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Review

3D printing: State of the art and future perspectives

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ABSTRACT

In the last years, the development of 3D technologies applied to the field of Cultural Heritage (CH) has led to results of the utmost importance from the point of view of preservation, valorisation, communication and fruition of our assets. In particular, we experienced many interdisciplinary projects in which, thanks to the cooperation of different fields of research, incredible results have been obtained, through the technological collaboration of computer graphics and documentation, of industrial engineering and preservation and access of CH. This paper aims at drawing attention to the actual technologies in use for solid printing (digital fabrication) used for the realization of material copies, therefore tangible, of three-dimensional digital virtual models. Even though ulterior developments to these technologies are possibilities to be expected, the process of 3D printing has gradually gained levels of accuracy, which can nowadays be deemed as satisfying. This is even more true in the industrial field (from the manufacturing industry to the design industry), but also in other fields, such as the medical one, for example, for the realization of artificial limbs, and the CH field, which can benefit from new instruments for the restoration and preservation of cultural assets in museums. The metric characteristics of precision and accuracy of the model printed with 3D technology are the fundaments for everything concerning Geomatics, and have to be related with the same characteristics of the digital model obtained through the survey analysis. In other terms, the precision of the printed product must be evaluated in relation to the precision of the instruments used in the analysis. Thus, in the CH field there is the possibility of new systems of access, cataloguing and study, where the models, both virtual and tangible, represent the fundament of visualization and analysis of the form (also from the metric point of view) of each artefact of artistic and historical interest.

1. Research aim

In this paper, we present the state of art and the potential and large spectrum of applications of fabrication technologies in the CH. Through a brief history and characterization of the most common 3D printer technologies, we try to present a review of the applications of 3D printing on CH, considering our experiences or those of other researcher. In the final part of this paper, a particular aspect of solid printing is analysed: the level of accuracy reachable in the creation of material models. This level of precision must be related to that of the instruments of analysis through which the artefacts are converted into digital format. We must not forget that the process that leads to the realisation of a material copy must go through a numeric model and that in this process there is a progressive loss of definition, both from the qualitative and quantitative points of view. The simplification operations that the digital data must undergo might cause a difference between the geometry of the printed object and that of the original object.

2. Introduction

Digital technologies are able to offer an essential contribution to the documentation, analysis and subsequent use of the cultural assets, as they can be used in different forms and for different aims: study and research, diagnosis, repair, preservation, protection, communication-divulgation, fruition and formation of the cultural heritage.

In the last years the use of electronic and Information Technologies (IT) has increased exponentially, creating new sceneries and possibilities in the field of the CH. This evolution of instruments and methods is in partnership with a diffusion of instrumental techniques for surveys; in particular, the 3D scan, which allows observation of complex geometries impossible to analyse through traditional methods.

Solid printing has gained a special role in this technological development. The rapid creation of prototypes is a technique that

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allows the production of material copies of objects with complex geometries directly from the mathematical model in relatively short periods of time and often without being expensive. In recent years, this technique has experienced a very strong development thanks to the large diffusion on the market of desktop 3D printers, printers which are quite cheap and whose dimensions are reasonable. They use a FDM technology (Fuse Deposition Modelling), an additive kind of technology, as will be described later, which creates material models through the superimposition of material layers.

This innovative system has allowed a rapid growth of this technology for 'commercial' uses, allowing less expert users to enter the world of 3D printing, creating a community of makers, comparable to the one which formed after the introduction of Arduino [1] to the general market.

The material objects are realised quickly and with quite low budgets, starting from numeric models, often with complex geometries, converted in *G-code*, which is the programming language of the machines working with numeric control (CNC). We are also experiencing a reduction in size and cost of these printers (Desktop 3D printer), a process which contributed to the growth of this technology and favoured its commercialisation. The opening of FabLab in Italy (laboratories including machines for digital creation, able to transform ideas in prototypes and products and open to the general public) proves the development of this technology: in a study published at the beginning of 2015, Make in Italy reports in detail on the birth of FabLab and of makerspaces in our country and its growth in the last two years. There are more than 70 active labs spread throughout Italy, a community of more than 1000 FabLabs distributed throughout 78 countries according to the Fab Foundation, an organization that emerged from MIT's Center for Bits & Atoms Fab Lab Program (http://www.fabfoundation.org). Thousands of people, along with associations, industries, museums, universities and institutions of all kind, are investing time, resources and energies in order to open laboratories including machines for digital fabrication to the public.

3D printers have demonstrated effectiveness in many other fields of application, in particular that of the Cultural Heritage. Thanks to the recent innovations in the IT technology and multimedia it is now possible to develop new forms of analysis and fruition of the Cultural Heritage, which are used along with more traditional methods.

Models, first digital, then material, have introduced new possibilities of access, cataloguing and study of the cultural assets as they form the basis for both the visualization and the metric analysis of any artefact both from the artistic and historical point of view. As far as museums are concerned, for example, there is the possibility of creating identical replicas, both digital and material, of spaces and three-dimensional objects. Exhibitions and collections can take advantage from digital fabrication as the access to their information becomes customised according to the user, the content and the complexity of the given message. All this brought 3D printing to repute as one of the most important possible outputs, at the same level of more traditional digital or paper.

3. The subtraction and addition process

In order to realise an object we might use two techniques radically different from each other: the subtractive, referring today to Computer Numerically Controlled (CNC) machining, and the additive, concerning the Additive Manufacturing (AM) processes [2].

AM, popularly called 3D printing, technologies today are used by makers all over the world, but its inception can be traced back in the 1980s, at which time it was called Rapid Prototyping (RP) [3]. RP was conceived as a fast and more cost-effective method for prototypes realization for product development within the industry [4].

Before describing AM main technologies, we want to fix some important dates to tell shortly how 3D printing was born:

- in 1984 – Chuck Hull invented and patented a sterolithography aparatus (SLA) machine. Hull went on to co-found 3D Systems, the first organization nowadays operating in 3D printing. The STL format file was born;
- in 1986 – Carl Deckard, Joe Beaman and Paul Forderhase (with other researchers) developed the ideas of Chuck Hull and filed a patent in the US for the selective Laser Sintering (SLS);
- in 1988 Crump patented the Fused deposition modelling – which is printing with fuse material. This technique does not involve the use of laser or dust and uses fused plastic to spread in strata to create the object. Crump also founded Stratasys, another leading business in the field;
- 1993 – was patented the Electron beam melting (EBM);
- 2005 – Mcor Technologies Ltd – an Irish company – starts the Paper 3D laminated printing: a machine, which superimposes sheets of paper and prints on them. The result is an additive method, which includes the use of colours;
- in 2005, thanks to the technology of the Self replicating rapid Prototyper a 3D printer which prints itself is first realised (open-source RepRap and FAB@Home projects). The RepRap Project [5] is an abbreviation Replicating Rapid Prototyper, and it aims to develop a 3D printer, which prints on its own the majority of its own components. All the products created with this project are published with open source licences;
- in 2008, Bre Pettis, Adam Mayer, and Zach "Hoeken" Smith found MakerBot Industries.

Digital fabrication technology is characterized by the basic physical process employed for the tangible object to be obtained.

The subtraction process consists in removing the unnecessary material from a block to obtain the final object. The lathe is a tool that allows to remove the exceeding material from a block placed on a rotating platform, thanks to a series of tips of different shapes. It has been used for centuries: the first hydraulic lathe is more than 500 years old, but the Ancient Greeks and Egyptians used it as well, creating the first tools which allowed them to rotate a plate using a pivot with their feet.

Modern lathes are more complicated and versatile; they use engines instead of human strength and can have quite a high level of automatism. However, they are based on the same principle with which our ancestors created the first vases regularly shaped.

Milling machines are more modern machines, which allow the realization of complex products.

They work very similarly to drills, but instead of creating a hole, thus using the tip of the tool, they cut laterally. The simplest milling machines work on three axes, while the most complex ones work on five or even six axes, supporting rotation around multiple axes, so that they can reach almost any part of the product.

Milling machines can work with a vast range of resistant materials, from wood to metals.

Lathes and milling machines are born as tools controlled manually, but in the meantime some numerically controlled machines were created, called CNC (Computer Numerical Control), and controlled by a computer which handles the passage from a 3D model realised through a CAD application (Computer-Aided Design) to the production of the object. The linking chain is a new kind of software called CAM (Computer-Aided Manufacturing), which transforms the digital model of the object in a series of commands to impart to the machine. The file format is a standard one called G-code, which includes information like N40; G82; X1500, automatically generated by specialised software.

3D printers are also CNC machines; the only difference is that instead of removing material they add it, which makes them an

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