TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 69, Issue I, March, 2026

INTEGRATION OF ARTIFICIAL INTELLIGENCE IN THE 3D PRINTING PROCESS. LITERATURE REVIEW

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Abstract: *This study provides a comprehensive literature review on the integration of artificial intelligence (AI) into the 3D printing workflow. It specifically investigates AI's contribution to parameter optimization, product quality enhancement, and waste reduction. The methodology for selecting pertinent research is detailed, involving an analysis of scientific articles and patents that address the advantages and disadvantages of AI integration in 3D printing. Finally, it identifies a path for future research to further improve the efficiency of 3D printing.*
Key words: *3D printing, artificial intelligence, parameters optimization, process optimization.*

1. INTRODUCTION

3D printing, also known as additive manufacturing, is a process in which a structure can be built in the design form, from bottom to top, regardless of complexity, using a layer-by-layer approach. It is fundamentally different from traditional removal or forming techniques such as milling, drilling and cutting, forming and casting processes. 3D printing has the potential to significantly reduce or even eliminate the use of traditional tools, considerably reduce the degree of mechanical assembly and failure points, enable fully customized projects through software modeling, and substantially reduce the costs of prototyping and manufacturing steps [1].

Additive manufacturing is becoming increasingly common in large industries, leading to a constant trend of optimization and development. Its benefits include design flexibility, product customization, waste reduction, rapid prototyping, low costs for mass production, and the use of various materials, as well as sustainability.

However, it also presents several disadvantages, among the most common are: environmental sensitivity, poor part adhesion on the print surface, material limitations and difficult printer adaptation to these materials, the constant need for printer calibration, quality dependent on the correct choice of parameters.

The key to minimizing risks and preventing resource losses during 3D printing is to have staff with consistent training and experience, both in the design and execution phases.

An effective way to optimize the 3D printing process is to integrate available advanced technologies. These technologies enable the reduction of resource losses, improved quality of finished products, and optimization of the printing process by adjusting parameters.

One advanced technology that could solve the problem of lack of trained and experienced 3D printing personnel is artificial intelligence, which can mimic certain human cognitive functions such as perception, reasoning, learning and problem solving [2].

The objective of this article is to conduct a literature review and analyze the methods by which AI is integrated into different stages of the 3D printing process, to improve its efficiency. The purpose of this review is to identify a new direction for research and practical applications in this field.

Received: 17.01.26; **Similarities**: 10.02.26: **Reviewed**: 17.01. /17.01.26: **Accepted** 24.03.26.

During the article, the methodology used to identify the relevant literature in the research will be discussed, highlighting the selection criteria and the analysis process. The results obtained from the selection of the most relevant materials will be presented and interpreted.

Also, a brief description of the applications identified in the analyzed literature will be provided, highlighting the advantages and disadvantages identified in them. Finally, the future direction of research will be outlined, highlighting possible developments and perspectives in the field.

2. METHODOLOGY

In the research, the following types of literature were selected for analysis: scientific articles, review papers, and patents. These sources have been chosen to provide a comprehensive perspective on the field under study, including both original research and critical summaries of existing progress, as well as patent-protected innovations.

In the first phase of the research, data analysis was carried out using statistical methods, allowing a quantitative assessment of the information collected. Afterward, based on the results, the literature was analyzed in a qualitative manner, involving the identification and selection of relevant sources, beginning with the title, then examining their summary, and then the complete articles for relevance. The use of a combined approach has resulted in material filtration that is rigorous, ensuring the inclusion of the most relevant studies for the research objectives.

The databases consulted for patents were: Espacenet, Google patents, and for articles: Science direct, IEEE, Springerlink, Google Scholar.

The keywords used initially were “3D print” and “artificial intelligence”, and later to expand the search were “3D printing”, “AI”, “machine learning”, “ML”, “additive manufacturing” and “advanced technology”.

To identify the relevant resources in the direction of optimizing the 3D printing process, the following were introduced: “Optimization” AND “control”.

They were also selected as areas of interest for the search for “engineering” and “computer science” articles.

The selection of research for this article was based on identifying diverse AI technologies and their integration methods in 3D printing. Even though the methods and technologies are completely different, they have been selected to create a clearer view of the possibilities of improvement and to identify new ways of developing 3D printing processes.

3. RESULTS AND DISCUSSIONS

The review of the literature shows that the focus is on improving the quality of the product from the dimensional point of view, of mechanical, optical and/or electrical properties. In most research, artificial intelligence was integrated into additive manufacturing processes, but the following concepts and technologies were also involved: Robotic arm, 4D printing, machine learning, digital twins etc.

In the following, the methods identified in the most relevant scientific papers for integrating artificial intelligence into the 3D printing process will be briefly described.

In the article “3D Printing with Robotic arm with Artificial Intelligence elements”, authors Rafał Siemasz and others developed the mobile arm motion algorithms, which perform the role of the mobile element, for example a 3D printed with fusion deposition [3]. And several authors such as Jeremy Straub, Tian Xiaoyong, Charles Howard and others have integrated artificial intelligence for image recognition into their methods/systems to monitor and collect product data during and at the end of production, however, they do not influence the product or parameters during printing, these data being used only to validate or reject the already 3D printed product [4-6].

In their studies, researchers Vadim Pinskiy, Ugandhar Delli, and their co-authors developed the principles described above, and used artificial intelligence for image recognition, to check the last layer made, in order to identify the unrecoverable defects in the product, in order to stop printing, to reduce as much as possible the waste of resources [7], [8]. However, the process under the article “Automatic process Monitoring

in 3D Printing using supervised machine learning" identified two major disadvantages. The first disadvantage of the proposed method is that the printing process has to be interrupted during image capture, which results in a significant increase in printing time and a potential risk of malfunction when the printing process is restarted. The second disadvantage is generated by the angle from which the images are taken, namely the top view, so the proposed method could not detect defects on the vertical plane, which can lead to the validation of the printing process until the end of a non-conforming part.

Advanced machine learning technology has been approached and used in the works written by Alfonso Alexander [9], Wojciech Matusik [10] and others, the method of optimizing the 3D printing process used, is based on improving the parameters of the printer or product over time, through learning, this means that it does not affect the model during the actual time of printing. This means that a part or series of test parts is made, and after analyzing them and using AI algorithms, the optimal parameters for the printer are established. After this, another part is made according to the necessary changes, until the finished part can be obtained with the required parameters, and this involves a lot of wasted time and resources.

The same principle is addressed in research by researchers Guo Zhenyu and Que Jinlong [11], which is based on the creation of the 3D printer training database over time.

It is formed by performing numerous 3D prints and analyzing the resulting parts, which will then be used to create other parts within the necessary parameters. Also, this method involves a lot of waste of time and resources.

In their research, Izabela Rojek [12], Zhang Hao [13], Que Jinlong [14], approached the methods of calculation, simulation and prediction, which help to optimize the 3D printing process.

Izabela Rojek and her coauthors propose a concept of a digital twin. This involves creating a highly detailed virtual model of a physical 3D printer that is constantly updated with real-time data. Using artificial intelligence and machine learning algorithms, this model can predict and identify possible optimizations for the printer's performance. However, the system only provides recommendations, leaving the final control and decision-making to the user [12].

Patented research [13] involves performing a numerical simulation experiment and building an artificial neural network, then determining the optimal parameters. Thus, the simulation's conclusions are utilized to construct and educate an artificial neural network for prediction, which accurately predicts the optimization effect. In the case of extremely complex 3D printing scenarios or when working with many process parameters, the computational load could become an issue. It may require access to high-performance computing (HPC) clusters or powerful workstations, which may not be affordable for many users.

The patented study [14] also involves identifying the rule of operation between technical parameters in 3D print records and print result evaluation values, to be able to create an algorithm using AI, which will be able to intelligently optimize the technical parameters of the 3D printer.

Researchers Wang Junchao and others [15] have developed an initial automatic calibration method of the 3D printer. The method involves printing a reference part/calibration, and through an automatic image recognition program and a neural network, based on AI, accuracy is calculated: The ratio between the actual dimensions of the part and the dimensions of the 3D printed part, taking into account also the material used; AI algorithms are used to automatically calibrate the dimensions of 3D printed and designed models [15]. However, this method offers only advantages regarding the dimensional accuracy of 3D printed landmarks, but it cannot guarantee the absence of print defects.

In their patent, Wang Xiaomei and others [16] describe a method that involves image processing and a 3D printing control system based on artificial intelligence. After analyzing the images using a computing device, the key feature set is obtained. And instructions to adjust print parameters are generated using a pre-established pattern for recognizing print obstacles. However, this method can require a

long time to process the images, during which the printer will produce the part with inappropriate parameters, and the result may be of lower quality.

The study conducted by Shui Liu Un and Jiao Huang [17] resulted in an AI control system capable of optimizing print parameters by learning historical print data and automatically adjusting the printing parameters to improve print quality and used resources, but this method does not require photo/video monitoring of the printing process, thus, unexpected system failures could not be identified.

A very effective method of integrating artificial intelligence into the 3D printing process and controlling this process is detailed in the patent authored by Matthew Putman and collaborators [18], this involves an additive manufacturing system that uses artificial intelligence, which can identify anomalies in an object's printed layer from a generated topographic image of the printed layer, it can also identify a correlation between the identified anomaly and one or more print parameters and adjust one or more print parameters adaptively. However, the analysis performed only at the end of the last printed layer may be less effective compared to continuous analysis, even if it requires more input data to analyze.

4. CRITICAL ANALYSIS

The centralization of methods by article or patent is presented in Table 1.

Table 1

Centralization of methods by article or patent.

1st author of article/ patent	Method
Rafał Siemasz	Creating the algorithm for robotic arm movement with AI
J.Straub, T. Xiaoyong et al., C. Howard et al.	Image processing and data collection during printing with AI
V. Pinskiy et al., U. Delli & S. Chang	Image processing at the completion of the last printed layer using AI and defect identification
A. Alexander et al., W. Matusik & D. Chen.	Analysis of test parts and identification of optimized parameters using AI algorithms
Z. Guo & J. Que	AI-based creation of 3D printer training database for parameter optimization
I. Rojek et al., H. Zhang et al., J. Que et al.	Artificial neural prediction networks for efficient prediction of the optimization effect
J. Wang et al.	AI-based image recognition and neural network for printer calibration
X. Wang	Image processing and an artificial intelligence-based 3D printing control system that also generates instructions for adjusting printing parameters
S.L. Un & J. Huang	AI control system, which can automatically adjust the printing process to improve print quality and resource utilization
M.C. Putman et al.	Additive manufacturing system that uses artificial intelligence, which can identify anomalies in a printed layer and adaptively adjust one or more printing parameters

In the methods described above, it can be noted that: environmental sensitivity, poor adhesion of parts to the printing surface, material limitations and difficult adaptation of the printer to these materials, the constant need to calibrate the printer quality according to the correct choice of parameters, all the problems listed can be partially or completely solved, by integrating artificial intelligence in the 3D printing process.

The first methods analyzed are based on data collection and AI recognition of images captured during the 3D printing process to monitor quality. However, the approaches proposed by authors such as Jeremy Straub, Tian Xiaoyong and Charles Howard are less effective compared to the methods developed by Vadim Pinskiy and Ugandhar Delli. The solutions of the last are distinguished by the fact that they are aimed at reducing resource losses – both material and time – in case of non-compliant 3D prints. Although Wang Junchao and his team's solution improve product quality by calibrating the printer using AI neural networks, this approach cannot guarantee compliant printing throughout the process. However, these solutions only focus on quality assurance and/or reduction of resource losses, as opposed to other studies

aimed at an overall optimization of parameters and the 3D printing process.

Although the solutions proposed by Alfonso Alexander, Wojciech Matusik and Guo Zhenyu, among others, are aimed at optimizing the process. Creating a complete database can be extremely time-consuming and human resources. Moreover, the industrialization of new materials or more complex parts may require the repetition of the entire process.

The solutions proposed by Wang Xiaomei, Shui Liu Un and Matthew Putman seem to be the most effective. Even if it requires initial data collection to train AI systems, they offer a high level of automation of 3D printing processes, automatically adjusting the required parameters.

However, there are also significant disadvantages: implementation requires very advanced training of personnel, and the initial costs for the equipment needed for the system are considerable. In addition, these methods require increased computational capacity.

5. CONCLUSION

In the analyzed articles and patents, there is a positive trend of integrating artificial intelligence into 3D printing processes, for their optimization or for their control. The methods used in the studies described assume image analysis using AI, for detecting certain non-conformities, which requires the existence of a database of images for comparison, making simulations and predictions, calibrations using AI algorithms, and last but not least generating instructions for adapting printer parameters using AI.

The creation of mobile arm motion algorithms was made possible by researchers using AI, simulations and prediction algorithms for 3D and 4D printing. The authors have successfully integrated a particular type of AI - machine learning into 3D printer systems. The goal of all methods is to achieve a higher standard than the usual 3D printing process and to optimize the process of creating printed parts.

In conclusion, a research direction could focus on developing an intelligent system for monitoring and adapting the printing process, by integrating environmental sensors (such as humidity, brightness, temperature) and a continuous-transmission camera, not just at the completion of a layer. By using an artificial intelligence-based algorithm, it will aim to automatically generate codes that will optimize the printing parameters in real time, thus ensuring the quality and efficiency of the process. A key aspect of this solution would be its structural and operational simplicity, which will allow for efficient operation without requiring high computational capacity. Thus, this research direction will propose an affordable and sustainable alternative to automating processes in the field of 3D printing.

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Revizuirea literaturii privind integrarea inteligenței artificiale în procesul de printare 3D.

Prin revizuirea literaturii, lucrarea analizează aplicarea inteligenței artificiale (IA) în procesul de imprimare 3D, evidențiind rolul acesteia în optimizarea parametrilor, îmbunătățirea calității produselor și reducerea risipei. Se prezintă modul de identificare a literaturii relevante și revizuite articole științifice și brevete evidențiind modul de integrare a inteligenței artificiale în procesul de printare 3D și avantajele și dezavantajele acestei integrări. De asemenea, sunt analizate direcții viitoare de cercetare care ar putea optimiza și eficientiza procesul de printare 3D.

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