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Application of Additive Manufacturing to the Digital Restoration of Archaeological Artifacts

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Abstract

This paper reports a substantial body of work that has been done in this area, which has been used to determine how Additive Manufacturing (AM) and subsequent processes should be optimally applied, and introduces a series of process maps that have been generated to guide future practical work with a combination of questionnaires and expert interviews for validating the process maps. The outputs from the research should prove to be valuable to anyone working in this field. The main contribution to knowledge is the characterisation of archaeological artefacts and the resultant process maps derived from this characterization.

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1. Introduction

Throughout the development of additive manufacturing (AM), the capability and adoption of AM in finely detailed complex surface creation remains limited, especially in the area of archaeological artefact restoration. This is demonstrated by the relative lack of published work in this area when compared to the use of AM in engineering and medical applications.

Although reverse engineering (RE) and AM capabilities are theoretically adequate, there is a gap between knowledge and practice. Museum curators desire an easier and more precise way to reproduce their artefacts, in

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order to generate virtual models and high-quality replicas for restoration and souvenir design. Consequently, engineers are needed to optimise digital technology and process chains to support this market, and provide acceptable solutions to the curators. This will result in the simplification of complicated manufacturing processes and a reduction in the reliance upon lengthy, repetitive and tedious manual production work.

This paper presents some case studies undertaken in this area and reports how they have been used to develop a formalised approach to digital restoration of archaeological artefacts. It begins with description of research questions and methods, reports the case studies undertaken and then presents the novel approach that has been developed. Verification of the approach is discussed and finally, conclusions and suggestions for future work are given.

2. Research questions and methods

The specific research questions addressed by this research can be summarised as follows:

- What are the specific requirements of digital restoration in terms of aesthetics, materials and manufacture?
- What is the relationship between digital restoration and the conjunctive areas of virtual visualisations and artistic souvenir production?
- What are the potential benefits of applying AM to digital restoration?
- To what extent might the use of 3D technologies be accepted within the field of artefact reproduction?
- How can the optimal combination of reverse engineering, digital data manipulation and the use of computer aided design systems be achieved?

The research was designed to address each of these questions in turn and then to draw conclusions in relation to them. Following an initial literature review, action research [2] was employed as the main research method for generating results. This work was used to build up knowledge about the relative merits of the various process chains available. With the completion of each case study, the authors' level of knowledge increased to the stage where it could be formally represented in a structured manner.

3. Artifact restoration case studies

An overview of the experimental work conducted with the Forbidden City's (Palace Museum) huge renovation project is now presented. A film about the project premiered at The British Museum in May 2010 [1]. Several objects from The Palace Museum were chosen to provide case studies in digital restoration. These were a hardwood fan base (Fig 1), a multi-material mosaic plaque (Fig 2), and a dragon plaque made as a bronze shell with gold-plated surface (Fig 3).



Fig. 1: Wood fan base



Fig. 2: Multi-material mosaic plaque



Size about 2.2m * 0.8m Both sides have the same relief sculpture Thickness of high relief should be less than 6cm Material: Bronze shell with gold surface

Fig. 3: Dragon plaque

These were selected for their varying characteristics in terms of the complexity of their shapes, material, overall size, surface finish and minimum feature size. Benchmarking experiments involving the above objects were undertaken by the authors. These were aimed at investigating feasibilities and benefits of digital processes in comparison with the traditional methods for the purposes of archiving, repairing, and creation of artistic souvenir products. Traditional processes involving photographing, measuring, 2D engineering drawing, modelling, moulding, finishing, etc. are all done manually, which requires highly skilled craftspeople and specialists with rich experience working for a long time (Fig 4 and 5).

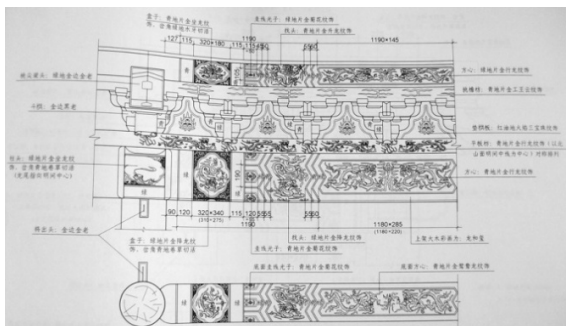


Fig. 4: Manual Engineering Drawing



Fig. 5: Repairing using Manual Techniques (upper left: mark the change/defect; bottom left: measuring; upper right: repairing; bottom right: finishing)

3.1. Digital restoration process

Alongside photography, archiving also involves collecting data via non-contact 3D scanning, (Fig 6). The 3D scan data is manipulated using RE software such as Geomagic, Freeform and GOM, to produce 3D CAD models, on which defects can be annotated. The 3D models can be used to produce simplified engineering drawings (Fig 7) and also optimised to fulfil a variety of needs such as the creation of virtual tours.



Fig. 6: 3D Scanning

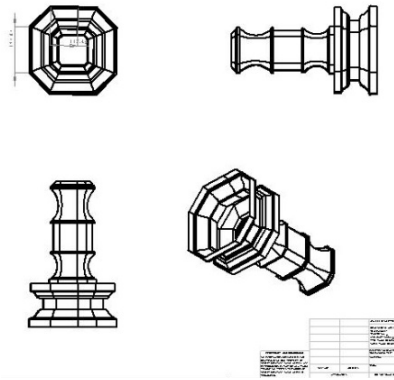


Fig. 7: Simplified Engineering Drawing

The repair process can be started in much the same way as before, but with analysis of the defects being based on the 3D digital models as well as the photographs. Reproduction of missing parts can be addressed virtually by making changes within the CAD environment with all the advantages that this offers, such as the ability to copy, rotate, mirror and transform similar parts. Parts which are too complex to be built easily via the CAD software can be reproduced by sculptors with clay and imported via 3D scanning. New parts can be produced using AM techniques and materials (Figure 8) and external effects can be created by various finishing techniques (Figures 9 and 10). The new parts can then be combined seamlessly with the original antiques. The need for hand finishing to make parts fit is reduced because of the greater accuracy of using the digital data.

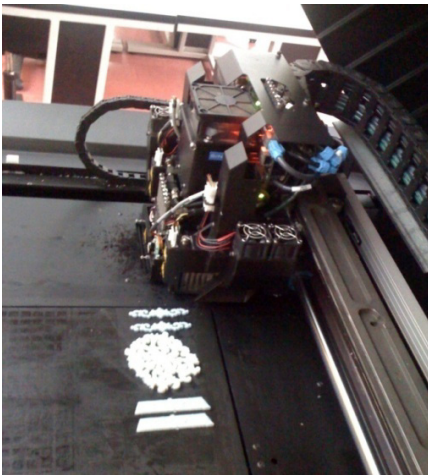


Fig. 8: Additive Manufacturing



Fig. 9: Creating Rubber Moulds From RP Parts



Fig. 10: Material Effects by Finishing Techniques

The souvenir product design process can be similar to the repair process, but using both forward and reverse engineering techniques to create souvenir or functional products with elements taken from historical artefacts (Fig 11, 12, 13). Also, innovative multi-material effects can be created by utilising AM in combination with CNC machining, casting and manual techniques. Since the souvenirs are faithful replications of the original geometry, they are seen by customers as having greater artistic integrity and therefore higher value.



Fig. 11: Transparent dragon plate (25 cm diameter)



Fig. 12: Hollow dragon plate (15 cm diameter)



Fig. 13: Full size gold dragon plaque (50 cm diameter)

4. Development of restoration process chain maps

The artifact categories were defined in terms of complexity of shape, overall size, material and/or surface finish, (as shown in Table 1) and the means of replication were a range of combinations of digital and manual modelling processes. The blue shaded boxes in the table indicate experiments for different types of art works that have so far been undertaken by the authors. The case studies presented in this paper all lie within Category D: Antique Restoration but some of the other replication work has been reported elsewhere [3].

A two-dimensional “paper-based” process mapping technique was used as it was relatively quick to generate and readily accessible by anyone involved in artifact restoration. An example of one of the process maps is shown in Fig 14. The map consists of a series of process stages (shown as rectangles) interconnected by route arrows with decision points shown as diamonds.

Table 1: Artefact Category Matrix

	A. Realistic Body			B. Realistic Animal			C. Abstract / Modern			D. Antique Restoration		
	L	M	S	L	M	S	L	M	S	L	M	S
1. Stone (Marble)												
2. Bronze/Copper												
3. Stainless Steel												
4. Gold												
5. Silver												
6. Wood												
7. Bamboo												
8. Lacquer ware												
9. Ceramic												
10. Bone/Ivory												
11. Jade												
12. Amber												

In the maps, manufacturing process chains are summarised according to the information collected from all research activities, and they are designed to show the process in a visual way. An overall map that will be the final outcome of this research will be a rather complicated system consisting of a number of smaller maps, which have integral relationships between them. The maps can be used individually or integrally in any combination as decision support tools for manufacturing process selection that meets several user needs. The main users of the maps would be project managers in charge of arranging the entire process.

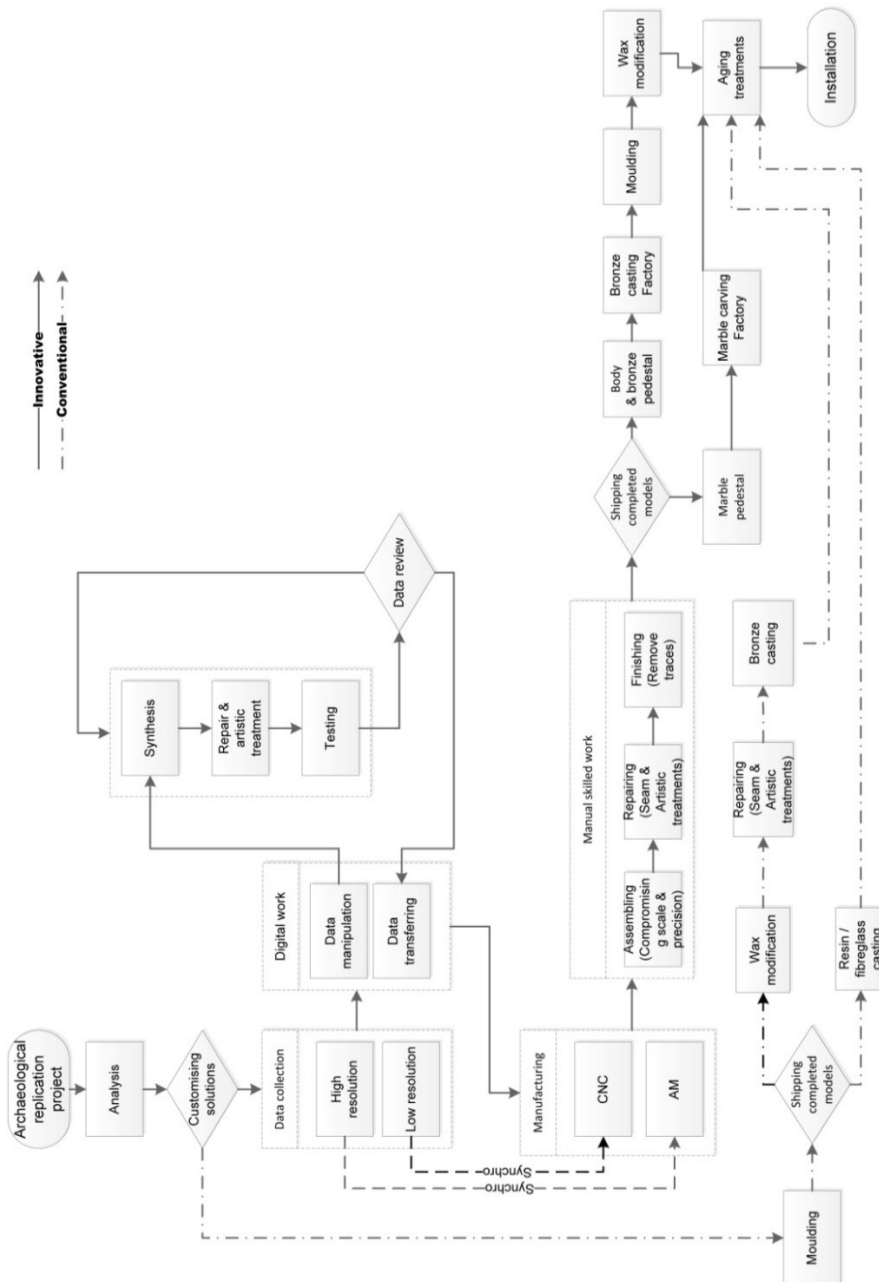


Figure 14: eg. One of the process chain maps

5. Verification of process chains

A questionnaire was designed to evaluate the application of digital technologies in antique restoration, souvenir design, archiving in 2D and 3D data-bases and defect analysis/repair by both experts and non-specialists. The results (as shown in table 2) were mainly positive and indicated that the use of the process chain maps resulted in the production of high quality, cost effective outcomes. A wider group discussion was held involving people from

additional departments, a summary of comments is shown in table 3.

Table 2: Evaluation results

Criteria		Feedback & No. of Experts who gave it	Feedback & No. of Non-specialists who gave it	
1. Quality	Accuracy	Measurements	Excellent 3	
		Visual effects	Excellent 1 Good 2	
	Resolution/Details		Excellent 2 Good 1	
	Colour		Good 2 Acceptable 1	
	Texture		Good 2 Acceptable 1	
	Surface roughness		Excellent 1 Good 2	
	Aging treatment/match with the original		Needs further experimentation	
	2. Time	Measuring		Excellent 2 Good 1
Design solution		Good 2 Acceptable 1		
Manufacturing		Excellent 2 Good 1		
Finishing		Good 1 Acceptable 2		
Transport		Needs further experiments		
Installation		Good 3		
3. Cost		Labour		Good 3
	Material		Excellent 1 Good 2	
	Error/Failure		Excellent 2 Good 1	
4. Accessibility	Labour		Acceptable 3	
	Facility		Excellent 2 Good 1	
	Material		Excellent 1 Good 2	
5. Feasibility of remote working		Excellent 2 Good 1		

Table 3: Summary of comments and group discussion

Advantages	Issues to be solved
Accuracy is better than that achieved by traditional methods	Storage and manipulation for mass of data
Multiple perspective and omni-directional measurements	Feasible and easily operated process chains need to be applied
Regular 3D scanning and comparative analysis	universally in relic preservation area
Repairing accurately, combining with the original parts seamlessly	
Diversity of materials and effects brings developing prospects	
Database can be used for archiving, repairing, demonstration and replication	

6. Conclusions

Digital technologies are already proving to be useful tools in improving on the traditional approach, by reducing the tedious and repetitive aspects of the work, and allowing greater emphasis on artistic and skilled activities. The impact of RE and AM on archaeological restoration may bear similarities to that which photography has had on painting over the last 2 centuries, i.e. (digital) technology will not replace skilled professionals, but in some way become absorbed from the scientific into the artistic domain. Although at present some concerns exist, and productive communication between artists and engineers is quite isolated, AM can certainly be further optimised and integrated within the artefact restoration industry, just as it has developed in other fields.

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