APPLICATION OF HIGH RESOLUTION SCANNING SYSTEMS FOR VIRTUAL MOULDS AND REPLICAS OF SCULPTURAL WORKS

G. Tucci*[a], V. Bonora[b]
[a] Università degli Studi di Firenze, Facoltà di Architettura, - grazia.tucci@unifi.it
[b] Politecnico di Torino, II Facoltà di Architettura, DINSE - valentina.bonora@polito.it

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ABSTRACT

The paper presents a project aimed at setting up methods and tools for creating virtual moulds of sculptural works using laser tracking technology in tandem with an hand-held scanner. In the second part, the employment of the obtained high density model for the *replica* of artefacts, using numeric control machines with different reverse engineering techniques, is described. The scientific focus was centered on the processing pipeline from the acquisition to the reproduction and the first results are here presented. The study is conducted in cooperation with the Superintendence of Architectural Heritage and Landscape of Tuscany under the guidance of architect Vincenzo Vaccaro and with the Opera di S. Maria del Fiore, lead by Paolo Bianchini.

1. INTRODUCTION

The use of scanning technology for three-dimensional probing of art sculptures with highly complex contoured shapes has recently undergone considerable progress. It has actually become one of the most promising innovative methods in analyzing art.
The need to have information on artistic historical heritage can be seen from different viewpoints: there are presentation purposes on the one hand, study and preservation purposes on the other. Instrument and technologies applied to acquire data and further elaboration must agree with specific 3D numeric model objectives:
- In the field of documentation and classification of artistic heritage, true and thorough recording of form-size characteristics of the work aimed at investigation under the historical-artistic viewpoint. In this way, it is possible to create a database for accurate comparative evaluations of different works.
- Repeated measurements over time provide an accurate picture of the degree of degradation and the easy setting up of effective maintenance programs with regard to inspection, so the state of preservation of a work of art and of the evaluation of the details of the degradation processes can be assertained.
- Simulation of restoration works (if necessary) and documentation of previous works. Virtual anastylosis and reassembly of fragmented works both for educational and study purposes, and for evaluation of the feasibility and accuracy of the action.
- Manufacturing supports for packaging works of art for minimizing transportation damages.
- Manufacturing moulds and replicas for replacements of sculptures and monumental works of arts in open spaces in case their preservation requirements do not allow them to remain in their original place.

1.1 Work of art replica

The conceptual implications of an analysis of recording methods and representing the morphology of the physical world to produce an exhaustive model have long raised many questions. These very questions are made even more interesting by the considerations on the technical reproducibility of the work of art introduced by Walter Benjamin in his essay "*The work of art in the Age of Mechanical Reproduction*" (1935). Photography and films, allowing new mechanical reproduction form of a work of art, transform its own nature. We can consider these media as *virtual*: the most important effect of the dematerialization of their content is just its reproducibility.
Digital revolution extended this concept further, changing the mechanical reproduction techniques to the numeric reproduction ones: virtual, in the meaning of immaterial, numeric or, rather, described by number and not by *materia*, has become not only the content of the work of art but even its "support", placing side by side the concept of reproducibility with that of transmissibility. Both, however, are applied to the representation of the object and not to the object itself.
The developing of visualization systems able to produce high quality representations (photorealism - I look at the model as I would look at the object itself) and of haptic device (I touch the model as I would touch the object itself) gives the possibility to take away, in time and in space, the observer from the original work of art, also increasing the possibility of fruition.
Today, we are in the last decisive phase of a story which began with the gradual refinement of the techniques of data acquisition and documentation of 3D work of art, that has its cornerstones in the

Figure 1: The Prophet survey, using a combined application of tracker system (left, on the back) and a hand laser scanner device (left, front); data during acquisition phase are immediately aligned and referenced (right, top) thanks to mirror reflectors measured from both tracker positions.

* corresponding author

19th century – the use of moulds and, later on, the use of procedures which were the origins of modern photogrammetry.
Today, with the application of *Reverse Engineering* it is possible to have a mathematic description of any physic model and, with *Rapid Prototyping* instruments, its reproduction.
The high level of correspondence, from the geometric-dimensional point of view, and the wide chose of materials that can be used with this techniques, give an interesting point of depature to review the concept of the unicity of the work of art.

2. THE PROJECT

The current laws of the Italian Code of Cultural Heritage and Landscape prohibit the reproduction of cultural heritage artifacts that consist of obtaining moulds from original sculptures and reliefs in general. In exceptional cases, reproduction is allowed on stable surfaces, with no polychromes, gilts and other finishes; also if copies are missing and when it is based on proven scientific needs. Specific reference is made in this law to reproduction procedures with non-contact methods such as photogrammetry and three-dimensional scanners. So, scanning with optical means is preferred so as not to damage surfaces with delicate parts; furthermore, the new technologies allow us to accurately scan miniature details.
To sum up the problems that arise from possible applications of measurement instrumentation in artistic and architectural modeling we can say that:

- Scanning of forms is often difficult due to numerous delicate details in undercuts and difficulty of physically reaching these parts.
- The scanning instrument must be portable and handy. Often, it is impossible to remove the object from its location.
- In most cases, the scan jobs are one-off applications, making permanent equipment installations cost-prohibitive.

The aim of this project is to analyse the problematic aspects of the entire pipeline: from the acquisition to the realization of the solid model with non-contact methods, and to summarize the available current technologies, to periodically evaluate the best solution in terms of performance and cost.
A large number of works and scientific papers are available in technical literature related to available acquisition techniques (Callieri, 2004; Beraldin, 2004; Blais, 2004; Boelher, 2004; D. Skarlatos, 2003; Monti, 1994). For this project, a *Local Positioning Technology*, manufactured by Leica Geosystems and normally applied in industrial measurement, was used. This technology, combining tracking, photogrammetry and laser scanner methods, proved to be a flexible solution in the acquisition of complex shapes like that of sculptures and *bas-relieves*. Density of points and accuracy are the strong points of such a system. Starting from the high density digital model exported in STL file format, different kind of systems were tested to obtain a replica of the object.
The object of this study is one of the two Prophets originally located on both sides of the Porta della Mandorla, side entrance in the S. Maria del Fiore Cathedral (Florence). They were made in 1406-1409 but they weren't placed on the portal gable no until 1431. The artist is unknown. Some credit Donatello due to their similarity with his early works, others credit Bernardo Ciuffagni, a student and an apprentice to Lorenzo Ghiberti.

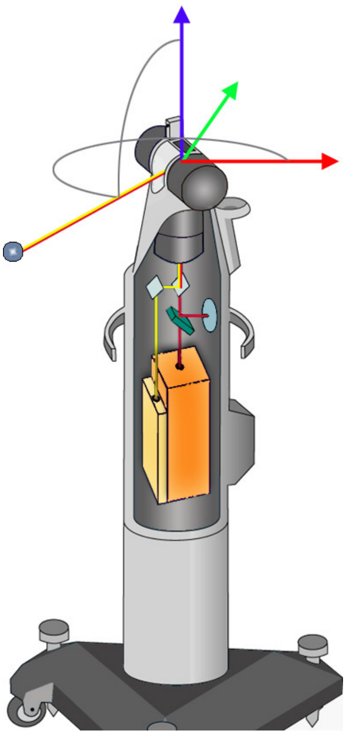


Figure 2: The tracker is able to measure the 3D location of a reflector with respect to the base unit: a laser interferometer measures relative distances and optical encoders measure azimuth and elevation

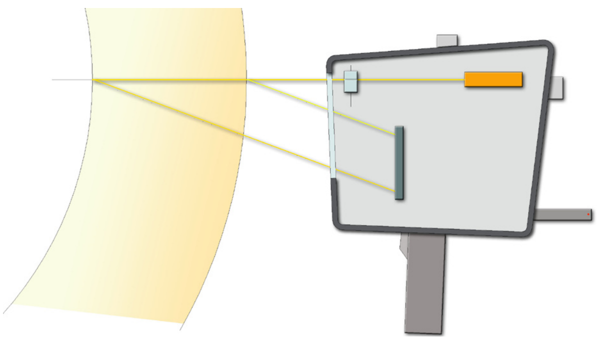


Figure 3: T-Scan use triangulation principle: a laser beam is deflected by a rotating mirror, projected on the object and then reflected and focudes on a CCD sensor that determine its position

3. PROPHET 3D SURVEY

3.1 Instruments

A Leica *Laser Tracker* was used in tandem with a hand scanner (Leica T-Scan) to digitize the work of art in question.
Laser Trackers are portable *Coordinate Measurement Machines* (CMM), that are able to measure the 3D location of a spherical mirror retroreflector with respect to the base unit, with the accuracy of a few microns, with a range of tens of meters. The structure of these systems is based on a laser interferometer to measure relative distance, and optical encoders to measure azimuth and elevation of a beam-sterring mirror, to determine the orientation of a target which can be moved almost anywhere within line-of-sight of the base unit. With this system it possible to measure volumes up to 80 meters at a speed of 3000 points per second.
Leica Laser Tracker augmented with a camera (T-Cam) combines the advantages of tracker technology with those of photogrammetry.
In this way, it is possible to have the 6 degrees of freedom of an object (the hand device of the system). The camera, using the mathematics of a parallel projection, follows any rotation of a rigid body (Euler angles - i, j, k) while the Laser Tracker pinpoints the location of the object (x, y, z).
This Local Positioning Technology enables seamless communication between Laser Tracker and the other components of the system, using remote detectors, armless and wireless probing (T-Probe) as well as non-contact hand-held laser (T-Scan). The camera features include an high-precision Vario Optic (with distortion less than 3μm) and lens that quickly changes focus dependent on distance with a zoom that adjusts field of view to 30cm @1.5m - 15m. The frontal lens is of constant dimension as well as the framed

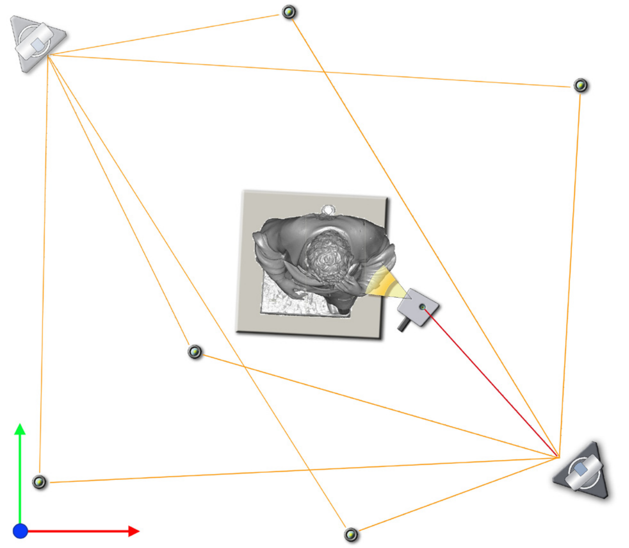


Figure 4: For the survey a Leica Laser Tracker with T-Cam was placed in two positions; a common reference system was defined by a set of spherical reflectors acquired by both positions. Thanks to reflector and LEDs located on the T-Scan, its position was continuously tracked in the space, while it digitalized the whole statue

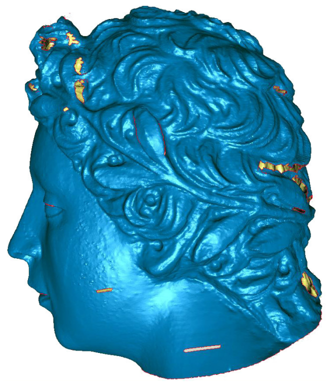


Figure 5: The surface model: point accuracy and reduced noise produce a good mesh quality: just some holes are still present where the shape of the original model was really complex (see detail on top)

image. The remote detectors (T-Scan, T- Probe) are provided by one reflector and ten LED's. From the distortion of the image of the detectors it is possible to have a homogenous orientation and consistently accurate measurements.
T-Probe reaches a measuring volume of 30 meters without support arms and it is insensitive to room light.
T-Scan uses the triangulation principle. A laser generates a measurement beam which is deflected, by a high -speed rotating mirror, and projected on the object. The measurement beam, point by point, is reflected from the object's surface and focused on a CCD sensor, that determines its position. This one-of-a-kind, "flying-dot" scanner digitizes large surfaces in one step, within a measurement volume of up to 30m. It uses a class 2 eye-safe laser, it measures up to 7,000 points per second and works at a distance of between 41 – 119mm with a measurement depth of 78mm. Every reflected intensity signal in a point determines an adjustment of the power of the next one, so it is possible to adapt it to measure critical parts, such as white or black surfaces, and also under standard lighting conditions. There is also a navigation laser for staying in the measurement field.

3.2. Data acquisition

In general, the acquisition of a surface like that of the Prophet presents a number of difficulties that have to be considered in choosing the appropriate instrument.
In the triangulation based system the important factors are the scanner field of view and the measurement depth, that are always related. As is well known, in a triangulation device, any point on the surface has to be simultaneously framed by two points of view: it must lie on the light beam trajectory and be acquired by the CCD. In the more traditional scanner systems, the dimension of the triangulation base is larger and the longer distance from the object creates larger shadow area. Instead, a T-Scan has a small base so its low dimension allows us to reach undercut points better.
But, as said before, a smaller base produces a reduction of the field of view so that a greater number of range maps is required to cover the same area so increasing the alignment problem. The combined application of a tracker system with a laser scanner device eliminates this problem.
To look in more detail at the technical aspects. The freedom of the sensor movement, from the point of view of geometry acquisition, multiplies the sensor device positions, reducing drastically the shadow areas. With this system, all those surfaces of the Prophet that would have been hidden for a normal triangulation sensor have been acquired. Furthermore, the visualization in real time of the whole model, already aligned, instead of a single range map, gives an immediate control of the covering. Obviously there are those points impossible to record, for example the Prophet's curls, with any laser scanner devices: so, manual editing is needed to reconstruct the continuity of the surveyed surface.
A Leica Laser Tracker with a T-Cam, at a few meters away from the sculpture, was kept in a fixed position for the acquisition of the Prophet, while the operator was free to move at a few centimeters from the object with a scanner whose position was continuously tracked in the space. As said before, thanks to strategically located reflectors on the scanner itself, the Leica Laser Tracker can track the Leica T-Scan with six degrees of freedom (6 DoF), determining not only its coordinates in a 3D space but its pitch, yaw and roll, as well. Therefore, the hand scanner can digitize even hard-to-reach parts as long as it is within the line of sight of the tracker. In our case, only half of the object could be acquired by the scanner without losing the tracker, so it was useful, in the measurement preparation stage, to define a reference system to re-orientate the points acquired from two different positions of the Laser Tracker. A set of spherical mirror retroreflectors were placed on the scene and fixed with a custom-made metallic ring that held the ball in a specific position; their positions were estimated with the accuracy of Laser Tracker, in the first position. For the second Tracker location, the same targets were measured again in order to determine the rototranslation transformation with respect to the first one, and to eliminate the need of range map alignment, typically required in any modeling project. This feature speeds up the 3D model generation. So the whole digitization of the work of art required only 1 day, generating a total of 25 million points prior to selective data filtering. It is an extremely interesting result, it is complete in terms of digitized information as well as in terms of speed at which the data was acquired and processed.

Experiments carried out with other systems have shown a few working problems, such as the difficulty in measuring details in undercuts. The acquisition speed is also decisive: operating costs can be being considerably reduced, especially when dealing with large, complex objects.

4. REPLICA AVAILABLE SYSTEM AND TECHNIQUES

4.1 Instruments

Rapid Protoyping (RP) is an expression indicative of technologies used to fabricate physical objects directly from CAD data sources; they are also called three-dimensional printing, solid freeform fabrication or layered manufacturing.
RP application is widespread in the industrial field as it is an effective way to reduce time to market in manufacturing.
CNC *(Computer Numerical Control) machine* can make different kinds of manufacturing: turning, trimming, drilling, planing, grinding, spark erosion, etc.. The manufacturing machine used in this project are millings.
Rapid ptototyping and CNC machines are often defined as:
- *additive techniques*, working by processes of layered technologies; they make the object by stacking thin layers of material, one section above the other, so that each successive layer is glued to the previous one.
- *subtractive techniques*, working by processes of material removal.

While prototyping systems are usually employed in the industrial processes where the prototype is previously planned in a CAD environment, in the described application, the shape of interest is taken from a real-world object that doesn't have a pre-existing computer model. In our case its mathematical description was obtained as mentioned in paragraph 3.
In industrial applications, the term *Reverse Engineering* is used to describe a process that involves measuring an object and then reconstructing it as a 3D model. With the cross-migration of techniques to the Cultural Heritage documentation sometimes there are confused uses of terminology. For example, "prototype" is used for the first element of a subsequent production of a series, helpful for design evaluation or tests. It is clear that the aim of our project isn't to start a mass production of prophets; better terms to define this work could be "replica" or "solid model", depending on whether its scale is 1:1 or not.

4.2 Rapid Prototyping techniques

Following, only factors related to the processing that involves the superficial aspect of the solid model are analyzed.
Some important aspects useful in other application, for example, mechanical behavior of the used material or the method to realize the internal structure or possible supports of the model, are neglected. Just a list of alternative techniques is provided, while a

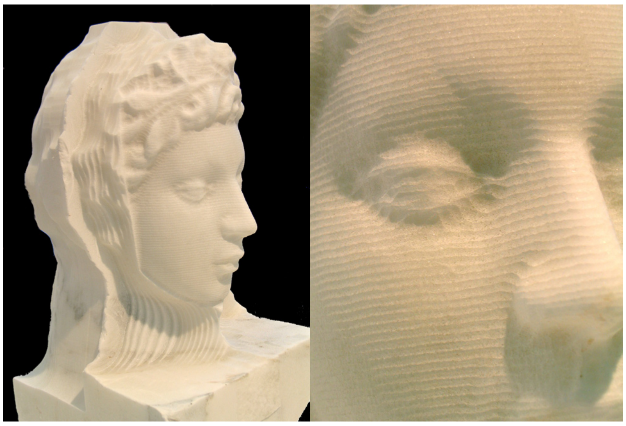
Figure 6: The solid model of the statue, made in polystyrene at scale 1:1 during machining by a robotic milling machine and the final result (right)

Figure 7: The solid model of the head, made in ABS by a FDM printer (working scheme on the left, see 4.2.1)

more detailed description is done for what was applied (see 5.1).
- *Stereolithography* (SLA): it was the first generation of machines for RP; builds plastic parts or objects a layer at a time by tracing a laser beam on the surface of a vat of liquid photopolymer.
- *Selective Laser Sintering* (SLS): it is based on bonding powders.
- *Laminated Object Manufacturing* (LOM): a laser cutter or a knife which cuts profiles of object cross sections from paper or plastic.
- *Three dimensional printing*: a jetting which deposits a liquid adhesive compound onto the top layer of a bed of powder object material.

4.2.1 Fused Deposition Modeling (FDM): It works by extrusion of thermoplastic materials.
For the first test we chose to print the head of the Prophet by a FDM printer (*Dimension sst1200 3D).* Maximum dimensions of the volume that can be reproduced with this technique are 686mm x 914mm x 1041 mm (254mm x 254xmm x 305mm the printer model we used). Obviously, the model parts could be successively reassembled and glued together.
The raw material of FDM is in a coil of filament. The filament is fed to an FDM head where the material is melted and extruded through an FDM tip onto the model surface.
For down-facing another tool tip on the same FDM head is also needed for support. The support material is water-soluble and can be easily melted off in a slightly basic solution after model production.
The surface of a solid model obtained with these systems shows a staircase effect. It is determined by the layer thickness and the local part geometry: if the layer thickness is small, one obtains a smooth part; it may however result in many layers and long build time. On the other hand, if the layer thickness is large, the build time is short, but one may end up with a part having a large staircase effect.
The surface quality (and the build time too) is also affected by the part build orientation. A good strategy is to orient vertically those surfaces that demand a higher level of finish; surfaces of lesser importance are oriented horizontally so that they are either a bottom or top surface. Another point to note, in the orientation phase, is that pieces are vertically weakest.
The model of the head of the Prophet has been oriented head-down in order to reach a good level of detail on the whole model and to print using the least support material.
The material used for the model test was ABS; FDM technique could also make use of polycarbonate and poly(phenyl)sulfone,

Figure 8: The marble model of the head: subsequent step of machining are visible; the level of detail showed in the right is the last finishing obtained.



that further extend the mechanical skills of the models even at high temperature and in medical applications (PC-ISO could be sterilized).

4.3 CNC machines

CNC machines make solid models by removing material from a stock shape of material. An important element of a CNC machine is how many axes it has: more axes means more complexity but also more complex shapes that can be worked. To make simple work, i.e. drilling holes, the motion control along three axis is needed: two of them in order to position the tool over the hole to be machined and the third to machine it. It is clear that working all around a full relief piece needs more complex movements.
The directions of motion can be linear (driven along a straight path) and rotary (driven along a circular path). All movements are related to a "zero point", useful in case of repositioning of the work in following steps to refinish it. The motion type, the axis to move, the amount of motion, and the feedrate are controlled by software. Machines with 5 axis have the highest flexibility: a rotating table can be added to have the 6th movement direction.
The main advantage of 5 axis machining is the ability to work complex shapes in a single set-up. Additional benefit comes from allowing the use of shorter cutters that permit more accurate machining.

5. PROPHET REPLICA

5.1 Finding the appropriate technology...

No technology is appropriate for every situation. One must choose the best tool for the task at hand: the strengths and weaknesses of every technology have to be, time to time, faced by needs and goals.
Since the project aim is to compare and evaluate different technology, we tested, both a subtractive system (CNC milling machines, on a robotic arm) and an additive one (FDM).
Even though this is work in progress, we can show the first obtained results:
1- a solid model of the Prophet's head, made in ABS by an FDM system;
2- a solid model of the whole statue, at 1:1 scale, made in polystyrene by a robotic milling machine (Kuka kr240L180 with a rotaty table). For this, a cylindrical cutter with 40 mm diameter for the roughing, a spherical cutter with 20 mm diameter for the finishing and a spherical cutter with 10 mm diameter to retouch the surface and to produce finish geometry have been used. Finish pass was of 1 mm;
3- a solid model of the Prophet's head, at 1:1 scale, made in marble by another robotic milling machine (Robostone 3000). The three subsequent steps of machining are visible on the same model: the roughing on the back (made by a cutter of 50mm diameter), the semi-finishing of the face (with the same cutter) and the finishing (with a "V" widia point of 5mm, with passing of 0.9mm). The working direction for the finishing pass was at right angle to the working direction for the roughing pass.
In both cases CNC machines have used a 3 axis tool path; the front finishing of the marble model has been made at 5 axis.

5.2 From the virtual model to the solid model

At the end of the scanning phase, the acquisition device (shown in paragraph 3.1), immediately gave a complete and referenced unstructured model of points of the statue. The alignment of multiple range maps was not necessary, neither was the elaboration aimed at reducing the oversampling effect produced by their overlapping.

The mesh model has been directly calculated; the mesh quality is very good: triangular faces are quite regular, with few manifold triangles and overlapping ones, and only some small holes in regular surfaces (probably where T-Scan movement was a little too speedy). In the more articulated area there have been some isolated surface patches. These problems, which would prevent an RP machine from successfully generating a useful solid model, have been quickly fixed. More demanding has been the reconstruction of the holes where the shape of the original model was so complex that acquiring data was impossible, as in some curls.

Mesh generation and elaboration was carried out by Geomagic Studio, who store data in a proprietary format and allow exporting in several formats including STL. RP equipment as well as CNC machine require an input file in STL format. STL is a facet-based representation that approximates surface. To have a solid model from the virtual model, sometimes, two different softwares are necessary, a CAM software and a post processing software.

FDM printer, on the contrary, is directly controlled by a unique software that imports the STL file and manages it: it orients and it places the piece respecting the machine reference system, it calculates the slicing (that is the subdivision of the continue surfaces of the model in horizontal sections that will be materialized by the ABS filament), it plans the support, it sets up the work parameters and controls the printer.

To mill the polystyrene model the tool path has been calculated with PowerMill (Delcam) CAM and postprocessed by ROBOmove (QDesign); stone model milling has been controlled by AlphaCAM software. The control software generally requires a human operator with much knowledge and skill of machining to select the milling cutters and define the necessary parameters and strategies that will generate an effective tool path. A simulation allows to check settings and show the 3D view of the tool path.

5.3 Secondary operations

During the manufacturing, the most articulated parts of the model are more fragile. With the FDM system, a support made of soluble material, is realized, so that it is possible to easily remove it without leaving traces on the model.

The working flow of the milling process, instead, needs subsequent progressive steps of finishing. It is important to carefully consider the weakening caused from the reduction of the section of the material.

Some external treatments, such as infiltration (applicable when the model is made by plastic material or composite powder), improve the mechanical characteristics of the artwork.

If a mould-ready or paint-ready surface is required, the parts will require benching removal (by sanding). In this case, the skill of the finisher plays a critical role in the final results.

The more or less accurate finishing of the solid model is, in the case of the statuary, an interesting topic of debate, that makes a reference to the just mentioned problems about the recognizability of the "original", and collocate the model in the undefined space between the concepts of "copy" and "representation"

Today, a proposed guideline is to leave replicas without any superficial finishing in order to distinguish them from the original work of art.

6. CONCLUSION

Today, it is possible to have a replica with a high level of exactness, thanks to the high density system of acquisition and reproduction. In every case, it is necessary to study and evaluate the technological solutions in all phases of the work: the operative pipeline is only, in appearance, similar to that of an industrial processes, but probably it is more difficult to propose standard procedures because of the particular characteristics of the object dealt with. Each time different aspects have to be considered, such as: the difficulty to move the object from its collocation, the state of conservation of the original, the accurate reproduction or possible integration of its shape. Our objective is to produce a unique replica from an original work of art rather than the general "prototype" production.

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