Integration of Additive Manufacturing into Process Chain of Porcelain Preservation

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Abstract. Relic restoration and preservation is a huge market. Antique Chinese Porcelain, which is regarded as a symbolic type of artefacts representing Chinese art, craft and culture, has attracted significant study into its preservation, crossing the fields of policy-making, science and emerging technologies. In recent years, Additive Manufacturing (AM) has demonstrated its advantages in the restoration of relics made of a variety of materials. However, the study of its implementation with antique porcelain, which not only has different shapes, but also glossy surface and rich colours, still remains in its infancy.

This paper presents the case studies into the application of AM of antique porcelain preservations and creation. The studies include one practice converting the image of a vase on a Chinese painting to a 3D object with AM and another practice that applied AM to replicate an antique Famille-rose porcelain piece featuring rich colour in order to restore the missing pieces on a window in the Palace Museum, Beijing. The aim is to use AM polymer to simulate the visual features of antique porcelain. It was found that with the proper set-up of parameters and integration of other technologies and skills, AM with polymer materials also can support the replication of the features of antique porcelain to a significant extent. However, the glossy surface of porcelain made it difficult to acquire the surface details. In addition, the rich colours of Famille-rose porcelain were not only presented challenges with regard to directly obtain its colour features through 3D scanning, but also limited the application of AM owing to the limited colour series of 3D printing materials. In this paper, integrated methods were proposed and tested to address the above challenges which could impact on the application of AM in imitating porcelain features while attempting to contribute to its preservation and creation.

Keywords: Additive manufacturing · Antique porcelain · Integrated · Archaeological preservation

1 Introduction

As the origin of the English name of the country, porcelain reserves an irreplaceable position in Chinese cultural heritage and played top roles in connecting China and Europe through trade [1]. However, due to the natural calamities and man-made misfortunes, numerous pieces of antique porcelain work were missing or damaged. On the

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other hand, there is a big shortage of the number of craftsmen who are able to restore or duplicate the porcelain with the conventional manual craftsmanship.

Additive Manufacturing (AM) is a well-acclaimed emerging and disruptive technology [2, 3]. Thanks to its advantages in producing intricate and customized parts, the application of AM in heritage preservation has attracted continuous research attentions. This can be proved by the ample number of publications in the application of AM to the restoration/reproduction of different types of historical artefacts [4–6]. In these studies, the application of digital fabrication has been investigated for the restoration of a variety of types of antiques such as wood furniture, bronze and stone sculpture, enamel, and so on. In summary, AM has shown its benefits in these applications in several key aspects, such as:

1. AM is able to produce objects with intricate geometry [7]. This is an important feature since most antiques were made by crafting and thus have diverse shapes that are usually difficult to be reproduced directly with traditional manufacturing processes.
2. As a type of digital fabrication, AM has the strength in its precision compared to manual work. In addition, the digital model of the AM is more editable than the manual work handling the real materials in the physical world, which can further save cost and time.

Although AM has already shown its advantages in the aforementioned applications, it is found that the related work on one important relic material, porcelain ware, is still in its infancy. Within the limited publications, it is realized that some desired requirements are difficult to meet if AM is used alone, which indicates that the integration/hybrid way that involves AM and other emerging or traditional technologies could be a valuable approach to problem-solving in such practices.

This paper will review the related work that could influence the application of AM in these practices, then introduce and analyze two relevant projects completed by the research team and conclude with discussions and suggestions for the future research.

2 Related Work

In this section, the Chinese porcelain is briefly reviewed to understand its key features that should be reproduced through additive manufacturing; the relevant technologies including colour 3D printing and hybrid technologies are also investigated to clarify the advantages and disadvantages of AM.

2.1 Chinese Antique Porcelain

Porcelain is a type of translucent ceramic material made by heating, generally including kaolin (a fine white clay), in a kiln to high temperatures between 1,200 and 1,400 °C. The materials and the heating process give porcelain the glossy surface.

Chinese porcelain has a long history of around 2,000 years and became well known in Europe through trade from the Ming Dynasty (AD 1368-1644) onwards [8]. By then there were two types of porcelain-ware popular in the market: 1, the well-known white and blue porcelain; 2, single colour porcelain ware, such as, white, black, or celadon.

From Qing Dynasty, another type of Chinese antique porcelain, Famille-rose, became popular as well. Different from other types of porcelains, Famille-rose is distinctive for its great range of colours. In addition, different from underglaze blue-and-white porcelain, which has smooth surface, Famille-rose porcelain's colours are overglazed and the colour pigments cause textures on the surface after heating.

The application of AM to porcelain can be for preservation/restoration, historical and educational purposes. Currently, the study of this type of application still remains limited. One possible reason is: as a type of historical relic, porcelain-ware are not as popular in the rest of the world as in China, and hence have not attracted global attention. For instance, within the limited relevant publications, the project completed by Miller 3D in the United States was able to create the replica of a Chinese artefact, a blue and white antique Chinese porcelain vessel from Qing Dynasty [9].

2.2 Colour Additive Manufacturing

Currently, Additive Manufacturing is still in the research era of monochrome with a focus on materials [10–13], printing precision [14, 15] and speed [16]. As an emerging and advanced technology of prototyping and manufacturing, AM has been applied in multiple fields [2, 17], particularly with its strength introducing complex components [7]. However, in some applications, other important attributes have challenged the development of this technology. For instance, to simulate the rich colours as well as the glossy and translucent surface of Chinese antique porcelain wares, it is necessary to investigate how to add colour and required surface effect to the 3D printed objects. Basically, there are two ways to have colours on 3D printed objects, one is direct 3D printing with colour materials and another is to add colours to the surface of the print through post-processing.

Direct colour 3D printing here refers to that the printing substrates have colour property so the printed objects can have two or more colours [3, 16]. Compared to monochrome, colour 3D printing has its advantages in some applications, such as customized decorative accessories and teaching models [18], which make it attract many investments to explore the methods for colour 3D printing [2, 14]. Among these explorations, the researchers try to produce colour printing through different perspectives, for instances, colour 3D printing based on UV ink technology [19]; single and multiple nozzle colour 3D printing [2] (Yang et al. 2018); new algorithms [20] or even the integration of Artificial Intelligence (AI) into colour 3d printing technology [21].

Although the research into the direct colour 3D printing has become quite popular, there are still lots of limitations to apply this technology to practice. Firstly, the variety of colours that be 3D printed are very limited and hard to print more than two colours [2] and usually have poor colour feature quality [22, 6]. Secondly, when compared to 2D printing, there is a lack of standards related to the evaluation of the colour quality of 3D printing [3]. The last but might be the most important, despite vast academic research into different colour 3D printing methods, only a few are commercialized to market and can be used in practice, such as Connex 3 from Stratasys [23], Zprinter850 from 3Dsystem [24] and Mcor IRIS from Mcor Company [25]. Therefore, in many practices, it is hard to use direct colour 3D printing to obtain the required colour properties in terms of colour variety and quality.

2.3 Ceramic Additive Manufacturing

The study of AM on the material of ceramics has started since 1990's [26, 27]. Attempts to apply AM of ceramic have been made in various areas, such as the construction industry [28], prothesis [29] and fine art [30]. However, compared to state-of-the-art polymer and increasingly developed metal, the application of AM ceramics is much more limited [31].

Although ceramics are an ideal material for use in the production of porcelain, the high cost of the technology and the brittleness (which is the same weakness as antique porcelain) of materials [31, 32] limit its application. In addition, porcelain is the combination of ceramic and glaze. Therefore, the AM of ceramic cannot solely create the features of porcelains and conventional post processing is still needed and aforementioned problems still remain. Therefore, given the advantages in accessibility, cost performance and mechanical toughness (not as brittle as ceramics) of polymer AM [33], it is worthwhile to investigate the application of polymer in simulating the features of porcelain.

2.4 Hybrid Technology with Additive Manufacturing

Like most technologies, Additive Manufacturing is not all-powerful but unavoidably has both strengths and limitations. To obtain optimal results in applications, attempts have been made to create hybrid technologies that combine the advantages of AM and other technologies to solve practical problems, e.g. CNC with AM or 2D with 3D printing [34–38].

These studies acknowledged the disadvantageous side of the Additive Manufacturing and showed the necessity of the hybrid approach in solving practical problems. Although these findings from these studies cannot be directly deployed in this study, it provides an inspiring methodology that in the application of AM, integration with other technologies can be proactively considered to explore a better solution than using AM alone.

3 Practices

To investigate the integration method on Chinese porcelain, two projects collaborated with museums were conducted. In both projects, AM was integrated into process chain that include AM, 3D scanning, 2D printing and Manual work, in order to complete the tasks in a proper manner of time, cost and quality.

3.1 3D Creation from 2D Chinese Painting

The first project is 2D-to-3D creation to produce a physical model for exhibition purpose, based on the Emperor Qianlong's painting: 'Shi Yi Shi Er Image' in Qing Dynasty (Fig. 1). To understand the size, colour and material of the objects on the painting, especially the porcelain vase, comprehensive literature reviews were conducted and experts were consulted. It is believed that, the vase on the painting is a type of 'Ru Yao' porcelain which is from the Song Dynasty with blue colour.

Regarding the technologies for the project, although direct coloured ceramic or plaster 3D printing is possible, several constraints were discussed with stakeholders, such as the fact that texture base on powdered printing is not good enough, the choice of colour 3D printers is limited and needs unexpected experiments to adjust, technical difficulties of finishing and the overall cost and time scale. Given these limitations, the integrative method with other technologies was decided as the best compromised solution for this project at this current stage.

The Integrative process was adopted using forward engineering - digital modelling to produce a virtual vase, reverse engineering - 3D scanning data of real lotus followed by data manipulation for the lotus, after the virtual testing, high resolution AM photopolymer physical model with traditional finishing techniques, such as manual assembly and refining with modelling knife, to create the physical model of the vase, as shown in Fig. 2. After that, the colour and gloss were added with hand painting.

Fig. 1. Chinese painting from the Qing Dynasty

Fig. 2. The porcelain and lotus produced through AM

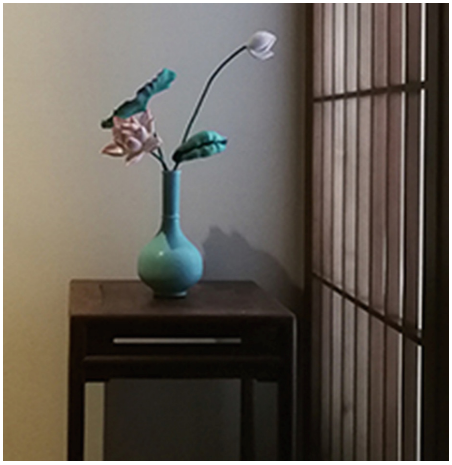

Fig. 3. The finished creation of the 3D prints for exhibition

The final model (Fig. 3) was accepted in the 'Painting and Calligraphy Exhibition of Emperor Qianlong's Meeting with Ministers' after it passed the experts group evaluation, displayed as the first exhibits at the entrance to welcome up to 80,000 visitors daily views for three months.

3.2 Replication of the Antique Famille-Rose Porcelain Piece (More Detailed Process)

Palace Museum is one of the biggest and most famous imperial palaces around the world and also has the biggest collection of Chinese historical relics. The second project is to replicate a missing Famille-rose porcelain piece, which used to be a decorative part on the window of the museum.

As aforementioned, the features of Famille-rose porcelain cause several challenges to the application of AM, which can be summarized as follows:

1. The glossy glaze layer of the porcelain makes it difficult to conduct 3D scanning to acquire surface geometry. In addition, the use of contact 3D scanning and contrast intensifying agent is prohibited on the precious royal porcelain relic.
2. The painting on the Famille-rose has very rich colour including gradient change colours. In addition, different from the modern artificial paint, the painting on the antique piece was made with natural mineral dye, which gives Famille-rose 3D embossment-like texture.

With similar considerations to the first project, the project team decided to use the integration approach that, adopt AM to build the monochrome shape and 2D printing to create the colour painting.

The 3D data of the piece was collected through a non-contact 3D scanner and then printed with Stratasys objet24 with rigid white opaque material (VeroWhitePlus) as printing materials. The colour of the material is suitable since the white is suitable as base to add other colours later on. To get the best texture quality, the model was placed in four orientations to compare the results, as shown in Fig. 4. It was found that the prints from No. 1 and No. 4 can show the texture more clearly than No. 2 and No. 3, mainly due to the staircase effect.

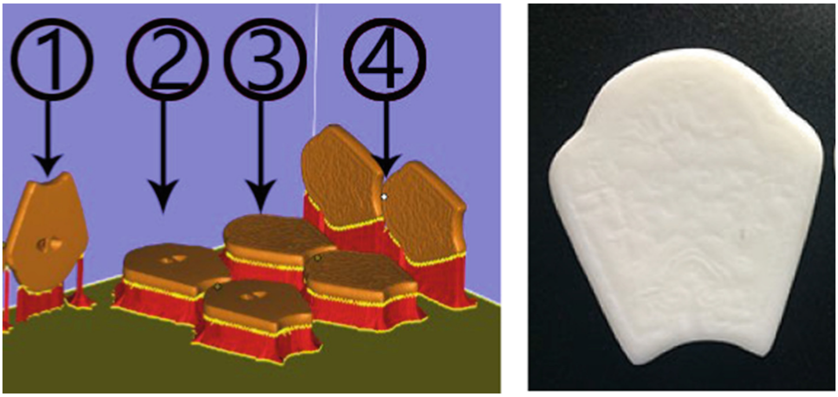

Fig. 4. 3D printing set-ups and printed samples with VeroWhitePlus

Figure 5 shows the acquisition process of the porcelain piece 2D image. From left to right, first of all, the photograph needs to be taken in a professional environment with proper set-up on lighting condition and DSLR camera to get high-resolution picture. After further editing, the picture was printed on the AM piece surface with printer UJF-3042HG which can provide over-coating on transparent and coloured materials as well as glossy finish, which is exactly needed in replicating Famille-rose porcelain. UJF-3042HG is a type of 2D printer produced by the company Mimaki. There are no official specifications from the product booklet stating that it can print on surface with uneven textures and depth. However, through experiments in this study and later expert evaluation, it has acceptable performance in printing pictures on uneven surfaces and matches the texture pattern. Further study is needed to investigate the maximum depth of texture the printer can work on. Figure 6 shows the results of the project at the moment.

Fig. 5. The acquisition of high-resolution image of the porcelain piece

Fig. 6. Final result after the combination of 2D and 3D printing process

The results were then presented to the staff the from Palace Museum to evaluate and give feedbacks on the quality. There were five people invited including three experts from Architecture, Technology, and Exhibition Department respectively and two non-specialists, from Sales Department and Administration. The evaluation is presented in Table 1. The numbers refer to the number of participants in that category. The data showed that in general the reviewers gave positive feedbacks to the results. Overall speaking, non-experts gave higher scores than experts who have higher expectations on some specific parameters, such as the colour and texture quality. However, both experts and non-experts agreed that the results can be beneficial for temporary exhibition, tourism and product design, with comments, such as: ‘Overall, the range of experiments and efficiency are impressive, digital technologies are very useful for relic preservation’

Table 1. The feedbacks from the participants on the quality of the prints (the numbers refer to the number of participants in that category)

Quality parameter	Excellent		Good		Acceptable		Poor	
	Participants (E: expert; N: Non-expert)							
	E	N	E	N	E	N	E	N
Measurements	3	2						
Visual effects				1	3	1		
Resolution			2	2	1			
Colour					2	2	1	
Texture				2	1		2	
Surface roughness			1	2	2			

4 Discussions

From the application view of AM, the case studies explored integration approaches to create Chinese antique porcelains. These approaches set additive manufacturing as a core technology and the materials, machines and printing orientation should be properly chosen and tested. In addition, a process chain that flexibly used pre- or post-processing methods, such as 2D and 3D image acquisition, manual work, 2D and 3D printing, will be employed to complete the task and meet the customer's requirement. The feedback from experts and non-specialists showed the advantages of the integration in terms of flexibility, quality, cost and time. However, although exploratory in nature, the studies still possess many limitations.

Due to the constraints on budget and time, the projects did not systematically test the quality of direct colour 3D printing to reproduce the porcelains and make comprehensive comparison with the proposed hybrid methods. Therefore, these studies only proved the effectiveness of the methods on the two projects, but cannot indicate they have advantages over direct 3D printing on all dimensions.

Chinese antique porcelain has a great diversity in terms of age, shape, colour, texture and surface features. The presented practices indicate that more work needs to be done to simultaneously solve various visual and geometrical attributes when using Additive Manufacturing. In the future, it is expected that, through more practices in this area, some guidelines can be generated which will provide a positive impact on the development of Additive Manufacturing.

5 Conclusions

The exploration of application is essential to the sustainable development of Additive Manufacturing. Although the research on aspects such as materials, precision and speed are fundamentally important to the technology, critical thinking is also needed when considering the research investment. For instance, in some applications, the current precision and printing speed have well met the requirement; behind the vast researches on colour 3D printing, only a few color 3D printers are successfully commercialized. Continuous exploration of the application of AM will open more markets to this technology and could inspire research directions for the above fundamental aspects. For example, the industry can develop AM materials with particular glossy effect to meet customer's requirement on the surface.

In recent years, apart from industrial manufacturing, Additive Manufacturing has been applied into different fields, such as medical science, education, fine art and culture heritage preservation. The practices in these areas showed that, to complete the tasks more efficiently and effectively, more in-depth studies into the integration approach are needed to combine the advantages of Additive Manufacturing and other methods or technologies.

The study presented in the paper indicated that Additive manufacturing is an effective means to bridge the 'old' and 'new', to work on one of the oldest objects with the most modern technology. In addition, it also proved that polymer, which is the most popular and state of the art material of AM, can be used to simulate other material, such as porcelain.

The study presented in the paper also indicates that some applications may not have global significance but under specific cultural background, Additive Manufacturing still can play an important role, e.g. in the cultural heritage of Chinese porcelain in this study. In the field of cultural heritage preservation, different countries could have completely different historical relics to be preserved that have different materials and features, therefore, the integration of local resources, such as craftsmanship and other technologies, into Additive Manufacturing could contribute to the problem-solving. In addition, the successful application of AM in this area will not just benefit the archiving and repairing, but also can develop a new medium for the creativity in product design, for instance, the derivative souvenir products, which will create economic benefits to financially support heritage preservation and the development of AM in turn.

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