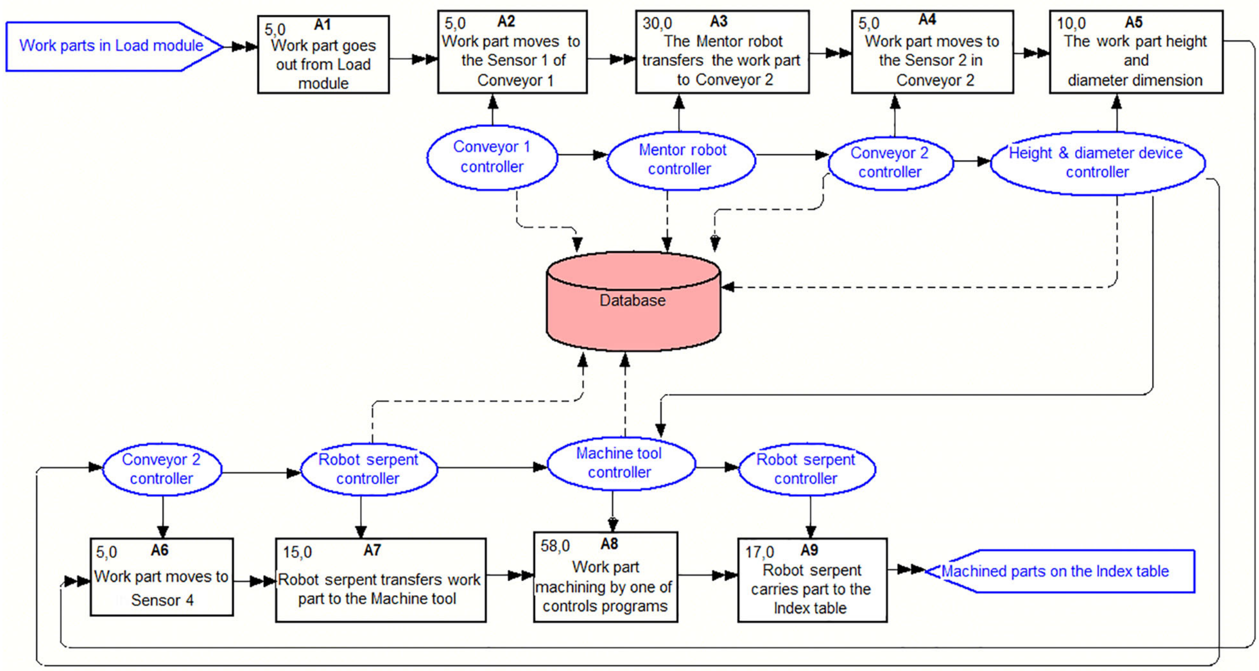

Fig. 7. The process model of the manufacturing system.

records. Since the database is orientated in process time regulation, the system objects contain only attributes which affect the function duration. The yellow marked process activities (A1, A2–A9) reflected the start time and end time tags of each activity. This IDEF3 model includes the duration of every activity, simulation of the model contains the activities duration deviations according to certain laws of distribution. Precise finish-

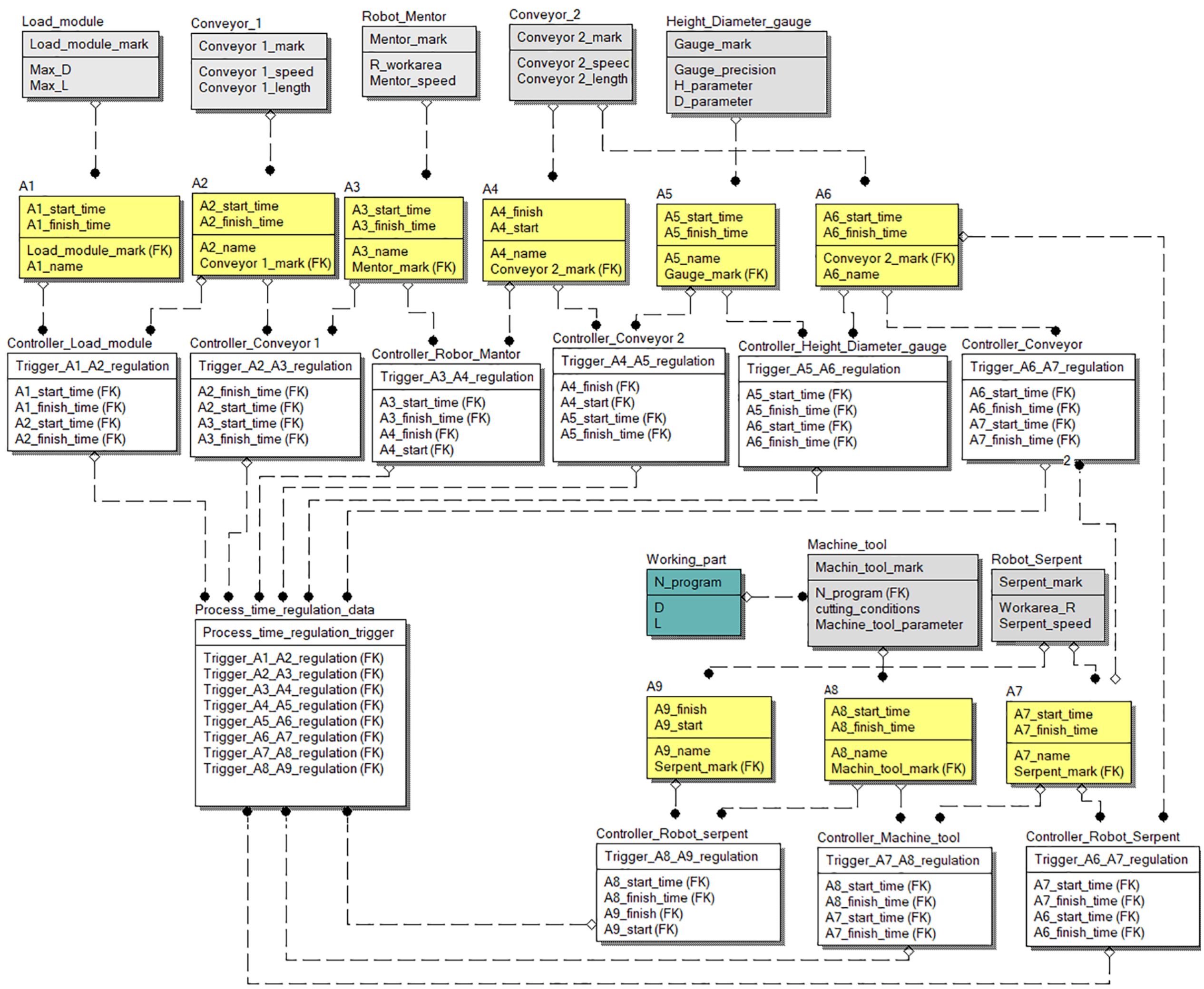

Fig. 8. The database structure of the system.

time and start-time of the next activity can be regulated only by controllers. It means:

$$\text{start-time\_A2} - \text{finish-time\_A1} \rightarrow 0.$$

The tables of the object controllers include the time attributes from previous and following activities. Process time regulation triggers calculate the time intervals for common activity time. The parameters showed in the DB are connected with time regulation.

5. DISCUSSION AND CONCLUSION

The overall improvement in the operating time of the system was observed as the inclusion of smart gauge sensor cut down the activity time used for measuring dimensions of the parts. Thus, the whole process would be balanced if the machining activity time could be decreased. This could be achieved through the appropriate cutting tool such as a solid end mill of steel alloy. Furthermore, the other main goal is self-organizing of the process route, if one component of the system malfunctioned the other components should figure out, how to complete the work cycle, e.g., if the mentor robotic arm stopped working then the serpent, robotic arm would do the additional activity of picking and placing to complete the cycle. Implementation of distributed control system enabled to communicate with some manufacturing execution systems (MESs), hence the system activities can be monitored at the higher. The components such as conveyors, can be reprogrammed to do anything they are physically capable of and they can perform the job with superior control, faster speed and with better adaptability.

All in all, in this paper digitalization and upgrading an old manufacturing system was developed, which is based on the Industrial Internet of Things (IIoT). A model of redesigning existing automatic manufacturing system to CPPS through process and data modelling was described. The proposed method was partially implemented to a manufacturing test system that was used for academic purpose case studies. Moreover, the proposed approach enables better planning, controlling and monitoring of the system, and that leads to proactive decision making. The detail implementation process can be extended and described in future work with a further demonstration of the system reliability analysis.

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Küberfüüsiliste tootmissüsteemide arendamine modelleerimistehnoloogiate põhjal

Kashif Mahmood, Tatjana Karaulova, Tauno Otto ja Eduard Shevtshenko

Asjade Internet ehk nutistu (IoT) tungib üsna kiiresti nii füüsilistesse kui ka virtuaalsetesse tootmiskeskkondadesse. IoT hõlbustab tootmissüsteemide digitaliseerimist ja seda peetakse tootmise tõhususe suurendamisel oluliseks teguriks. Et ülemaailmselt konkureerida ja kiirete turumuudatustega toime tulla, peaksid tootmisettevõtted orienteeruma tootmissüsteemidele, mis on iseorganiseeruvad ning vähendavad inimeste sekkumist miinimumini, hoides protsessi siiski inimkontrolli all. Käesolevas artiklis on kasutatud Tööstus 4.0 kontseptsiooni, mille mõistes nimetatakse tootmissüsteeme küberfüüsilisteks tootmissüsteemideks (CPPS).

Teisalt aitavad modelleerimistehnoloogiad, nagu protsesside ja andmete modelleerimine, tootmissüsteeme luua ja mõista nende toimimist, kuna automatiseeritud tootmissüsteemide juhtimise hindamine võimaldab need ümberkonfigureeritavaks muuta ning ühtlasi tõsta need CPPS-i kategooriasse. Uurimuse eesmärk on arendada modelleerimistehnoloogiatel põhinevat CPPS-i ja välja töötada kontseptsioon traditsioonilise tootmissüsteemi uuendamiseks.