Proceedings of the 6th World Congress on Mechanical, Chemical, and Material Engineering (MCM'20)
~~Prague, Czech Republic~~ Virtual Conference – August, 2020
Paper No. ICMIE 135
DOI: 10.11159/icmie20.135

Mobile robot models for manufacturing systems

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Abstract-The complex task of the integration of industrial mobile robots into manufacturing systems means a serious challenge to engineers and researchers. To solve these issues there are modern simulation tools which handle the whole manufacturing system in one unit. Based on the fourth industrial revolution, the manufacturing system structures commonly used for decades have undergone a significant change, as a result of which modeling solutions must also be much more flexible in design than their predecessors. In addition to the use of the achieved results, simplifying and further developing them, our goal is to create and systematize an easy-to-use model that focuses primarily on mobile robots. For this, simple models of production systems were used, and the connectivity of mobile robots and production system parameters and models were examined. The new modeling method for mobile robot manages the manufacturing system separately, so that the robots are easily interchangeable and thus we can analyze the same system with several robot manufacturers.

***Keywords*:** Manufacturing systems, Mobile robot, Petri-net, Industry 4.0, Mobile robot model

1. Introduction

We are witnessing a continuous transformation of the manufacturing processes today. While conveyor belts and pallet systems are still extremely popular as a core component of most production lines, new opportunities are emerging in response to new demands. As a result of Industry 4.0, custom mass production, additive manufacturing and robotics will be key components of the factories of the near future, thus serving a wide range of unique needs in a wide variety of industries. The interaction of mobile robots and production systems raises a number of process issues and their optimization will be of paramount importance in cost effectiveness.

The main goal of our research in this article is to create a manufacturing system model that focuses on mobile robots. During the development of the new approach, the basic ideas were simplicity and the most efficient applicability in the industry. In this article, we analyze the currently commonly used, conservative manufacturing system modeling solutions in details, and then introduce the new type of modeling structure.

2. Literature review

Mobile robots have long been a part of manufacturing systems, but due to the Industry 4.0 term, their use has taken different approach. We briefly review the relevant parts of Industry 4.0 and the current role of mobile robots in this system.

In their article, Alcacer et al. [1] summarized the impact of digitization on modern production systems, the main concepts and connections. In their publication, they concluded that, as a result of digitization, virtualization can be the solution to the requirements generated by digitization in the design of manufacturing processes, be it a factory design or production planning. Digitization also affects the management and control of the physical process within the extended manufacturing environment, the communication within and between factories, and smart factory designs. According to the researchers the fourth industrial revolution will finally close the traditional production structures and develop new-looking, highly flexible solutions that fully meet the ever-changing needs.

Mabkhot et al [2] investigated the theory of the intelligent factory concept as well as its application in practice. The aim of the research in this article was to highlight the perspective that shapes the intelligent factory and to make suggestions in terms of approaches and technical support. The research analyzed the structure of intelligent factories in details, as well as the possible identification methods of the units that shape the factories. The researchers proposed a framework for summarizing existing study results that will provide an excellent basis for future studies.

Takahasi et al [3] examined the "Unified Reference Model - Map & Methodology (URM-MM)" model as guidelines for the development of an open ecosystem. The model supports users to integrate individual components developed by diversified manufacturers and helps to complexly address challenges generated in different manufacturing areas. One of the results and conclusions of the research in this article is the discovery of deficiencies related to functionality. Another result is the process of building open ecosystems, which has been developed through the survey of existing reference models and architectures. Another implemented element of the URM-MM model is the development of units, which can also be used as a development guideline in the future when fulfilling tasks aimed at the implementation of intelligent manufacturing.

In their paper, Zhong et al [4] developed a theoretical framework that includes complete design and production planning, machining, monitoring, control and scheduling (decision making) in order to modernize typical manufacturing systems to meet the requirements of the fourth industrial revolution. A number of case study-based scenarios are presented in order to illustrate the development potential of each member of the implementation of appropriate solutions as companies begin to shift to new approaches generated by Industry 4.0. Over the past 10 years "ubiquitous manufacturing" (UM) has received increasing attention among researchers in the manufacturing community as the related computational model and technology (UCT) can be applied to almost all sectors of the manufacturing industry, where it can provide effective answers to many questions, such as production process planning, equipment installation, production management applications and real-time production process management.

However, according to Wang et al. [5] a comprehensive and detailed overview of the state-of-the-art UM and its holistic systems are lacking. The aim of the research is to provide a concise overview of the technical characteristics and application possibilities of UM systems published between 1997 and 2017. The unique aspect of this article is that it summarizes and analyzes a wide range of (state-of-the-art) implementation of UM systems based on holistic and comprehensive manufacturing technology, including UM for manufacturing processes and production control systems, logistics, remanufacturing, cloud-based manufacturing, production scheduling, production quality control and evaluation. In addition, conclusion were drawn about current limiting factors and expected future trends in the further development of UM systems.

The fourth industrial revolution requires the increasing flexibility and reconfigurable (C-R) capabilities of the future factories (FoF). This is true for both new types of production system models and robot models. In their article Brand et al [6] present and analyze research findings that show how the C-R model and the requirements for the (total cost ownership) TCO model can be incorporated into FoF technical solutions. The findings of the research include an indicator to measure the C-R capacity of production resources, a model to assess the economic viability of FoF and a methodology and related tools for design smart, interconnected production resources with embedded functions. As a result of analytical and research work, researchers have been able to facilitate the changeability and reconfigurability of manufacturing systems in FoF systems. For the theoretical conclusions, a case study of a robot manufacturing cell that can be quickly and flexibly transformed was also written.

Lu et al [7] analyzed application scenarios and research issues for a "digital twin"-based intelligent manufacturing theory. The research activities of the digital twin increased significantly in the second half of the 2010s. The use of the digital twin increases the forecasting of the efficiency of a new production process, the determination of the sufficient amount of tools and equipment to be used, and the utilization of capacities as much as possible. However, for digital twin systems, the most detailed visualization of virtual simulation possible must be used in order to bring the digital twin world closest to reality. The goal of the research by Lu was to built a "digital twin" generally applicable in the industry.

Gershwin et al [8] examined future possibilities for the development of manufacturing systems from an engineering perspective. In this study, he examined how human intuition can help design autonomous manufacturing systems and how intuition could be applied to the development of artificial intelligent-based (AI-based) design and selection systems. As a result of the research the author also describes the successful applications that have already been implemented. They make proposals for the organizational structures of the new generation of production systems that meet the requirements of the fourth industrial revolution. At the end of the study the researcher expresses his idea to develop AI systems with expert knowledge he has examined, and to produce a concept in the field of designing new generation production systems based on their results.

The fourth industrial revolution also played a significant role in the creation of system models for robots used in manufacturing systems. The daily use of autonomous mobile robots will be the next big milestone in digital manufacturing processes. However, the effective development of these units requires the continuous improvement and expansion of decision-making systems based on AI, the development of new types of approaches and the development of algorithms based on these approaches. In Felix Ingrand's research [9] mobile robots have been selected as the basis of the study that require different considerations and decisions to accomplish their mission. The article summarized the five main deliberation and consideration functions that can be used in the areas of planning, movement, monitoring, observation and learning. The article examined what different parameters and characteristics a robot should consider in different environments when it needs judgement and clear decision. The article demonstrates the actual application of these features based on case studies.

Limosani et al [10] examined the effectiveness of the practical use of indoor and outdoor mobile robots from the end-user perspective. The research is based on three different environments and three mobile platforms. The user experience can be affected by the reliability of the system, and based on this, suggestions have been made to improve the system. The cyber security of various robotic systems is an increasingly significant and burning issue. The cyber security of robots is taken to a higher and higher level of implementation and management due to the increasing involvement of robots in everyday task in various industries and services. Spanish researchers [11] have been working to develop methods and algorithms that can be used to detect cyber-attacks in various research institutes. A specific case study was also carried out in the Applied Science Research Institute of the Cyber Security Research Institute in Spain. Necessary researches have also been made in the field of mobile robots. The first priority given to the issue of cyber security of mobile robots is the fact that in many cases these robots are internet-based with real-time data collection and processing. Typical examples are the robotic use of maps or real-time positioning. During the development of defense mechanisms against cyber attacks, a number of different algorithms were analyzed, such as adaptive gain linear discriminate analysis or machine learning. The result surveillance system is able to detect computer attacks on mobile robots with increasing efficiency through learning algorithms.

Going beyond the FMS systems, Yoram Koren [12] examined the design theory of reconfigurable manufacturing systems (RMS). In the derived theory a number of configurations were compiled and in addition, findings were made for investments, highlighting the issue of capacity of the production system which must follow the changing needs of the market. It is also important how easily a new product or product family can be adapted to a production line. Also in the example presented the configured systems were ranked based on the following criteria: customizability, convertibility and scalability.

The possibilities and applicability of modeling procedures are presented in the work of Murat Uzam [13]. The two defining modeling possibilities of finite event systems (automata and Petri-nets) were combined in a hybrid system (mixed PN/automaton). The method they developed has been successfully applied to the monitoring of a real-time PLC-based production system.

3. Manufacturing system models

The first step of our research was to map the modeling solutions of discrete event systems in detail. As a result of the analysis, we obtained an accurate picture of the general modeling solutions of the period before industry 4.0. In this article, the two most common methods are briefly presented to see their advantages and the procedure with which we can achieve the results that are important to us more easily.

We present two common solutions for modeling discrete event systems. One is the finite state automata and the other is the Petri-net. In the analysis, production systems are understood here as a series of machining or assembly equipment, the purpose of which is to produce a given product (finished or semi-finished) with given resources (money, time, raw material, expertise).

3.1. Material transfer with conveyor system

The manufacturing background associated with the automation trend following the third industrial revolution was characterized by the fact that during large-scale and mass production manufacturing systems produced either completely identical or very similar (e.g. product families) components and products. Linearly designed production systems were an excellent solution to meet this requirement, as the order of production operation was fixed. A typical workpiece transfer solution was the conveyor belt, and the semi-finished product was transferred from the conveyor belt to the given cell by either human force or a robot. This production system structure can be seen in Figure 1.

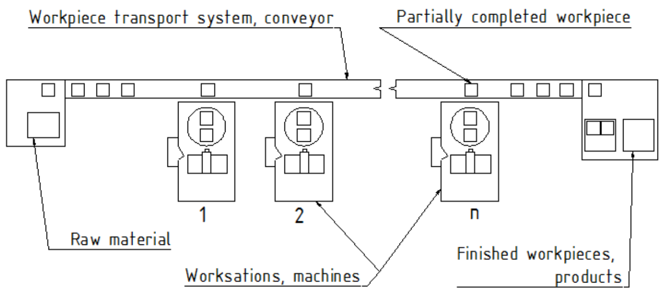

Fig. 1: Traditional conveyor based manufacturing system.

The production system can generally be described as a finite state automaton. In this case some states can be switched to other states by the input signals. For a more complex mode of expression and additional extension options we choose the Petri-net model. According to the Petri-net model there is no existing branch in the simplest case, as in this case demand for flexible material flow is not generated in structures called conservative production systems.

3.2. Flexible manufacturing systems, FMS

The next qualitative leap in the development of production systems was when the workpieces were not placed in a linear sequence in a series of machine tools, but the system selected the pieces to be manufactured from a buffer storage and delivered them to the machines by a central manipulator. This increased the flexibility of production, making some operations parallel, while others could be omitted. This manufacturing system structure is already much closer to the needs of the fourth industrial revolution, which is based on the fact that integrated manufacturing systems can produce the most varied geometries, sizes and shapes possible, overlapping each other in time. A schematic of this flexible manufacturing system is drawn in Figure 2.

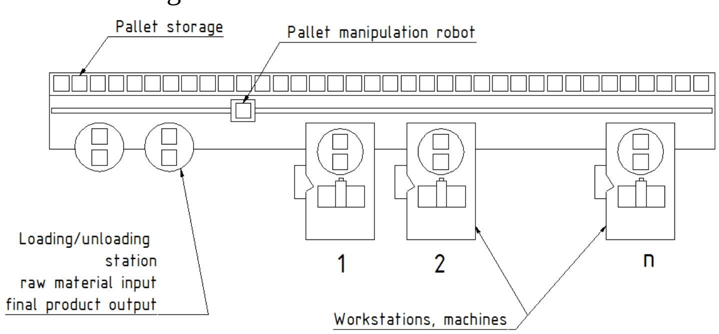

Fig. 2: Schematic of the flexible manufacturing systems.

A Petri net model [made with online editor - 14] of the FMS system is shown in Figure 3, which can be used to examine the manufacturing process.

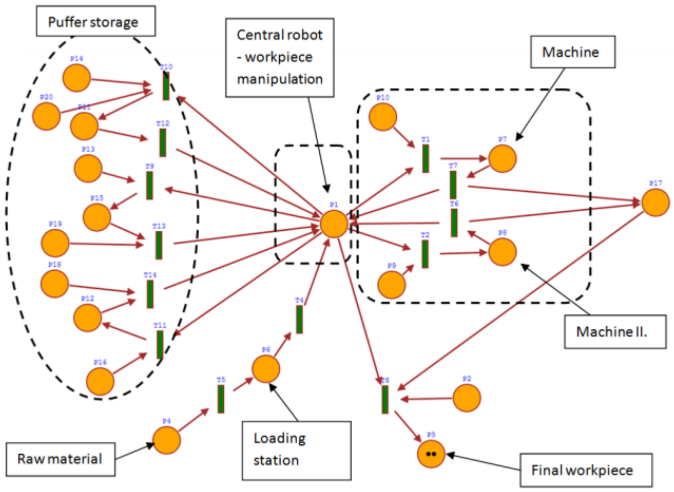

Fig. 3: Flexible manufacturing systems Petri-net model.

In the case of production systems based on the model in Figures 2-3, the central element of the system is the pallet transport manipulator, which can be filled with raw material at the loading station. After this the robot places the pallet in one of the multiple pallets storage. The pieces are taken out of the buffer by the robot and taken to one of the machine tools. After the process is finished the workpiece is taken out of the machine by the robot and returned to the storage. As a final step, the finished pieces are transported to the unloading station from where they can be taken away. The input conditions for starting production: the raw material must be in the storage, the machine must be equipped with the required tools, and the appropriate program must be available. If one of the machine tools fails, another can take its job if the previous conditions are met. This feature increases the flexibility and reliability of the system.

3.4. Manufacturing with AGVs

One of the main limitations of flexible manufacturing systems is the pallet manipulator itself, which determines the speed of service and the optimal (maximal) size of the whole system, taking the manipulation and the cycle time into consideration. This could be increased by placing more robots in the system. A solution for this can be the design of islands production system, with mobile robots (firstly automated guided vehicle, AGV) transport the pallets between production islands and production cells. Figure 4 shows a general schematic of the production system served by AGVs.

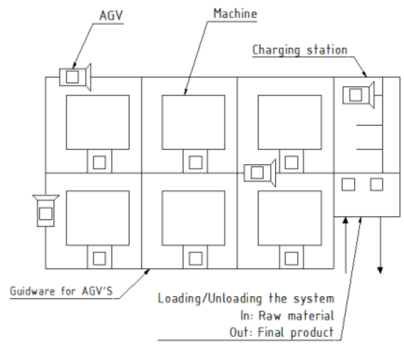

Fig. 4: Manufacturing system with AGVs.

The model that can be connected to the system is shown in Fig.5, which shows the system of connections between machines from the perspective of the workpiece. In this case, serving robots have not yet been built into the model.

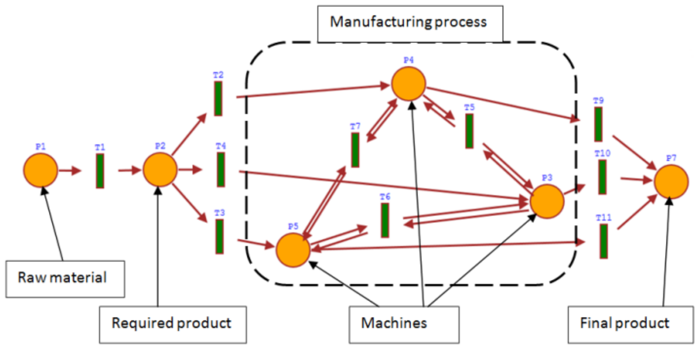

Fig. 5: Manufacturing system without robot - Petri-net model.

The main goal of our research is to develop a new type of production system model by focusing on mobile robots. To do this, the first step is to separate the production line in the common model from the line of robots that serve it. As a result of the separation and then re-joining operations, a new type of approach, shown in Fig.6, is formed where the workpiece can move in any order between any machines in the model.

4. The mobile robot model

The robots are detached from the model so that the machines only appear as emitters or recipients of the products moved by the robots. The movement of the workpiece with robots has been introduced and the robot has been drawn into the model. After this we can separate the machines and the robot.

According to the concept shown in Fig.6 the process of the robot can be divided into three stages: the starting position, the goal position and when the robot is on its way. All three machines can function both as starting and goal position. The model contains the process elements in a simplified way because the main point is to separate the states of the robot from the whole production system model.

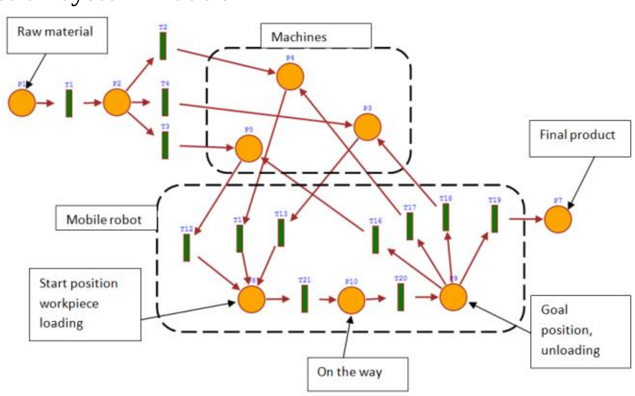

Fig. 6: Manufacturing system with mobile robot - Petri-net model.

Then the processes of the robot are shown in more detail, distinguishing between the empty and loaded states of the robot apart from the start and target positions.

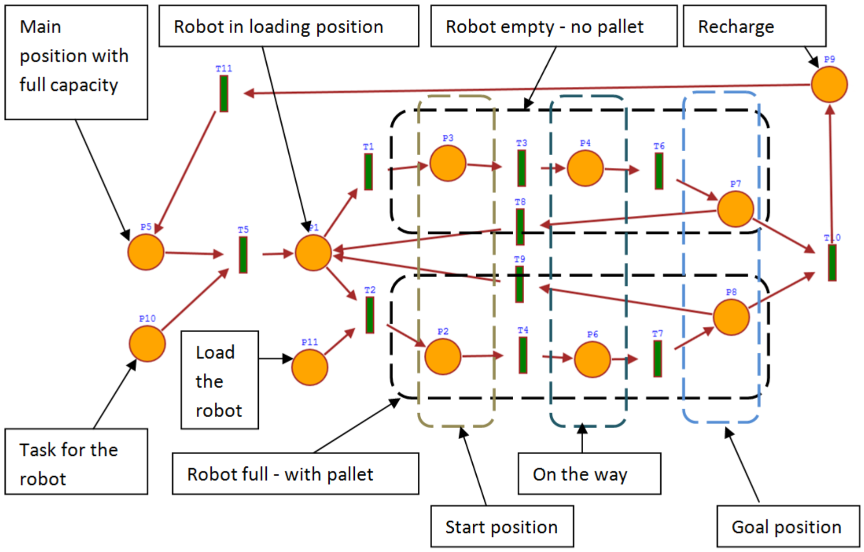

Fig. 7: Mobile robot - Petri-net model.

The developed detached robot model can be seen in Fig.7. From the robot's point of view, according to the machine service process, the robot goes from one dispatch point to another with or without a workpiece. When the robot is instructed, it goes to the loading position (this can be a starting position as well) and then, depending on the task, picks up the product and heads towards the destination. It places the product in the target position, and the model returns to the initial position, i.e. the previous target state becomes the new initial state and the process starts all over again.

Different mobile robots are suitable for different tasks. The most common task is to move the workpiece between the warehouse and each stations. A characteristic of Petri-nets is that the basic model can be extended. The most common extension is the timed Petri-net, but there is also a coloured and constrained version. For us, this means that conditions can also be added to each state, e.g. the weight and size of the workpiece. The parameters for the robot that the model can include are the load capacity of the robot, speed, battery capacity, but also the manufacturer, the investment and the operating costs. Furthermore, the compatibility of different robots with each machine can be interpreted from both the hardware and software side. The navigation of some robots does not require environmental changes during installation. Others may need various markers on either the floor, wall or ceiling. These can be integrated into the extended model.

Due to the generality of the model, it supports several scenarios and even unplanned scenarios can be deduced from the model, for which it is already possible to solve a specific task.

The loading stations can be a specific machine in the production system, a production island, a conveyor, a reject box, a measuring laboratory, or even a buffer storage. From the point of view of the robot, the emphasis is on the execution of the tasks, we can determine their measurements with the model and then measure them in the specific case. These parameters can be the following: how long the robot carries the workpiece, how much time it spends delivering, waiting, and how much capacity the robot uses.

5. Interfaces between production system and mobile robot models

The focus of the study is on the function of the mobile robot in the manufacturing process. To achieve this, the above robot model must be connected to the production system, which is more efficient than the previous approaches, because it allows fast connection of several robots to a production system and their comparison with each other. It is possible to evaluate and measure the utilization and reliability of different robots and the optimal number of robots, i.e. how suitable the robots are for the given task. Analyzing the costs, we can also decide whether it is worth investing in a mobile robot for a given task or the investment pays off in a given period of time. When making a decision, we do not limit ourselves to the existing structure but expand the possibilities as our model can quickly generate and compare to the existing ones.

This model allows you to go through the various tasks of robots step by step. In addition to the same tasks, it is also possible to perform tasks such as picking up a workpiece at one station, then picking up another piece at another station and going to the drop position with the two products.

6. Conclusion

The aim of our research was to write a simple but expressive model to study the multitude of mobile robots serving production systems. We first examined the entire manufacturing system and then separated the industrial mobile robot model from it.

The interconnection of the models allows us to simplify the model of the production system, except for the parts that are important for the robot, e. g. loading points. In this way the relationship between the production system and the mobile robot is placed in an easy-to-examine model with which the goodness of the robots (utilization, cost, return of investment) can be qualified for each task or the entire production system.

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