Application of Additive Manufacturing to the Digital Restoration of Archaeological Artefacts

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ABSTRACT

A review of literature showed that published applications of Additive Manufacturing (AM) to digital restoration of archaeological artefacts was rather limited. This paper reports a substantial body of work that has been done in this area. It has been used to determine how AM and subsequent processes should be optimally applied, and introduces a series of process maps that have been generated to guide future practical work. The research methodology employed was predominantly action research, where the researcher undertakes practical work in a reflective manner to develop answers to specific research questions, with a combination of questionnaires and expert interviews used for validating the process maps. The results generated from the work indicated that archaeological artefacts can be characterised according to subject, material, complexity of shape, overall size, minimum feature size, and surface finish. The optimised application of AM and subsequent processes can then be specified in response to these requirements. The outputs from the research should prove to be valuable to anyone working in the field of digital restoration and fine art sculpture, particularly when digital capture of shape and the creation of physical replicas are required. The main contribution to knowledge is the characterisation of archaeological artefacts and the resultant process maps derived from this characterisation. However, the range of projects undertaken was not representative of every combination of artefact characteristics, and some requirements could not be met fully by current AM capabilities, so there remains a need for further research on process development.

Type of paper: Research paper

KEYWORDS: Additive Manufacturing, Digital Conservation/Restoration, Process Chain, Downstream Finishing, Reproduction

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1. INTRODUCTION

Throughout the development of Additive Manufacturing (AM), applications have arisen in many areas. Technology specific to particular applications often benefits from rapid improvements as user take-up accelerates. However, 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. (A review of the related work that was found is given in Section 2).

Although Reverse Engineering (RE) and AM capabilities are theoretically adequate for many archaeological restoration needs, there is a gap between knowledge and practice. Museum curators desire an easier and more precise way to reproduce their artefacts, in order to generate virtual models and high-quality replicas for restoration and souvenir design. Consequently, engineers need to optimise digital technology and process chains (work-glow) to support this application, 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 case studies of three projects 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 a review of related work, goes on to describe the research methods employed, reports the projects undertaken and then presents the novel approach that has been developed. Verification of the approach is discussed before conclusions and suggestions for future work are given.

2. RELATED WORK

As far back as 2000, AM researchers recognised the value of digital reconstruction techniques in the field of palaeontology (Zhang et al, 2000), (D'Urso et al, 2000). Using medical imaging technologies, they were able to create digital models of fossil bones and use these to drive stereolithography systems. However, the production and manipulation of the imaging data was time consuming, expensive and not accurate enough to capture fine details. Data manipulation problems were greatly reduced by the enhancement of medical image software leading to improved model accuracy (Peres et al, 2004), but the use of medical scanning techniques was still a bottleneck. The combination of digital scanning and AM techniques with more traditional skills was expertly demonstrated by Materialise (2010) in the reproduction of King Tutankhamen's mummy for an exhibition in New York. Once again, medical imaging was used to create the 3D data and stereolithography used to build the physical parts. The final appearance of the replica was created through the manual application of detail, colour, and texture. This was an extremely time-consuming part of the work but the results were very well received by both experts and the general public.

With more recent advances in laser and optical scanning techniques, the cost of obtaining 3D data and the accuracy of the models that can be obtained have improved dramatically, enabling data capture to be undertaken in a more efficient manner (Fantini et al, 2008). Consequently, research into archaeological reconstruction using a combination of digital technologies has expanded greatly, although peer-reviewed publications are still quite rare.

The Foundation for Latin American Anthropological Research reported that research on digital imaging technologies was aiding archaeologists, art historians and museums concerned with Mayan antiquities (FLAAR, 2009). A significant point revealed was that overall process chain design is a key connection between these technologies and user needs. It is not just a matter of understanding the technologies and needs, but also deciding how to optimally adopt the available technologies for specific relic restoration.

Roberto and Santos (2011) investigated the combination of 3D scanning and AM technologies in archaeology and palaeontology research projects. They investigated the feasibility of obtaining accurate data by 3D laser scanning and non-invasive medical imaging technologies. They used the scanning data to produce physical replicas of rare and fragile parts via AM. The technical requirements for accurate and non-invasive 3D scanning of antiques were also explored. This work demonstrated that it was feasible to produce accurate replicas through the use of AM and was an example of using scanning data in a public didactic exhibition.

Recent work carried out at the Computer Aided Design (CAD) Laboratory of the Indian Institute of Technology, Kanpur (Kumar and Dhande, 2012) was an interesting demonstration of the application of RE and AM in archaeological modelling and heritage preservation. The work aimed to allow archaeologists and researchers to view, analyse and even reproduce artefacts in the absence of the original object. Reconstructing artefacts from fragmentary material required morphological and artistic talents and involved intensive CAD modelling. However, the use of the digital domain enabled researchers to perform accurate work without any risk of damage to the original artefacts – not always the case with traditional reconstruction methods.

Ferschin et al (2011) reported the use of AM in archaeological building reconstruction. Conventionally, physical models of existing or reconstructed buildings were often manufactured by manual casting techniques using materials with wood-like properties. They found that although digital technologies were increasingly entering related disciplines, the automated production of physical models from virtual models was still uncommon in the field of archaeology. Thus, further research into extending the “model making chain” with digital manufacturing techniques (including both AM and CNC milling) was deemed to be necessary, and this helped drive the research reported here.

3. RESEARCH QUESTIONS AND METHODS

3.1 Research questions addressed

The research context is one where most archaeological museums have yet to benefit significantly from AM, especially when viewed alongside the many success stories in other fields. Theoretically, complex surface creation is one of the strengths of AM and it is clear that complementary needs and opportunities exist. So, what are the issues to be tackled when applying AM in the world of digital restoration, and how should AM be optimised for artefact reproduction? 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 related 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 CAD systems be achieved?

The research was designed to address each of these questions in turn and then to draw conclusions in relation to them.

3.2 Research methods employed

Following an initial literature review, action research was employed as the main research method for generating results. Action research can be defined as a method where the researcher undertakes practical work in a reflective manner to develop answers to specific research questions (Louis et al, 2007). The derivation of the knowledge is usually iterative with each phase of the research being informed by lessons learnt from previous phases. Outputs from the action research are typically 'triangulated' using other research methods, in this case questionnaires and interviews, to gain greater confidence in the results. The action research took the form of undertaking a range of digital restoration projects from several museums in China. This involved the 3D scanning, data manipulation, CAD modelling, AM production and manual finishing of many artefacts. This work was used to build up knowledge about the relative merits of the various process chains available, particularly in relation to different classes of artefacts, as defined by subject, material, complexity, size, and surface finish. With the completion of each project, the authors' level of knowledge increased until it reached the stage where it could be formally represented in a structured manner.

4. ARTEFACT RESTORATION CASE STUDIES

The traditional restoration processes will be described in section 4.1 to provide a general comparison with the digital processes described in section

4.2. Three artefact restoration projects using AM with other digital technologies have been selected to present as detailed case studies.

4.1 Traditional restoration processes

Archiving involves photographing the antiques from various angles and the pictures being compiled in order to analyse defects and degradation over time. 2D engineering drawings are also produced by hand according to measurements obtained by manual methods and annotated for future discussions (Figure 1).

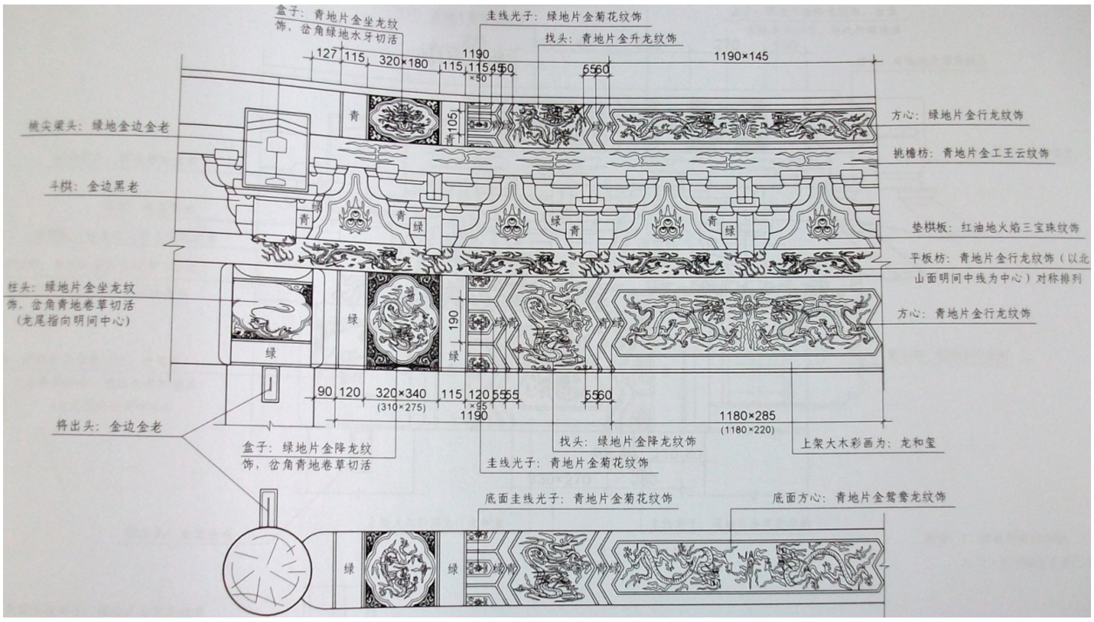


Fig. 1: Manual Engineering Drawing (coutesy of Palace Museum)

The repair process starts by marking any defects on the photographs and engineering drawings of the antiques. Materials for replacement sections are then sourced that are as close as possible to those of the original object. The dimensions of these replacement sections are specified manually and manufactured using traditional craft skills. The manufactured sections are artificially 'aged' using a variety of finishing techniques (both superficial treatments, e.g. painting, and also chemical/mechanical aging techniques are used) before being combined with the original antiques. The defect surfaces need to be polished carefully several times to minimise the gaps between the original and new parts.

4.2 Digital restoration processes

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

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 that 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, and external surface effects can be created by various finishing techniques. 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.

4.3 Case Studies

Most of the research was undertaken in partnership with the Palace Museum in central Beijing and the Summer Palace, a short distance away. Built during the 15th Century, the Forbidden City houses the Palace Museum and is the location of a renovation project that started in 2006 and planned to last for 10 years. The project, involving buildings, gardens, furniture, objects, clothes, paintings, etc., entails both extensive restoration and the reproduction of lost or destroyed artefacts. A database of engineering drawings, virtual tours, publications and other media is also being compiled. The project is managed by the Museum's Ancient Architecture Department, with support from the Technology Department of the Chinese Government and others. The restoration project members are investigating the use of new technologies to improve both quality and efficiency. Several institutions from the USA, Japan and the UK have provided their support, and a film about the work premiered at the British Museum in May 2010 (Anon, 2010).

Two objects from the Palace Museum and one from the Summer Palace were chosen as suitable digital restoration projects. These were a hardwood fan base (Figure 2a), a dragon plaque made as a bronze shell with gold-plated surface (Figure 2b), and a pair of bronze lions (Figure 2c). These objects were carefully selected for their varying characteristics in terms of the complexity of their shapes, materials used, overall size, surface finish and minimum feature size. Benchmarking experiments involving these objects were undertaken by the authors. These were aimed at comparing the traditional and digital processes for the purposes of archiving, repairing, and replication.

(a) Fan base

(b) Dragon plaque

(c) Pair of lions

Fig. 2: Artefacts selected for digital restaration case studies

4.3.1 Case study one: Wooden fan base – simulating material replacement. After taking photos from various angles, a Konica Minolta Range 5 1.3 M non-contact laser scanner was used to collect data of the entire artefact (Figure 3). The scanning process took two technicians about half a day (without touching the surface or applying any developing agent) under normal office conditions. Data manipulation was first conducted in the scanner support software to register different scans together. Then the digital model was imported into the RE software (Geomagic) to 'fix' the model including filling the holes, removing bad triangles and edges, repairing flipped normals, etc. This was followed by extracting the complex relief and hollow parts from the body and saving them separately, which was for convenient use at a later stage. The main body part was exported to generate simplified engineering drawings with only a few key dimensions, and the relief parts were used as the basis for the restoration research.

Fig. 3: Non-contact 3D Scanning

In the light of earlier analysis, the fan base was treated as being a geometrical shaped body with a simple hollow structure together with rotationally symmetrical relief patterns. A relief on one side was cracked and needed to be repaired by reproducing a replacement. Digital models were retrieved from the database, and using the same pattern on the opposite side as a reference, the relief with the defect was repaired virtually using the modelling software ZBrush. Although the geometry was theoretically symmetrical, the patterns on opposite sides were actually slightly different because they were originally made manually. Therefore, it was decided not to simply replace the cracked one with a copy of the perfect one from the opposite side. Instead, a digital reproduction of the original slightly different shape was created.

The digitally repaired part was then exported as a single STL file for AM. The file was imported into Magics for final error detection before building it in an AM machine. As the part was about 100 x 100mm with low relief and no inner structure or sharp corners, both an SLA 4500 set at 50µm layer thickness and an Objet Connex 500 machine were deemed adequate to produce the fine details. The Objet machine was chosen, in this case, for its better surface finish properties. Four copies of the relief model were produced for further research purposes.

A series of finishing techniques were applied to three of the resin models to simulate the original wood material effect. Firstly, this involved removing the support material and polishing the ‘stair-steps’ off the surface with fine sandpaper. Secondly, mixing of the appropriate colour was performed and a brush was used to apply the mixture onto a piece of resin for inspection. Since the colour of the wood was not even because of its grain, applying the pigment mixture with a brush required artistic skill and it was necessary to practice this a few times in advance before applying it to the AM part. Thirdly, a layer of clear varnish was applied on the surface to protect the colour after the pigment was completely dry. Finally, a little aging treatment was applied to adjust the final effect (seen in Figure 4). When combining the replacement with the original, the interaction needed to be carefully recorded to observe if the original was compatible with the new part. This was done by restoration experts from the Palace Museum who were generally satisfied with the result.

Fig. 4: Finished AM replica of the wooden relief

Another experiment was undertaken using the remaining replica AM model to test the simulation of other material effects. A silicon rubber mould was produced from the resin model, and a plaster support mould was applied to the rubber mould. When the plaster was dry, the moulds were turned over and the plaster support mould removed. The rubber mould was then peeled off to take out the original AM model. The rubber mould was then put back into the plaster support mould to avoid any distortion. Different liquid mixes were prepared in order to simulate jade and amber by mixing clear resin with talcum powder to adjust transparency and then adding translucent pigment for the uneven colour and grains inside the translucent texture. Then, the mixture was poured into the rubber mould layer by layer to minimise bubbles since the uneven colour prevented the use of a vacuum casting system. The resin was allowed to dry completely and then taken out from the rubber mould for the last step which was polishing. To simulate lacquer, the same rubber mould used for resin casting, was this time used with colour resin mixture that was opaque. The lacquer effect was also achieved using a brush to apply a layer of pigment mixture onto the resin model and applying a little aging treatment where necessary after polishing. The results are seen in Figure 5.

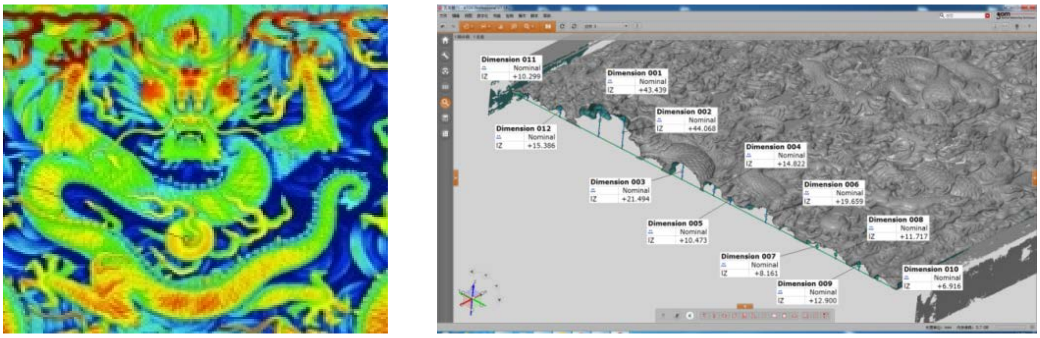
(a) Amber and jade effects

(b) Lacquer effects

Fig. 5: Results of material simulation trials

4.3.2 Case study two: Gold plated dragon plaque – AM material replication.
A 2.2m × 0.8m bronze plaque with a five-dragon high relief had a highly reflective gold surface and could not be touched. Therefore, an ATOS 5M blue light scanner was chosen to collect data for the overall shape and for fine details. The scanning process took two technicians around two days without applying a developing agent, with some areas needing up to eight scans to obtain complete data including undercuts of the high relief. The scanning data was registered in GOM metrology software to generate a digital model, and exported in a compatible format (STL file) for manipulation in Geomagic RE software.

The area of the original digital model that was selected for AM production is shown Figure 6a. The different coloured fringes represent surface curvature and were used to indicate defects in the artefact. For example, concave or convex areas should have a continuous gradation of colour. If there is a small gap on the continuous curvature surface then a contrasting colour will be shown at that place. In this case, a sectional cut was taken at the defect region to analyse and view with detailed dimensions (Figure 6b). This model, together with notes, could be saved in the archive to record the changes caused by weathering or human interaction to aid future research and restoration.



(a) Coloured fringe analysis (b) Section view with annotations

Fig 6: Analysis of the area of dragon relief that was to be built using AM

A 500mm diameter area was cut out from the digital model of the entire plaque, and some small defects were repaired virtually. A shell of the model with 1mm thickness was exported as an STL file for AM, and Magics was used to check for any problems in the file that needed to be fixed. Since the plaque had high relief with fine details and therefore contained a large amount of data, the triangles were optimised in Geomagic to reduce the file size to fit with the data-handling capability of the AM machine software. An Objet Connex 500 AM machine that could achieve 16µm layer thickness was chosen to meet all the model production requirements. However, although the working platform could theoretically handle diameters up to 500mm, the machine software limitations required that the file was divided into two parts to fit into the build envelope. The division was made in Magics following the dragon tail contour as a dividing curve to give the best result in terms of an 'invisible join'. White photosensitive resin (known as Vero White) was adopted to produce the two parts separately. After the support material was washed off in a pressurised water spray machine, the two parts were registered together and combined with Epoxy Milly Putt (Figure 7a). Using fine sandpaper to polish some of the model surfaces eliminated all traces of printing and gluing. Gold leaf was chosen as a finish since it was close to the colour of the original and could be applied in the same way as for the traditional method. This was done by firstly applying a layer of clear coat blending agent as a binder and then using a brush to stick every piece of gold leaf onto the surface very carefully. This was done by the author and took approximately four hours. The final result (see Figure 7b) was evaluated by members of the Palace Museum staff who were extremely impressed by the overall appearance and fine detail of the partial replica.

(a) Two AM parts joined together (b) Finished model

Fig 7: Replicated area of dragon relief

4.3.3 Case study three: Bronze lions – AM support for replication in original materials.

This project required the accurate replication of a pair of bronze lions with bronze and marble pedestals, located in the Summer Palace. The project was undertaken to validate previously derived process chains and to verify the use of additional alternative processes. Thus, it aimed to utilise the process chains to guide accurate reproduction of full size replicas in the same material as the originals, using an optimised combination of technologies. It involved 3D scanning, AM, CNC machining and manual techniques. One of the reasons for using digital technologies was the historical failure of taking silicon rubber moulds from the originals since there were too many fine detailed reliefs with undercuts.

The two original lions were located in a fixed position outdoors and had dimensions as follows: the lions themselves are 1.96m tall ×1.59m × 1.11m with the bronze plinths about 0.6m tall, marble pedestals are 0.92m tall × 1.94m × 1.46m. Collecting accurate 3D data was the foundation of this project, and after considering the combination of large object size with fine details, an ATOS 5M blue light scanner with a TRIPOD calibration system lens was adopted. All scanning work was conducted during the night to avoid affecting and being affected by visitors and completed intensively within 10 days. For a large scale artefact like this, the TRIPOD system was used to collect the global data similar to taking photos. After that, local data was collected by the scanner with a maximum 600 × 600mm area per scan. The local data was registered with the global data at a later stage. Following a visual analysis, the symmetrical patterns on the pedestals were scanned on two sides only with the other two sides being generated by reflection in Geomagic RE software (Figure 8).

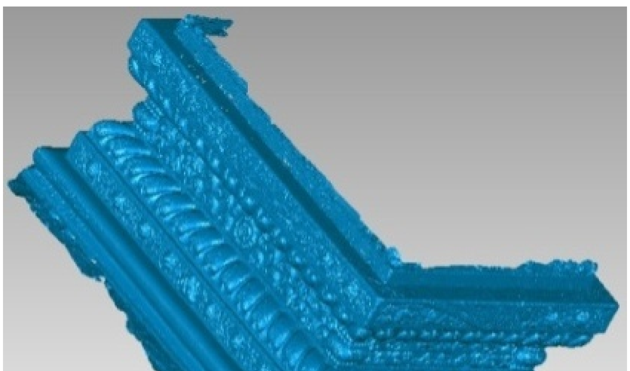


Fig. 8: Half marble pedestal with symmetrical patterns

Besides basic data manipulation work after scanning, such as filling holes, the main data manipulation task was to organise all the files and to register the global data and local data together to complete an entire surface. Therefore, it was necessary to register adjacent surfaces scanned from different angles to form the complete shape, as well as registering mirrored symmetrical surfaces and repeated surfaces. Two strategies were adopted to deal with the large file sizes this created. One was to optimally reduce the triangles in the STL file, which kept more triangles for areas with more complex geometry and reduced triangles in areas with relatively simple curved surfaces. Another was to divide the whole model into several sections according to the processing methods to be used at later stages, i.e. some sections needed to be exported for AM while others would be exported for CNC machining. All the individual sections needed to fit the working platforms of the specific machines used. The dividing curves were designed virtually to follow the geometry to help hide divisions, to allow easy assembly, and to form robust structures for long distance shipping and subsequent post processing.

After the STL files were checked using Magics software, the AM shells were set between 1.5 and 2mm thickness depending on their size, the complexity of their geometry and their position in the sculpture, e.g. where they might support more weight or bear more forces during moulding. Two SLA RS 6000 machines worked together to produce all the complex or important parts without tooling or monitoring. An example part is shown in Figure 9. Other parts with simpler geometries or flat surfaces with low relief were processed by four CNC machines working simultaneously. To save material cost, this was done using high density foam and ABS plastic (Figure 10).

Fig. 9: AM part for a lion's face

Fig. 10: CNC machining of foam model

After all the parts were taken out from the machines, the AM parts were put into an oven for full curing with UV light and the support material was then removed by hand. Then, three groups of models representing the lions' bodies, the bronze pedestals and the marble pedestals were assembled separately with AB glue and Milly Putt, with the connection areas needing some polishing to eliminate the traces of joining. At the time of assembling, wood and ABS bars were installed inside the models to act as an internal support structure. The lions' bodies together with the bronze pedestals (Figure 11) were shipped to a bronze casting factory to act as master models for a moulding process. The models of the marble pedestals (Figure 12) were shipped to a marble carving factory where they would be used with a replication device that would follow the surfaces and guide the sculpting process. The bronze casting and marble carving processes were generally the same as traditional methods and the final replicas with aging treatments were shipped and installed at the new China Garden Museum (Figure 13), two months after scanning. The final results of the work showed that accurate replicas were successfully achieved using digital methods with relatively low costs and within the scheduled time of three months.

Fig. 11: Final assembled models ready for bronze casting process

Fig. 12: Marble pedestal model

Fig. 13: One of the finished replica lions

5. EVALUATION OF DIGITAL PROCESSES

To gain further data in response to the research questions, a questionnaire was designed to evaluate the application of digital technologies in antique restoration, archiving in 2D and 3D data-bases, and defect analysis/repair. Experts and non-specialists from the Palace Museum were asked to evaluate various outcomes in comparison to those produced using traditional methods using the criteria of quality, time, cost, accessibility and feasibility of remote working. The questionnaire was completed by three experts from the Architecture, Technology, and Information Departments, and two non-specialists from Sales and Administration. The experts evaluated the outcomes against all the criteria whereas the non-specialists only evaluated the quality of the finished parts produced. They were asked to rate the digital method as being excellent, good, acceptable or poor in comparison to the traditional methods used previously. The results (as shown in table 1) were mainly positive and indicated that the use of the digital processes resulted in the production of high quality, cost effective outcomes. There were some issues arising that needed to be investigated with further experiments, such as aging treatments on AM materials, and transportation for remote working. In addition, a wider group discussion was held involving people from additional departments, and a summary of comments is shown in table 2.

Criteria			**Feedback & No. of Experts who gave it**	**Feedback & No. of Non-specialists who gave it**
1. Quality	Accuracy	Measurements	Excellent 3	Excellent 2
		Visual effects	Excellent 1 Good 2	Excellent 2
	Resolution/Details		Excellent 2 Good 1	Excellent 1 Good 1
	Colour		Good 2 Acceptable 1	Excellent 2
	Texture		Good 2 Acceptable 1	Excellent 1 Good 1
	Surface roughness		Excellent 1 Good 2	Excellent 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. Access-ibility	Labour	Acceptable 3	
	Facility	Excellent 2 Good 1	
	Material	Excellent 1 Good 2	
5. Feasibility of remote working		Excellent 2 Good 1	

Table 1: Evaluation results

Advantages	**Issues to be solved**
Accuracy is better than that achieved by traditional methods	Storage and manipulation for large data-sets
Multiple perspective and omnidirectional measurements	Feasible and easily operated process chains need to be applied universally in all relic preservation areas
Regular 3D scanning and comparative analysis	
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	

Table 2: Summary of comments and group discussion

6. DEVELOPMENT OF RESTORATION PROCESS CHAIN MAPS

Having acquired a substantial first-hand knowledge of effective means for creating replicas of artefacts across various categories, the next challenge was to record this knowledge in a way that would be useful to others. The artefact categories were defined in terms of subject, material, complexity, size, and surface finish, (as shown in Table 3) 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 been undertaken by the authors to date. The case studies presented in this paper all lie within Category D: Antique Restoration; other types of replication work have been reported elsewhere (Zhang et al, 2011).

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												

Table 3: Artefact categories

A number of possible methods were considered for representing this knowledge, including a set of written guidelines and a searchable database tool. In the end, a two-dimensional “paper-based” process mapping technique was used as it was relatively quick to generate and readily accessible by anyone involved in artefact restoration. The process maps were initially developed using a trial version of the SmartDraw software that could be easily printed out to create paper-based reference sheets. An example of one of the process maps is shown in Figure 14. The map consists of a series of process stages (shown as rectangles) interconnected by route arrows with decision points shown as diamonds.

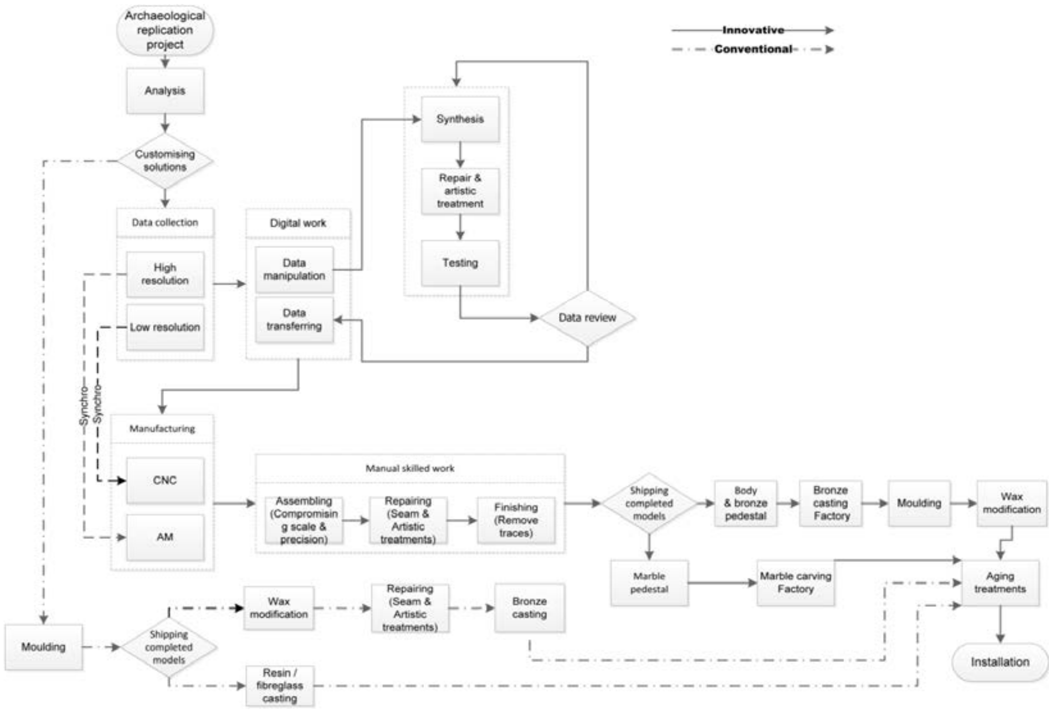


Fig. 14: One of the process chain maps

In the maps, manufacturing process chains are summarised according to the information collected from all research activities, both literature review and action research, and they are designed to show the process in a visual way. The overall map, that is the final outcome of this research, is a rather complicated system consisting of a number of smaller maps, which have integral relationships between them. Therefore, work is ongoing to build a website that will offer an easier-to-understand representation of the maps. The maps can be used individually or integrally in any combination as decision support tools for manufacturing process selection that meets specific user needs. These needs include communications between co-workers with different backgrounds, accessing interdisciplinary knowledge, understanding the requirements of each step, and connection/cooperation of individual parts of the work. The main users of the maps will be project managers in charge of arranging the entire process.

7. CONCLUSIONS AND FUTURE WORK

Using traditional methods for archiving purposes (i.e. taking photos and creating manual drawings) requires considerable professional skill and takes a long time. Accurate dimensions are required for building 3D digital models from 2D images – and this is a difficult undertaking for even small objects, especially when measurements are not sufficiently accurate when taken manually using hand tools. For antique repair, every manufacturing step requires many hours of input from skilled practitioners in a variety of different professions, all who have been trained for many years. Materials are expensive and are easily wasted when mistakes are made. Some special materials and geometric structures are almost impossible to repair.

This work has shown that using digital technologies, the measurements are much more accurate, and engineering drawings and digital models are much easier to obtain for archiving purposes. Reproducing and repairing parts virtually by copying and translating similar parts is also easier. AM allows much more accurate replicas to be made when compared to hand-made replicas based on photos and drawings. In addition, AM brings greater possibilities for repair. All three of the projects presented in this paper resulted in repair and replication being completed more quickly and at a lower cost than possible using traditional methods. Digital technologies improve upon the traditional approach by reducing the tedious and repetitive aspects of the work, and allowing greater emphasis on artistic and skilled activities. The optimal application of RE and AM technologies to specific replication cases requires in-depth knowledge of processes and their outcomes. This paper presents a possible solution through the use of process chain maps that embed the knowledge acquired in this research.

Further Research

At the time of writing, the following problems were still being investigated:

- 3D scanning of translucent objects (e.g. jade and amber) and objects with very high or low reflective surfaces (e.g. gold and hardwood), especially those antiques where contact and the use of powders is prohibited.
- 3D scanning of finely detailed objects in awkward situations (e.g. confined spaces) that prohibit the use of a robot arm and yet require higher resolution than hand-held equipment currently provides.
- Finishing techniques to complement suitable and reasonably priced materials for RP / AM. Currently, time-consuming artistic methods must be used incurring a high cost.
- The communication between sculptors, designers and engineers and also the relationships between co-workers involved in the innovative process chains these projects are creating.

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