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3D PRINTING AS AN ALTERNATIVE TO SPARE PARTS FOR FIELD REPAIR OF RADIO-ELECTRONIC EQUIPMENT

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ABSTRACT *The application of three-dimensional printing technologies for the rapid restoration of radio-electronic equipment in field conditions, in cases of limited access to logistics infrastructure and as an alternative to traditional spare parts kits is considered. The technical and economic aspects of choosing three-dimensional printer models are analyzed depending on the level of structural complexity of radio-electronic equipment, the dimensions of parts and the features of their operation. It is shown that the use of three-dimensional printing technologies allows the manufacture of not only individual parts of equipment structures, but also elements of its fastening to the corresponding installation objects, parts, assembly units of installation objects and components for the printing devices themselves. The main stages of preparing products for manufacturing by the three-dimensional printing method are considered. The possibilities of automatic selection of materials, formation of technological parameters of printing, verification of model geometry, preparation of control programs and control of the manufacturing process of products are analyzed. An experimental study of the effectiveness of using artificial intelligence to prepare parts of the field radio station housing for manufacturing was conducted. A comparison of printing parameters proposed by experienced specialists and the artificial intelligence system was carried out. A high degree of compliance of the received recommendations with the requirements for strength, reliability and durability of the product was confirmed. The timing of preparatory operations was carried out and it was established that the use of artificial intelligence provides a significant reduction in the time of preparation for printing due to the automation of analytical and calculation procedures. The feasibility of using artificial intelligence to increase the efficiency of field repairs and reduce the requirements for the level of personnel training was confirmed. The prospects of combining the technologies of three-dimensional printing, reuse of polymer materials, multi-material printing and manufacturing of metal parts by the cold spraying method for further development of the concept of operational restoration of radio-electronic equipment directly at the places of its operation were shown.*
Key words*: 3DP-SP, additive manufacturing, field repair, print preparation, spare parts, artificial intelligence.*

3D-ДРУК ЯК АЛЬТЕРНАТИВА ПОШУКУ ЗАПЧАСТИН ПРИ РЕМОНТІ РАДІОЕЛЕКТРОННОЇ АПАРАТУРИ В ПОЛЬОВИХ УМОВАХ

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АНОТАЦІЯ *Розглянуто застосування технологій тривимірного друку для оперативного відновлення радіоелектронної апаратури у польових умовах, в випадках обмеженого доступу до логістичної інфраструктури та як альтернативи традиційним комплектам запасних частин. Проаналізовано технічні та економічні аспекти вибору моделей тривимірних принтерів залежно від рівня конструктивної складності радіоелектронних засобів, габаритів деталей та особливостей їх експлуатації. Показано, що використання технологій тривимірного друку дозволяє виготовляти не лише окремі деталі конструкцій апаратури, а й елементи її кріплення на відповідні об'єкти установлення, деталі, монтажні вузли об'єктів установлення та комплектуючі для самих друкувальних пристроїв.Розглянуто основні етапи підготовки виробів до виготовлення методом тривимірного друку. Проаналізовано можливості автоматичного вибору матеріалів, формування технологічних параметрів друку, перевірки геометрії моделей, підготовки керуючих програм та контролю процесу виготовлення виробів. Проведено експериментальне дослідження ефективності використання штучного інтелекту для підготовки до виготовлення деталі корпусу польової радіостанції. Виконано порівняння параметрів друку, запропонованих досвідченими фахівцями та системою штучного інтелекту. Підтверджено високий ступінь відповідності отриманих рекомендацій вимогам до міцності, надійності та довговічності виробу. Проведено хронометраж підготовчих операцій та встановлено, що застосування штучного інтелекту забезпечує суттєве скорочення часу підготовки до друку*

завдяки автоматизації аналітичних та розрахункових процедур. Підтверджено доцільність використання штучного інтелекту для підвищення ефективності польового ремонту та зниження вимог до рівня підготовки персоналу. Показано перспективність поєднання технологій тривимірного друку, повторного використання полімерних матеріалів, багатоматеріального друку та виготовлення металевих деталей методом холодного напилення для подальшого розвитку концепції оперативного відновлення радіоелектронної апаратури безпосередньо в місцях її експлуатації.
Ключові слова: *ЗІП-принтер, 3D-друк, польовий ремонт, підготовка до друку, запасні частини, ШІ*
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Introduction

Radio-electronic equipment (REE) is an important component in almost any sphere of activity of modern society. During its operation, for various reasons, situations may arise in which it becomes necessary to carry out appropriate repair work. Usually, the availability of service support, spare parts and qualified personnel allows you to avoid significant inconveniences with repairs, but under certain circumstances (impossibility of timely delivery of damaged or failed parts, complete lack of communication or transport links, etc.) the equipment may partially or completely cease to perform its functions for a long time. Such risks should be considered, for example, when using REE on spacecraft, submarines and surface boats, Arctic stations, during military operations, etc.

In such situations, as an alternative to searching for spare parts, the use of 3D printing technologies can be proposed, which to date have already achieved certain successes in the manufacture of products with satisfactory quality characteristics for many applications [1-7]. An objective need exists to improve repair methodologies for equipment with rare earth elements. The most promising solution is the use of 3D printing to manufacture spare parts on-site, directly at the equipment operation locations.

Objective

The objective of this work is to enhance the efficiency of field repair of radio-electronic equipment through the use of 3D printing technologies and artificial intelligence.

Core of the work

3DP-SP printer selection options

Modern 3D printers have a wide range of technical characteristics [8-11], which can be used to make a reasonable choice of the appropriate model, which is actually included in the set of radio-electronic equipment instead of a certain number of spare parts, typical replacement elements or structural parts with a regulated service life or those that work in difficult operating conditions. At the same time, the printer itself is easily disassembled and in this state does not take up much space. However, the list of parts potentially suitable for printing is significantly affected by the size of the printer's working field – the printing platform. Such a limitation also determines the economic feasibility of using 3D printing as an alternative to the traditional set of spare tools and accessories (SPA), since the price of 3D printers is proportional to the size of their printing area [12, 13]. In turn, a comparison of the minimum and maximum possible sizes of parts that can be printed on a 3DP-SP printer and typical sizes for radio electronic equipment (REE) indicates that at present such a repair concept applies, first of all, to structural parts of REE of the first and second levels of the hierarchy in a conventional or on REM1, REM2 in a modular design. For the above-mentioned conditions of use, which are mostly characterized by the presence of restrictions on the size of the volumes for placing equipment, available 3DP-SP printers provide printing of structural parts of equipment of such levels of complexity. In addition, it should be noted that the concept of 3DP-SP printers can be extended to the repair and manufacture of structural parts that are associated with the fastening and installation of REE on installation objects, as well as to the manufacture of some parts of such objects. For example, these may be original brackets for mounting video equipment and additional power sources on UAVs, the number of models of which already exceeds hundreds today [14-18]. The lack of standardization of such design solutions will keep such tasks relevant for a long time. In these cases, the cost-effectiveness of using a spare parts printer increases significantly.

The quality of parts and products using 3D printing technology is largely determined by the properties of the materials used. The raw materials are filaments, granules, powders from the most common materials: ABS; PLA; PETG, nylon, as well as secondary plastics.

With a long autonomous stay at remote stations, etc., it is especially advisable to use recycled used or secondary plastic material. Products made from recycled material without its purification and stabilization of characteristics have lower quality indicators than from original materials. However, equipment for implementing the recycling process for 3D printing already today reaches satisfactory indicators and continues to be improved. This indicates the possibility of combining both printing and recycling functions in 3D printers in the near future, which will reduce material costs, energy consumption, and increase environmental friendliness.

The implementation of the concept of 3DP-SP printers is also facilitated by the simplification of the printing preparation process, which includes all stages from creating a sketch of the part to generating and saving the G-code that controls the operation of the 3D printer. A typical preparation process consists of the following operations: object modeling – creating a three-dimensional model using CAD software (for example, Blender, Fusion 360, SolidWorks); object optimization – checking for errors: models are checked for holes,

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polygon intersections or incorrect geometry; model export - saving the model in formats supported by 3D printers (the most common: STL, OBJ, 3MF); settings in the slicer program – importing the model into a layer-by-layer slicing program, for example, Cura, Prusa Slicer, Simplify3D, setting up print parameters, as well as cutting the model into layers (slicing) and saving it in G-code format; 3D printer preparation – cleaning and calibrating the printing platform, loading the material; uploading G-code to the 3D printer via SD card, USB or Wi-Fi. After that, the model is printed.

Reducing the duration of the preparation process can be achieved by using a 3D scanner at the modeling stage. For scanning medium and large objects (REM1, REM2), the most promising are portable (hand-held) laser scanners, which are especially effective for objects with complex geometry (Artec Eva, Creality CR-Scan Lizard). Scanning takes several minutes (15–30 min) for those parts of REE structures, the manual design of which takes hours (5–15 hours). In this case, the verification stage is minimized and the export stage is not required, a ready-to-print STL or OBJ model is automatically generated.

The role of AI in prepress

In addition, a significant reduction in work can be achieved by involving the capabilities of artificial intelligence (AI) at all stages of preparing the model for printing. At the stage of object modeling, AI can simplify the process of creating a 3D model by automatically correcting errors in geometry, optimizing topology, and even generating models based on a text description. For example, generative AI can quickly create a model adapted for printing based on drawings or technical requirements.

At the stage of object optimization, using analysis algorithms, AI can check the model for holes, polygon intersections, incorrect geometry and offer automatic correction. In addition, the system can evaluate the mechanical characteristics of the part and adjust its shape to increase strength.

When exporting a model, AI can automatically determine the best file format for export, taking into account the features of the printer and the type of material used.

To the greatest extent, artificial intelligence helps at the stage of setting up in the slicing program (slicer). It can automatically select printing parameters (layer height, printing speed, infill density, extruder and platform temperature, etc.) taking into account the characteristics of the material, the complexity of the model geometry and the features of the printer. Chat GPT-4o, for example, can instantly generate optimal settings and warn about possible problems associated with printing a specific part.

At the stage of preparing a 3D printer, AI can be used to calibrate the printing platform, diagnose the printer and assess the condition of the material (for example, warn about possible filament moisture, which can affect print quality). AI can also be used to predict printer maintenance to avoid unexpected failures.

When loading G-code and starting printing, artificial intelligence can be tasked with checking the generated G-code for errors, as well as providing recommendations for changes to improve printing efficiency. In addition, AI can monitor the printing process in real time, identifying defects and suggesting parameter corrections during printing.

The feasibility of using AI increases when replacing the printer model with one that has different characteristics, printing platform dimensions, active thermal camera, etc.; when changing the printing material or increasing the number of controlled parameters. The use of Chat GPT-4o and similar systems demonstrates the effectiveness of integrating AI into the 3D printing process, which allows reducing preparation time, improving product quality, and automating the control process.

Discussion

As an experimental confirmation of the possibility of using AI in the process of preparing models for 3D printing, a request will be formulated for Chat GPT-4o to determine the settings of printing parameters for one of the parts of the REE design. According to the parameters generated by AI in the response, the part was manufactured, the timing of all operations was carried out, the recommendations received were compared with the conclusion of an expert with extensive experience in the field of 3D printing, and the quality of the resulting part was assessed.

User request to AI

The part is the back cover of the field radio station case with printed circuit board mounting clips. It is used to protect the internal components of the radio station from dust, moisture and mechanical damage, as well as to fix the printed circuit board in the case. Ensures the tightness and structural integrity of the device when operating in field conditions.

Operating conditions:

1) Temperature range: from –20 °C to +50 °C (extreme temperatures typical of field conditions, including winter and summer).

2) Mechanical stability: the part must withstand shocks, falls, vibrations and other loads typical of mobile equipment.

3) Fastening: integrated latches are provided for fixing the board, which must be sufficiently flexible, but not brittle.

4) Weight: it is important to maintain the lightness of the design, especially for portable equipment.

Tables 1-3 show the results of comparing the parameters set by an expert engineer in 3D printing (Table 1) and those generated using AI (Table 2), as well as estimates of the time spent on performing the relevant work by the expert and AI according to prepared queries (Table 3).

Table 1 – Parameters recommended by an expert engineer in 3D printing

Parameter	Value	Expert's comment
Material	PETG	It has good chemical resistance to oils, moisture, dust, is not brittle, and withstands loads well.
Printing temperature	230 °C	Optimal range for PETG, provides reliable interlayer adhesion.
Layer thickness	0.2 mm	The balance between surface quality, detail and strength is optimal for technical parts.
Wall thickness	1.5+ mm	Provides the necessary rigidity and strength of the body part.
Filling	30 %	Sufficient level for mechanical resistance without excessive material consumption.
Form to fill out	Hexagonal structure	Optimal shape to achieve high strength with minimal weight.
Alternating walls and filling	Active	Increases the contact area between the outer walls and the inner filling, increases rigidity.

Table 2 – Parameters generated using AI

Parameter	Value	AI Commentary
Material	PETG	Recommended for field conditions due to its combination of flexibility and chemical resistance.
Printing temperature	235 °C	Provides an optimal compromise between layer adhesion and thread prevention.
Layer thickness	0.22 mm	A slightly thicker thickness speeds up printing while maintaining sufficient detail.
Wall thickness	2.0 mm	A reliable solution to ensure structural integrity during vibrations.
Filling	28 %	The system recommends slightly reducing the infill to save material without losing quality.
Form to fill out	Hexagonal structure (hex-grid)	High efficiency in terms of weight and strength. Hexagrid is chosen as a universal solution.
Alternating walls and filling	3 exterior walls before filling	The additional layer increases the strength of the outer shell and reduces the risk of delamination.

Table 3 – Results of the timing

The stage of preparation for 3D printing	AI can be implemented	Time (AI), min	Time (expert), min	Comment
Formulation of requirements for the part	+	1	5	AI can collect and structure the technical requirements of a typical product specified by the operator.
Material selection	+	1	5	AI selects the optimal material according to operating conditions.
Generating print settings	+	2	15	AI quickly generates parameters based on the database.
Part design analysis	Part	1	10	AI can provide a basic assessment, but an expert does the in-depth analysis.
Model preparation	Part	3	5	AI can configure a slicer or suggest G-code.
Preparing to print (printer settings)	Part	2	5	AI hints on parameters, but manual intervention is still necessary.
Visual inspection before printing	–	–	5	This stage is performed only manually.
Total time		10	50	AI significantly reduces training time, especially in the early analytical stages.

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General comment of an engineer-expert in 3D printing, regarding the printing parameters generated by AI: the data generated by AI is correct and meets the requirements for the part. PETG is the optimal material for the case of a field radio station, and the recommended printing parameters provide the necessary strength and durability of the part.

Even more useful may be the use of AI in the manufacture of parts using multifilament 3D printing technology, which uses interchangeable heads with materials with different properties, colors, etc. When changing the hotend, AI allows you to optimize printing parameters almost instantly.

This approach not only reduces the time for performing the preparatory stage, but also provides the opportunity to involve less qualified workers without reducing the requirements for the quality of the parts being manufactured.

The design process can also be shortened by using ready-made 3D models from available libraries (Thingiverse, MyMiniFactory).

But the greatest effect when implementing repair work according to the concept of a spare parts printer can be provided by the timely creation of G-code libraries for all parts of the REE structures at the design stage and during their prototyping, which in modern conditions usually occurs using 3D printers. In this case, the set of radio equipment supplied to the user, in addition to the 3DP-SPprinter, should also include a pre-created G-code library for all parts of the REE structures. This allows you to minimize the preparation period for printing parts to two stages – loading the G-code and preparing the 3D printer.

Conclusion

Thus, the implementation of the concept of rapid printing of parts when they need to be replaced at the place of operation of the REE (field repair) may be appropriate, firstly, in conditions of impossibility of timely delivery of spare parts, secondly, when reducing the time spent on preparing the necessary parts for printing by using laser scanners, artificial intelligence or libraries of ready-made G-code for all parts, the replacement of which is provided for by the operating regulations, or/and those that may be damaged during their operation.

The prospects for implementing this approach are increasing due to the decrease in prices for 3D printers, which can be used as spare parts printers, as well as due to their integration with devices for processing secondary plastics, which reduces the cost of materials and, accordingly, products made from them and expands the areas of application of 3D printing technologies in general (including multifilament 3D printing technology). An important aspect is also the possibility of printing replacement parts for the spare parts printer itself, if necessary, for its repair or for the purpose of its modernization. The decrease in the cost of 3D printers with cold spraying technology for the rapid production of metal parts opens up even greater prospects for the implementation of this method.The comparison of the estimates of the technological parameters of the 3D printing process, recommended by two independent experts and proposed by artificial intelligence, conducted in the work comprehensively confirms the effectiveness of the use of AI and indicates even greater prospects for the application of AI in this area with its further improvement.

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