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Digital Fabrication Technologies for Cultural Heritage (STAR)

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Abstract

Digital Fabrication technologies exploit a variety of basic technologies to create tangible reproductions of 3D digital models. Even though current 3D printing pipelines still suffer of several restrictions, the reproduction accuracy has gradually reached an excellent level. Thanks to this advancement, the interests of manufacturing industry with respect to 3D printing techniques has significantly grown during the last decade. However, digital fabrication techniques have been demonstrated to be effective also in other contexts, such as medical applications and Cultural Heritage (CH). The goal of this survey paper is to introduce briefly the different fabrication technologies, to discuss some successful utilization of 3D printing in the CH domain and, finally, to review the work done so far to extend fabrication technology capabilities to cope with the specific issues that characterize the usage of digital fabrication in the CH domain.

Categories and Subject Descriptors (according to ACM CCS): I.3.1 [Computer Graphics]: Hardware Architecture— I.3.3 [Computer Graphics]: Picture/Image Generation—

1. Introduction

Most of industrial manufacturing processes start by modelling a digital shape representation with computer aided design. This initial step is followed by a sequence of intermediate steps whose main purpose is to create a tangible copy of the digital model. The set of techniques implied on this process are usually referred as digital fabrication techniques. While most of the traditional industrial fabrication techniques are implied for large scale production, an emerging class of fabrication devices aims to reduce the gap between digital modelling and tangible reproduction. While, at its current state, this class of techniques are not convenient for large scale production, they represent the best resource for the production of prototypes in industrial manufacturing processes.

Usually, this class of technologies is referred also as *3D printing*. The main advantage of 3D printing techniques is that the manufacturing process is independent from the geometric complexity of the digital shape. This characteristics is, in general, not true for the usual large scale industrial production pipelines. Thanks to this advantage, 3D printing allows for producing prototypes in a reduced amount of time (thus the origin of the term *rapid prototyping*). Each digital fabrication technology is mainly characterized by the basic physical process used to produce the tangible representation. Because of the physical constraints involved in the process, each technology is able to employ only a subset of the possible materials (plastic, glued gypsum, steel, ceramic, stone, wood, etc.).

Thanks to the increase of accuracy reached by current technologies and the reduction of reproduction costs, Digital Fabrication has been applied in many other contexts, going beyond its initial use for industrial prototyping and manufacturing. In particular it has been effectively applied for the reproduction of artworks, for museum exhibitions and for supporting CH restoration. The traditional reproduction approach for CH artworks requires the production of rubber molds over the original artworks; rubber molds are then used for the subsequent production of gypsum or resina copies. This process has several undesired drawbacks: it is a manual process; it is time consuming; it is strongly influenced by the complexity of the input shape; and, finally, it forces the reproduction to be an exact 1:1 copy of the input shape. On the other hand, 3D printing provides more flexibility: for example, we can exploit all the advantages of being able to edit the digital representation before producing it as a physical object (we may scale, deform a reproduction, or simply print selected portions of the object). We believe Digital Fabrication offers a significant improvement with respect to the usual CH reproduction pipeline, also because it provides the possibility to customize and enrich the information provided by a tangible representation of a CH artefact.

In this State of The Art Report (STAR) we present the potential and the large spectrum of applications of fabrication technologies in the CH framework. This STAR is organized in three major parts: a brief characterization of the most common *technologies* (Section 2), a review of the possible *CH applications* (Section 3), and one final section presenting the major issues and open problems in the CH domain (Section 4).

2. Brief characterization of Digital fabrication technologies

Digital fabrication techniques can be divided in two major classes: *subtractive* and *additive* processes. The former have been widely used for industrial applications since the late 80s while the latter encountered a huge success in the last few years.

2.1. Subtractive Techniques

The term *subtractive* characterizes those reproduction methods based on the idea of producing the replica by carving a block of material, usually by using computer-controlled milling tool (CNC machinery). The main advantage of this class of approaches is its wide range of reproduction material. Milling machines can operate on almost any kind of material, like wood, stone and metal. This is an strong point if fabrication techniques are used to create as accurate as possible physical copies of existing artifacts. See Figure 1 for an example of the use of this approach in the CH context. Moreover, CNC milling machines provide a very large workspace, which is usually sufficient for the creation of 1:1 replicas of life sized statues.

On the other hand, most of CNC milling machines present a wide number of geometric and kinematic constraints that significantly reduce the domain of application. In practice, the problem of driving the carving head of a milling machine is a very complex one and the capability of the available devices can vary a lot. The most common and economic devices are able to carve bas-reliefs (2.5 height fields). However they impose limitations on the size of holes and cuts depending on the size of the drilling tool. The less sophisticated 2D cutting machines are another class of devices that could be used to produce replicas. These tools are able to cut sheets of a variety of materials, from cardboard to ABS, to plywood. Even if these devices are not able to directly produce a 3D replica, they can cut flat pieces that users can assemble into an all round object or into an approximation of the original shape (see Fig.8).

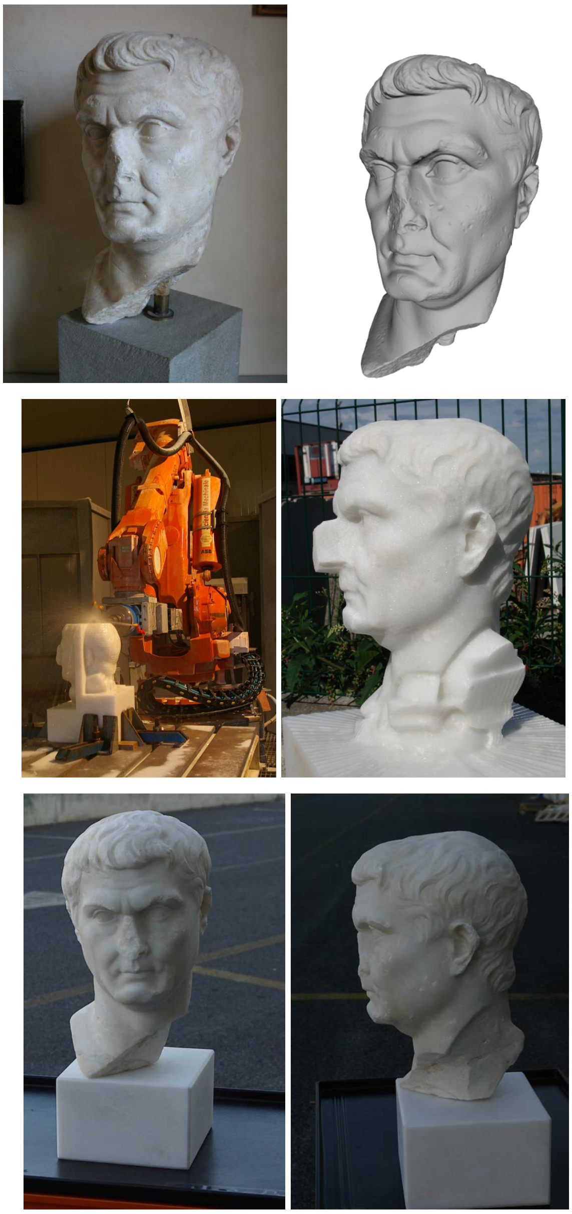

Figure 1: *An example of a rapid prototyping project, developed by CNR-ISTI in collaboration with the company* Scienzia Machinale*. First row: the original artwork; the digital 3D model obtained using a laser triangulation scanner. Second row: the prototyping machine in action; the reproduction at the end of the automatic reproduction phase. Third row: two images of the final result, after a final manual refinement pass.*

On the opposite side of complexity (and cost) there are the 6-axis CNC machines that allow more degrees of freedom and are able to rotate the drill all around the object. However, they also encounter physical limitations due to the movement of the drilling tool and are quite complex to be operated. The design of the tool path is also a time-consuming operator-assisted phase, which increases the cost of this type of reproductions.

While subtractive techniques are on the market since early '80s, the limitations listed above (and the implicit difficulty of driving milling machines) are the main reasons why they have not gained a widespread use: adoption of milling machines has been mostly limited either to very simple cases (like the production of bas-relieves) or to very specific projects having a strong commitment on the material to be used for the reproduction.

2.2. Additive Techniques

The last ten years have seen the rise of the consumer market of 3D printing with the appearance of many low cost devices that are moderately simple to use with a low operating cost. The vast majority of these devices is based on the *additive* approach; an example is Fused Deposition Modeling (FDM), where a thin filament of plastic is melt, extruded and deposited to form, slice by slice, the desired shape until the complete replica is produced.

Figure 2: *Two small buddhas fabricated in ABS using two different FDM machines. Given the limited size of the objects the layer structure is quite evident. Notice how the appearance properties of the material can make more or less evident both the small scale details and the printing artefacts.*

Fused Deposition Modelling (FDM). An advantage of this extrusion-based approach is to require a fairly simple mechanic (very similar to the printing head of a 2D printer). Therefore, this class of devices is, by far, the cheapest on the market: from a few hundreds Euro up to a 2K-3K Euro. On the other hand, the quality of the results can vary a lot (Fig. 2). Various parameters may considerably affect the final result. First of all the used material is, in most of the cases, a single kind of plastic (usually ABS or PLA). Such materials provide an artificial appearance to the printed object, which is often undesirable for CH uses. Moreover, depending on the quality of the device, the layered structure generated by the deposition scheme can be quite visible.
A viable solution can be to apply manual, artistic finishing (sanding, smoothing the surface with a primer/filler and then possibly painting it), but this makes the whole process a lot less automatic and straightforward.

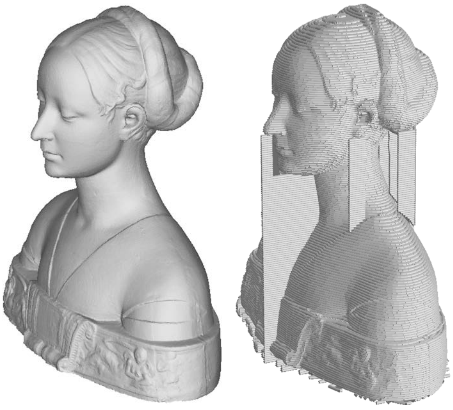

Figure 3: *Using the FDM approach, printing involves the previous automatic conversion of the 3D model (left) into an approximation composed by the extruded filament (right). This process also includes the creation of some vertical columns to support the most protruding parts of the model (like the chin, nose and hairs of the bust in this figure.*

From a purely geometric point of view, the main constraint is that the deposition strategy of FDM imposes the absence of strong overhangs, then all the significantly protruding part must be supported by an adequate scaffolding structure. This stucture has to be printed together with the object itself (Fig. 3). While such structure is automatically generated by the software driving the printer, the removal may become seriously problematic for complex and intricate shapes. Some of the more advanced devices allow to build support structures using a usually a water-solvable plastic; this solution get rid of the tedious manual process of removing the supporting structure.

FDM is not the only additive technique on the market; at least two other techniques are worth mentioning: *granular materials binding* and *photopolymerization*; both of them work *layer by layer* building the object replica one sheet after the other.

Granular materials binding. These techniques uses thin slices of very small particles that are selectively aggregated, layer by layer, using various techniques. One common ap-

Techniques	Cost	Ease of use	Geometric Freedom	Material Adequacy to CH	Precision
Subtractive Techniques					
2.5D CNC Carving	medium	low	low	high	high
6-Axis CNC Carving	high	very low	medium	high	high
Additive Techniques					
FDM	very low	medium/high	medium	low	medium/high
Gypsum binding	medium	medium	very high	medium/high	medium/high
Metal Sintering	very high	low	very high	medium	medium/high
Photopolymerization	high	medium/high	medium	low	medium/high

Table 1: *Summary of Fabrication techniques for CH. For most of the techniques discussed in Section 2 we draw a qualitative evaluation based on CH criteria.*

proach is to use gypsum powder and a liquid binder deposited on selected locations (the discretized internal section of the object cut by the current layer) by mean of an inkjet printer head. This approach allows also to include colours in the printing process. Even if the printed gamut (in terms of color and saturation) is much lower than the one of traditional 2D colour printers, this approach is the only one that allows the production of coloured replicas.
Other material/binding approaches include resin gels and a polymerizing agent that solidify the gel, or metal powder and laser sintering (known as *Selective Laser Sintering, SLS*).
The main advantage of all these techniques is that the unbinded material provides the necessary support for all the overhanging structures and therefore these techniques offers the widest liberty in terms of geometric complexity of the printed shapes. On the other hand, for the vast majority of the material/binder pairs the model is not yet ready at the end of the printing process, since the binding component is not usually sufficient to create a robust object and it has to be treated to make it robust. For example, gypsum-based materials require to soak the reproduction with a cyanoacrylate-based binder that strengthen the model. Similarly, metal based sintered objects produce very porous replicas and the remaining cavities have to be filled with other metallic alloys.

Since objects produced with gypsum-based materials present a sand-stone appearance, they are more suitable for CH contexts than the ones generated by FDM techniques, which are characterized by a plastic look and feel.

Photopolymerization. A last set of techniques is based on the selective polymerization of a liquid resin, operated by treating the resin with UV light. These approaches proceed layer by layer. The surface of the top-most layer of liquid resin is polymerized selectively by exposing it to UV light, either by a UV laser or by a digital projector. Similarly to FDM approaches these devices can work on a rather limited set of materials; from a geometric point of view, they still require support structures (even if in a more limited way given the nature of the material). On the other hand, such techniques are able to reach a very high precision and can be faster than other approaches (depending on the light curing approach used).

2.3. Conclusion on fabrication technologies.

Table 1 summarizes the fabrication technologies that we have just described and presents a qualitative evaluation, focusing on the following CH requirements and criteria:

- The *Cost* column refers to the overall cost of use. It is a qualitative evaluation that involves both the material cost and the operational cost. For example, CNC approaches have a rather low material cost, but the devices and the cost/time to operate them can be very high.
- The *Ease of use* column indicates how accessible is the technology to an average user (e.g. CH scholars or curators rather than computer technicians). This includes both the ease of use of the devices and their compatibility with a standard office. For example, currently, only FDM and some of the Photopolimerization devices are compatible with a standard work environment, while CNC machines and most of the Granular materials binding devices require industrial workspaces.
- The *Geometric Freedom* column reports how constrained are the devices in terms of the shape complexity of the models to be reproduced. For example, among additive technologies, only granular binding techniques do not require support structures and have minimal constraints.
- The *Material Adequacy to CH* column indicate in a very subjective manner, from our experience, how the reproduced products are perceived by generic CH scholars or curators. Each fabrication technology would get a very different response taking into account the *look and feel* of the reproduction. CH scholars consider the material, colour and texture as very important aspects of a reproduction. This is clearly not a solved issue in additive manufacturing technologies, since often FDM models have a quite "plastic-like" look, with the reproduction layers often quite visible. Therefore, FDM results usually make a worse impression than the granular, sandstone-like finishing of the gypsum binding devices. Even if, from a geo-

metric point of view, the precision of two different fabrication approaches is similar, the perceived quality can be quite different (Figure 2 and 4).

- The *Precision* column indicates how accurate will be the replica, in terms of geometrical accuracy. An indicator of the accuracy could be the printing resolution (i.e. the size of the smaller unit of material added by the device).

Figure 4: *Hand painting and accurate finishing can significantly improve the final appearance of a fabricated replica (head of the Arringatore statue, Archaeological Museum, Florence). The head on the right is in white resin printed by a Photopolymerization technique and painted to look as bronze; the one on the left is actually in bronze. Please note that the original patina of the Arringatore statue is more similar in color to the painted replica version that the new, bright bronze one.*

Orthogonal to all methods is the manufacturability issue, since the manufacturability of any possible shape of interest is an issue. Many aspects affect what can or cannot be printed using additive manufacturing technologies. New algorithms for the production of inner structures and support structures are required if we have to produce a replica of a complex shape (which is a common case in the CH domain). Similar problems emerge also for subtractive techniques, where the reproduction of very thin components (wire- or sheet-like) can create problems at the carving stage.

In conclusion, printing techniques are nowadays accurate enough to reproduce copies of tangible CH artworks, as we show in the following section on Applications. However, there are still many limitations that should be overcome to make these technologies more suitable to the specific requirements of the CH domain. We will expand the discussion of the issues mentioned above in Section 4.

3. Applications

3.1. Production of copies in any scale

The usual approach for producing replicas (e.g. molds and gypsum copies) was based on the *calco* approach (moulding). This method is now forbidden in several countries since it could severely affect the conservation status of the original artwork (since while we remove the rubber mold, we could peel off the patina or produce damages on fragile parts of the artwork). This opens a wide application space for digital fabrication in CH, since it is the only technical solution to produce high-quality copies ensuring safety of the artwork.

An example of a practical application has been performed in year 2007, and it is shown in Figure 1. The subject of the work was a marble head of Mecenate (conserved at the National Archaeological Museum, Arezzo, Italy). The German Research Ministry commissioned CNR-ISTI and the SME Scienzia Machinale (www.grupposcienziamachinale.com) the production of an accurate marble copy, to be used in the context of the German "Maecenas" research program. The customer wanted a marble copy of high quality, virtually indistinguishable from the original. This reproduction project was supervised by a prominent German archaeologist. 3D scanning was performed on the original artwork using a laser triangulation scanner, producing an extremely accurate and high resolution model. This digital model was the input for computing proper carving paths for a robotic drilling system, which was able to sculpt a marble block with great accuracy and repeatability. The carving process was executed by a succession of carving phases, each one executed with a progressively smaller carving cutter. With a final manual intervention for carving the finer details and polishing the surface, a very detailed 3D reproduction of the original artwork was obtained, which fulfilled completely the expectations of the customer.
Another example of reproduction of a sculpture with subtractive technology is reported in [TB07].

A peculiar example of reproduction in 1:1 scale was also the reproduction of a portion of a wall in Pompei covered by inscriptions, produced for a temporary exhibition (Ferrara Restauro 2004). The focus was to produce a high-quality replica, enhancing with colours the many hand-made Latin inscriptions in order to increase their readability. To reduce reproduction cost and weight, this reproduction has been done by using a 3D printing machine (additive technology, gypsum). The large model (270x330 cm) was divided in 125 tiles, each one printed on a ZCorp 3D printer. All those pieces have been mounted in correct position by means of a complex supporting structure (Figure 5). This work was a collaboration involving DIAPREM and CNR-ISTI [BCF*04].

Finally, fabrication technology was adopted in [LBM*13] to support the study of the very complicated structure of a small ivory Cantonese chess piece, which has been digitized

Figure 5: *The Pompei wall reproduction. Top: The supporting structure, finished and mounted, over which all the tiles have been glued. Middle: the re-assembled physical reproduction (1:1 scale) is hand-painted by a restorer, to make all engravings more evident and increase readability. Lower image: a small portion of the re-assembled physical reproduction*

using CT scanning and reproduced at a larger scale to make easier the visual analysis and the study of the artwork.

Digital fabrication of tangible 3D replicas can be used in several ways in CH:

- **Temporary or permanent replacement of originals.** A tangible replica can replace any artwork which has to be removed from its original position. The replacement can be temporary, for example when a museum lends an object for a temporary exhibition; or it can be permanent, for example when endangered statues are removed from a facade to protect them from further degradation caused by pollution. In this way, visitors can appreciate the artwork in its original location (note that from a medium distance, the difference between the original and the replica becomes imperceptible) and, at the same time, the original artwork can be protected and preserved.

Figure 6: *The reproduction (on the left) and the original Kafazani boat, by Cyprus Institute.*

- **Temporary loan of artworks for temporary exhibitions.** Reproductions are never the real object, since the real artworks has an aurea that any reproduction could possess. On the other hand, if the replica is an high-quality one, than it may fake most of museum visitors. The use of reproductions could reduce both the complexity of organisation and the cost (transport plus insurance) of temporary exhibitions, or could enrich significantly the permanent exposition of museums (this is an approach definitely accepted for museums exposing fossils, where usually most of the specimens showed are reproductions). A practical example is the reproduction of an archeological artefact (an ancient terracotta model of a boat) that was produced by the Cyprus Institute to avoid a complex loan for a temporary exposition ([HAIR10], see on the web at: http://exhibition.3d-coform.eu/?q=KazafaniSeminar).
- **Production of tailored packaging for shipping cultural objects.** Fabrication technologies can have a major impact on the creation of tailored packaging structures for storage or shipping of fragile CH artworks. In this domain the issues are: developing solutions that can produce a safer packaging (if compared with the usual solutions); reducing the overall cost (cost-effectiveness should be mostly evaluated as the cost for the design of the tailored packaging components and their fabrication cost, since we can assume that a 3D scanned model might be already available, or should be done in any case for insurance purposes - documentation of the conservation status before shipping).
  The design of a customized packing apparatus [GH06] can be done both by using standard 3D modelling systems or following recent research approaches, usually based

on milling technology. Milling solution are based on the idea of cutting an approximation of the artwork shape from a block of soft material (e.g. styrofoam or polyethylene foam). A rather different approach has been proposed in [MeSREK*12], where a wire-frame lattice structure is designed to tightly fit the artwork. An open issue in this domain is the use of multi-material fabrication devices which, hopefully, should allow to build supporting structures having a progressively softer behavior as far as we approach the artwork surface.
Finally, in order to have a real impact on the application domain, the proposed solutions should be automatic, since we cannot require a museum to invest in personnel with CAD or geometry processing skills just for managing packaging tasks.

- **Support visually-impaired people.** 3D replicas are an ideal support to allow visually impaired people to explore sculptures, artworks or even paintings [Zam13, RMP11] with their fingers, without harnessing the original [RNR*12]. This can be done in a simple and naive manner (just produce a tangible replica) or devising more sophisticated approaches (design/adopt methods that allow to enhance the perception of the shape detail over the surface of the replica).
- **Wide-scale production of accurate physical copies.** An interesting commercial application is the possibility to produce at affordable cost accurate small-scale replicas (e.g. for producing museums merchandising). This brings up several issues about copyright, opportunity and the level of quality that could be obtained with cheap reproduction technologies. On the other hand, merchandising is one of the few options for funding the activities of a museum or a CH institution; moreover, producing high quality and certified replicas could also be considered as part of the cultural mission of a museum (given the poor quality models that we see on many shops nearby our main cultural institutions, any effort in this sense will be beneficial).
- **Sensorized replicas in museums.** 3D replicas can be enhanced with different types of sensors to transform them into *active* replicas, for example to enable more rich interaction with the physical replica in the framework of a museum installation [Ple07, Too14]. This is a promising application domain, which is still in its infancy.

3.2. 3D printing to support restoration

3D printing technologies can contribute also to CH restoration methodologies. One direct application is the design and reproduction of the missing components of an artwork. Many artworks are discovered with important missing parts (e.g. arms or legs in archaeological sculptures). The design of a proper completion is an action that allows to better explain to the large public the original structure of the artwork. 3D technologies allow to model the missing parts and to produce them in a fast and accurate manner. A nice example is the reproduction and reversible installation of missing parts (the right arm and the left hand) on a statue by Antonio Canova [Uno13].

Another different use concerns the generation of support structures, usually needed in the reassembly of fragmented artworks. A recent example has been the restoration of the Madonna of Pietranico, a terracotta statue fragmented in several pieces due to the earthquake in Abruzzo [ASC*13]. The restoration of this artwork included a first phase where the fragments have been 3D scanned and a recombination hypothesis was built by working in the digital domain; and a second phase where the reassembly of the pieces was helped by the use of 3D printed supporting structures.
The recombination of the fragments was not possible by simply gluing them, due to the eroded fracture surfaces and the missing components. Moreover, structural properties should be considered while designing a proper holding structure (e.g. minimal visual impact, resistance to vibrations and transportation hazards).
The idea was that the support should be created by exploiting the cavities of the reassembled statue, printing in solid the shape of the internal cavity and to use this element to provide a rigid support to the fragments. Starting from the high-resolution 3D models of the reassembled fragments an innovative supporting structure was designed, which precisely fills the void space inside the body of the artwork (transformed into a physical object by 3D printing). The cavity in the back of the torso of the statue (see Figure 7) was modeled in the digital domain by starting from the surfaces of the fragments oriented towards the center of the bust.
This innovative method proved to be highly efficient, although the reassembly of the fragments over the support structure was not so easy as initially believed. The very rough surface of the internal void region of the terracotta made the design of the surface of the supporting structure not easy. A more sophisticated design approach would be required, that should take into account not only the shape of the pieces to hold, but also the possible self-intersections which can be created at the physical reassembly time. This could be an interesting algorithmic problem to investigate in future research.

3.3. Going beyond canonical reproduction: Creative applications

Digital fabrication technology is a powerful medium that can be exploited in many different ways, not only to represent the shape but also to contribute to entertainment or creative uses. We will explore some of these directions in this subsection.

Some methods have been designed to employ either cheaper materials and/or cheaper hardware devices. An example of the latter is to use widely available 2D cutting devices (very common in industrial applications); laser cutting machines have been used to reproduce/design and test ancient astrolabes [Zot08].

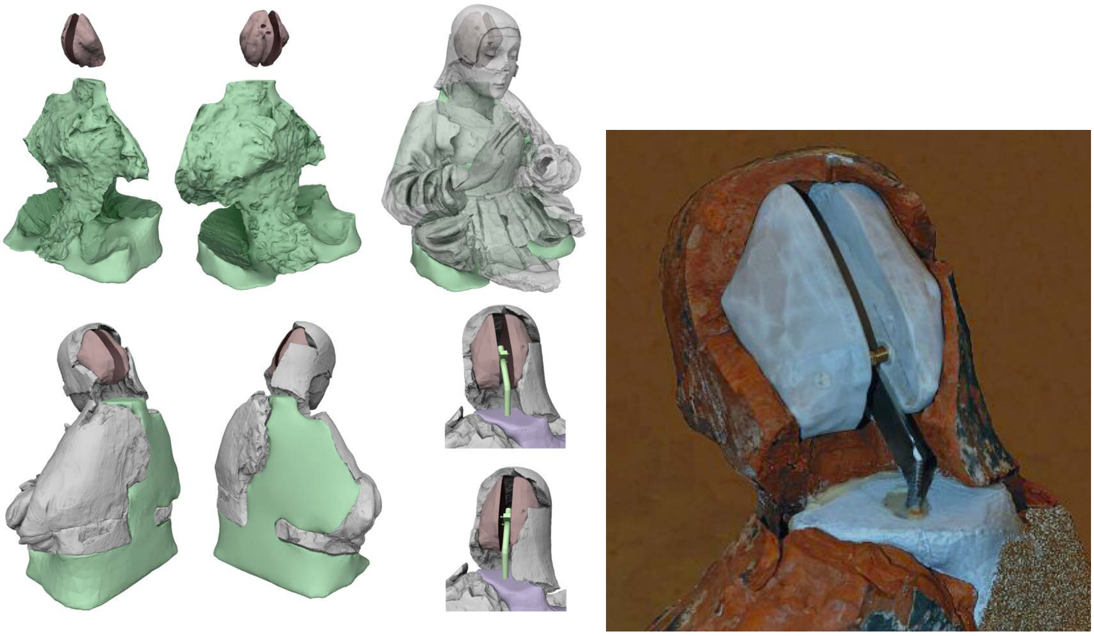

Figure 7: *The supporting elements produced to reassemble the Pietranico Madonna: the green component is the one used to fill up the chest, while the light brown is to hold in place the head of the statue (see image on the left); a photograph of the reassembled statue (shot from the back) is in the image on the right.*

Another approach aims to generate an approximate replica of the given object, exploiting cheap 2D materials and more simple printing techniques. Several methods [MS04, STL06, MGE07] reproduce the input model by means of a set of paper strips (or similar materials) which can be folded and glued together to create a 3D representation. Holroyd et al. [HBLM11] described a method to fabricate a three-dimensional shape through a stack of 2D colored slices. The use of planar material was exploited also by Hildebrand et al. [HBA12]; they proposed a method to semi-automatically fabricate objects made up of interlocking planar slices. This method produces a wide range of nice results, however it does not fit well with complex geometries and was extended to generate better approximation in [SP12, SP13, CPMR14].

In all the latter examples, fabrication technology is used to produce a set of pieces that, once mounted together, will give the creative replica. The mounting process becomes part of the experience and, hopefully, entertainment for the final purchaser of the replica. This type of reproduction technologies might be used for the production of museum merchandizing.

4. Issues and limitations

4.1. Going beyond the working space

Due to the limited workspace of most 3D fabrication technologies, replicas are usually very small. The working space of common 3D printers is between 15 and 40 cm (cubic volume size). This limitation severely restricts the usage of digital fabrication to small objects or to adopt very low reproduction scales. Many tangible cultural heritages (e.g. sculptures, low reliefs, buildings) have relevant size and printing them in a reduced scale may lead to a very inaccurate copy. Several details may eventually disappear or become very hard to perceive in the printed object if the printing scale becomes too small.

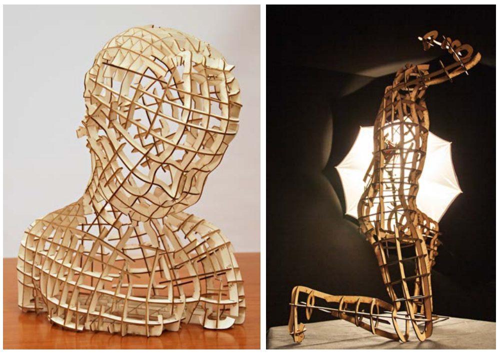

Figure 8: *An example of creative reproductions fabricated using a 2D cutting device [CPMR14].*

A solution could be to decompose the artwork in pieces, to widen the size of the resulting reproduction well beyond the working space of the fabrication device. This approach (where the decomposition was hand-made) was adopted to reproduce in 1:1 scale a large artwork [BCF*04].

Recently, an approach to overcome this limitation was proposed in the Chopper paper [LBRM12], which proposes a framework for the manual or semi-automatic decomposition of the original object into different components which are reproduced separately and then assembled and glued together (see Figure 9). The proposed framework includes a number of desirable criteria for designing the partition, including assemblability, having few components, unobtrusiveness of the seams, and structural soundness. Chopper optimise these criteria and generates a partition either automatically or with user guidance. The final decomposed parts include customized connectors on the adjoining interfaces.

Figure 9: *The Chopper approach, designed to overcome the working space limitations of current 3D printing technologies.*

A similar approach was proposed also in [ACP*14]. This work presents an algorithm for decomposing a 3D digital shape into a set of interlocking pieces that are easy to be manufactured and assembled. The pieces are designed so that they can be represented as a simple height field and, therefore, they can be manufactured by common 3D printers without the usage of supporting material. The decomposition of the input (high-resolution) triangular mesh is driven by a coarse polygonal base mesh (representing the target subdivision in pieces); the height fields defining each piece are generated by sampling distances along the normal of each face composing the base mesh. A innovative interlocking mechanism allows adjacent pieces to plug each other to compose the final shape. This interlocking mechanism is designed to preserve the height field property of the pieces and to provide a sufficient degree of grip to ensure the assembled structure shape to be compact and stable.

These types of approaches based on shape decomposition have ideal application in the CH domain. The specific constraint is that the replica should mask as much as possible the seams between the adjoined components (to ensure high visual quality of the reproduction). Therefore, the decomposition process should take into account the visual impact of the seams.

4.2. Improving the quality of the output

Current generation of 3D printers still present some limitations in terms of geometric precision of the generated shapes. Even if the size of the minimal portion of material layered by the printing devices reduced in size (current technologies allow to lay down layers whose thickness is in the order of 1/10 mm), when we observe a reproduction we are still able to see the single layers. This aliasing effect could be reduced by treating the replica (e.g. sanding its surface), but this process is time consuming and could also reduce the quality of the reproduction if not implemented correctly (by sanding off important small scale details).

A different solution could be to optimize the orientation of the replica to reduce as much as possible the layered effect on the main surfaces (since this effect is more visible on all the large, nearly-planar sections of the shape).

Another issue is the minimal thickness of layers and therefore the minimal size of the detail that can be reproduced and perceived. Moreover, some peculiar optical and physical properties of the reproduction material(s) used might reduce the perceptual quality of the replicas (e.g. translucent plastic). This issue could be reduced by adopting shape enhancement approaches which allows users to increase readability of the tiniest details in physical replicas, for example by exploiting the color reproduction capabilities of some 3D printers. An example is the approach proposed in [CGPS08], which overcomes the perception problems due to an optical property (sub-surface scattering), by exploiting color reproduction capabilities of some 3D printers. In particular, this approach carefully pre-compute an ad hoc surface shading, to color the surface of the replica in order to enhance the perception of its geometric shape once it has been printed (see Figure 10). Therefore, this approach allows to counterbalance the sub-surface scattering (SSS) effects that hinder the perception of fine surface details.

Figure 10: *The colour-enhancing technique: a comparison between the plain replica (left) and the version with colour enhancement (right).*

However, in many cases an approach based only on color enhancing is not sufficient. For instance, even though printers claim sub-millimetric resolution, the real, printed geometry is often affected by the physical properties of the material used, that might drastically worsen the surface resolution and decrease detail perception in the replica. A geometry enhancement technique was presented in [PGCS10]; it counterbalances the effects due to the not ideal behavior of the materials used in the printing process, increasing physical replicas quality in terms of visual and tactile perception and detail preservation. The method is based on a volumetric representation of the geometry. The main idea of the approach is to simulate on this volume the physical behavior of the printer, to compare the result to the original geometry, and to modify the input data in order to reduce the difference between original model and printed one.

Finally, the amount of *internal volume* of the replica has an impact on cost and time or reproduction. Some approaches have been proposed for the construction of internal filling structures that replace the naive solid interior with a structure (usually based on segments or sheets) that ensure the rigidity of the replica and, at the same time, reduce its weight and the consumption of reproduction material (e.g. see [MeSREA13]).

4.3. Improving the reproduction of color or of specific surface reflection properties

The visual accuracy of the reproduction is a key element in many CH applications, e.g. when restorers want to experiment and propose hypotheses about the original colours of a statue or of an architectural decoration. A few 3D printing devices are able to produce coloured replicas, but the quality of the result is still not sufficient for the very demanding requirements of CH applications.

Therefore, colouring of reproductions is usually made manually to obtain good quality results (by an accurate selection of color tints and of the layout of color). This peculiar application might help restorers or art scholars in their practical work, with the possibility to produce and compare several hypotheses. But using a manual approach has several disadvantages: quality will depend on the skill and time of the operator, accuracy is subjective; cost could be higher than those required by plain 3D fabrication; mass production becomes a problem. Therefore, any significant improvement in the color reproduction features of available technology could be really beneficial for CH applications.

Some recent research efforts have considered the specific problem of producing approximations of specific surface reflection properties [WPMR09, RBK*09]. But these approaches should be still developed further to reach the level of visual quality and accuracy required by CH applications.

4.4. Reducing the reproduction cost

One major defect of *Free 6-Axis Carving* approach is the reproduction cost, that depends linearly with: (a) the time required to define the required path for the milling instrument and (b) the time required to produce the replica (i.e. how long the usually expensive milling machine will be busy). The second component is usually not easy to reduce, unless new and lower cost 6-Axis Carving instruments will appear on the market. The first component is quite expensive since usually the shape of a CH artwork is quite complex and the design of the milling path is still mostly driven by a human operator, using CAD tools. This is acceptable in industrial applications, where usually the operator designs an optimal path and than the same path is reused thousands of times, e.g. for the medium or large scale productions of a mechanical component. Conversely, the case of CH reproductions is usually based on the request of producing either a single or a few high-quality copies; therefore, the incidence of the milling path design cannot be shared on a large number of copies and it becomes an important fraction of the overall reproduction cost. Any improvement in geometric processing technologies (e.g. making the milling path design a completely automatic task) would have a considerable impact on the usage cost of this reproduction technology.

5. Conclusions

Digital fabrication technology is a wide domain, using a variety of basic technologies and enabling curators, scholars and researchers to create accurate physical reproductions out of 3D digital models. Even though current 3D printing technologies still suffers of several restrictions, the accuracy of the reproduction has gradually reached an excellent level of quality. We have shown various successful applications of 3D printing in the Cultural Heritage domain, making digital fabrication an enabling technology that opens new possibilities for study and fruition of CH assets. On our opinion, this domain shows also an interesting potential for future research on geometry processing, motivated by the specific needs of CH applications.

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