Civil Engineering

OVERVIEW OF GLOBAL DESIGN EXPERIENCE AND A DESIGN OF A MOBILE CONSTRUCTION 3D PRINTER

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Abstract
Introduction: The paper presents a brief overview of current construction 3D printing possibilities and a detailed analysis of a design of a mobile construction 3D printer. The authors analyze advantages, disadvantages and development prospects of the construction method. Based on the analyzed data, they describe the development of a conceptual design for such a printer characterized by the structure built-up of basic modules with a length of 1 m, the possibility of printing in the field without preliminary site preparation, the use of construction wastes as a concrete mix aggregate. The authors highlight that the design can be used both in the system of logistical support of the Russian Federation Armed Forces and for civil purposes to construct various facilities. They conclude that it is reasonable to perform further studies in this area and describe prospects of project development. **Methods:** In the course of the study, the authors compared and analyzed specifications of construction 3D printers to refine the specifications of the design developed. **Results:** Based on the analysis and comparison of structures and application fields of analogs, a conceptual design of a mobile construction 3D printer for the Russian Federation Armed Forces was proposed. **Discussion:** A prototype in scale 1:5 was presented at the International Military-Technical Forum “ARMY-2019” (Popov, 2019).

Keywords
Construction 3D printing, logistical support of the Russian Federation Armed Forces, gantry 3D printer, construction site.

Introduction

The construction industry is leading in the number of jobs around the world. It ensures economic development and improves living standards. It is also one of the major industries in Russia accounting for 8% of the GDP (Electronic Scientific Journal “Apriori”, 2018). As in the rest of the world, the construction industry is the least automated in comparison with mechanical engineering and other industries. It is evident that to automate construction it is necessary to replace manual labor with innovative technologies for the manufacturing of building structures. Construction 3D printing is an example of such technology improving manufacturing automation manifold. With 3D printing, speed and technological efficiency of structural construction significantly increase, and labor intensity and expenses significantly decrease. The use of a mobile construction 3D printer at a construction site is a step towards modernization, cost-cutting regarding the cast-in-place construction method.

Scope and tasks of the study

Subject of the study: Construction 3D printing technology.

Scope of the study: Mobile construction 3D printer for the printing of temporary and permanent structures in-situ.

Tasks of the study:

1. Reviewing global experience in project design, engineering and industrial use of construction 3D printers.
2. Identifying advantages and disadvantages of the technology, studying various types of printers.
3. Determining the rationale for the use of the studied technologies both in the system of logistical support of the Russian Federation Armed Forces and for civil purposes.
4. Developing a conceptual design, creating a preliminary 3D model.
5. Performing test runs of the project at technical forums, innovative displays.

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6. Obtaining a utility model patent.
7. Preparing detailed design documentation to create a prototype.

Results of the studies

Literature review

Construction mixes and their use in 3D printing were considered in detail by Torshin and Potapova (2016). The following conclusion was made: introduction of water-retaining, thickening and other additives into a concrete mix makes it possible to use construction mixes in 3D printing.

Analysis of printed samples tested under different types of loading confirmed the proposed theoretical framework regarding the behavior of a concrete mix (Perrot et al., 2016).

To print a building, a 3D mathematical model is required. Such a model can be developed in 3D modeling or 3D BIM software. Using Autodesk Revit, Edenhofer et al. (2016) studied the development of a structural model for printing.

Additive technologies are successfully used in many areas, such as mechanical engineering, shipbuilding, astronautics, medicine and pharmacology, agricultural industry. Global experience in construction includes examples of implementing projects using a construction 3D printer, and features numerous versions of printer structures.

Reviewing global experience in project design, engineering and industrial use of construction 3D printers

To get a general idea of construction 3D printing development, an infographic developed by Langenberg (2015) can be used. It covers manufacturing projects, i.e. with a manufactured prototype (Figure 1). The infographic represents a map where projects are classified by location, time and material.

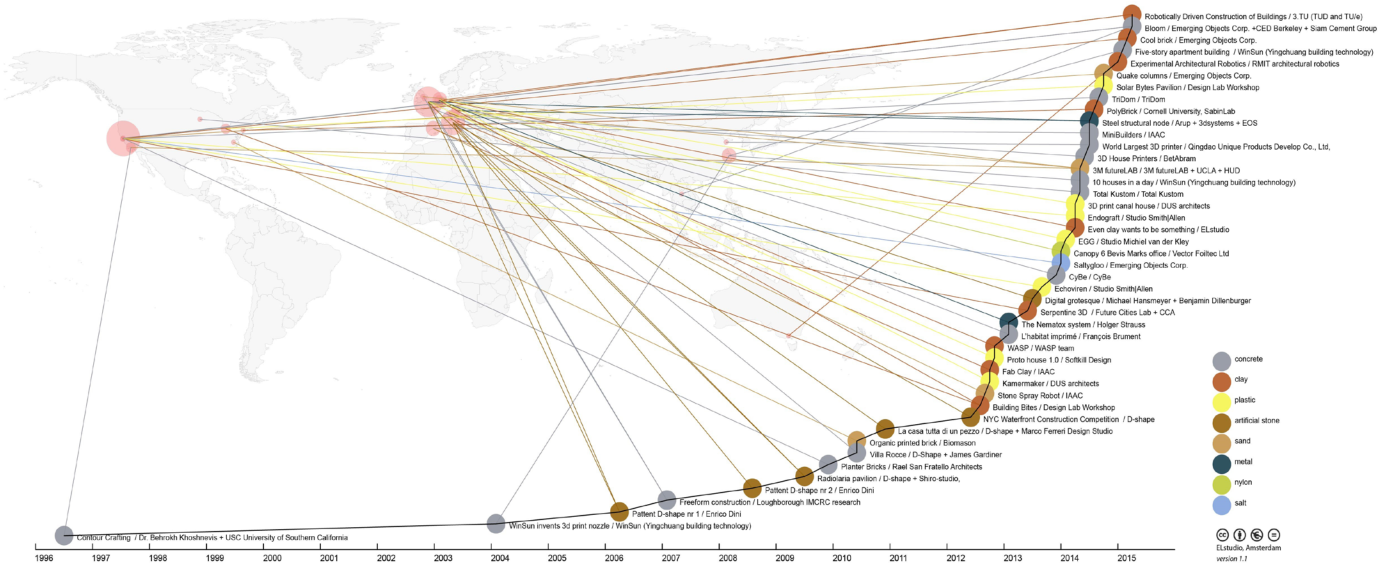

Figure 1. Diagram for the appearance of construction 3D printing projects (from 1995 to 2015).

As can be seen, 2012 was a turning point. The number of designed 3D objects increased manifold, _and the linear progression turned into an exponential one._

According to the diagram, the most major representatives of the industry are:

1. WinSun (China);
2. SpecAvia (Russia).

Chinese company WinSun remains a global leader in the application of construction 3D printing technologies and the number of constructed residential buildings (Demidenko et al., 2017). Its construction printers are stationary. They are located in large workshops and print parts of buildings and their deliverable assemblies. Then buildings are assembled from large modular units at construction sites (Figure 2).

Figure 2. Assembled building at a construction site.

On the practical level, WinSun implemented the largest number of construction projects using the 3D technology. The company plans to develop further and build more than 100 3D printing plants (Litvintseva, 2016).

As one of its projects, WinSun constructed a five-story residential building with an area of 1100 sq. m. The building was assembled at a construction site from large deliverable assemblies printed at a plant. After the assembly, heat insulation and HVAC systems were provided, window and door openings were made.

At the end of the construction, the following conclusions were made:

1. As compared with the traditional method (regarding the construction of an equivalent building), savings in construction materials amounted to 60%.
2. The building was constructed three times faster.
3. The amount of construction wastes decreased by 30–60%.
4. The labor costs decreased by 50–80%.

The last two conclusions result in the improvement of the environmental friendliness of construction products and a significant reduction in the rate of occupational injuries at a construction site.

In Russia, scientists and engineers carry out researches in the field and develop prototypes of construction 3D printers as well. SpecAvia company (www.specavia.pro) reached the level of practical use and commercial sales for its products, and now it offers several types of such printers (Figure 3).

Figure 3. AMT S-6044 LONG2 construction 3D printer.

Currently, approximately 35 companies are engaged in the development of construction 3D printer prototypes. These 3D printers can be classified by the type of structure:

- Gantry printers (WinSun, SpecAvia).
- Circular printers (Apis Cor).
- Robot printers (Batiprint3D, ProTo R 3DP).

Identifying advantages and disadvantages of the technology

Advantages (in addition to those indicated above)

Minimum labor costs: Human operators are needed only for equipment monitoring, maintenance and installation.

Minimum construction wastes: The construction process results in the production of dozens of tons of solid wastes. Using a waste grinder, it is possible to re-use construction wastes as a part of a concrete mix.

Architectural freedom: The technology gives architects, designers, and builders an opportunity to create any complex curvilinear surface in the automatic mode.

Disadvantages

Currently, the main disadvantage is the fact that only vertical structures (walls) can be printed.

Codes and standards: To ensure large-scale implementation of this construction method, corresponding codes and standards are required to be embedded in the construction industry of the Russian Federation. This is possible only after thorough research.

No coordination of developments: There is no unified scientific database in the world that would combine the results of developments. All companies and initiative groups conduct independent developments. Moreover, each of them starts works almost from scratch.

Due to specifics of printer operation, it is impossible to print a smooth wall surface. Plastering and cladding are required.

Structures of walls erected using a construction 3D printer

Irrespective of the construction method, any wall shall meet all strength and heat insulation requirements. In plan view, a wall represents a lattice framework with cavities. These cavities are filled either with a concrete mix with principal vertical reinforcement or heat insulation material. Such wall cavities are also used to lay required utility lines.

Determining the rationale for the use of the studied technologies both in the system of logistical support of the Russian Federation Armed Forces and for civil purposes

Considering the above, we can conclude that the method shall be embedded in the system of logistical support of the Russian Federation Armed Forces. They need a mobile construction 3D printer that would print field camp and military town infrastructure. Such a building construction method can also be useful in emergency response and recovery.

The design of a mobile construction 3D printer has dual purpose:

To be used in the system of logistical support of the Russian Federation Armed Forces:

Construction 3D printing of barracks using local materials, energy-efficient buildings in places of temporary settlement, retained formworks for fortification structures in-situ, and for the repair of existing structures.

The use of 3D printers makes it possible to improve the automation of settlement for the Armed Forces of

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the Russian Federation Ministry of Defense, increase the efficiency of units in the field, reduce time for the setup of a temporary settlement.

To be used for civil purposes at a construction site:

Printing of individual building structures (in particular, complex non-standard elements), small buildings and architectural forms. Recycling of construction wastes by their grinding and adding to a concrete mix as an aggregate.

Due to the use of 3D printers, it is possible to significantly reduce the volume of manual labor, time required for erection, and cost of works. It is also possible to reduce time for the preparation of detailed drawings as printers use 3D models of structures, taken from BIM models, directly.

3D printers can also be used for printing of structures in temporary transfer areas, fast construction in places of natural disasters.

Developing a conceptual design, creating a preliminary 3D model

Analysis of an AMT S-300 construction 3D printer analog

AMT S-300 (SPECAVIA, 2019) is a large-format gantry construction printer with a production capacity of 2.5 cubic meters per hour (Figure 4).

Figure 4. AMT S-300 construction 3D printer.

The printer has a frame with four columns attached to the foundation at a construction site. Electric hoists (stepper motors with planetary gearboxes) mounted on the columns gradually lift a frame consisting of two beams with another mobile beam mounted on them, which has a boom with a direct-flow print head for fast printing. To ensure fast printing, a station that prepares and feeds concrete to the print head is provided. The set also includes a high-pressure washer for equipment cleaning. The printer is equipped with a laptop (with licensed software installed), control cabinet, electric hoists, station for automated preparation and feeding of a concrete mix. The construction printer uses commercial and structural concrete based on 400/500 cement with a fraction up to 6 mm, as well as geopolymer concrete.

This construction 3D printer has a simple frame, a large printing area up to 120 m^2 (maximum dimensions: 11.5x11.0x5.4 m), and a service life of 60,000 hours.

The design aims to resolve the following task: to develop such structure of a printer that would allow for transportation, installation in-situ without special machinery, and printing of buildings and structures directly on an uneven surface.

Using the design, it is possible to obtain the following technical results: simplified transportation and quick assembly of a construction 3D printer without special machinery, its installation at a site with difference in elevation.

These results can be achieved by dividing the frame into uniform modules with a length of 1 m, to which gear and mechanisms are attached, and by using adjustable bases with the maximum difference in elevation of 30 cm.

The uniform module structure has a number of advantages: durability, stability, and low weight. Therefore, it is possible to assemble a printer manually.

Based on the performed analysis, the designed 3D printer (Figure 5) adopts a gantry structure due to its simplicity (which is especially important in the field) and relatively low price.

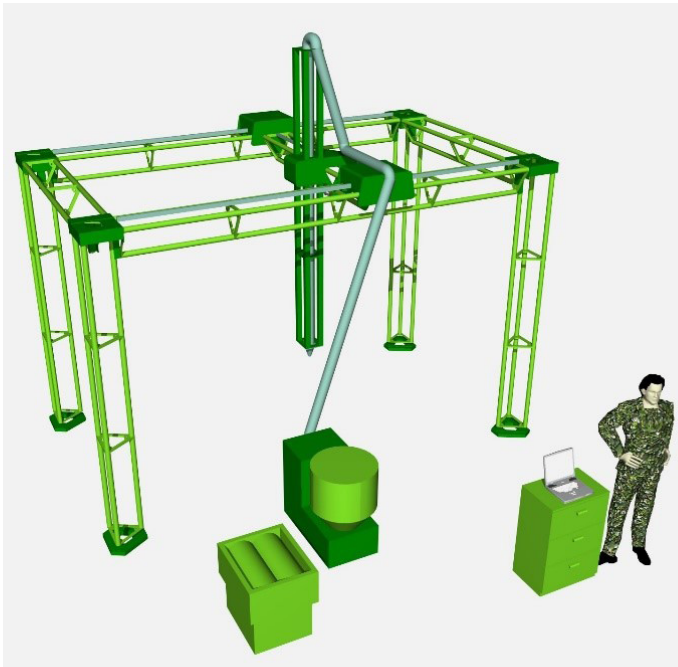

Figure 5. Mobile construction 3D printer for the printing of temporary and permanent structures in-situ.

The construction 3D printer has adjustable bases, which bring the printer to the active position and align it horizontally and vertically. Basic modules are the main elements of the frame composing rail beams, joining beams, a mobile beam, and columns. The rail beams are installed along the long side of the frame and intended for the movement of the mobile beam with an extruder column mechanism. The joining beams are installed along the short side of the frame and intended to join the frame of the main columns and the beams. By means of an X-axis device, the mobile beam moves along the rail beams together with the extruder column, which, in turn, moves relative to the mobile beam along the Y and Z axes by means of a corresponding device.

The construction mix is supplied through a flexible hose by the automatic device that prepares and feeds it. This device reminds an automatic concrete mixer. It has a pump to feed the mix and ensure the required pressure in the hose. During printer operation, it is possible to use construction wastes and local materials. To grind those and turn them into an aggregate, a shredder is used. The printer is controlled with hardware used by an operator. The hardware includes a control unit for the mix preparation and feeding device, a CNC unit, and an operator workstation.

The printer and its components are shown in Figure 6.

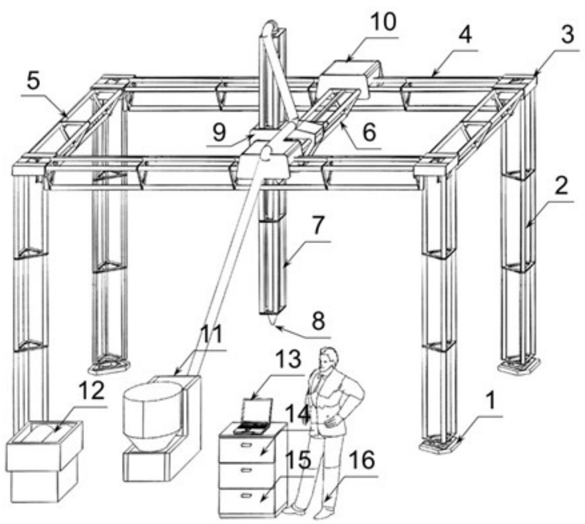

Figure 6. Schematization of the printer and its components.

The device has the following components:

1. adjustable bases
2. basic modules
3. rigid assembly joints
4. rail beams
5. joining beams
6. mobile beam
7. extruder column
8. extruder
9. Y- and Z-axis device
10. X-axis device
11. device for mix preparation and feeding to the print head
12. shredder
13. hardware
14. control unit for the mix preparation and feeding device
15. CNC unit
16. operator workstation.

The power supply is provided by standard mobile diesel generators (220 V) used in field camps of the Russian Federation Armed Forces. Design performance characteristics are provided in Table 1.

Table 1. Performance characteristics

Characteristics	Values
Loaded weight, t (max)	0.35
Type	gantry
Dimensions of a basic module, mm – Length – Width/Height	 1000 300
Operating conditions – temperature, °C	–25…+50
Production capacity, m^3/hour	0.5…2.5
Power consumption, kW*h	3–5
Maximum dimensions of the built-up frame, m – Length – Width – Height	 12 6 5

Relevance of the task being solved

Economic relevance: Modernization of the construction industry and application of new technologies are priority tasks of development. Economic advantages related to the 3D printing of structures and low-rise buildings are the following:

- Reduction of material consumption due to a decrease in demand for extra construction materials and tools.
- Reduction of power costs.
- Reduction of costs for the construction of buildings with unique architecture.
- Significant reduction of costs for the recycling of construction wastes.

Environmental relevance: During construction of buildings with traditional methods, a large amount of construction wastes is generated, which is not processed or recycled. Construction by means of a 3D printer is zero-waste. In this case, construction debris can be recycled and re-used if a shredder is used to grind it and add it to a construction mix.

Social relevance: A 3D printer can be very useful in emergency response and recovery, construction of comfortable temporary and permanent buildings for victims of natural disasters.

Technical and economic efficiency of design utilization

Based on the experience in using 3D printers manufactured by WinSun (Demidenko et al., 2017), SpecAvia (www.specavia.pro) and Apis Cor (Mukhametrakhimov and Vakhitov, 2017), the following utilization efficiency can be expected: a decrease in the amount of construction wastes by 30–60%, reduction of construction time by 40–70%, and a decrease in labor costs by 50–70%. The printer is built-up of basic modules with a length of 1 m (Figure 7). This makes it possible to disassemble and move the printer easily, and adjust the dimensions of the area from 3 to 12 m.

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Figure 7. Basic module (with a length of 1 m).

Options for the arrangement of the printing area (8x4, 8x2) are shown in Figure 8.

Figure 8. Options for the arrangement of the printing area.

Conclusions

Construction 3D printing makes it possible to significantly reduce:

Construction costs

Construction time

Labor intensity, volume of manual labor

Construction wastes

The use of 3D printers in the Russian Federation Armed Forces will make it possible to increase the efficiency of units in the field, reduce time for setup and automation of settlement for the Armed Forces of the Russian Federation Ministry of Defense, implement innovative solutions with regard to the construction and repair of military towns and posts.

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АНАЛИЗ МИРОВОГО ОПЫТА КОНСТРУИРОВАНИЯ И РАЗРАБОТКА МОБИЛЬНОГО СТРОИТЕЛЬНОГО 3D-ПРИНТЕРА

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Аннотация

Введение. В статье приводится краткий анализ возможностей строительной 3D – печати на настоящее время и подробно рассмотрена разработка мобильного строительного 3D – принтера. Проанализированы достоинства и недостатки технологии, перспективы развития. На основе проработанной информации показано создание эскизного проекта принтера с отличительными особенностями: сборная конструкция с основным модулем длиной один метр, возможность печати в полевых условиях без предварительной подготовки площадки, использование строительных отходов в качестве заполнителя бетонной смеси. Указано практическое применение проекта как в системе материально – технического обеспечения Вооруженных Сил Российской Федерации, так и в гражданских целях для возведения различных объектов. Сделаны выводы о целесообразности дальнейших исследований в данной области и перспективах развития проекта. **Методы.** Было произведено сравнение и анализ технических характеристик строительных 3D – принтеров для уточнения характеристик разрабатываемого проекта. **Результаты.** На основе анализа, сравнения конструкций и области применения аналогов был предложен эскизный проект мобильного строительного 3D – принтера для ВС РФ. **Обсуждение.** Разработка в виде макета в масштабе 1:5 была представлена на Международном военно-техническом форуме «АРМИЯ-2019» (Попов, 2019).

Ключевые слова

Строительная 3D – печать, материально – техническое обеспечение ВС РФ, портальный 3D – принтер, строительная площадка.