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Digital Fabrication Techniques for Cultural Heritage: A Survey

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Abstract

Digital fabrication devices exploit basic technologies in order to create tangible reproductions of 3D digital models. Although current 3D printing pipelines still suffer from several restrictions, accuracy in reproduction has reached an excellent level. The manufacturing industry has been the main domain of 3D printing applications over the last decade. Digital fabrication techniques have also been demonstrated to be effective in many other contexts, including the consumer domain. The Cultural Heritage is one of the new application contexts and is an ideal domain to test the flexibility and quality of this new technology. This survey overviews the various fabrication technologies, discussing their strengths, limitations, and costs. Various successful uses of 3D printing in the Cultural Heritage are analysed, which should also be useful for other application contexts. We review works that have attempted to extend fabrication technologies in order to deal with the specific issues in the use of digital fabrication in the Cultural Heritage. Finally, we also propose areas for future research.

Categories and Subject Descriptors (according to ACM CCS): I.3.8 [Computer Graphics]: Applications—I.3.5 [Computer Graphics]: Computational Geometry and Object Modeling—

1. Introduction

Industrial prototyping aims to create a tangible representation of the abstract concept of an arbitrarily complex object. The starting point is usually the design of a digital 3D model, often using CAD tools. Most traditional industrial fabrication techniques (like casting, injection moulding or milling) are affordable for medium or large scale productions. This process is usually specifically tuned for a given object and is expensive to set up. The more complex the shape of the object, the more complex the manufacturing process will be. Clearly, implementing such a process to create a single (or a few) prototype(s) is an inefficient approach.

To deal with these specific industrial needs, fabrication devices have been created for the small scale production of arbitrary shapes. This class of technologies is usually referred to as *digital fabrication* or *3D printing*. These terms refer to any processes for producing/printing a three-dimensional object, which is usually robotized in some way. The main advantage of *3D printing* techniques is that the manufacturing process is independent of the geometric complexity of the digital shape.

This characteristic is, in general, not true for large scale industrial production pipelines. Indeed, *3D printing* techniques are not used for large scale industrial production. However, *3D printing* is able to produce prototypes in a reduced amount of time (thus the origin of the term *rapid prototyping*).

Originally, 3D printing devices were too expensive for the mass market, however cheap 3D printers are now available thus widening the potential applications. Each digital fabrication technology is mainly characterised by the basic physical process used to produce the tangible representation. Because of the physical constraints involved in the process, each technology can only employ a subset of possible materials (plastic, glued gypsum, steel, ceramic, stone, wood, etc.). Thanks to the increase in accuracy of current technologies and the reduction in reproduction costs, digital fabrication has been applied in many new contexts, for example in the reproduction of artworks for museum exhibitions or to support Cultural Heritage (CH) scholars or restoration.

The traditional reproduction approach for CH required the production of rubber molds over the original artworks, which were then used for the subsequent production of gypsum or resin copies. However this process is manual, time consuming, and strongly influenced by the complexity of the input shape. It also means that the reproduction has to be an exact 1:1 copy of the input shape.

3D printing provides more flexibility. For example, the digital representation can be edited before producing it as a physical object. It can thus be scaled or changed in shape or just selected portions of the object can be printed. Therefore, digital fabrication can considerably enhance the information provided by a tangible representation of a CH artefact.

In this survey we present the potential and large spectrum of applications of fabrication technologies in the CH. The paper is organized into three parts: first, a brief characterization of the most common *digital fabrication technologies* is presented in Section 2. A review of the *applications* of 3D printing on CH testbeds is presented in Section 3, considering both applications already presented in literature and some suggestions for new uses. Finally, the major issues concerning its wider use in the CH are presented in Section 4.

2. Overview of digital fabrication technologies

Digital fabrication techniques can be divided in two main classes: *subtractive* and *additive* processes. The former have been widely used for industrial applications since the late 1980s, while the latter have 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 a computer-controlled milling tool (CNC machinery). The main advantage is the wide range of reproduction materials available. Milling machines can operate on almost any kind of material, such as wood, stone and metal. This is a strong advantage if fabrication techniques are used to create physical copies of existing artifacts as accurately as possible. See Figure 1 for an example of the use of this approach in the CH. CNC milling machines also provide a very large workspace, which is usually sufficient for the creation of 1:1 replicas of life-size statues.

However, most CNC milling machines have a wide number of geometric and kinematic constraints that significantly reduce the domain of application. In practice, driving the carving head of a milling machine is a very complex problem and the features and functionality of the available devices varies considerably. The most common and economic devices are able to carve bas-reliefs (2.5D). However they impose limitations on the size of holes and cuts depending on the size of the drilling tool.

Less sophisticated 2D cutting machines are another class of devices that could be used to produce replicas. These tools

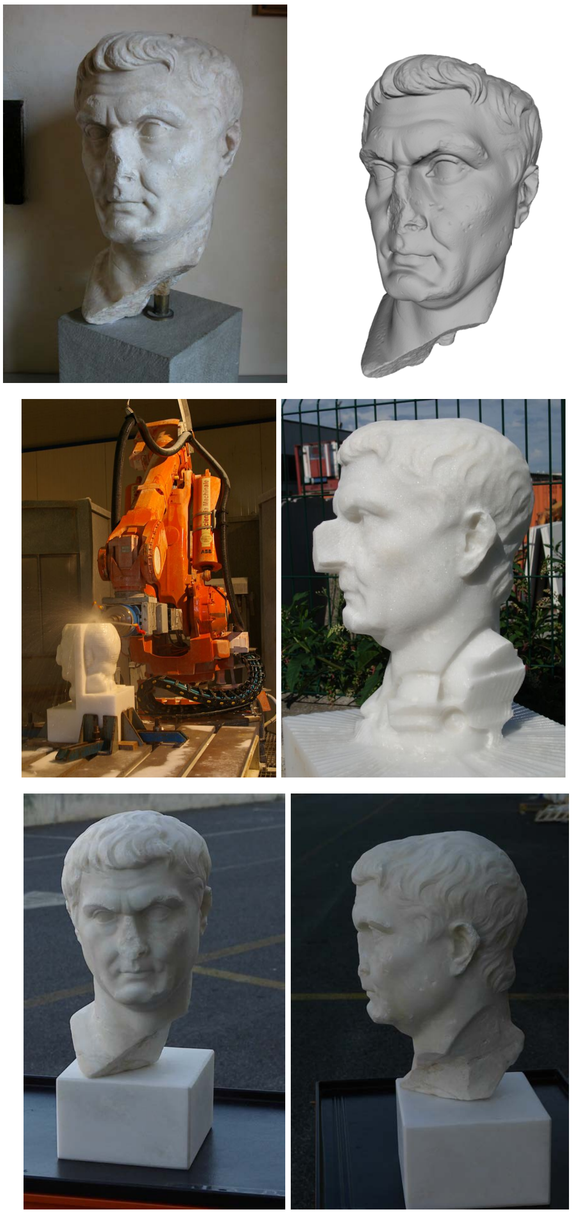

Figure 1: *An example of a rapid prototyping project, developed by CNR-ISTI in collaboration with* Scienzia Machinale. *First row: the original artwork; the digital 3D model obtained using a laser triangulation scanner. Second row: the prototyping machine in action; the reproduction at the end of the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

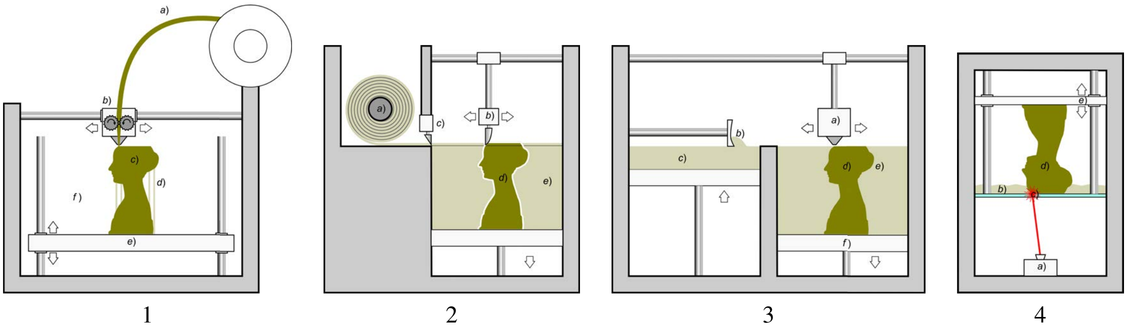

Figure 2: *The four main additive fabrication technologies described in section 2.2; from left: Fused Deposition Modelling, Laminated Object Manufacturing, Granular Binding, and Photopolymerization*

can cut sheets of a variety of materials (e.g. cardboard, ABS, plywood). Although 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 Figure 12).

There are also 6-axis CNC machines that allow more degrees of freedom and are able to rotate the drill all around the object. However, they have physical limitations due to the movement of the drilling tool and are quite complex to operate. The design of the tool path is also a time-consuming operator-assisted phase, which increases the cost of these types of reproductions.

While subtractive techniques have been on the market since the early 1980s, the limitations listed above have prevented them from gaining widespread use. Milling machines have tended to be used either in simple cases (such as the production of bas-reliefs) or to very specific projects with limitations on the number of different materials that can be used for the reproduction.

2.2. Additive Techniques

The last ten years have seen the rise of low cost 3D printing devices, which are moderately simple to use with a low operating cost. The vast majority of these devices are based on the additive approach. Figure 2 shows the four main additive technologies.

Fused Deposition Modelling (FDM). In FDM devices (Figure 2.1), a thin filament of plastic (*a*) is melted in a extruding head (*b*) and deposited to build the desired shape (*c*) slice by slice on a moving platform (*e*) . This approach only requires fairly simple mechanics (very similar to the printing head of a 2D printer). Therefore, this class of devices is the cheapest on the market with prices ranging from a few hundred euros to two or three thousand. The quality of the results, however, varies considerably (Figure 3). Various parameters may significantly affect the final result. First of all, the material used is, in most cases, a single kind of plastic (usually ABS or PLA). These materials give 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. One solution is to sand and smooth the surface with a primer/filler and then possibly paint it, however this makes the whole process much less automatic and straightforward.

Figure 3: *Two small buddhas fabricated in ABS using two different FDM machines. Given the limited size of the objects, the layer structure is quite evident. Note that, depending on the appearance properties of the material, the small scale details and the printing artefacts can be evident to a greater or a lesser extent.*

From an appearance point of view, some of the more advanced devices offer the possibility of using simultaneously a few different materials (usually limited to just two different materials, allowing very limited colorisation processes). From a purely geometrical point of view, the main constraint is that the deposition strategy of FDM precludes strong overhangs, therefore all the significantly protruding parts must be supported by adequate scaffolding (*d*). This scaffolding has

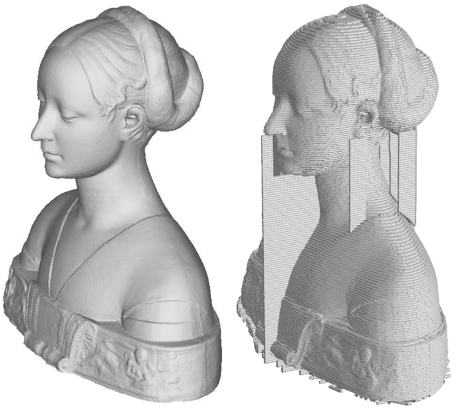

Figure 4: *Using the FDM approach, printing involves the previous automatic conversion of the 3D model (left) into an approximation composed of the extruded filament (right). This process also includes the creation of vertical columns to support the most protruding parts of the model (such as the chin, nose, ears and hairs of the bust in this figure).*

to be printed together with the object (Figure 4). While scaffolding is automatically generated by the software driving the printer, removing it may be problematic for complex and intricate shapes. Some of the more advanced devices build supporting structures using a water-soluble plastic, which eliminates the tedious manual process of removing the supporting structure.

FDM is not the only additive technique on the market. At least three other techniques are worth mentioning: *Laminated object manufacturing*, *granular materials binding* and *photopolymerization*. These approaches work *layer by layer*, building the object replica one sheet after the other.

Laminated object manufacturing (LOM). This additive approach (Figure 2.2) is based on the idea of cutting out with a blade (*b*) slices of the object to be fabricated from sheets or a roll (*a*) of raw material and glue/join them one on top of the other. At the end of the process the fabricated object (*d*) is embedded in the raw material (*e*). Different materials can be employed like paper, plastic, or metal. If paper is used, color can be added in the process. The cutting and glueing process may impose several geometric constraints, particularly because of the removal of the rigid unused material that surrounds the fabricated object. A notable aspect of LOM technologies is the extremely low cost of the basic material.

Granular materials binding (GMB). This technique (Figure 2.3) is based on very small particles (*c*) that are uniformly deposited (*b*) layer by layer on a descending platform (*f*); at each step the topmost layer is selectively aggregated by a dedicated moving head (*a*). One common approach 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) using an inkjet printer head. This approach also enables colours to be added in the printing process. Although the shades of color and levels of saturation are fewer than in traditional 2D colour printers, this approach is the only one that produces coloured replicas.

Other material binding technologies include resin gels and a polymerizing agent that solidifies the gel. Alternatively, a laser heat source can be used to drive a sintering process (solidification without melting) over metal or plastic powders (a technique known as *Selective Laser Sintering, SLS*). The main advantage of all these techniques is that the unbound granular material (*e*) remains together with the bound material and provides the necessary support for all the overhanging structures (*d*). These techniques offers the widest liberty in terms of geometric complexity of the printed shapes, in fact the only main geometric constraints are minimal thickness of the generated object and the fact that there are no enclosed volumes where the unbinded material could remain trapped. On the other hand, for most material/binder pairs, the model is not ready at the end of the printing process, since the binding component is not usually sufficient to create a robust object which thus needs to be treated to make it robust. For example, gypsum-based devices need the reproduction to be soaked with a cyanoacrylate-based binder to 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 have a sandstone appearance, they are more suitable for CH contexts than objects generated by FDM techniques, which are characterized by a plastic look and feel. Unfortunately, this class of devices is also among the less accessible in terms of hardware costs. There are a few companies offering this technology with prices ranging from a few thousand Euros up to hundred thousand Euros.

Photopolymerization. Photopolymerization is the selective polymerization of a liquid resin (Figure 2.4), operated by treating the resin with UV light. These approaches proceed layer by layer. The surface of the bottom most layer of liquid resin (*b*) is selectively polymerized (*c*) by exposing it to UV light, either by a UV laser or by a digital projector (*a*). A moving platform (*e*) raises the already solidified resin (*d*). As in FDM approaches, these devices can only work on a limited set of materials. Moreover they still require support structures (although in a less restrictive way way, given the nature of the material). However FDM techniques are very precise, and fabrication can be faster than other approaches (depending on the light curing approach used).

This class of devices was usually among the most expensive. In the last years, two different companies have introduced low cost devices in the range of a few thousand euros.

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

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.*

However, the operating cost of these devices is still higher than FDM, both in terms of raw material costs and complexity of the procedure. Advanced techniques [LSZ*14] has been developed to reduce the printed volume while preserving the physical robustness of the object.

2.3. Conclusion regarding fabrication technologies.

Table 1 summarizes the fabrication technologies that we described and presents a brief qualitative evaluation. This table is based on our personal direct experience. We have tested, by servicing or by direct owning all the discussed technologies. Specifically, it focuses 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 costs and the operational costs. For example, CNC approaches have a low cost in terms of materials, but the devices and the cost/time to operate them can be very high.
- The *Ease of use* column indicates how accessible the technology is for the average user (e.g. CH scholars or curators rather than computer technicians). This includes both the ease of using the devices and their compatibility with a standard office. For example, currently, only FDM and some of the photopolymerization devices are compatible with a standard work environment, while CNC machines and most of the granular material binding devices require industrial workspaces.
- The *Geometric Freedom* column reports how constrained the devices are in terms of the shape complexity of the models to be reproduced. For example, of the additive technologies, only granular binding techniques do not require support structures and have minimal constraints.
- The *Material Adequacy to CH* column indicates how the reproduced products are perceived by generic CH users. Each fabrication technology will receive a very different response depending on the *look and feel* of the reproduction. CH practitioners consider the material, color and texture as very important aspects of a reproduction. Additive techniques usually produce models with a quite "plastic-like" look, with visible reproduction layers. Other techniques, like gypsum binding, produces sandstone-like models which are more suitable for CH venue. Even if, from a geometric point of view, the precision of two different fabrication approaches is similar, the perceived quality can be quite different (see Figure 3 and 5). Moreover, if replicas have to be shown to the public (e.g. in a museum), robustness and cleaning possibility are two other important factors. This is clearly not a solved issue in additive manufacturing technologies.
- The *Precision* column indicates how accurate the replica will be, in terms of geometrical accuracy. An indicator of the accuracy could be the printing resolution (i.e. the size of the smallest unit of material added by the device).
- The *Working Size* column indicates approximately the size of the working space of the most common devices for each technologies. Given the wide range of different devices for each technology, we have just indicated the order of magnitude. In many cases, these limits have been overridden by specially constructed devices; for example there are special photopolymerization devices that are able to build up to two meters length objects.

Every fabrication technique has its specific manufacturability issue. If we have to produce a replica of a complex shape (which is a common case in the CH domain) some fabrication technologies may require the creation of an internal support structure. Similar manufacturing 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 currently 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 re-

Figure 5: *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 like ancient bronze; the one on the left is actually in bronze. Note that the original patina of the Arringatore statue is more similar in color to the painted replica version than the new, bright bronze replica.*

quirements of the CH domain. We will expand the discussion on these issues in Section 4.

3. Applications

3D fabrication technologies are becoming a major resource for many applications. Cultural Heritage (CH) represents a challenging domain of use. A wide range of 3D fabrication technologies has been tested in CH. Previous surveys have focused mainly on the technical details of acquisition and production [TB11] or on applications in museum contexts [NRRK14]. This section is intended to provide a broader perspective of the possible applications, outlining their impact in several CH subfields, such as restoration, education, creativity and dissemination.

3.1. Production of copies in any scale

Replicas of artworks (e.g. molds and gypsum copies) used to be typically produced using the *calco* approach (moulding) [DF04]. This method has now been banned in several countries since it can severely affect the conservation status of the original artwork (while removing the rubber mold the patina may also be peeled damaging fragile parts of the artwork). This opens up a wide application space for digital fabrication in CH, since it is the only technical solution to produce high-quality copies keeping the artwork safe.

An example of a practical application was performed in 2007, and 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) to produce 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 project was supervised by an archeologist. 3D laser scanning was used to gather an extremely accurate digital representation on the original artwork. This digital model was the input for computing appropriate carving paths for a robotic milling system which has been used to sculpt a marble block. At the end of the carving process a final manual intervention has been performed to carve the finer details (such as recreating the fractured nose by actually breaking it) and polishing the surface; as a result a very detailed 3D reproduction of the original artwork was obtained, which completely fulfilled the expectations of the customer. Another example of the reproduction of a sculpture with subtractive technology is reported by Tucci et al. [TB07].

An interesting case of fabrication in a different scale was the reproduction of the very small cylinder seal of Ibni-Sharrum, a Mesopotamian artefact considered as one of the absolute masterpieces of glyptic art [PCMA08]. This 4cm high seal was digitally acquired at the C2RMF (the French restoration institution) at a very high resolution using a variety of 3D scanning techniques (microprofilometry, x-ray tomography, photogrammetric techniques). The scanned model was used to create an accurate virtual unrolling of the seal, i.e. an inverse shape is obtained when the seal is rolled over a soft substance like clay or wax. In order to present the fine details of the ancient seal in a particularly appealing way, this digital unrolled model was physically reproduced at a 50:1 scale, generating a 4 meters long replica and shown in a temporary exhibition at Louvre (see Figure 7).

A particular example of a reproduction in 1:1 scale was also a portion of a wall in Pompei covered in inscriptions, produced for a temporary exhibition (Ferrara Restauro 2004). The aim was to produce a high-quality replica, enhancing the many Latin inscriptions with colours in order to increase their readability. To reduce the reproduction cost and weight, a 3D additive printing machine (glued gypsum powder) was used. The large model (270 × 330 cm) was divided into 125 tiles, each one printed on a ZCorp 3D printer. All these pieces were mounted correctly using a complex supporting structure (see Figure 6). This work was a collaboration involving DIAPREM and CNR-ISTI [BCF*04].

The production of *architectural models* or *maquettes*, especially in the architectural field, is still quite common. The reproduction of low-scale architectural models for museums can take advantage of digital fabrication techniques to allows novel interaction paradigms [GPH13], such as projections onto the surface of the model, hybrid video-physical models and sensorized models.

Figure 6: *The Pompei wall reproduction. Top: The supporting structure, finished and mounted, over which all the tiles were glued. Middle: the re-assembled physical reproduction (1:1 scale) is hand-painted by a restorer, to make all the engravings more evident and increase readability. Lower image: a small portion of the re-assembled physical reproduction*

Additive fabrication technology (plastic sintering) has been adopted by Laycock at al [LBM*13] to support the study of a Cantonese chess piece (a few cm tall) with a complicated structure. It has been digitized using CT scanning and reproduced at a larger scale to make easier the visual analysis and the study of the artwork.

Figure 7: *The reproduction of the cylinder seal of Ibni-Sharrum. Top left: The original seal. Top right: the fabricated large scale unrolled model. Bottom: a rendering of the unrolled model used for the reproduction.*

3.2. Applications of fabricated replicas in CH

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

Supporting visually-impaired people. 3D replicas are an ideal support to allow visually impaired people to explore sculptures or artworks with their fingers, without getting in direct contact with the original [RNR*12]. This can be done by simply producing a touchable replica or by designing/adopting methods that enhance the perception of the shape detail over the surface of the replica). Interesting methodologies have been designed to also transform paintings [RMP11, VRV14] or photographs [NR13] into 3D models (see Figure 8) which can be experienced by visually-impaired people by physical replicas [NRRK14]. The use of colored relief printing technologies can be effective to implement these approaches [EZV*14] . The tactile power of a replica is not just limited to visually-impaired people: it can also be a valuable resource for children or other visitors of a museum, since touching is one of our main approaches for experimenting, understanding and enjoying the external world [NRRK14]. In this sense, 3D replicas can go beyond the current visual-based perception mode to richer multi-sensory experiences.

Figure 8: *A painting, Raphael, Madonna of the Meadow (Kunsthistorisches Museum, Vienna, ©KHM-Museumsverband), can be converted into a 3D relief, which can be fabricated and experienced by visually impaired people [RMP11].*

Temporary or permanent replacement of originals. A tangible replica can replace any artwork that needs to be removed from its original location. The replacement may be temporary, for example when a museum lends an object for a temporary exhibition, or 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. While this represents a big potential for museums, the issue of "cheating" the visitor with a copy must be taken into account. A solution proposed by curators is to keep the copy together with the original.

Figure 9: *The reproduction (on the left) and the original Kafazani boat, by the Cyprus Institute.*

Temporary loan of artworks for temporary exhibitions. Reproductions are never the real objects, since the real artworks have an aura that no reproduction could possess. On the other hand, high-quality replicas can provide a detailed idea of the original object. The use of reproductions could reduce both the practical issues and the overall cost (transport plus insurance) of temporary exhibitions. A digitally fabricated reproduction could significantly enrich permanent museums (this approach has been used especially for museums exposing fossils, where usually most of the specimens on display are digital reproductions).

A practical example is the reproduction of an archeological artefact (an ancient terracotta model of a boat) shown in Figure 9. This replica was produced by the Cyprus Institute [HAIR10] to avoid a loan for a temporary exhibition (see on the web at: `http://exhibition.3d-coform.eu/?q=KazafaniSeminar`). It was obtained with a 3D printer (glued gypsum), which was chromatically characterised by a restorer (he painted the gypsum surface in order to produce a similar surface to the ancient terracotta).

Production of tailored packaging for shipping or displaying cultural objects. Fabrication technologies can have a major impact on the creation of tailored packaging or support structures for storage, shipping or displaying fragile CH artworks. It also reduces the manipulation of fragile artworks, since the usual trial and error manual process (take measurements of the artwork, produce the packaging, test if the artwork fits well, modify the package, check again, ...) is replaced by a computer-driven process that starts from an input digital 3D model and automatically produces an customized supporting structure. In this domain the main issue is developing a novel solution that can produce a safer packaging at a lower cost.

A customized packing apparatus [GH06] can be designed using standard 3D modelling systems or following recent research approaches, usually based on milling technologies. Milling solutions 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). Recently, Sanchez and colleagues [SBVVSL*15] proposed an algorithm for semi-automatic production of customised housing for artifacts using CNC milling machine. The adoption of a milling technology allows to choose the reproduction material (softness, chemical composition) which better fits the characteristics of the artwork to be protected. The algorithm computes an optimal pose for the artwork (the one that maximises the contact surface and the perpendicularity of the contact surface normal wrt. the box base plane); then produces the CNC milling path that allows to cut the material and to produce a fitting cavity.

A different approach designs wire-frame lattices [MeSREK*12] to tightly fit around the artworks (see Figure 10). The lattice is produced using additive fabrication. An open issue in this domain is the use of printing devices offering *multi-materials*, which hopefully, should build supporting structures with very soft elements near to the artwork surface.

Regarding objects displayed in museums, another methodology is devoted to the design and printing of support mounts for antique fans [Bri12]. The mounts were designed not only to support the object, but also to provide an optimal display.

Finally, in order to have a real impact on the application domain, the proposed solutions should be automatic, since a museum cannot invest in personnel with CAD or geometry processing skills to oversee packaging.

Figure 10: *An example of a wire-frame lattice structure designed and produced to tightly fit around the shape of the artwork, for packaging and transport.*

Education and experimentation in museums. Science museums tend to be the only museums where visitors have the opportunity to see, touch, and try out objects. In science museums digital fabrication is already becoming a standard. Fabrication technologies open up possibilities for even more complex types of objects. The impact is not limited to museums, but could also affect schools, universities and researchers. A repository of printable content for teaching purposes, which could also be in museums to enhance visits, has been proposed by Knapp et al [KWL08]. Cornell University started a project focusing on 3D printing cuneiform tablets, to enable students and scholars to access and manipulate their archive of cuneiform tables [KWL08,Cor14]. The availability of excellent quality copies protects the originals and enables visitors to study these archaeological assets.

As an interesting didactical application, we also remember the study of moulding techniques [HR13], and the creation of working copies of astrolabes using laser cutting [Zot08].

Large-scale production of accurate physical copies. An interesting commercial application is the production of accurate small-scale replicas at an *affordable cost* (e.g. for museum merchandising). This raises several issues regarding copyright, and the level of quality that could be obtained with low-cost reproduction technologies. On the other hand, merchandising is one of the few options for funding the activities of a museum or a CH institution. In addition, producing high quality and certified replicas could also be considered as part of the cultural mission of a museum, especially in relation to the poor quality models in tourist shops. The availability of 3D models already prepared for 3D printing may also have an important role in education; see the example already mentioned [KWL08], in terms of a repository of printable content for teaching models, which could also be used in museums to enhance visits.

Sensorized replicas in museums. 3D replicas can be enhanced with different types of sensors to transform them into *active* replicas, for example to facilitate richer interactions in museum installation [Ple07,Too14,LWNG05]. The physical replica could become part of a more complex installation, enabling the use of multi-sensory access to the artwork and to the related knowledge, using multiple communication channels. This is a promising application domain, still in its infancy, which could be stimulated by the availability of low-cost sensors inserted or fabricated in the replica.

3.3. Digital fabrication to support restoration

Digital fabrication technologies can also contribute to CH restoration methodologies. Many artworks are discovered with important missing parts (e.g. arms or legs in archaeological sculptures). The design of the right completion would help to better explain to the public the original structure of the artwork. Hence, 3D technologies could model the missing parts and produce them in a fast and accurate manner. An example is the reproduction and reversible installation of missing parts (the right arm and the left hand) on a statue by Antonio Canova [Uno13].

An even simpler example is the completion of vessels or vases, which has been already explored in the literature for "virtual" reconstructions: digital fabrication can be used to create the missing parts, and possibly show the entire object [ACM*11]. The usual incompleteness of pre-historic skulls has also been recovered using 3D technologies, since the missing parts can be modelled and fabricated using similar examples [FDCP*08].

Digital fabrication technologies can also be used to generate support structures, usually needed in the reassembly of fragmented artworks. The Madonna of Pietranico, a terracotta statue, was fragmented in several pieces due to the earthquake in Abruzzo [ASC*13]. The restoration of this artwork included a first phase where the fragments were 3D scanned and a recombination hypothesis was

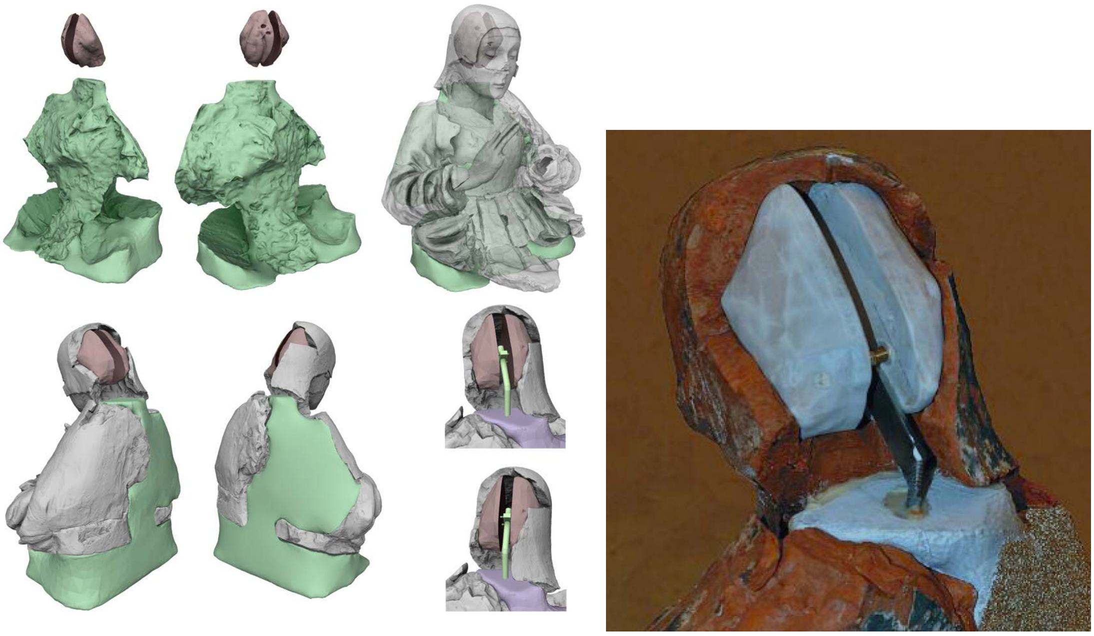

Figure 11: *The supporting elements produced to reassemble the Pietranico Madonna: the green component is used to fill up the chest, while the light brown holds the head of the statue in place (see image on the left); a photograph of the reassembled statue (shot from the back) is in the image on the right.*

built by working in the digital domain. The pieces were then reassembled through the use of 3D printed supporting structures.

The recombination of the fragments was not possible by simply gluing them back together, due to the eroded fracture surfaces and the missing components. Structural properties also need to be considered while designing the holding structure (e.g. minimal visual impact, resistance to vibrations and transportation hazards).

The idea was that the support could be created by exploiting the cavities of the reassembled statue, printing the shape of the internal cavity and then using 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 hollow 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 11) 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 as 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 difficult. A more sophisticated design is needed, which should take into account not only the shape of the pieces, but also the possible self-intersections which can be created at point of the physical reassembly [ASC*13]. This could be an interesting algorithmic problem to investigate in future research.

Similarly, digital fabrication techniques were also used to create full size replicas fragments and for assembly testing for the case of the restoration of the unfortunate shattering of the Tullio Lombardo's Adam [RMW*14],

Digital fabrication can also have an impact in virtual restoration projects. Any time the original status of an artwork is reconstructed , the results could be disseminated to experts or to the public either in a visual or physical format. A virtual restoration application that is heavily based on digital fabrication is the reconstruction of the facial appearance from bone remains. In many cases, facial reconstruction is performed by experts by first producing a digital model of the skull, then 3D printing it and finally working with wax on the printed skull, reproducing the shape of soft tissue and skin appearance [CMG*04].

3.4. Illustrative fabrication methods

Various radically new paradigms for shape fabrication have been proposed [MS04, STL06, MGE07, LSH*10, MI07]. The main idea of these approaches is to drastically simplify the overall printing procedure by fabricating a plausible representation of the digital model, instead of its exact copy. This class of methods relies on a simple concept: approximating an object does not necessarily lead to a visual or comprehension deficit. We refer to this class as *illustrative methods*.

Illustrative methods are generally designed to employ materials and devices that are very popular and inexpensive, often without requiring sophisticated fabrication devices. Several methods [MS04, STL06, MGE07] reproduce the input model by a set of paper strips (or similar materials) which can be folded and glued together to create a 3D representation. Mori and colleagues [MI07] proposed a sketching interface to design plush toys. Other techniques [LSH*10, LJGH11] put forward a strategy to automatically fabricate pop-up models made of paper. More recent methods include inflatable structures [STK*14] and Burr puzzles [XLF*11].

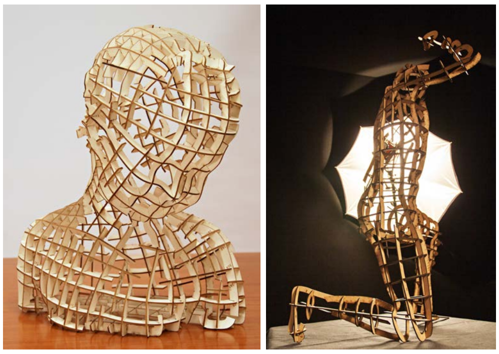

Figure 12: *An example of creative reproductions fabricated using a 2D cutting device [CPMR14].*

Other approaches reach a sufficiently high level of approximation by building an abstraction of the input shape, based on interlocking planar slides. The interest in these technologies is testified by the recent release of software tools devoted to planar slice fabrication (such as Autodesk 123DMake [Aut13]) and the number of inexpensive, accessible, servicing companies that provide support for the fabrication process. The first methods for generation of slice-based approximations [MSM11, HBA12] was recently extended [SP12, SP13, CPMR14] enabling more degrees of freedom in slice placing, thus producing more sophisticated representations (as shown in Figure 12). These methods are capable of arranging planar slices in a visually appealing manner, by capturing the overall structure of a given shape. All the above cited methods require manual mounting, however this can become part of the experience and entertainement for the final purchaser of the replica. These types of reproduction modalities could be used for the production of museum merchandising.

Figure 13: *The wire meshes proposed by [GSFD*14].*

Wire meshes are grid shells made of metal that can be bent and tied together to approximate freeform shapes. While in the past these kinds of structures were created manually, using an incremental trial-and-error approach, the method proposed by Garg and colleagues [GSFD*14] defines an automatic framework that bounds the overall approximation error. A wire mesh constitutes a valid accurate representation of an input shape (as shown by Figure 13) with relatively low production costs. Similarly to the above paper, Wireprint [MIG*14] creates wireframe previews for rapid prototyping.

3.5. Low- and High-Relief

A *low-relief* (or bas-relief) is essentially a way to represent a given 3D object using only a thin layer of material. It can be considered a strictly 2.5D geometric representation of a more complex 3D geometry. Similarly, an *high-relief* projects a 3D geometry onto a thin layer of material; but, in this case, it keeps part of the original “tutto-tondo” sculpting volume.

The use of low- and high-reliefs to illustrate three-dimensional shapes is widely used in arts, to decorate cameos, pottery, sarcophagi and architectural elements, or to create the engravings minted on coins. Low- and high-reliefs considerably reduce the production costs of fabricated copies, for example by cheap subtractive techniques that work on a 2D plane. Due to the reduced amount of material used, this reproduction technique scales very well to cover large surface areas.

The quality of a relief is measured by the perceived quality of the represented 3D shape. The first method for the automatic generation of a low-relief was presented by Cignoni et al [CMS97]. The bas-relief was produced by performing and automatically scaling the depth of field of a given view which had to fit a prescribed reproduction volume (see Figure 14). Then, this technique has been extended to use histogram equalisation [SRML09].

Another class of methods [WDB*07, SBS07, KTB*09,

Figure 14: *A bas-relief of a cloister generated with the approach proposed in [CMS97].*

BH11, ZZZY13] achieves better results by compressing the gradients of the surface, instead of compressing the depth values. Consequently, the generation of high and low reliefs has reached very high standards [JMS14,SPSH14], as shown by Figure 15.

Figure 15: *Two examples of high- and bas-relieves automatically generated with the approach proposed in [SPSH14].*

The generation of a bas-relief is the final result of all the methods that convert a painting or a picture into a tangible 3D reproduction [NR13, RMP11], such as the methods presented in 3.1 .

4. Issues and limitations

While digital fabrication technologies has significantly advanced in the last years, a number of limitations, issues and constraints still limit and broader adoption of fabrication technologies in CH. In the next subsections we highlight the most common limitations of digital fabrication technologies and the proposed solutions, pointing up to possible research directions.

4.1. Going beyond the working space

Due to the limited workspace of most 3D fabrication technologies, reproducible replicas are usually very small. The working space of common 3D printers is between 15 and 40 cm (size of the edge of a cube). This limitation severely restricts the use of digital fabrication to small objects or very small reproduction scales. Sculptures, low reliefs and part of buildings can be very large and when printing them in a reduced scale details may disappear or become very hard to perceive in the printed object.

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

To overcome this limitation [LBRM12] proposed 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 16). 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 optimises these criteria and generates a partition either automatically or under user guidance. The final decomposed parts include customized connectors on the adjoining interfaces. A similar approach to automatically decompose and pack the resulting pieces for optimized printing has been recently presented by Vanek and collegues [VGB*14].

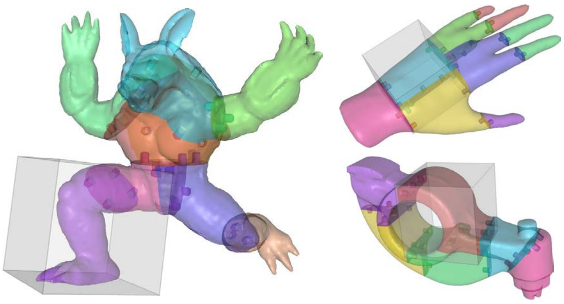

Figure 16: *The Chopper approach, designed to overcome the working space limitations of current 3D printing technologies.*

A similar approach was also proposed by Alemanno et al [ACP*14]. This work presents an algorithm for decomposing a 3D digital shape into a set of interlocking pieces that are easy to manufacture and assemble. The pieces are designed so that they can be represented as a simple height field and, therefore, can be manufactured by common 3D printers without the supporting material. The method additionally enables pieces to be printed with subtractive techniques. 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. An innovative interlocking mechanism enables adjacent pieces to plug into each other in order to create 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 that the assembled structure shape is compact and stable. Figure 17 shows an example of this technique used for the reproduction of the Ruthwell Cross, an Anglo-Saxon tall stone cross (slightly more than 5 meters in height), 8th century AD, conserved in the Ruthwell Church, Dumfriesshire, Scotland.

Figure 17: *The approach proposed in [ACP*14] breaks down the original shape into a set of height fields that can be individually manufactured without requiring support material and can be assembled manually to build a self-supporting structure.*

These types of approaches based on shape decomposition are ideal for CH domain. To ensure a high visual quality of the reproduction, the replica should mask the seams between the adjoined components as much as possible. Therefore, the decomposition process should take into account the visual impact of the seams.

4.2. Improving the quality of the output

The current generations of 3D printers still lacks geometrical precision in the generated shapes. Although the size of the minimal portion of material layered by the printing devices is reduced in size (current technologies allow layering with a thickness in the order of 1/10 mm), when the reproduction is observed the single layers are still visible. This aliasing effect could be reduced by sanding the surface, however this process is time consuming and could also reduce the quality of the reproduction, e.g. by sanding off important small scale details.

Another solution is to optimize the orientation of the replica in the working space of the 3D printer, to minimize the layered effect on the main surfaces since this effect is more visible on all the large, nearly-planar sections of the shape.

Figure 18: *The colour-enhancing technique: a comparison between the plain replica (left) and the version with colour enhancement (right).*

Another issue is the minimal thickness of layers and therefore the minimal size of the detail that can be reproduced and perceived. In addition, some particular optical and physical properties of the reproduction material(s) used might reduce the perceptual quality of the replicas (this is often the case with translucent plastic). This could be reduced by adopting *shape enhancement* approaches which enable users to increase the readability of the tiny details, for example by exploiting the colour reproduction of some 3D printers. It is possible to overcomes perception problems due to an optical property (sub-surface scattering), by exploiting the color reproduction features of some 3D printers [CGPS08]. This approach carefully pre-computes an ad hoc surface shading to colour the surface of the replica in order to enhance the perception of its geometric shape once printed (see Figure 18). This approach therefore counterbalances the subsurface scattering effects that hinder the perception of finer surface details.

However, in many cases an approach based only on color enhancing is not sufficient. Although printers claim submillimetric resolution, the real printed geometry is often affected by the physical properties of the material used, which might result in poor surface resolution and decrease the perception of small details in the replica. The geometry enhancement technique presented by Pintus et al. [PGCS10] counterbalances the effects due to the non ideal behavior of the materials used in the printing process, increasing the quality physical replicas in terms of visual and tactile perception and detail preservation. The method is based on a volumetric representation of the geometry. The main idea is to simulate how the material will behave, predicting the final shape of the fabricated objects. This method then compares the prediction with the original geometry, and modify the input data to reduce the differences between the original and the printed model.

Finally, the amount of *internal volume* of the replica has an impact on cost and time of reproduction. Several approaches are already available in most printers for the construction of internal filling structures which ensures the rigidity of the replica and, at the same time, reduces its weight. However, there is significant possibility for optimizing them [MeSREA13, LSZ*14] .

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 regarding the original colors of a statue or an architectural decoration. Only few 3D printing devices are able to produce colored replicas (mainly the ones based on gispum binding technology); however the quality of the result is still not sufficient for the very demanding requirements of CH applications.

Therefore, reproductions are usually coloured manually to obtain good quality results. This manual application might help restorers or art scholars in their practical work, in order to produce and compare several hypotheses. However the quality will depend on the skill and time of the operator, and thus accuracy is subjective; the cost could be higher than those required by plain 3D fabrication; and mass production becomes a problem.

Recent research has been devoted to the production of approximations of specific *surface reflection properties*. While some methods are based on a specific hardware or are limited to produce planar surfaces [WPMR09, MAG*09, PRJ*13, LGX*13], others can be applied to current printing devices [HFM*10, LDPT13, RBK*09]. However, we believe that these approaches need to be further developed to reach an accuracy level suitable for CH applications. Very recently the advances in Computational Hydrographic Printing [ZYZZ15, PDP*15] have opened new possibilities to apply color over fabricated object in a automatic and accurate way.

4.4. Reducing the reproduction cost

While the cost of many additive technologies have decreased substantially in the last few years (thanks to cheap materials and the availability of low cost devices), the cost of subtractive processes has not improved. Nevertheless, the flexibility of natural materials makes this later approach ideal for many CH applications.

The cost of reproduction is the main drawback of the *free 6-axis CNC carving* approach. It depends linearly on: (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 is used for). The second cost item is usually not easy to reduces, unless new and lower cost 6-Axis Carving instruments will appear on the market. The first cost item 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 CAM tools. This is acceptable in mass-production applications, where usually the operator designs an optimal milling path and then this same path is reused thousands of times, e.g. for medium or large scale production of a mechanical component. On the other hand, CH reproductions usually entail producing either a single or a few high-quality copies. Therefore, the milling path design cannot be shared for a large number of copies and becomes an important fraction of the overall reproduction cost. Any improvement in geometric processing technologies (e.g. making the milling path design completely automatic) would have a considerable impact on the usage cost of this reproduction technology.

5. Conclusions

Digital fabrication has become a wide domain. A variety technologies allows to create physical reproductions of 3D digital models with a great accuracy at low costs. Although current digital fabrication technologies still have limitations, the accuracy of the reproduction has reached a an excellent level of quality.

We have shown various successful applications of digital fabrication in the Cultural Heritage, making digital fabrication an enabling technology providing new possibilities for the study and exploitation of CH assets. We have also highlighted some suggestions for future research. In our opinion, this domain shows an interesting potential for future research on geometry processing, motivated by the specific needs of CH applications. Beyond the strive for accuracy (that involves also colour and texture) there are other issues that still need to be addressed. An increased effort is also needed regarding standardisation and the definition of guidelines for the production of good quality replicas. It is not easy to decide which technology best suits a specific application or the material characteristics that best fit a specific replica. Guidelines are also needed to help users prepare the digital 3D model before fabrication. Some examples are the complex pipelines required to convert a 2D asset into a 3D instance (e.g. from a painting to a bas-relief) or how much we should edit a 3D model to enhance low-scale shape details with the aim of ensuring an improved tactile perception.

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