ISSN 1846-6168 (Print), ISSN 1848-5588 (Online)
https://doi.org/10.31803/tg-20240430191724

Preliminary communication
Received: 2024-04-30, Accepted: 2024-05-08

Possibilities of Automating the Additive Manufacturing Process of Material Extrusion – MEX

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Abstract: The article presents the possibilities of automating production pre-processing and post-processing operations for the Material Extrusion - MEX process based on Fused Filament Fabrication technology. Automation is based on hardware and software solutions. For this purpose, a special research station was developed, equipped with a warehouse of working platforms, a 3D printer and a collaborative robot that integrates individual elements of the manufacturing process. The developed solution allows for increasing the efficiency of the manufacturing cell and reducing the operator's involvement in manual operations at the pre-processing and post-processing stages.

Keywords: 3D Printing; Collaborative Robot; Material Extrusion; Rapid Manufacturing

1 INTRODUCTION

Manufacturing products using additive techniques involves the need to prepare the 3D printer for operation (pre-process operations) and remove the model from the 3D printer and clean the working space (post-process operations) with human participation. For this reason, in the case of large-scale production, a more economical solution is to use traditional manufacturing methods, e.g. material injection. One way to reduce production costs using additive techniques may be to automate pre- and post-process operations, enabling it to be carried out continuously.

Automation of additive manufacturing processes also allows 3D printing to be moved into the era of Industry 4.0/5.0, where one of the main assumptions is to minimize human physical work as well as control and measurement operations [1, 2]. The use of artificial intelligence to monitor the process can significantly reduce the operator's working time. Additionally, the introduction of collaborative robots may result in the physical presence of the operator at the production station being required only to arm it and prepare the machines for the process, and further activities will be performed remotely [3, 4].

Current trends in the development of 3D printing show that the topic of automation of additive manufacturing processes has recently become very popular. Manufacturers of 3D printing machines present both prototypes and serial solutions of scalable production systems. However, these are solutions dedicated to specific devices from a given manufacturer. Currently, both on the market and in the equipment of many companies, you can find a large number of 3D printers with very good production parameters, but not having the characteristics of automated systems. Therefore, it is reasonable to develop a methodology for integrating such machines into networked, automated production units.

The MEX (Material Extrusion) method of layered extrusion from thermoplastic polymer materials involves extruding a plasticized material called a filament, which is most often in the form of a thread wound on a spool. Standard filament diameters are 1.75 and 2.85 mm. The extrusion process takes place in the head, which includes, among others: heating part, extruder and nozzle. The material is delivered to the heating block, where it is plasticized and then forced through the nozzle. The second function of the head is retraction, i.e. the withdrawal of material in order to prevent material leakage during idle movements of the head. A 3D printer using this method usually has one or more heads. Many heads are used, for example, when printing support structures from a material other than the main building material or when using various combinations of construction materials. Depending on the way the print heads move, the following designs can be distinguished: Cartesian, delta, polar or using a robot arm. In the first three cases, it is possible to apply flat layers of material on a leveled work platform. Structures based on a robot arm allow you to build curved layers, eliminating the need to use support structures. Additionally, in solutions of this type, the working platform can be placed on a robotic table with three axes of freedom. There are also solutions in which several robots work on one printout in parallel, shortening the time of the incremental process of a single model [5, 6]. There are also systems in which integrated printing robots move on mobile platforms or are suspended from flying drones. Additive processes are also subject to standardization in terms of terminology, design and production supervision [7, 8].

2 ANALYSIS OF DESIGN SOLUTIONS FOR 3D PRINTERS

The analysis covered 3D printing devices commonly used in scientific research, industrial applications and amateur applications, which are part of the machinery of the Department of Machine Design of the Rzeszów University of Technology. These devices may constitute a set of separate production machines, or it is possible to combine them into one coherent, heterogeneous production environment, which would increase the level of comfort and efficiency of their management. As part of the work carried out, an analysis was undertaken of the possibility of integrating printers into a common network structure with the possibility of automating selected processes. The possibilities of physical automation and integration through network interfaces available in individual devices, communication protocols used and possible ways of connecting to the network were analyzed.

Among the analyzed machines, we can distinguish those that cooperate only with the software of a given manufacturer, using classified communication protocols. An example would be brand devices equipped with a USB interface. They can only be connected to the network structure by providing remote access to a computer connected to the 3D printer via a USB cable. Such solutions are used, among others, in Objet Eden 260 and Objet 350 Connex 3 3D printers. These machines are additionally equipped with a wired LAN network interface enabling connection to a local network [9].

The second group of devices are machines with extensive network integration capabilities, including Stratatys F170 and Ultimaker3 3D printers. Both are equipped with the possibility of wired connection to the network, and Ultimaker3 also has a wireless WiFi interface. In both cases, device manufacturers provided documentation of communication protocols. Stratatys has also prepared a set of programming tools SDK (Software Development Kit) that facilitates the integration of 3D printers with the IT systems of modern, intelligent factories [10].

The third group of 3D printers are devices without factory network interfaces, the integration of which is possible using external print servers. Two types of solutions can be distinguished here: closed and open [11]. The first of them only work with the software of a given supplier (e.g. Repetier or 3DQue). The possibilities of their configuration and customization are very limited. Open solutions, however, allow for a flexible and comprehensive approach to the topic of network integration. This type of solutions includes, for example, Octoprint software. The third group of printers includes the Gence F340 3D device. Although its manufacturer does not provide information about the device's network operation capabilities, as part of the work carried out, a network connection was established using an external Repetier print server. The second example is the Prusa i3 MK3 printers. The Rzeszów University of Technology has several dozen such devices in the Rapid Prototyping Laboratory (Fig. 1). Printers are used for research and educational purposes.

Figure 1 Research and teaching Rapid Prototyping Laboratory

Prusa i3 MK3 3D printers can be extended with network functionality in several ways. One of them, used in the Rapid Prototyping Laboratory, involves performing a hardware modification. To perform it, you need a miniature single-board computer Raspberry Pi Zero and installing the Octoprint software. The assembly elements were made using 3D printing (Fig. 2). The electronic system should be connected directly to the serial port connector on the 3D printer controller board. This solution does not require an additional power supply.

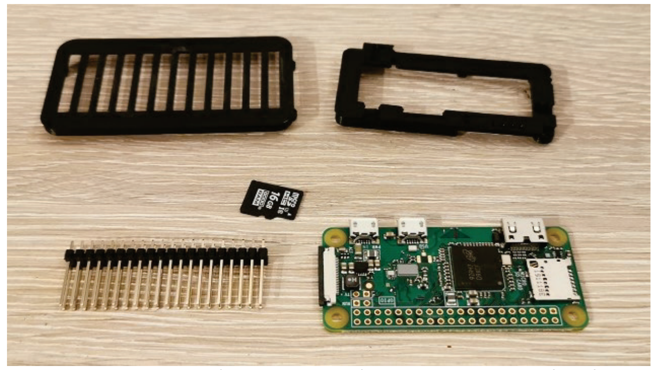

Figure 2 Elements used for hardware modification to extend Prusa i3 MK3 with network functionality

A computer of this class has relatively low computing power. In this case, software developers do not recommend installing more additional plug-ins and extensions. However, during the tests, the OctoEverywhere plug-in was installed, enabling remote access from anywhere, and during printing, no negative impact on the 3D printing processes was found. Octoprint software can also be installed on a much more powerful single-board computer, e.g. Raspberry Pi 4. However, in this case, a USB cable is used to connect to the printer. Additionally, it requires an additional power supply. This method was used during the construction of a laboratory research stand for the presented solution.

Video monitoring is an extremely important element of automatic and network-capable additive manufacturing systems. Its implementation allows for remote viewing of printing processes from anywhere. This saves the time needed for the operator to approach individual production machines to be visually inspected the correctness of its progress. Additionally, the implementation of artificial intelligence algorithms for real-time defect detection allows for quick response, which consequently reduces production time and material consumption.

3D printers are rarely equipped with video cameras as standard, and cameras are also rarely used as optional equipment. The camera is most often installed by the user himself. Often, the camera is connected to a previously integrated print server. Depending on its type, the connection is made via a universal USB interface or another specialized interface, e.g. CSI (Camera Serial Interface).

3D printer directed at their worktables. For this purpose, electronic systems of "open-frame" cameras were used, having a 5Mpx matrix and allowing image recording in 1080p resolution at 30 FPS. The systems were built into an articulated handle manufactured by 3D printing (Fig. 3) and then connected to previously retrofitted print servers. This solution enabled remote viewing of the process via the OctoEverywhere cloud platform and real-time supervision of the correctness of printing by the artificial intelligence algorithm - Gadget. A similar solution was used during the construction of the research station. However, in this case, web cameras connected to the print server via a USB interface were used.

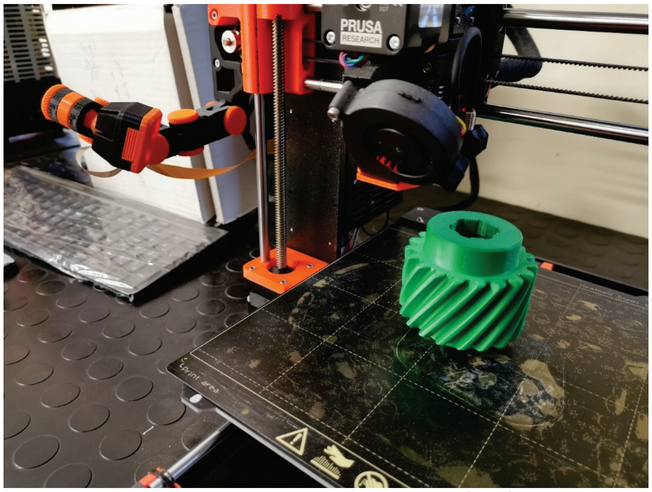

Figure 3 External camera installed on the Prusa i3 MK3 printer

3 STAND FOR TESTING 3D PRINTING AUTOMATION IN THE MEX PROCESS

As part of the research carried out, a concept of 3D printing automation based on the MEX process was developed based on a designed sorting and feeding device intended for 3D printers and applicable to pre- and post-process operations (Fig. 4). The presented concept is related to the use of a completely new approach to manufacturing processes. It involves the integration of various elements necessary to produce products or semi-finished products using additive technologies in a small area. Such a system is equipped with feeding, control, production, storage and control devices, e.g. in the form of 3D scanners and other devices. This solution was created in close cooperation with the socio-economic environment and was submitted for patent protection by PROXIMO AERO Sp. z o. o., application no. P.441182 [WIPO ST 10/C PL441182] of May 14, 2022. The co-authors listed in the patent application are employees of the Rzeszow University of Technology.

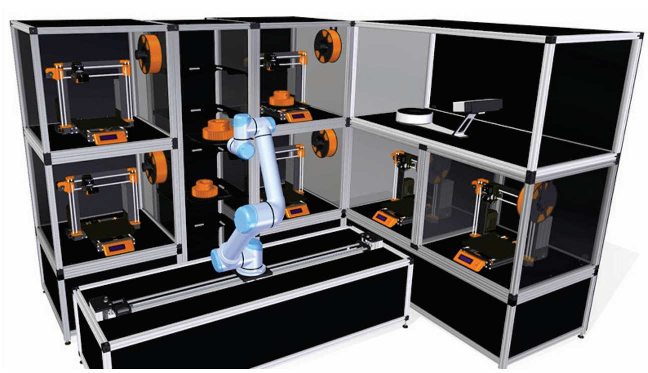

Figure 4 3D-CAD of an automated 3D printing station

The presented system allows for the implementation of works using a collaborative robot as a sorting device and feeding platforms to 3D printers. This solution can be used in a real production environment. The presented solution is based on 3D printers with an open working space, e.g. PRUSA MK3S, thanks to which the robot handle can freely remove the working platform from the printer. To ensure continuity of production, limited by the amount of free resources (filament, work platforms), the solution in question used the Universal-Robots UR5e collaborative robot with an arm reach of 850 mm and a load capacity of 5kg. The robot arm is equipped with a special gripper adapted to work with a specific 3D printer (Fig. 5). The designed solution also enables the station to be expanded with additional segments using a special track on which the robot can be placed.

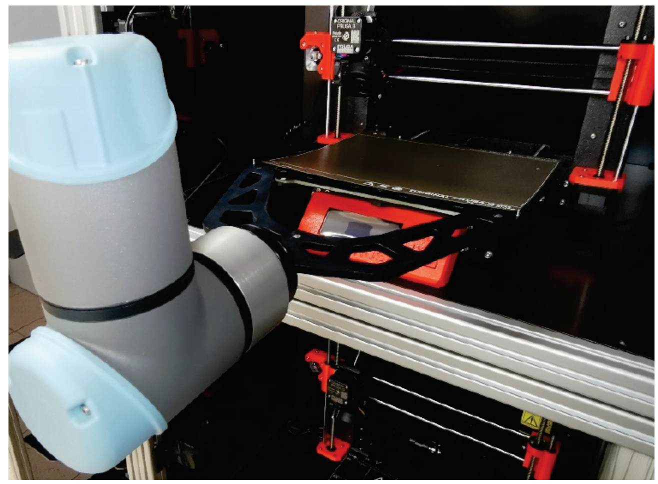

Figure 5 Robot gripper designed for the PRUSA MK3S 3D printer

However, to make this possible, it was necessary to develop a methodology for automating and computerizing the 3D printing process using the layer extrusion process of polymer thermoplastic materials. Within it, two main phases can be distinguished: preparatory and production. The first one aims to summarize the production environment. The phase begins with the preparation of preliminary assumptions regarding the desired production capacities, technological limits and the planned degree of process automation. Subsequent conceptual work concerns determining the type of manufacturing machines planned to be used, quality control systems and the movement of finished products. It is also important to make assumptions for management systems for machines and production materials. The developed concept allows for the selection of machinery. The result of his analysis is a summary of limits regarding possible production materials, maximum dimensions of manufactured objects and their production speed. A view of the material spool holder equipped with a scale and a wireless RFID communication sensor is shown in Fig. 6.

Identification takes place wirelessly when the spool is placed on the holder by reading information from RFID (Radio Frequency Identification) tags in the form of stickers. The read information includes a unique reel ID number allowing it to be uniquely identified in the database. The ID number is programmed once by the operator when the reel is accepted into the production materials warehouse. Reading data from the tag is also possible via most mobile devices. This makes it easier to physically locate a specific reel in the production materials warehouse.

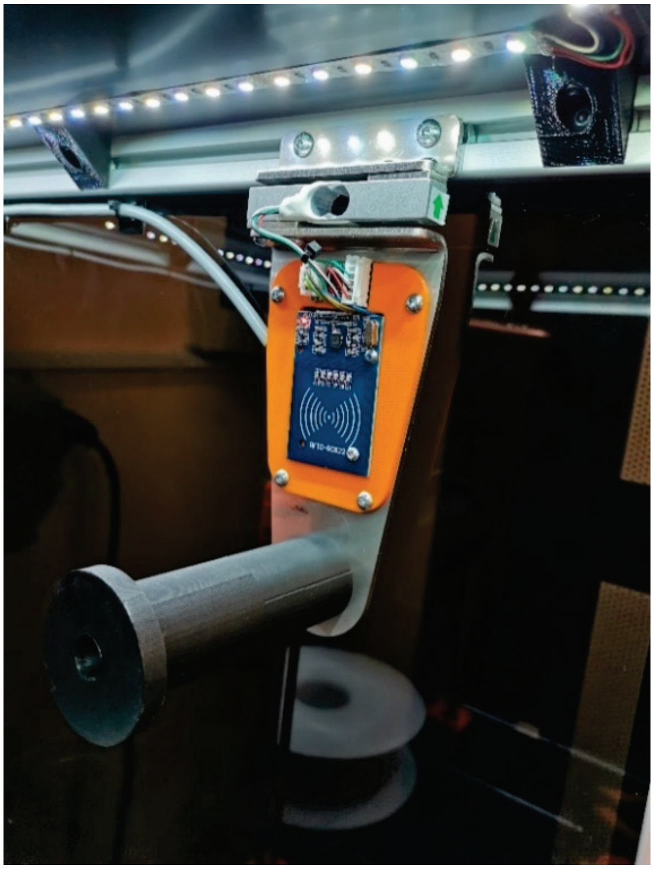

Figure 6 RFID tag reader built into the spool holder

The next step is to carry out network integration of selected devices. This process includes the compilation of network functions and the development and implementation of communication and data transfer protocols, including access authorization methods. One of the key elements of the preparatory phase is the development of an IT supervision system. Correctly designed, it allows for efficient management of machinery, production materials and the manufacturing process. It is important to design a user interface that is user-friendly and effective. Therefore, at this stage it is worth conducting a requirements analysis among potential process operators. The preparatory phase ends with the implementation of automation mechanisms such as quality control systems, optional measurement systems and robotic product transport systems. The manufacturing phase concerns pre- and post-process activities and the actual additive manufacturing process. The phase begins with the operator configuring the manufacturing system using a computer application. The operator selects production files and determines the number of elements to be produced. It is assumed that production files will be prepared in advance using cutting software. After system configuration, resources are automatically allocated to a given process and production files are transferred to appropriate devices via the network. Depending on the level of automation of the production station, the machines are equipped with working platforms by an operator or a robotic system. During the actual production stage, 3D printers and other devices remain under the control of the IT system. Manufactured objects are continuously monitored by artificial intelligence algorithms to detect defects. The operating parameters of 3D printers and the amount of available production material are also monitored. Data is collected in a central database. The operator can visualize them from an application with a graphical interface. According to the adopted approach, two production modes can be distinguished, depending on the degree of process automation. A manufacturing environment with a second degree of automation is characterized by the fact that after production is completed, the physical model together with the working platform is transferred by a robotic arm to the finished products warehouse or to the quality control station. Then the robot equips the 3D printer with an empty platform, and the IT system prints the next object. In a manufacturing environment with the first degree of automation, these activities are made manually by an operator.

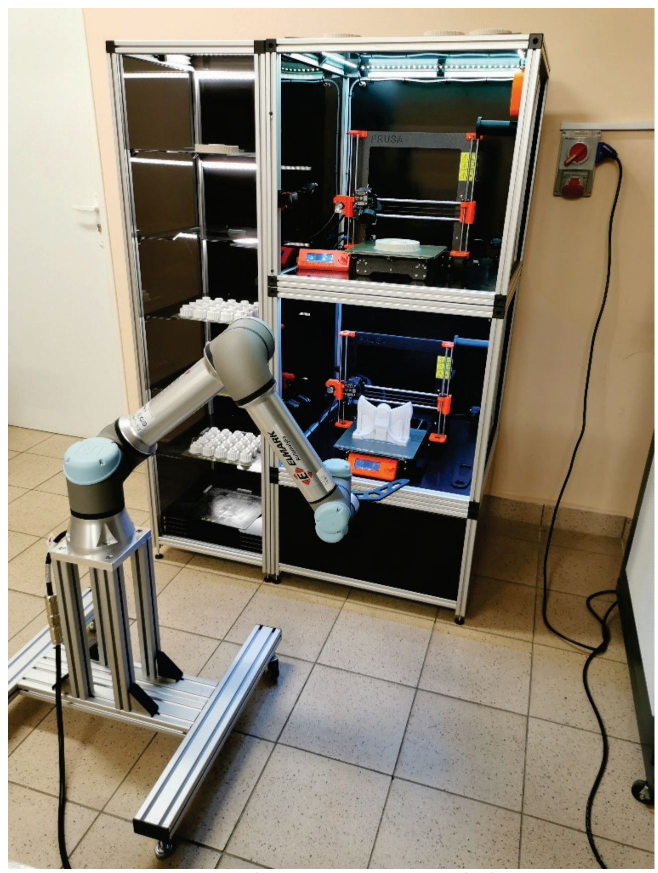

Figure 7 Automated feeding and sorting device for 3D printing

In order to implement the concept of a feeding and sorting station for elements printed in a system of multiple 3D printers, it was necessary to perform work on the analysis of methods of network integration of 3D printers, remote control and monitoring systems of the manufacturing process, mechanisms for controlling the amount of available production material and methods of transferring the manufactured models using collaborative robot. Based on the developed methodology, a research station was built in the form of an automated 3D printing station (Fig. 7) with a monitoring application.

4 CONCLUSIONS

As a result of a series of analyzes and numerous experiments, a methodology was developed for integrating 3D printing systems and processes using network infrastructure, which is the result of achieving the goal of the work. The developed methodology assumes network cooperation of 3D printers, allowing the creation of heterogeneous production environments using layered extrusion technology. On its basis, a research station in the form of an automated 3D printing station with a modular structure was developed and constructed.

The station is operated by the operator remotely via an application from a web browser. The application manages the operation of printing devices and the work of the robot, whose task is to transport the produced models and install clean working platforms. This allows for continuous production until the filament runs out.

As a result of the experimental work carried out, the following conclusions can be drawn:

- The use of network structures enables remote control of the manufacturing process, in particular its starting, stopping and transfer of production files. This allows a printer or set of 3D printers to be armed in advance and ready to remotely start the process on demand when required.
- Transferring production files via a network is less time-consuming compared to conventionally transferring them on a storage medium. This is particularly important in the context of managing large teams of production machines and frequently changing production.
- Early detection of defects occurring during the printing of a physical object allows for reduction of wasted material and 3D printer operating time. This detection can be performed remotely by the operator by periodically inspecting the image from cameras monitoring the process. The operator can observe from one place, which is particularly important in the case of distributed 3D printing systems, in particular its starting, stopping and transfer of production files. This allows a printer or set of 3D printers to be armed in advance and ready to remotely start the process on demand when required.
- Knowing the type and quantity of available production material in a given 3D printer allows for effective management of the machinery. Thanks to this information, the print queuing algorithm implemented in the application that supervises the entire manufacturing environment can automatically redirect the print order to the appropriate 3D printer. This is particularly important in the case of individual or small-scale production to order and in the event of device failure or detection of a print defect.
- Automatic recording of the amount of filament in partially used spools allows for more efficient management of stored materials. Thanks to the knowledge of inventory levels, it is possible to automate certain activities related to logistics. Appropriate algorithms can assess the feasibility of completing a given production order or determine the amount of material needed for the order. It also allows you to quickly estimate the time needed to complete production, which is extremely important information for the ordering party.
- The additional introduction of robotic execution systems allows for the elimination of the operator's participation in activities between subsequent prints. As a result, its presence is only needed to equip the machines with production material.

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