Application of cyber-physical systems for additive manufacturing of polymer products

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Abstract: The article presents the use of IT systems and cooperative robots in the 3D printing process based on the layered extrusion of polymer materials, enabling the construction of autonomous production cells that meet the assumptions of cyber-physical production systems. This solution allows for an innovative approach to planning the production of products from polymer materials in terms of pre- and post-process operations using remote monitoring, and optionally allows the use of artificial intelligence to control the production process. An important feature of the proposed solution is its modularity and scalability, which is important when manufacturing products using the 3D printing method from thermoplastic polymer materials.

Keywords: additive manufacturing, polymers, cyber-physical systems, smart factories.

Zastosowanie systemów cyberfizycznych do wytwarzania addytywnego produktów polimerowych

Streszczenie: W artykule przedstawiono zastosowanie systemów informatycznych i robotów kooperacyjnych w procesie druku 3D opartym na wielowarstwowym wytłaczaniu materiałów polimerowych, umożliwiających budowę autonomicznych ogniw produkcyjnych spełniających założenia cyberfizycznych systemów produkcyjnych. Rozwiązanie to pozwala na innowacyjne podejście do planowania produkcji wyrobów z materiałów polimerowych pod kątem operacji przed- i poprocesowych z wykorzystaniem zdalnego monitoringu, a opcjonalnie umożliwia wykorzystanie sztucznej inteligencji do sterowania procesem produkcyjnym. Ważną cechą proponowanego rozwiązania jest jego modułowość i skalowalność, co ma znaczenie przy wytwarzaniu wyrobów metodą druku 3D z termoplastycznych materiałów polimerowych.

Słowa kluczowe: technologie przyrostowe, materiały polimerowe, systemy cyberfizyczne, inteligentne fabryki.

Cyber-physical systems (CPS) are the basis for the development of internet of things and Industry 4.0 [1-2]. By combining physical and digital components into a single structure, the level of automation is raised, creating a new generation of industry [3-5]. The integration of digital systems with the physical production process makes it possible to significantly improve the process in terms of efficiency, precision, and quality control [6]. One area of application for such systems is the incremental manufacturing of products from thermoplastic polymeric materials using layered extrusion MEX (material extrusion) [7]. By using CPS, it is possible to monitor the operation of individual devices and entire production lines. From the perspective of 3D printing, essential elements that can be continuously monitored are the status of the print, nozzle temperature, extruder speed, or material consumption [8]. CPSs also allow for the detection of anomalies in the device's functioning and the course of the entire process. Another important area of use for CPS is the ability to integrate 3D printing with other stages of the production of products and semi-finished products from polymeric materials, e.g. by automating the supply of polymeric materials, controlling the level of material consumption and scheduling subsequent tasks in batch production, as well as post-process operations. Cyber-physical systems

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also enable flexible personalized manufacturing, where 3D printing parameters can be quickly changed between assorted designs without significant interruption to production [9]. This makes it possible to create customized products, such as components with special shapes and properties with a reduction in wasted material. This saves polymer materials and reduces waste, which significantly reduces the environmental impact of production. CPS systems dedicated to manufacturing products from polymeric materials based on 3D printing can cooperate with other intelligent systems in the factory. The integration of 3D printing systems with a production network allows for seamless data exchange, automatic task assignment and monitoring of production line status, fitting in with the Industry 4.0 concept. The implementation of remote control and monitoring processes can add significant value [10]. The digitalization of production processes involves collecting and processing substantial amounts of data. These activities make it possible to optimize existing models, as well as to create new ones thanks to the obtained information and knowledge about the behavior of polymer materials during 3D printing.

The aim of this work is to present a cyber-physical system for designing, manufacturing and quality control of components from thermoplastic polymer materials based on layered extrusion, an arm robot and an information system.

EXPERIMENTAL PART

Analysis of available solutions

Despite widespread computerization and automation of industrial processes, there is still a lack of fully cyber-physical systems for manufacturing components based on 3D printing of polymeric materials. By analyzing the 3D printing technologies in use today, it can be seen that the layered extrusion method of polymer materials has a high potential for automating pre- and post-process operations. 3D printer vendors use solutions that have various levels of automation and robotization of the manufacturing process [11, 12]. One of the first 3D printing automation solutions was the Continuous Build 3D Demonstrator from Stratasys, unveiled in 2017. It consisted of modules, each containing three extrusion-based 3D printers. Printing took place on a film that was rolled out automatically on a worktable, and when the print was complete, the finished model was cut off and dropped into a collection basket. The next print started on a new layer of film without the need for intervention by technical personnel. The entire system was managed by cloud-based software, automatically assigning jobs to available print cells, and ensuring redundancy and load balancing of individual print units [13]. Another example of such a system is Prusa Research's solution. The company presented at EXPO 2020 a functional prototype featuring an important level of automation under the name "Automated Farm System." Printers are mounted on special rails in a cabinet like a server cabinet. Finished prints are picked up from the printer's workspace along with the work platform by an automated arm. After printing, the model is transported to a unit that separates it from the platform; the model goes into one of two baskets, and the empty platform returns to the printer, where the next print begins [14]. Another solution that takes the 3D printing process to the next level of automation is a solution consisting of a control unit, manufacturing cells and a post-processing station. Thanks to the use of a mechanical arm integrated with the linear track, it is possible to pick up finished prints and transfer them, for example, to the quality control process [15]. In early 2021, Canadian company Mosaic Manufacturing unveiled the MosaicArray system, consisting of four Element HT 3D printers. The system allows eight materials to be printed simultaneously by a single print head. A movable arm automatically picks up finished prints and deposits them into a magazine that moves on wheels for quick changes, eliminating unnecessary downtime [16]. There is also a known solution that provides an autonomous system for replacing work platforms in FDM 3D printers. The system is based on a robot from Universal Robots. The robotic arm manages several 3D printers in terms of unloading printed and loading empty working platforms. However, it should be noted that the system has extremely limited remote-control mechanisms, informing only when the print job is complete [17].

There are also other solutions focused on automating the printing process based on polymer materials. However, in most cases, the presented systems have only limited functionality of cyber-physical systems, e.g., network communication automation of receipt of printed products or information about the end of the printing process. Today's challenges of Industry 4.0, and especially attempts to realize the concept of Industry 5.0, require much broader integration of manufacturing systems with IT infrastructure and robots.

Proposed methodology for manufacturing products from polymeric materials

The developed concept (Fig. 1) dedicated to incremental manufacturing in terms of cyber-physical systems makes it possible both to automatically acquire, collect and analyze data from cooperating machines and to control it in real time, as well as to control the process and implement automation of sequences of activities at different stages of the process. The developed methodology is a significant extension of the rapid prototyping process [18]. However, the key to achieving the set goals is to integrate the machines and allow them to work in a network structure. It is also necessary to analyze the technologies in which individual machines work and establish their technological limits. The data collected during the verification of the machine park and manufacturing techno-

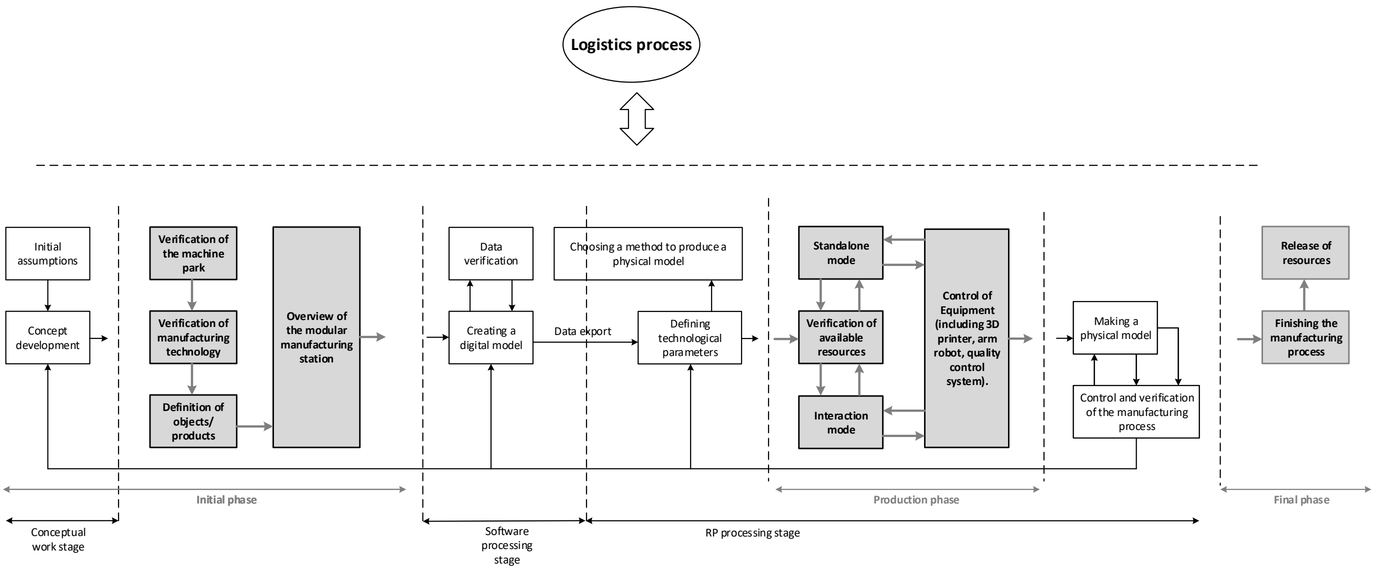

Fig. 1. Stages of the rapid prototyping process

logies will be used to define objects - digital equivalents of equipment and other components. These objects are the basis for the operation of an information system that supervises and automates the incremental manufacturing process.

Production in an integrated, automated environment can be conducted in standalone or interactive mode. In interactive mode, the operator supervises the process, manages the print queue, controls the equipment, makes decisions to stop printing in case of defects, and checks the availability of resources and the status of components. Autonomous mode is based on automatic decisions made by the system based on data from the machines and involves the use of robots to operate work platforms without the involvement of an operator. The operator's role may be limited to process initiation. The results of the production phase are fabricated physical models. To confirm its correct course, it is necessary to use mechanisms that will allow its control and verification of the manufacturing process. These mechanisms can operate in real time or periodically during the printing of individual models or once after they are completed. Among the first ones we can distinguish periodic visual inspection by the operator and continuous supervision through verification by artificial intelligence algorithms based on the image of the workspace provided by vision systems. The data acquired during the printing process makes it possible to decide whether to stop the print when a defect is detected and if it should be repeated. Early reaction contributes to reducing the amount of wasted time and material. However, among the methods applied to already finished products are hand tools (micrometer, caliper, gauges), coordinate machines and scanners (optical and laser).

The final phase is the beginning for the next manufacturing process. Resources are then released and can be allocated to the production of the next product.

The established methodology provides a basis that allows, in a further phase of work, the design and implementation of a cyber-physical manufacturing system based on 3D printing technology from polymeric materials.

RESULTS AND DISCUSSION

Cyber-physical system

Based on the developed methodology for the automation of the incremental manufacturing process, along with the consideration of cyber-physical systems concepts, a prototype of an automated 3D printing system of thermoplastic polymer materials was designed and manufactured (Fig. 2). The system has a modular design and includes a store of empty and printed work platforms, two boxes with 3D printers, a collaborative robot, and a computer with a supervisory application. The construction, after retrofitting the robot with a linear track, is also characterized by scalability. As a result, it is possible to expand it with additional storage and 3D printing equipment modules, increasing production capacity at the same time. In addition, it is possible to equip the system with quality control elements such as 3D scanners, cameras, etc. The data obtained in this way can be compared with the source model to assess the quality of the manufactured product.

The application layer allows planning and ongoing execution of manufacturing processes, controlling the status of polymer materials and operation of physical equipment. Moreover, both modes of operation have been implemented: autonomous and interactive. Fig. 3 presents an example of the software's operating window. In the case of a 3D printer, the interface shows the operating status, the amount of material, head and table temperatures, and the image from the camera in the 3D printer chamber. At this

Fig. 2. Automated 3D printing station for layered extrusion of polymer materials

level, it is possible to work manually or automatically. The operator can manually control the head, temperature, and fan, or run automatic scenarios such as platform installation. For the robot, the interface allows selection of motion sequences and control of operation. The warehouse interface shows the status of the shelves, allowing, for example, the robot to put down a print. Production files can be uploaded to a server, where they are automatically distributed to printers. The status and type of polymer materials can be controlled by RFID codes and the changing weight of the filament spool/cassette. When working in automatic mode, the cyber-physical system executes scenarios based on implemented algorithms that take into consideration a variety of elements, including: the state of the job queue, the load of individual 3D printers, the state of polymer materials on the printing equipment and in the machine part, as well as the range of activities to be performed for a given model.

Example experiments

As part of the verification of the performance of the developed cyber-physical system, several experiments were conducted. Fig. 4 shows a fragment of the gearbox housing produced using acrylonitrile styrene acrylate (ASA) filament. The amount of material required to produce one gearbox housing was 171 g, while the printing time was 14 h and 50 min.

An important aspect to verify the importance of creating automated cyber-physical systems is the reduction of human

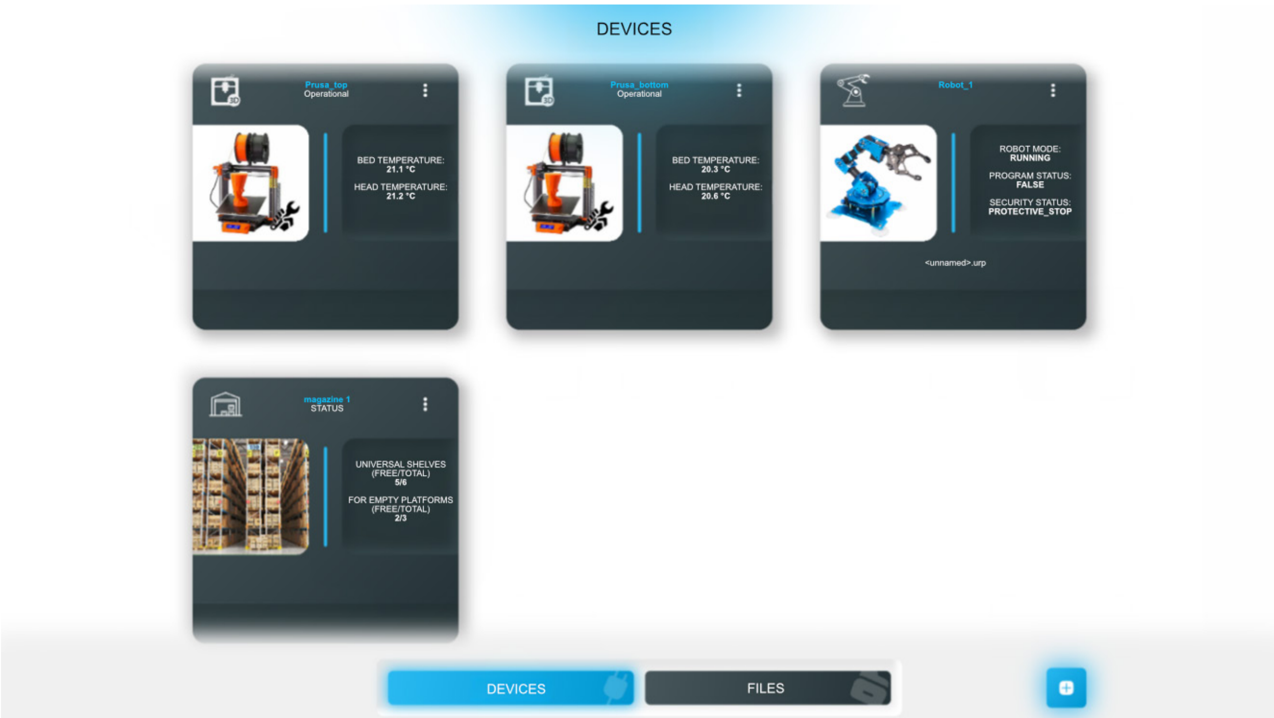

Fig. 3. Application user interface view - "Devices" tab

Fig. 4. Research model – the gearbox housing

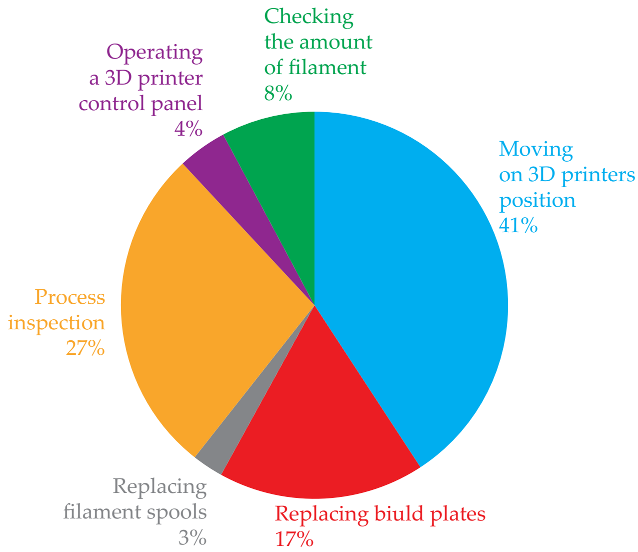

Fig. 5. Time shares in individual operator activities

interference in the manufacturing process. Therefore, for the assumed manufacturing of the gearbox housing part, the share of individual activities relative to the total operator time in a classic non-automated manufacturing process was determined (Fig. 5). It can be observed that there is a significant share of time associated with the passage and return of the operator from the manufacturing station, inspections of the process, as well as the replacement of platforms. The percentage was prepared for a batch print of 500 pcs for a machine park consisting of 6 3D printers.

By implementing an automated cyber-physical system, we can reduce the operator's work only to prepare production files and operating the application. As a result, the necessary activities performed by the operator in the traditional manufacturing model, such as process inspection, verification, and replacement of filament, handling the printer, as well as the time spent moving the operator, can be reduced to emergency situations only. Moreover, given the available functionality of remote supervision of the manufacturing process, it is possible to provide 24/7 manufacturing. Then the operator can be in another physical location, e.g., in another time zone.

CONCLUSIONS

The application of information systems and cooperative robots in the 3D printing process based on layer extrusion of polymeric materials makes it possible to build self-contained production cells that meet the assumptions of production cyber-physical systems. Such a solution allows an innovative approach to planning the production of products made of polymeric materials in terms of pre- and post-process operations using remote monitoring, and optionally provides the potential to apply artificial intelligence to control the manufacturing process. Such a solution makes it possible to schedule an autonomous work cell to work at a specific time without operator intervention, which contributes to lower production costs and higher productivity. It should be remembered that this is not a solution that eliminates the operator's work completely, but it allows for better use of production time, for example, during night hours or holidays. However, this requires the development of a novel approach to the production process. The issue presented in the article represents a certain amount of research work, in terms of concept development and preliminary testing of the solution. An important feature of the proposed solution is its modularity and scalability, which is important to produce products by 3D printing of thermoplastic polymer materials.

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Authors contribution

A.P. - methodology, writing-original draft; G.B. - validation, supervision; M.P. - research techniques, editing; D.R. - visualization; M.M. - visualization; methodology investigation; T.K. - validation; design data model.

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Conflict of interest

The authors declare no conflict of interest.

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