A study on 3D printing technologies and their applications

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3D printing turns digital 3D models into solid objects by building them up in layers. The technology was first invented in the 1980s, and since that time has been used for rapid prototyping. Currently, it is possible to 3D print in a wide range of materials, which defines the numerous applications for this technology. In the dawn of the 3D printing, its only application was prototyping, but now, with the modern technologies, there are many fields from medicine to fashion, where 3D printing is getting more appropriate. In this paper we analyse the applications, which are suitable for the different 3D printing technologies. The introduction section presents the process of 3D printing. The second section of the paper presents analysis on the three main steps in the process of 3D printing. The next chapter of the paper presents comparison between different 3D printing technologies. The last section of the paper presents analysis of the most common applications for the different 3D printing technologies. The paper is then completed by the conclusion section, followed by the acknowledgment and references sections.

Изследване на технологиите за 3D възпроизвеждане на обекти и областите им на приложение (Иванка Д. Цветкова, Пламен З. Захариев). *3D възпроизвеждането на обекти превръща цифровите 3D модели в солидни обекти, като ги изгражда слой по слой. Технологията е създадена през 80-те години на миналия век и от тогава се използва за бързо прототипиране. В днешно време има голямо разнообразие от материали за печатане, което определя и широкото разпространение и множеството приложения на 3D технологиите. В началото единственото приложение е било за създаване на прототипи на обекти, но днес с модерните технологии 3D възпроизвеждането на обекти е подходящо за широк кръг от приложения от медицината до модата. В тази статия се анализират кои приложения са подходящи за различните 3D технологии. Във въведението е представен процесът по 3D възпроизвеждане на обекти. Във втората част на статията са анализирани трите основни стъпки от процесът по 3D репликиране на обекти. В следващата част е представено сравнение между различните 3D технологии за възпроизвеждане на обекти, а в последната част от статията са представени различни области на приложение за тези технологии. Статията завършва със заключение, следвано от благодарности и използвани литературни източници.*

Introduction

3D printing, also known as additive manufacturing, turns digital 3D models into solid objects by building them up in layers. This involves several processes and technologies. All starts with the digitalization of the object or area, followed by the selection and the use of the right software for post-processing. The final step is the selection of the 3D printing technology, which depends on the planned application for the printed 3D object [1].

3D printing originated as rapid prototyping technology, which is based on the principles of the industrial prototyping. It presents a mean for speeding up the earliest stages of product development with a quick and straightforward way of producing prototypes. This allows implementing a multi-iteration approach for product development and results in a quicker and more efficient way to obtain the final version of the product [2]. 3D printing saves time and money at the outset of the entire product development process and ensures confidence in the results.

Currently, 3D printing is used in many sectors to create almost everything – vehicle parts, smartphone and fashion accessories, medical and dental equipment, toys, houses and furniture, etc. [3], [4].

Analysis and steps of the 3D replication process

The 3D object replication is a multistep process that requires detailed information about the target and involves its digitalization and slicing into layers.

First step: Digitalization of the object

Before the actual creation of a 3D model, the digitalization specialists must be well versed in the photogrammetry principles and its peculiarities. Photogrammetry can be used to make full colour highly accurate and realistically textured models of buildings, archaeological sites, landscapes (if the images are taken from the air) and objects. Close range photogrammetry of historical objects offers the possibility to digitally preserve artefacts before they get lost, damaged or timeworn. Additionally, it provides means to perform digital measurements, manipulations and other analyses, which present insights into the material and the structure of the objects that might not be visible to the naked eye. Photogrammetry represents a technique for taking multiple overlapping photographs and deriving measurements from them to create 3D models of objects or scenes [5], [6]. The basic principle is quite similar to the way the software of many cameras makes it possible to create panoramic pictures by stitching together overlapping photographs into one 2D mosaic. Photogrammetry takes the concept one step further by using the position of the camera, as it moves through 3D space, to estimate X, Y and Z coordinates for each pixel of the original image and create a detailed database about them.

A more simplified method for object digitalization is to use specialized 3D scanners. There are several 3D scanning technologies, mainly involving devices with laser or light sources for estimation of the distance to the object.

Second step: Processing of the images

When the photo-shooting of the object is finalized, specialized software is used to process the images. The first step of this process is to align all photos. This is done by comparing the pixels in the photos and finding matching sets, which are used to estimate the camera position and the 3D geometry of the object.

The second step is the creation of the dense cloud [7]. Once satisfied with the alignment, the sparse point cloud, a mere fraction of the total data, is processed into a dense cloud, in which each matching pixel is placed, based on its X, Y and Z coordinates in 3D space. The next step is to build a mesh by connecting each set of three adjacent points into triangular shapes, which are combined seamlessly to produce continuous mesh over the surface of the model. The final step is to build and apply the texture [7]. For this purpose, the original images are combined into a texture map and are wrapped around the mesh. This leads to a photorealistic model of the original object. The process is presented in Fig. 1.

The finished 3D model can be exported in different formats for visualisation, imported in 3D touch-up or animation software or printed with 3D printers.

Final step: 3D printing of the model

Before the actual printing of the finished 3D model it needs to be converted into printable file. For this purpose it is loaded, processed and aligned in the working plane of the 'slicing software'. This software breaks the object into thin cross sections, which are printed one on top of the other. There are many 3D printing technologies, which are suitable for different applications, but all of them can be generalized in four main categories – extruding of molten or semi-liquid materials, solidifying of photo-curable resins, fusing of powder granules and sticking of cut sheets of paper, plastic or metal. Some of these technologies are stereolithography (SLA), digital light processing (DLP), fused deposition modelling (FDM), binder jetting (BJ), material jetting (MJ), selective laser sintering (SLS), selective laser melting (SLM), electronic beam melting (EBM), laminated object manufacturing (LOM) and selective deposition lamination (SDL). Comparison of materials used for 3D printing using these technologies is presented in the next table (Table 1).

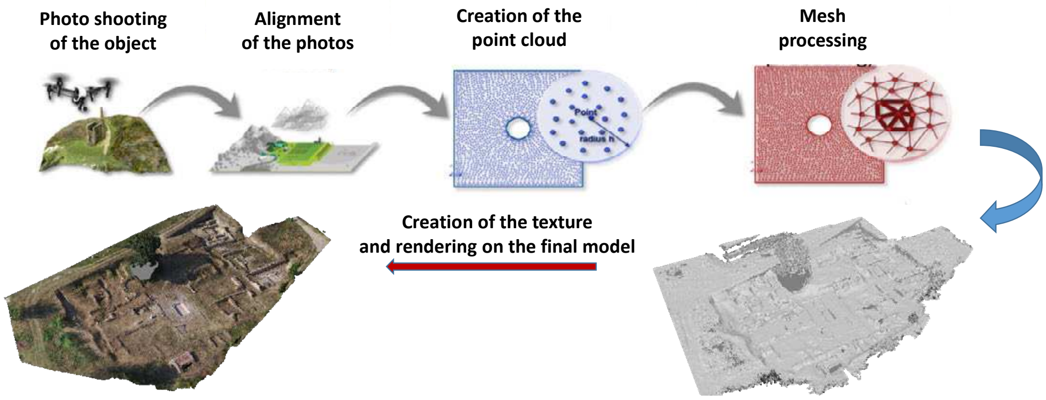

Fig. 1. Processing the digitalized data and creation of the 3D model.

Table 1

Comparison of the materials used in 3D printing technologies

Technology	Material
SLA	Photopolymer resins
DLP	Photopolymers
FDM	Thermoplastic material, ABS and PLA
BJ	Powders, including ceramics and food
MJ	Liquid photopolymers, resin, wax
SLS	Powders (nylon, ceramics, glass and some metals like aluminium, steel or silver)
SLM	Metallic powders (stainless steel, titanium, cobalt chrome, aluminium)
EBM	Metal or brass
LOM	Plastic or metal laminates
SDL	Standard paper

The complete process for 3D reconstruction of a small object (digitalization, processing of the model and 3D printing) is presented in Fig. 2. In the presented case scenario, the small object is digitalized using a static camera and a rotating table. An alternative to this method is to have a static object, which will be digitalized by a mobile camera that circles around it while maintaining the same distance. The results from both methods are equal and the selection of the right one is based on the size and the accessibility of the object.

The 3D reconstruction of large objects differs mainly in the digitalization process, where based on the size and the location of the object the ground camera images might not suffice and drones can be used to capture additional aerial pictures of the object or the surrounding area. In order to speed up this process and to use the drones more effectively, specialized software for flight planning can be used.

There are several free and paid software products, which facilitate the work of the drone pilots. In both cases, the software generates the mission plan, which is performed autonomously by the aircraft, but only after the user inputs the necessary setting, like altitude of the drone, area for the digitalization, number and quality of the photos, etc. During the flight, the pilot continuously monitors the flight information and if necessary can take immediate actions. The reminder of the reconstruction process remains the same – the images are processed and the digitalized model is put into the slicing software to provide the data for each layer that needs to be printed by the 3D printer.

Comparison of the 3D printing technologies

Objects, printed through SLA and DLP, are with excellent surface quality and with high resolution. The details completed using the FDM technology is not so accurate, but they are with excellent mechanical and chemical characteristics. Objects that are printed through MJ are very precise and with very smooth finish. The products printed through LOM are less accurate from those printed using SLA or SLS, but the latter require additional treatment and post processing like curing in UV oven. Objects printed through SDL are strong, resistible and eco-friendly. Parts produced with SLS and SLM are much stronger than those made using SLA or DLP, but their surface finish and resolution is not that good. The post processing of the objects, manufactured using the SDL technology, requires removal of the supporting paper when the printing is complete. Table 2 presents a summary on the advantages, disadvantages and the additional post processing requirements for SLA, DLP, FDM, MJ, LOM and SDL. Common disadvantage of the technologies compared in Table 2 is the need to remove the excess material, which is used as a

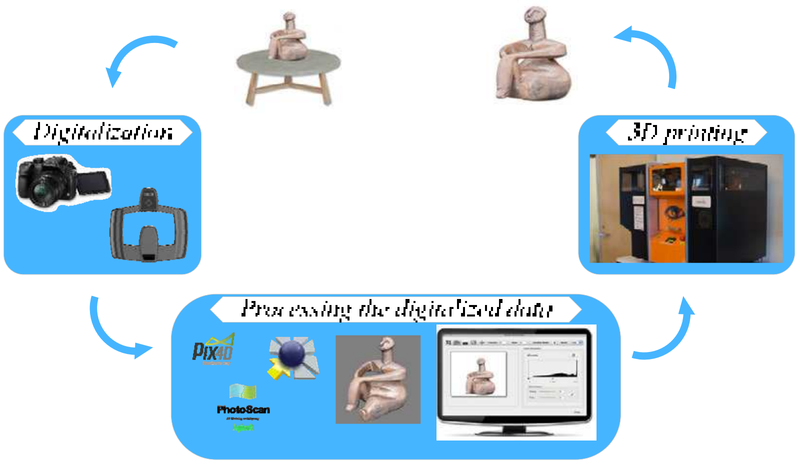

Fig. 2. The complete process for 3D reconstruction of a small object

supporting structure. In SLA and DLP post processing might require additional facilities, which complicates these technologies and makes them more expensive.

The basic principle of SDL is to selectively apply adhesive glue on the cross sections of the paper. This leads to little waste material and allows for quick and easy removal of the complete part out of the supporting paper. SDL is one of the few 3D printing technologies that can provide full colour printed objects, which are additionally strongly bounded together. The entire SDL printing process is environmentally friendly.

Selective laser sintering can be applied to plastic and metal materials, although the metal sintering requires high power lasers and higher in-process temperatures.

Table 3 provides a summary on the advantages, disadvantages and the post processing procedures for the technologies that use powder materials. The key advantage of these technologies is that the powder bed serves as an in-process support structure for overhangs and undercuts. This allows the creation of more complex objects and models, which are impossible for manufacturing in any other way.

Lasers are used in three of the four powder-based technologies. The last one (BJ) is different – the binding material is selectively jetted or sprayed into the powder bed and fuses the material at the specific

Table 2

Comparison between some of the 3D printing technologies

Technology	Advantages	Disadvantages	Post processing
SLA	Suitable for complex geometries, detailed parts, smooth finish	Requires post finishing, over the time the object becomes more brittle	Requires cleaning, some devices need to be strengthen in UV oven
DLP	Suitable for complex shapes in different sizes, high precision	Has thickness limitations and is usable with few types of materials	Requires chemical bath and UV curing
FDM	Provides strong parts, easy to print by untrained staff	The surface finish is not so accurate, very slow printing speed	All plastic parts require post processing and cleaning of the residue
MJ	MJ is characterized by good precision, good surface finish, use of different materials	Slow build process	The support structures need to be mechanically removed or melted away
LOM	LOM is a very fast rapid prototyping technology	Adhesive glue is applied uniformly in equal amount throughout the cross section	Drilling, sanding or sealing with a paint might be required
SDL	Good for fast obtaining of full colour objects, eco-friendly	The build size is limited to the size of the feedstock	Needs to provide means for protection from moisture

Table 3

Comparison between 3D printing technologies, which use powder materials

Technology	Advantages	Disadvantages	Post processing
SLS	high heat and chemical resistant, high speed	precision limited to powder particle size, rough surface finish	improve tolerances and surface finish
SLM	high density components	slow and expensive	thermally processed, as any welding part
EBM	good printing speed, less distortion	limited materials, the process is rather slow and expensive	thermally processed
BJ	lower price, enables colour printing, high speed	limited choice of materials, fragile parts	A starting point for further processes like infiltration, sintering or casting

points a layer at a time. The resulting printed parts are however not as strong as these obtained by the sintering processes and require post-processing to ensure durability. The objects printed through SLS are with excellent quality, but are also not that durable, compared to the ones obtained using SLM. Laser sintering can process plastic and metal materials, although metal sintering does require a high power laser and higher in-process temperatures. The parts produced with these processes are much stronger than those obtained using SLA or DLP, but their general surface finish and accuracy is not that good.

The EBM printers have the capability to create full-dense parts using a variety of metal alloys. These parts are even suitable for medical purposes.

Application of the 3D printing technologies

The developments and improvements of the printing process and the materials, since the emergence of 3D printing for prototyping, saw the processes being taken up for applications further down the product development chain. Tooling and casting applications were developed to utilize the advantages of the different processes. These applications are increasingly being used and adopted across industrial sectors.

In medical sector

The medical sector is viewed as being one of the early adopters of 3D printing. It is also a sector with huge potential for growth, due to the customization and personalization capabilities of the printing technologies and the ability to improve people's lives as the processes improve and materials are developed that meet medical grade standards. 3D printing technologies are being used for a host of different applications. In addition to making prototypes to support new product development for the medical and dental industries, the technologies are also utilized to make patterns for the downstream metal casting of dental crowns and in the manufacture of tools, over which plastic is being vacuum formed to make dental aligners. Examples of ear, synthetic skin, heart valve and implants are shown in Fig. 3 [8].

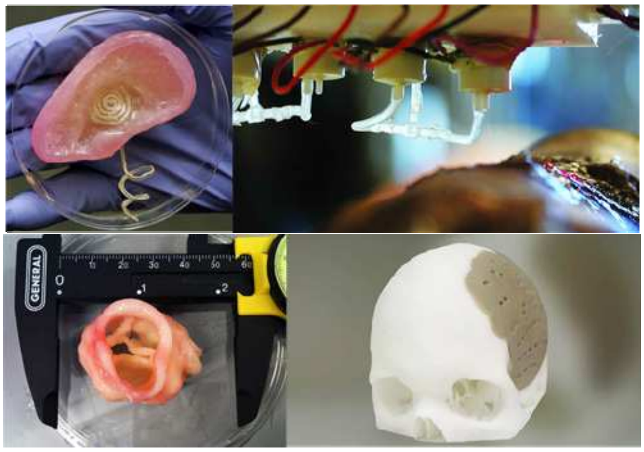

Fig. 3. 3D printing applications in the medical sector.

The 3D printing technology has found its gap in the medical market and is now used for manufacturing both stock items, such as hip and knee implants, as well as patient-specific products, such as hearing aids, orthotic insoles for shoes, personalized prosthetics and one-off implants for patients suffering from diseases such as osteoarthritis, osteoporosis and cancer, along with accident and trauma victims. 3D printed surgical guides for specific operations are also an emerging application that is aiding surgeons in their work and patients in their recovery. The technology is also being adapted for the 3D printing of medical equipment, skin, bone, tissue, pharmaceuticals and even human organs [9]. However, these technologies remain largely decades away from commercialization.

In aerospace sector

Like the medical sector, the aerospace sector was an early adopter of the 3D printing technologies, which were mainly used for product development and prototyping. The companies from this sector typically work in partnership with academic and research institutes to produce the sought results. An example of satellite parts created with 3D printing technology is presented in Fig. 4 [10].

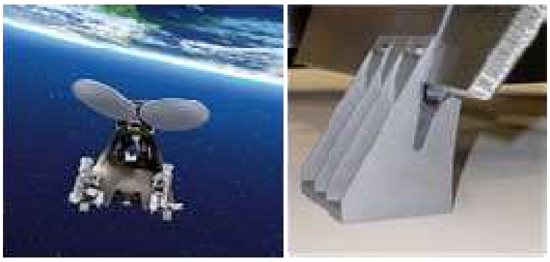

Fig. 4. 3D printed satellite components.

A number of key applications developed for the aerospace sector and some non-critical parts are already flying on different aircrafts. High profile users include Airbus, Rolls-Royce, Boeing and others.

In automotive sector

Another general early adopter of rapid prototyping technologies was the automotive sector. Many automotive companies, particularly at the cutting edge of motor sport and F1, have followed a similar trajectory to the aerospace companies. Initially, the 3D printing technologies were used for prototyping applications, but now the printing devices are being adapted to support the new manufacturing processes and to incorporate the benefits of the improved materials. Examples of some parts, which are 3D printed, are shown in Fig. 5 [11].

Fig. 5. 3D printed parts for automotive sector.

Many automotive companies are now also looking at the potential of 3D printing to fulfil after sales functions in terms of production of replacement parts on demand, rather than holding huge inventories.

Education

The education system plays an important role in aiding people achieve their full potential. 3D printing can revolutionize the learning experience mainly by providing alternative means for understanding specific functions, object characteristics, etc. Affordable 3D printers in schools may be used for a variety of applications, which can aid students in finding their field of interest easier and faster.

In art

Artists and Sculptors are engaging with 3D printing in different ways to explore form and function in ways previously impossible. Whether purely to find new original expression or to learn from old masters, this is a highly charged sector that is increasingly finding new ways of working with 3D printing and introducing the results to the world. There are numerous artists that have now made a name for themselves by working specifically with 3D modelling, scanning and printing technologies. Examples of 3D produced pieces of art are shown in Fig. 6 [12].

Fig. 6. 3D printed pieces of art.

The link between 3D scanning and 3D printing brings a new dimension to the art world. These technologies allow the artists and their students to reproduce the work of past masters and to create exact replicas of ancient (and more recent) sculptures for close study – works of art that they would otherwise never have been able to interact with in person.

In jewellery sector

For the jewellery sector, the 3D printing turned to be a two edged blade. There is a great deal of interest on how 3D printing can and will continue to develop this industry. The new design freedoms, enabled by 3D CAD and 3D printing, and the improvement of the traditional processes for jewellery production are found as significant steps forward for the jewellery industry. Nevertheless, some fear that the 3D printed products will eliminate many of the traditional steps and will lead to quality decrease and loss of jobs. 3D printed jewellery sets are shown in Fig. 7 [13], [14], [15].

Fig. 7. 3D printed parts for jewelry sector.

In architecture

Another major application area for the 3D printing technologies is the design and the creation of architectural models. The development of accurate demonstration models of the interior or the exterior of a building was one of the first application field for the 3D technologies. They were quickly adopted due to the fast, easy and economically viable methods for manufacturing of detailed models directly from the 3D CAD software or other digital products, which are used by the architects. Many successful architectural firms now commonly use 3D printing as a critical part of their workflow for increased innovation and improved communication. Examples of 3D printed models of buildings are shown in Fig. 8 [16].

Fig. 8. 3D printed models of buildings.

More recently some visionary architects have started looking at 3D printing as a method for direct construction. This technology can also help engineers rebuild and restore old heritage sites, buildings and monuments.

In fashion

The improvement of the 3D printing processes and the introduction of new materials, including flexible and wearable ones, has presented new application possibilities for the 3D technologies in fashion. Iris van Herpen is one of the pioneers in this area and uses 3D printers to create her models (Fig. 9) [17].

Fig. 9. 3D printed clothes.

In food

The Food industry is one of the many emerging application areas for the 3D printing technologies and the unlimited possibilities are getting people to the brink of ecstasy. 3D printing has presented new ways for both preparing and presenting the food. The initial attempts to print food were made with chocolate and sugar. They resulted in the development of specific 3D printers, which are now available on the market. Some other early experiments included the printing of meat at the cellular protein level. More recent research efforts are focusing on pasta as suitable solution for the 3D printing of food. Examples of different printed food products are shown in Fig. 10 [18], [19].

Fig. 10. 3D printed foods.

The application of this technology enables fast, automated and repeatable cooking processes, as well as freedom in the design of the meal. The technology is also scalable, can be adapted to the different cooking processes and can be customized for each region or individual. The shape and the decoration of the food can be easily modified based on the customer or the occasion. It is believed that the 3D printing of food will be one of the major future technologies and the solution for the global hunger issues.

Applications specific use of each technology

All of the analysed technologies are suitable for prototyping. The artists and the sculptors can create a piece of art using any of the presented 3D printing technologies. Depending on the requirement for accuracy and colouring of the models, they can choose from BJ, MJ, FDM or SDL. FDM is more suitable for the creation of earrings or other jewellery. But every technology has its advantages and disadvantages, which define some applications to be more suitable for a specific technology than other. SLA is used to create casting patterns. DLP is suitable for injection moulding and metal casting applications. FDM is used mostly for final end-use products. BJ and MJ allow the creation of casting matrixes, moulds and cores. SLS is more suitable for the production of parts in small quantities, jewellery prototypes, high quality industrial parts, including fuel injectors and other aerospace and rocket components. SLM is best suited for the production of parts with complex geometries and structures with thin walls and hidden voids or channels, aerospace applications, lightweight parts, medical orthopaedics and tools. EBM is good for limited parts and implants, and is used also for aerospace and automotive applications. LOM is excellent for the creation of models, moulds and functional parts. SDL can be used for prototyping, development of moulds, mechanical and moving parts, reconstruction of archaeological and historical objects and full coloured models.

Future applications

In the future instead of investing time and money to construct, fabricate, mould or cast tools, people will be able to design them using 3D CAD software and print them in 3D printers using different materials. Instead of throwing away a broken item, it will be used as a model, digitalized and then printed anew. The production of the replacement parts will expand. People will use 3D printing to customize the end products according to their desires and needs. Some designers believe that in the future people will travel without luggage and will just 3D print their clothes after checking in at their destination. 3D printers may also be used to make the buildings of the future. There are already several examples of 3D printed houses and 3D printed apartment buildings (Fig. 11) [20].

Fig. 11. 3D printed house and building

Another future application is the use of 3D printers to create replacement organs, and even to directly repair the human body.

Conclusion

The 3D printing technologies became widely spread and used for different applications. The most common technology among end users is FDM, because the materials are cheap, and because of the opportunity to build their own 3D printers. The only technology which can create full colour and durable objects is SDL. An additional advantage of this technology is that the process is eco-friendly.

In the past 3D printing has been used mainly for rapid prototyping, but in the next years it will be used for many more things – from industrial tools to final products. Already more than half a million 3D printable files are listed in the object sharing websites, and the available desktop 3D printers can fabricate them. Dentists already use 3D printed moulds for the creation of implants, crowns and bridges. 3D printing will provide companies and individuals with fast and easy manufacturing solutions for objects in any size or scale and only limited by their imagination. 3D printing will continue to expand in many areas in the future. Some of the most promising areas include medical applications, development of custom replacement parts and customization of consumer products. The expected improvements of the printing materials will lead to the general decrease of all expenses and will introduce new applications, which are now considered impossible or non-profitable.

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