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STRUCTURAL - MORPHOLOGICAL SYNTHESIS OF PARALLEL KINEMATICS-BASED HYBRID 3D-PRINTER AND CONNECTION WITH THE CHALLENGES OF INDUSTRY 4.0

Yurii Kuznietsov*, Oleksii Solntsev

National technical University of Ukraine "Igor Sykorsky Kyiv Polytechnic institute", Ukraine

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ABSTRACT

This article highlights the application of a systematic method, a structural - morphological approach to the synthesis of new technical solutions in the field of additive technologies to meet the challenges of Industry 4.0, namely the synthesis of a hybrid, fully automated 3D printer with parallel kinematic structures.

1. INTRODUCTION

The advent of Industry 4.0 has an important impact on manufacturing approaches and development processes and plays a key role in establishing sustainable production. Sustainability is one of the hottest trends in manufacturing today, and Industry 4.0 is playing an increasingly important role in its spread.The main topics and trends associated with the advent of Industry 4.0 are: (i) The trend for mass customization, achieved through an increase in the efficiency of technological processes; (ii) Digitalization and automation of production; (iii). Energy efficiency and cost reduction [1, 2, 4].

The benefits of integrating and using the principles of Industry 4.0 and Advanced digital production:

1. Upcoming of New and better products;
2. Increased production efficiency.

The key technologies that are driving the development of Industry 4.0 are digital technologies such as artificial intelligence (AI), machine learning (ML), big data analytics, the Internet of Things (IoT) and additive manufacturing/3D printing. They simplify manufacturing processes and efficient recycling and recovery programs.The main technologies that have the greatest impact on the businesses are shown in Fig. 1 [5].

Despite the lower position of 3D printing technology in terms of the degree of impact on business compared to other key technologies, 3D printing remains one of the most important technologies for the manufacturing sector.This technology enables the production of customized, unique industrial products and prototypes to accelerate the development process. 3D printing is one of the manufacturing methods that makes it possible by turning a digital model of an object into a three-dimensional physical object by adding materials layer by layer. The technology allows the creation of complex geometries that are not possible with traditional manufacturing methods, the design and manufacture of lighter components, and the control of various material properties such as density and stiffness [4].

However, despite all the above benefits, which brings technologies associated with Industry 4.0, in practice, the integration and popularisation of these technologies among industrial SMEs, which represent more than 70% of the European industry market, is rather slow. The main reason is the large input investment/entry costs and gaps in knowledge - the need to retrain the staff, as well as the operating costs that increase at the initial stages.Below, the problems of integration and distribution of additive technologies will be considered in more detail and one of the solutions to this problem will be proposed using a systematic method of searching for technical solutions [4,11].

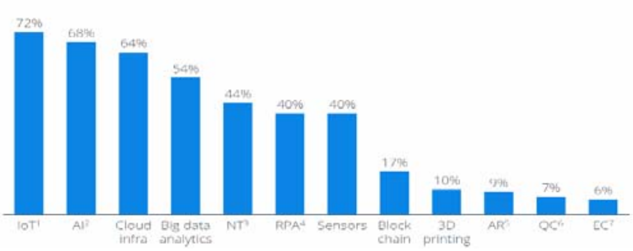


Fig. 1. Technologies expected to have the most significant impact on businesses [5]

2. MODERN EXTRUSION-BASED ADDITIVE TECHNOLOGY. PROBLEM OVERVIEW AND PROPOSED SOLUTION WAY

Despite the great development of various technologies within additive technologies (the most popular among users

* Corresponding author. E-mail: info@zmok.kiev.ua

in all segments (B2B, B2G, B2C) is still represented by the extrusion method (FFF-fused filament fabrication). The trend towards the popularity of this method continues to grow. First of all, this can be explained by the quantity and variety of materials offered by manufacturers and the growing availability of these materials. In the FFF process, melted thermoplastic material such as plastic, wax, or metal, is sprayed from a nozzle to create many layers, that are bonded to the each other. The bonding is done mainly by heat or adhesion. The most popular materials used here are nylon, high-density polyethylene, polycaprolactone, polycarbonate, and low melting point metals. FFF is the preferred method of rapid prototyping parts with standard tolerances due to its affordability and low turn-around times.

Now, there are three main groups of materials for conditional classification (Fig. 2): commodity, engineering and high-perfomance. In addition to conventional and composite polymers, which are typical for injection molding technology, exotic materials that are applicable for 3D printing are increasingly appearing. So, for example, in 2019, BASF announced the BASF Ultrafuse 316L Metal 3D Printing Filament, which allows to produce stainless steel metal products using a polymer FDM printer.

Despite all the advantages of FFF printing and the rapid growth in the availability and variety of materials, modern 3D-printers still cannot provide efficient printing with a wide range of materials/techniques, because of the narrow focus of printers and operating with one, maximum two printing modules/heads, which cannot effectively cover the entire range of existing materials and technologies inside the FFF technology (abrasive materials, high-temp. melting materials, engineering materials etc. and various subtypes of FFF-printing: precision printing, high-flow printing, granular printing).

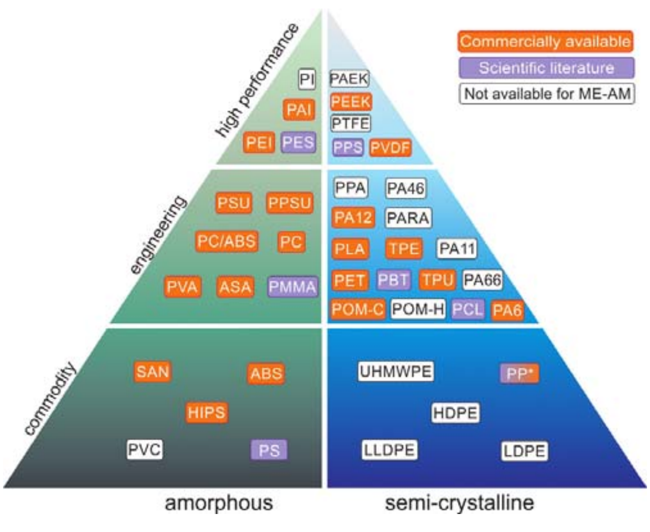


Fig. 2. Groups of materials for FFF 3D-printing technology

3. APPLICATION OF THE STRUCTURAL - MORPHOLOGICAL METHOD TO SOLVING THE PROBLEM OF MODERN FFF 3D-PRINTERS

Thus, from the previous analysis, we see that the main problem is the narrow focus of existing solutions for FFF technology, which affects the high cost of integrating this technology due to the need to purchase a large number of different equipment. Separately, it is worth noting the low level of equipment automation, which also does not correlate with the principles of Industry 4.0.

Morphological approach allows for a well-defined problem, by designing a new technical system, the purpose of which is to solve the given problems, highlight the important characteristics of the Technical system, highlight the options for implementing these characteristics and, based on the selected, prioritized criteria for the system, narrow the design task [6, 9].

Thus, based on the above problem, we can reduce the synthesis problem to the following: **Synthesis of a hybrid, flexible technical system for additive and subtractive manufacturing, which allows working with a sufficient amount of materials for printing and post-processing of printed products.**

For an automated hybrid 3D printer, the synthesis process will be narrowed down to three main stages: structural synthesis, layouts synthesis, and design synthesis. At each stage, morphological matrices are created with a set of object characteristics, from which the best options are selected using a group of criteria. As we approach the optimal design, the number of criteria increases, which makes it possible to specify the synthesis problem. In this article, the solution of the problem of structural synthesis is considered in detail, and the issues of solving the problem of layout synthesis are also touched upon [6, 12].

The following top-level requirements for the system being designed at the stage of structural synthesis can single out:

- Automated material (filament, granular), necessary both for facilitating the printing process and for multi-material printing;
- Automated tool change for ability to print with different material groups and operating with different nozzle diametrs;
- Ability to use tools for post-processing printed products in one cycle;
- Possibility of using additional tools such as adhesive sprays, measuring probes, etc.;
- Sufficient system dynamic characteristics to meet printing speed requirements;
- The above technical system would solve the problem of the high cost of a set of different equipment.

To solve the problem of synthesizing such a system, a complete morphological matrix was compiled that reflects the main characteristics of the designed system at the structural level

$$M_{HP} = M_{KS} \times M_{MC} \times M_{TC} \times M_{ET} \, .$$

Such morphological system charachteristics were identified: (1) Kinematics, (2) Material (Filament) change method (Fig. 3), (3) Tool change principle, (4) Tool change mechanism type, (5) Types of other possible tools.A complete matrix with all variants of morphological features is shown in Table 1.

$$M_{HP} = \left|\begin{matrix} 1.1 \\ 1.2 \\ 1.3 \\ 1.4 \\ 1.5 \\ 1.6 \end{matrix}\right| \cap \left|\begin{matrix} 2.1 \\ 2.2 \\ 2.3 \\ 2.4 \\ 2.5 \\ 2.6 \\ 2.7 \end{matrix}\right| \cap \left|\begin{matrix} 3.1 & 4.1 \\ 3.2 & 4.2 \\ 3.3 & 4.3 \\ 3.4 & 4.4 \\ 3.5 & 4.5 \\ 3.6 & 4.6 \end{matrix}\right| \cap \left|\begin{matrix} 5.1 \\ 5.2 \\ 5.3 \\ 5.4 \\ 5.5 \\ 5.6 \\ 5.7 \end{matrix}\right| \qquad (1)$$

This is the total number of possible solutions

$$M_{HP} = 6 \times 7 \times 6 \times 6 \times 7 = 10584$$

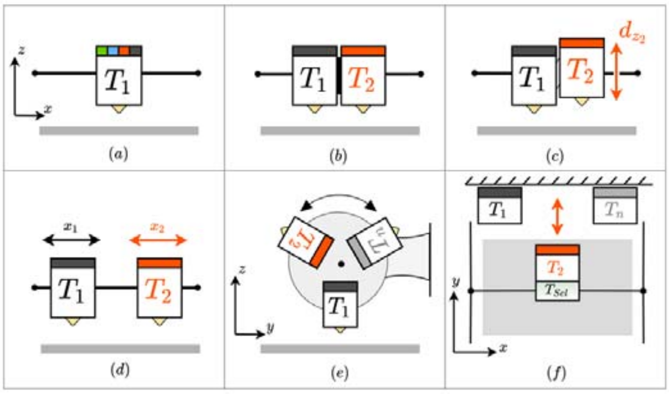


Fig. 3. Different options of one of the morphological characteristics for the designed system - the method of automatic filament change [13]

Commercially available hybrid 3D printers were analyzed. Morphological formulas showing their structure are shown in Fig. 4.

The Issue of existing solutions is that some manufacturers have taken the path of integrating 3D printing modules (heads) into the machine tool system, while others, taking existing schemes and structures of 3D printers, have tried to integrate tool change systems into them.The fist way faced the problem of low efficiency due to overall, heavy moving units, which did not allow achieving the necessary accelerations and speeds for modern 3D printing tasks [10].

The second way to solve the problem of narrow focus of printers by integrating tool change systems into existing 3D printer design. However, such a solution takes up part of the working area or requires complex additional systems, such as an industrial robot. Since, for example, in such a design, a material (filament) supply channel for each tool should be taken into account.

Also, a structural -morphological analysis was carried out to select the optimal frame layout (layoutsynthesis). For the analysis, the methodology proposed by Kuznetsov Y., Stepanenko O. was used. In this article, we considered a multi-level morphological synthesis applicable to the design of small-sized machine tools with mechanisms of a parallel structure. However, having changed the prioritization of the criteria for designing 3D printer, the best frame options were selected specifically for a hybrid 3D printer.

Considering the criteria for designing a hybrid 3D printer, the inverted pyramid option was chosen for frame layout (Fig. 6). This option allows to save the advantages of using the mechanisms of a parallel structure [7, 8], but significantly increase the working area compared to pyramidal layouts showed at Fig. 5,a,b,d. The working area of proposed layour has increased working area along the horizontal axes, compared with the classical „Delta-layout“ (Fig. 5,c,e). This allows to cover more typical objects for 3D printing.

Table 1 *Complete morphological table of the main characteristics for synthesis of the structure for a hybrid 3D-printer*

1. Kinematics	**2. Material (Filament) change method**	**3. Tool change principle**	**4. Tool change mechanism type**	**5. Types of other possible tools**
1.1 Industrial robot (open kinematic chain)	2.1 Option a. Fig4	3.1 No	4.1 Disc type+ arm	5.1 CNC Spindle
1.2 Parallel kinematics. XYZ Head	2.3 Option b. Fig. 4	3.2 Manual	4.2 Robot tool changer	5.2 Spray with adhesive
1.3 CoreXY. XY Head, Z Bed	2.3 Option c. Fig. 4	3.3 Automated. Pneumatics	4.3 Umbrella tool changer	5.3 Mixing-dosing tool heads
1.4 XZ Head, Y Bed	2.4 Option d. Fig. 4	3.4 Automated. Electromechanical	4.4 Turret head	5.4 Sensore probe
1.5 XY Bed Z Head	2.5 Option e. Fig. 4	3.5 Automated. Electromagnetical	4.5 Chain type	5.5 Scanning tool
1.6 Other	2.6 Option f. Fig. 4	3.6 Automated. Hydraulic	4.6 Manual	5.6 Laser head
	2.7 No			5.7 No

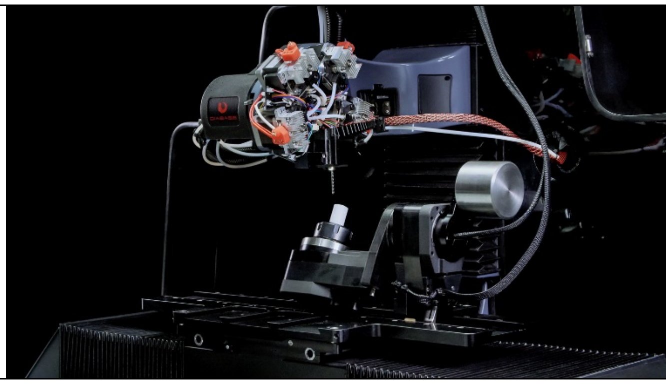
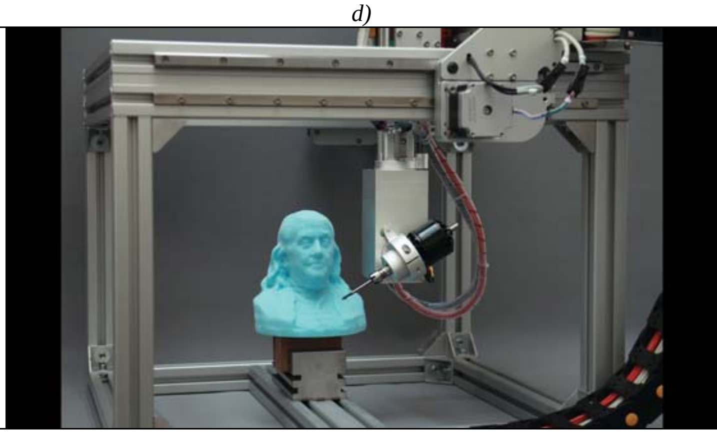
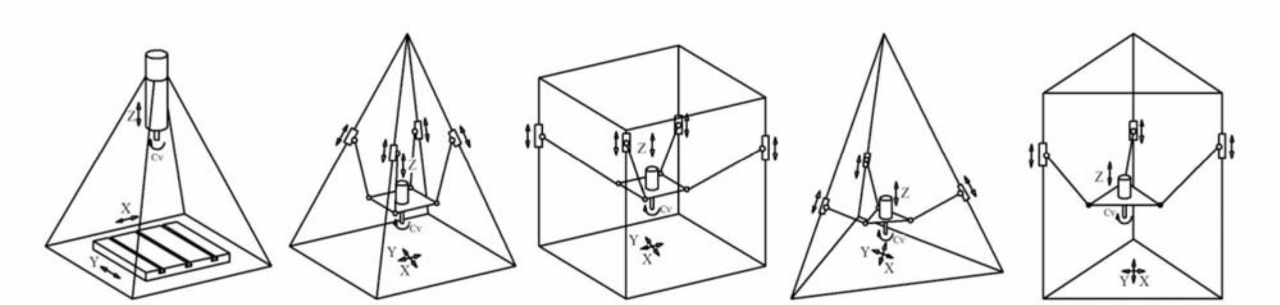
	
1.1 - 2.7 - 3.2 - 4.6 - 5.1	*1.5 - 2.5 - 3.4 - 4.4 - 5.1*
a)	*b)*
	
1.3 - 2.6 - 3.4 - 4.6 - 5.1	*1.4 - 2.7 - 3.1 - 4.6 - 5.1*
c)	*d)*
	
1.3 - 2.3 - 3.2 - 4.6 - 5.7	*1.6 - 2.7 - 3.2 - 4.6 - 5.1*
e)	*f)*

Fig. 4. Commercially available hybrid 3D printers and their morphological formulas:a – AI Build, b - Diabase Engineering H-Series, c – E3D ToolChanger, d – Zmorph Fab,e – Ultimaker S5 Bunlde, f – 5Axis Maker



a) b) c) d) e)

Fig. 5. Layouts of small-sized machine tools obtained by the method of multilevel morphological analysis [6]

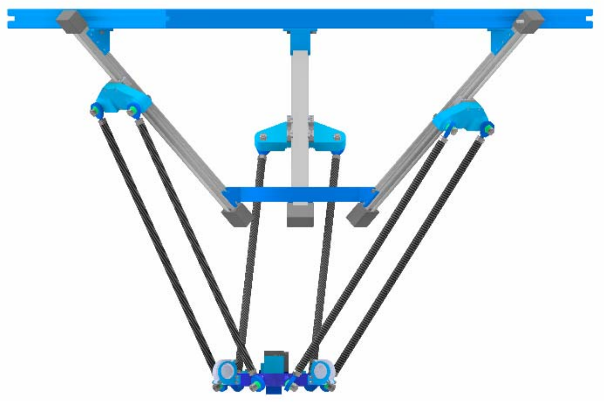


Fig. 6. Proposed frame layout for hybrid 3D-printer, obtained by the method of multilevel morphological analysis

4. CONCLUSIONS

1. Industry 4.0 is changing approaches to production by focusing on mass customization, digitalization of production and reduction of logistics lines. This is achieved through new technologies such as ML, AI, IoT and additive technologies.

2. Industrial SMEs, which account over 70% of the European market, have difficulties with integrating Industry 4.0 technology due to large initial investments, the need for personal training, etc.

3. One of the most popular additive technology is FFF. But despite the large number and availability of materials, due to the narrow focus and inflexibility of modern printers, the integration of this technology at the professional level is also associated with large investments due to the need to purchase a large number of different equipment.

4. Structural - Morphological approach allowed to clearly describe the problem and find the solution systematically: identify the main morphological charachteristics of the designed technical system.

5. On the basis of the developed morphological matrix, the morphological formulas for structures of existing solutions of hybrid printers were obtained. The analysis of existing solutions is described.

6. The article describes the appliacation of the structural-morphological method for the structural synthesis of a hybrid system for additive and subtractive manufacturing.

7. The article partially describes the use of methods proposed by Kuznetsov Y. for the layout synthesis of the frame of the hybrid 3D printer.

8. For the first time, a morphological structure for the synthesis of hybrid 3D printers was developed and the use of parallel structure mechanisms in combination with an inverted pyramid frame to create a hybrid 3D printer was proposed.

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