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A DIGITAL RECONSTRUCTION PROCEDURE FROM LASER SCANNER SURVEY TO 3D PRINTING: THE THEORETICAL MODEL OF THE ARCH OF TRAJAN (ANCONA)

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Abstract

In recent years, the technologies for creating reality-based 3D models were enhanced and propagated in a large number of applications and research fields. This great evolution is due to the fact that these technologies are very useful, or rather ideal, to preserve, disseminate and restore cultural heritage, thanks to digitization and the realization of digital copies based on additive printing. In particular, 3D printing and virtual reality have determined the increase of a new field for data survey: the museum fruition. Therefore, they are becoming increasingly important. The aim of this article is to show the connection and the relationship between the development of the latest technologies and the cultural heritage: a digital reconstruction procedure from laser scanning survey to 3D printing of theoretical model, realized with a virtual reconstruction reality-based.

Keywords

Archaeological heritage, cultural heritage, 3D printing, additive manufacturing, virtual reconstruction, reality-based model

1. *Introduction*

The technologies for creating digital reality-based 3D models have experienced an impressive evolution in the last decades. These technologies are enhanced and propagated in many applications and fields, transforming the approach of researchers and students with the cultural and architectural heritage. In fact, they are essentials and very useful tools to preserve, disseminate and restore cultural heritage, above all to protect and safeguard all those which have been damaged during wars and natural disasters of the last years.

These technologies and methodologies have to become necessary, a rule, a new standard way to operate in the cultural heritage field, to increase and expand the number of artifacts that can be studied, so all the users in the world could collaborate and share their works.

This is a great goal, but we have the chance to make it possible, preserve and disseminate CH, thanks to digitization and the realization of digital copies. In fact, another important instrument is 3D additive printing that, along with virtual reality, have determined the increase of a new field for data survey: the museum fruition.

All these latest technologies are becoming increasingly important for CH, and they are enhancing faster and faster.

One of the biggest problem is the high cost of the instruments e.g. laser scanner, 3D printing, cameras, etc., although recently the price has dropped. Another issue is the difficulty to obtain good results with these methodologies by non-skilled people albeit they have a simple use, experience and ability are needed.

The aim of the present project is to enhance the fruition of the Trajan's Arch sited in Ancona (Italy), which is collocated in an isolated area of the city, and to show its original status thanks to a virtual reconstruction and 3D additive printing.

2. *The Arch of Trajan*

The Arch of Trajan is a triumphal arch and is certainly one of the most valuable monuments of the Marche's Roman ruins. This arch is very particular, almost unique of its kind: it celebrates not the entrance but the exit from the city; in fact, Latin inscriptions are only on the side of the city, the exit one. It was erected most likely in the 100-115 A.D. by Apollodorus of Damascus, in honor of the Emperor Trajan, to thank him for the expansion and enhancement of the port, and it was also in favor of departing ships for the war in Dacia, for which the emperor Trajan embarked and returned victorious (Sebastiani, 1996).

Fig. 1: Overallview of the Arch in the ancient harbour

The arch is located in the city of Ancona, within the ancient harbour, and is considered one of the most significant monuments in the city (Fig.1). In last decades, for reasons of public safety and security, access to the ancient harbour has been strictly limited to the private vehicles, so the Arch is not immediately achievable, but requires a walk of almost one kilometre.

In all this background, we have a twofold aim:

- to enhance the fruition of the arch by a larger number of users, especially to those not physically present there;
- to give the possibility to find out the arch in its original structure, as far as the littlest details.

To work in this direction, we used various methods and interaction of different technologies and areas of expertise. First, we started with a laser scanner survey, to create point clouds of the current state of the arch in its dilapidated condition. Then a virtual reconstruction of a theoretical model in its original status was made by analysing literature and historical sources. In the end, we used this theoretical reality- based model for 3D printing with FDM (Fused Deposition Modelling) additive technology.

3. *Interaction between technologies and cultural heritage: state of art*

The heritage sites in the world (natural, cultural, or mixed) suffer from wars, natural disasters, weather changes and human negligence. The importance of cultural heritage documentation is well recognized, and there is an increasing pressure to document and preserve them also digitally. Therefore, 3D data are nowadays a critical component to permanently record the shapes of important objects so that they might be passed down to future generations. The actual technologies and methodologies for cultural heritage documentation allow the creation of very realistic 3D results (in terms of geometry and texture). These are used for many goals like archaeological documentation, digital conservation, restoration purposes, VR/CG applications, 3D repositories and catalogues, web geographic systems, visualization purposes etc. Despite of all the possible applications and the constant interest of international organizations, a systematic and well-judged use of 3D models in the cultural heritage field is still not yet widely employed as a default approach for different reasons:

a) the “high cost” of 3D;
b) the difficulties in achieving good 3D models by low-skilled people;
c) the consideration that it is an optional process of interpretation (an additional “aesthetic” factor) and documentation (2D is enough);
d) the difficulty to integrate 3D worlds with other more standard 2D material.

The availability of 3D computer models of heritages opens a wide spectrum of further applications and permits new analysis, studies, interpretations, conservation policies as well as digital preservation and restoration. Thus, virtual heritages should be more and more frequently used due to the great advantages that the digital technologies are giving to the heritage world (Remondino, & Rizzi, 2010).

Digital technologies are transforming the way of thinking of cultural heritage researchers, archaeologists and curators work by providing new ways to collaborate, record excavations and restore artifacts. The technologies for creating digital reality-based models have undergone an impressive evolution. Although developed for industrial applications such as rapid prototyping and dissemination of Cultural Heritage, these technologies are ideal for helping to preserve and restore cultural heritage. Thus far, virtual reconstruction has been the most common cultural heritage application of 3D graphics. Using available historical material such as photographs, maps, drawing and expert knowledge to reconstruct artifacts that no longer exist is a fascinating opportunity (Scopigno, Callieri, Cignoni, Corsini, Dellepiane, Ponchio, & Ranzuglia, 2011).

For nearly two decades, virtual reality technologies have been employed in the field of cultural heritage for various purposes. The safeguard, the protection and the fruition of the remains of the past have gained a powerful tool, thanks to the potentialities of immersive visualization and 3D reconstruction of archaeological sites and finds (Bruno, Bruno, De Sensi, Luchi, Mancuso & Muzzupappa, 2010).

Multiple sensors and other techniques such as laser scanning and photogrammetry must be used. This requires developing methods able to seamlessly combine different models together in order to remove overlaps and fill gaps between them to create one model suitable for documentation and visualization. 3D modelling can be either from reality (photogrammetry, surveying, laser scanning) or from computer graphic, CAAD or procedural methods, but all can be integrated to achieve more complete and photo-realistic results (Remondino, El-Hakim, Girardi, Rizzi, Benedetti, & Gonzo, 2009).

The virtual reconstruction of the archaeological landscape is a holistic process of great complexity, which is made of relations and includes in a virtual ecosystem many kinds of data, according to a multidisciplinary approach. This system of relations, interactions and behaviours assumes cultural, psychological and perceptive relevance. The archaeological landscape has been reconstructed through different techniques and data sources, integrated in a coherent methodology of elaboration and communication. An important issue is "transparency": 3D models, reconstruction of the actual and ancient landscape have to declare the methodology and the sources they come from, so to allow the discussion, the critical awareness of the public and therefore their cultural impact (Forte, Pescarin, Pietroni & Rufa, 2006).

3D models have to be constructed from accurate acquisition processes, semantically organized, low-cost and derived from many authors. The problem is extremely complex because a semantic model must be generated from measured data that is able to carry out the original design but at the same time to show all corrections necessarily occurred through the construction process. Various tacking techniques or modeling techniques are often compared or combined. The entire acquisition step is based on the new generation of 'all in one' instruments that are able to collect different types of data using different techniques: TOF, photography/panorama, photogrammetry, topography. The use of all-in-one instruments also provides obvious economic advantages to the process of acquisition. 3D models were conceived to uniquely identify buildings/artifacts and their related resources as elements connected to the 3D geometry. This requirement can be achieved by constraining the final model to allow a semantic reading of the real object and the design intent throughout the interpretation of the shapes described by the model itself. Unfortunately, automation of the process of semantic model creation and naming for all acquired 3D models is impossible because the variants exceed the recurrences. In general architectural expertise is required (Gaiani, Apollonio, Clini & Quattrini, 2015).

The idea of a construction made of repeatable, scalable and proportional modules, has an interesting development today. This method allows a better reading of the architecture thanks to semantic organization and the use of a shape-grammar paves the way for achieving semantic models. The model and related graphical apparatus can be used as a learning approach and allow a better reading of the architecture thanks to semantic organization. By doing so, it is possible to create a closer link among architectural objects, virtual models and users, leading to a greater spread of knowledge in the field of architectural heritage (Quattrini & Baleani, 2015).

The introduction of the third dimension aimed at storing and managing documentation about heritage objects. It offers a more intuitive way to access and manage different kinds of information. The availability of digital 3D rendered models exceeds, in fact, the simple possibility of developing photorealistic reproduction of the 3D real object and it makes available all information in a visual and integrated way by limiting errors due to granularity. 3D modeling pipeline must be based on the accepted and general convention of architectural analysis whereby structures are described as a series of structured objects using a specific architectural lexicon. Many experiences have presented a methodological approach to the semantic description of architectural elements, defined a method able to describe the shape of 3D objects or showed how attribute grammar formalism can be used as a 3D modeling language. Semantic classification has also been recently used for procedural modeling of architectures and city modeling applications. The multiple representations of architecture buildings and their associated information have been organized around semantic models. The 3D models semantic structure allow to organize each single sub-element as a node, linked to a file that can be stored separately from the other ones belonging to the same artefact. All geometry-parts are associated with a semantic meaning, and each semantic item is further described with specific attributes (Apollonio, Gaiani & Baldassini, 2010).

Additive manufacturing, if seconded by a paradigm change to the museum model, can be employed in many ways to reintegrate touch, and other non-retinal senses into our cultural experiences. 3D printing is in a phase of rapid technological changes and promises more enhancing experiences for the fields of cultural heritage. This would provide a more holistic appreciation of the produced objects, but make it necessary to develop basic guidelines for 3D printed models. We expect that 3D printing will not only become vital in the field of reconstruction of objects, but also for research, documentation, preservation and educational purposes, and it has the potential to serve these purposes in an accessible and all-inclusive way. Apart from the industrial and commercial use, there is a fast-growing community of people who use rapid prototyping to produce things in small numbers at home, using peer-to-peer networks to exchange their prototypes and designs. Rapid prototyping promises a more enhancing experience of 3D models, even if the majority of 3D printers can only print with a limited color-scheme and have little versatility in materials. Yet, it should be a mere question of time until more powerful full-color 3d printers will enter the realms of artistic production and cultural heritage; it seems not out of reach that they will be able to represent characteristics such as texture, weight and smell or mechanical characteristics, which provide a more holistic appreciation of the produced objects (Neumüller, Reichinger, Rist & Kern, 2014).

The great evolution of the 3D printing has involved also the museums, which can use and adopt the 3D printing techniques for making more useable their collections, for creating a greater interactivity with the potential public and generate a new business thanks to museum merchandising. In the last years, the price of the 3D printing devices has dropped enough to bring them to the reach of small businesses before and then individuals. 3D printing is indicated as a tool for enhancing the cultural and museum heritage of which Italy is obviously rich (Pignatelli, 2013).

Another recent connection between the real and the digital space is represented by the application field and Augmented Reality tool, that are increasingly growing. These new technologies allow the development and evaluation of a computer tool that enriches physical scale models of buildings, which are commonly used to explore concepts and ideas during architecture and civil engineering design processes, and assume several detailing levels, some only volumetric, others more detailed and even others fully detailed namely showing construction components. These models can be enhanced with digital characteristics that can be easily changed, allowing an enriched interaction of the designer with such models. In particular, some applications, allow to explore the interior of buildings by using features as sections and highlight on the virtual model in real time. The goal is to develop and evaluate an AR app able to augment scale models with dynamic design information, enabling architects and other stakeholders to interact with them in an easier and more effective way. This kind of approach promoted dynamism and simulation possibilities to the real scale models, previously unavailable (Costa, Eloy, Dias & Lopes, 2017).

Additive Manufacturing (AM) is a term to describe set of technologies that create 3D objects by adding layer-upon-layer of material that can vary from technology to technology. To create a solid object, the 3D printer deposits printing material on the print bed (also called build platform) following the design of a 3D file, often a STL format file. There are many types of 3D printing technologies currently available commercially or at the early development stage. Each of these additive manufacturing techniques requires a specific type of 3D printing material: from plastic filaments (PLA, ABS…) to photosensitive resin to powdered material (metals, plastics etc.). These 3D printing technologies have various advantages and can be used in specific applications and use cases. There are three main categories of 3D printing technologies:

- **Extrusion** (**FFF** for Fused Filament Fabrication and **FDM** for Fused Deposition Modeling): a plastic filament (PLA or ABS) is melted and deposited on the build platform of the 3D printer to form the object layer by layer. It is the most common 3D printing technique, used by the majority of desktop 3D printers, thanks to its lower price, despite its lower precision and printing dimensions.
- **Resin** (**SLA** and **DLP**): a liquid photosensitive resin is cured by a laser or a projector to form the object directly in the resin tank of the 3D printer. The most common 3D printing technology using photopolymerization (solidification of the photosensitive resin via a source of light) is called stereolithography (SLA).
- **Powder** (**SLS**, **SLM**, **DMLS**...): a powdered material is sintered or melted by a laser, the grains of powder are bonded or melted together (sintered) to obtain a solid structure. The Selective Laser Sintering (SLS) technology is the most common among powder-based 3D printing technologies, although several derived processes exist.

The aim of our project is to show the entire digital reconstruction procedure, from the laser scanner to the virtual reconstruction and the 3D additive printing. We used different technologies and methodologies to demonstrate that each of them is useful and important for the entire procedure. In particular, additive manufacturing is the new evolution field. It is growing and enhancing so fast, and it can offer a lot of applications and purposes, as the museum merchandising, the accessibility of cultural heritage for people with different difficulties, the rapid prototyping of an artwork for make it accessible also where it is not physically present, and to appreciate the original status of the artwork.

4. The digital reconstruction procedure

It's useful to divide the entire digital reconstruction procedure into its two essential phases: the first one is the modeling for the virtual reconstruction, preceded by laser scanner survey and sematic characterization; the second one for the 3D additive printing, with the model optimization.

4.1 3D modeling

The procedure was structured in four phases: the first phase included the survey campaign on the spot, the second one consisted of data processing, the third one concerned the semantic characterization thanks to treatises, and the final one was on model editing.

Fig. 2: Front view of the Arch

The first step of our project is the laser scanner survey to create point clouds of the entire arch in its current status, that is a little disrupted, above all eroded by atmospheric agents. The structure is still present while some mouldings and other decorations, as well as the whole ornamental parts, have been lost (Fig.2).

Laser scanning is a non-contact and non-destructive technology that digitally captures the shape of physical objects, in his exact size, using a line of laser light; it creates "point clouds" of data from the surface of an object. It measures fine details so is ideally suited to the measurement and inspection of contoured surfaces and complex geometries, which require massive amounts of data for their accurate description and where doing this is impractical with the use of traditional measurement methods or a touch probe.

The laser scanner survey was made with the Leica C10 instrument in flight time, by two operators on a day of on-site acquisition. We have made 5 scans with an average resolution of 1 cm to 10 m. The aligned and clean cloud consists of 2mln of points. Photo captures for point mapping were made both by the integrated camera and the Nikon D90 external camera mounted on the spherical head and collimated with the laser pocket center.

Fig. 3: Point clouds obtained from TLS survey

We used the Leica TruView software for web sharing, and for visualize and measure point clouds of the arch obtained with the laser scanning. Therefore, we have used the point clouds for measurements of the entire arch and also for almost each single moulding. Then we have combined these measurements with the collection of treatises (Morolli, Barresi, & Fantastici, 1986): we have compared the structure of the arch with the canonical architectural orders, so we have determined the ratio between the base of the column and each single moulding. For the final and correct dimensioning, we have made choices about values between the survey measurements of the point clouds and the ratio of the canonical architectural orders. In this way the model accuracy respects the nominal scale of the expected model as well as the survey data, considering the minimal feature. It has been a long and meticulous phase.

With this procedure, we have started the step of the reconstruction. Analysing treatises, we have realised a semantic characterization of the architectural artifact, with the division into modules, which is typical of classical architectural orders (De Luca, 2011).

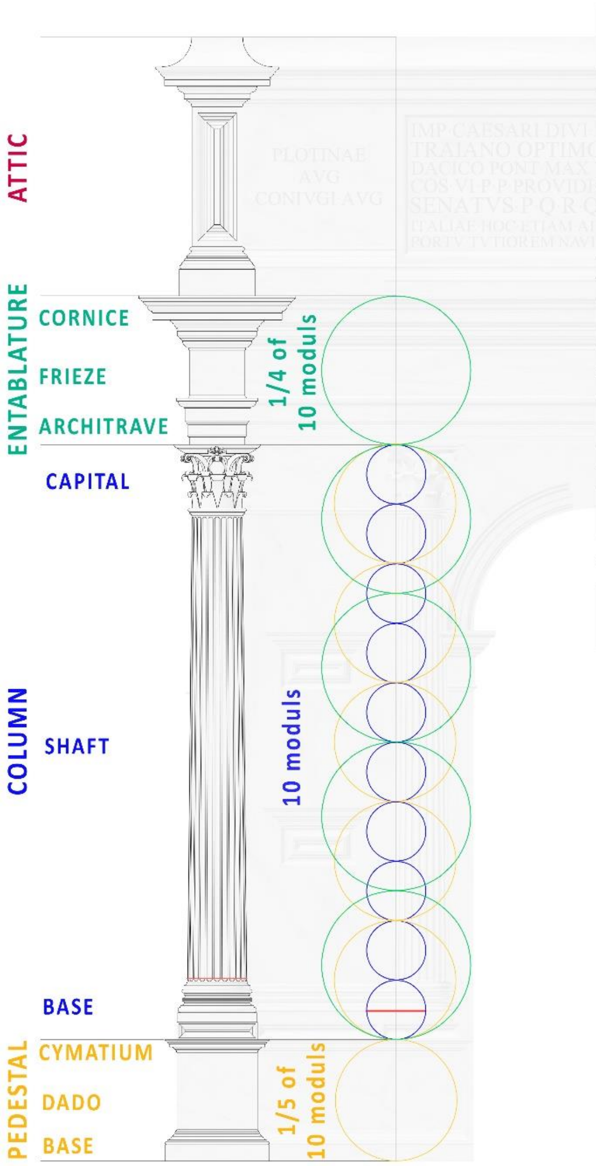

Fig. 4: Semantic structure of the arch Trajan

First, we have analized the composition of the arch, reading its architecture and comparing it with the classical architectural orders of the treatises. As from literature, we have broken up it and realized a shape-grammar of its semantic structure, which is composed by, from bottom to up (Fig. 3):

1. Pedestal:
   a) base;
   b) dado;
   c) cymatium;
2. Column:
   a) base;
   b) shaft;
   c) capital;
3. Entablature:
   a) architrave;
   b) frieze;
   c) cornice;
4. Attic.

Each sub-part of this structure is composed by several mouldings combined together, in different dimensions and ratio.

The essential mouldings have been identified in the monument and then have been constructed in 2D as well as treatises show.

We can show the workflow to reconstruct the model in the follow main steps:

- to set the dimension of the coloumn base;
- to determinate for each single moulding its height that is proportional to a specific ratio of the base of the column;
- to verify all the proportions according to the orders and treatises;
- to realize the 2D front view;
- to repeat the same procedure for the lateral view, realizing the other 2D view;
- to verify the symmetry of the arch;
- to extrude the 2D plan for realizing the 3D model.

In the second step: the virtual reconstruction has been realised completely from computer graphics CAD (Computer Aided Design), without the point clouds or slices as starting point. Considering that we have previously determined all the ratio and measures, according to treatises, we were able to modelled the entire structure such as every single moulding. This has been the hardest and longest phase of the project. The software used have been AutoCAD for almost the entire modelling and Rhinoceros for the capital that is the most difficult part for its decorations with volutes and acanthus leaves. We modelled throught BRep operators, preferring addition instead of subtraction of solids, because in some cases subtraction could generate problems with the normal of the object.

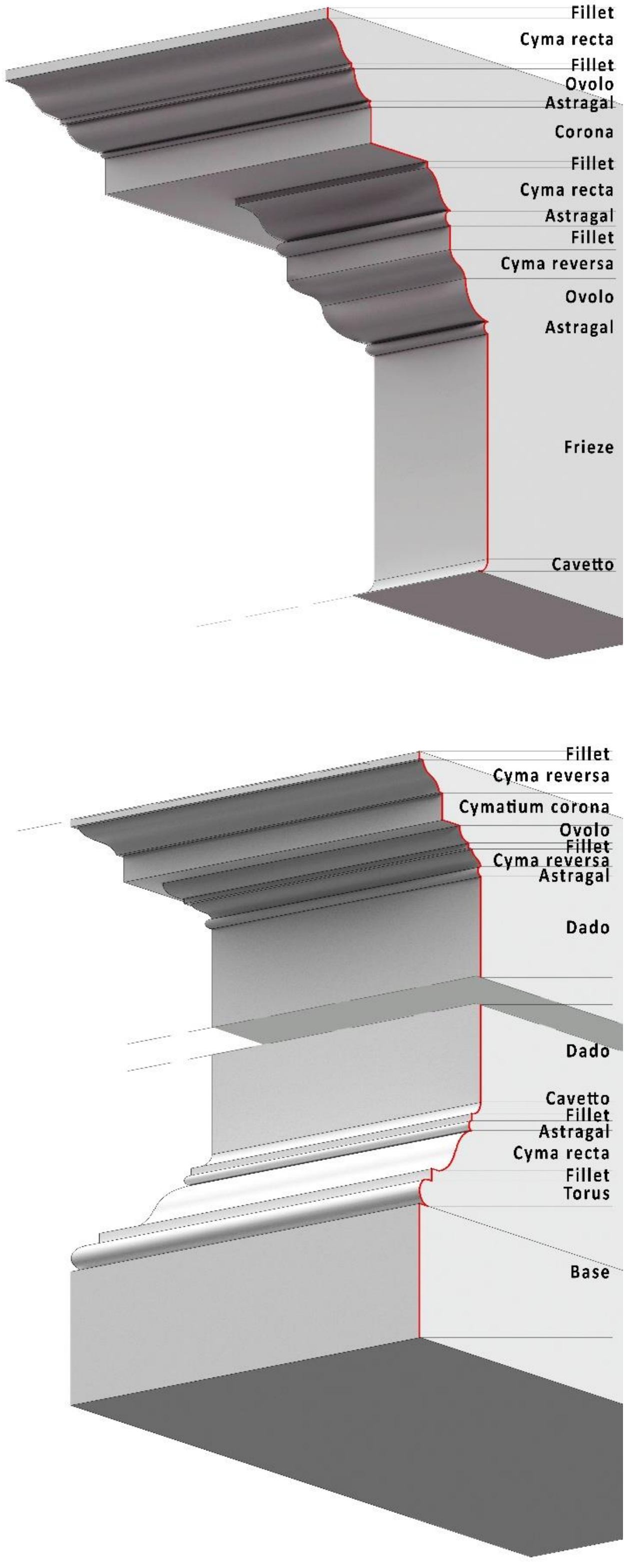

Fig. 5: The costruction and representation of the essential mouldings of classical architectural orders

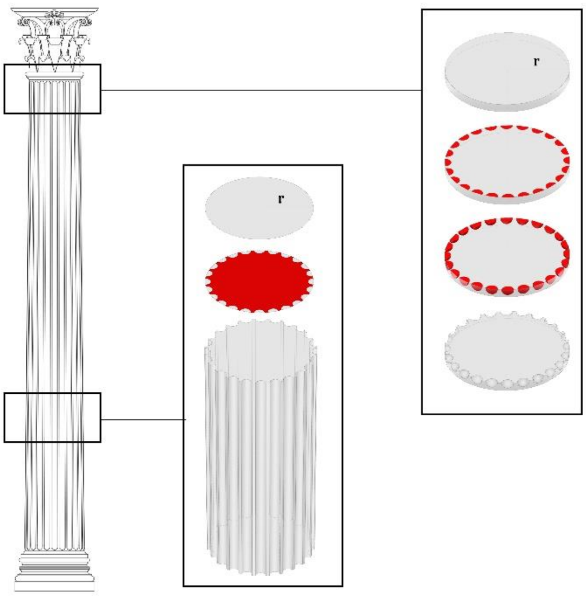

Fig. 6: Modeling scheme of the final part of the flutes of the column on the right, and modeling scheme of the fluted shaft of the column on the left

Fig. 7: Axonometric projection of the theoretical model of the virtual reconstruction

Fig. 8: From point clouds to 3D model, passing through dwg

The sources have been consulted only for the ornamental part of the bronze sculptures and decorations, which have gone completely lost, while for the marble structure, present for the most part, it was not necessary to consult further local bibliography. We have found two important hypotheses of the ornamental part (Luni, 1992), and we have decided to show both of them (Fig.9) because there are some critical points and none of them is recognized by the experts.

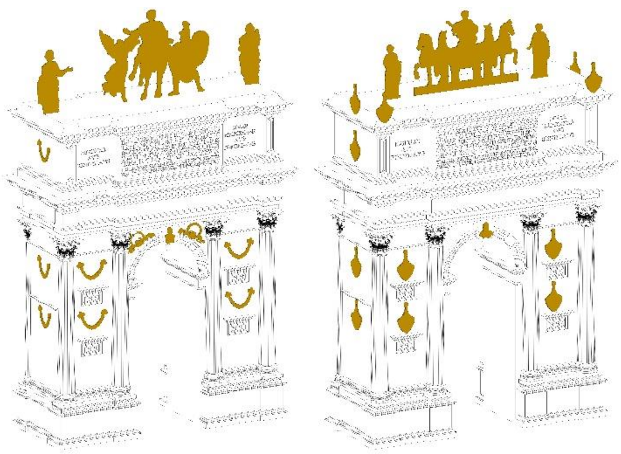

Fig. 9: The two hypotheses of the ornamental part; the left one of Rossini and the right one of Cirilli

Therefore, the ornamental part has been reconstructed bidimensionally, considering that this part has a secondary importance from the rest of the arch. These two ornamental parts could be printed in a second moment, maybe also with a different material or colour, in order to emphasize the importance between the ornamental part and the structural and architectural one.

4.2 3D printing

Now the theoretical reality-based 3D model of the arch in its original status on the dwg format is done, and ready to use. The dwg format has to be converted into the stl format for the 3D printing, but before we have controlled, with programs like Meshmixer and 3D Studio Max, that all normals are corrected, all volumes have to be full, perfect, with no intersections and superimposing. The first time, the model was incorrect, so it had to be as accurate as possible. Therefore, we have to come back and model again the most complex parts, in particular the capital with its decorations of volutes and acanthus leaves.

Finally, after a perfect modelling, the stl file is ready and generated for the additive manufacturing. We have used a FDM (Fused Deposition Modelling) 3D printing technology, in particular the Fortus 250mc model.
The computer connected to the 3D printing device has developed the stl file that was very heavy. A special software "cuts" CAD model into layers and calculates the way printer's extruder would build each layer. We have made several hypotheses with 3D printing software for realize the model in less time and with less material as possible. The best one was the full model, not emptied inside, double dense, enhanced and upturned. This solution needs 1306 cm^3 of model material, 303 cm^3 of support material, and 90 hours for printing. The model was in 1:50 scale, with maximum size of 22,4cmx9,6cmx27,6cm (length x width x height), so we can print it in a monolithic block. The minimum feature is less than 1 mm, so for the 1:50 scale we expected to have almost all the most important details. The inscriptions have been printing with a good result, while, as we supposed, the biggest lost of details have been in the capitals.

Thermoplastic filament in ABS-plus is heated and extruded through an extrusion head that deposits the molten plastic in X and Y coordinates, while the build table lowers the object layer by layer in the Z direction. The 3D printer deposits the melted filament by layer, each layer on top of the others, to build the object in 3D. When one layer is complete, the tray holding the object lowers very slightly and the extrusion process resumes, depositing a new layer of melted filament on top of the previous one. Deposited layers are fused together as the melted plastic quickly solidifies to form a solid three-dimensional object. Stacked layers of material form the final 3D printed object.
The precision and quality of the final result depends, among other factors, on the minimum layer thickness of the 3D printer (the thinner the layers, the higher the 3D print resolution), in our case less than 1 mm.

About this technology, is good that all parts printed with FDM can go in high-performance and engineering-grade thermoplastic, which is very beneficial for mechanic engineers and manufactures. FDM is the only 3D printing technology that builds parts with production-grade thermoplastics, so things printed are of excellent mechanical, thermal and chemical qualities.

Our model needs to extrude support material as well, so for each layer print both heads. Support material has a different composition; it has been removed after the printing is finished, thanks to the immersion in a swilling tank.

Fig. 10: The model during the 3D printing and at the end, surrounded by support material.

The 3D printed model surrounded by support material shown in Fig. 10 was submerged in a special salt bath in a washing device. Once the device turns on, it overheats the liquid inside, so that at 40°-50° C the previously inserted pads dissolve. When it reaches 70° C, the model is immersed in the liquid salt bath with stirring system, to facilitate the dissolution of the support material. The washing phase lasted about 12 hours. Once finished, the last step is the drying with compressed air for about 10 minutes. So, for all 3D printing procedure, we need about one week.

Fig. 7: 3D printed model in ABS

Fig. 12: Detail of 3d printed model in ABS

5. Conclusions and future developments

The virtual three-dimensional reconstruction and then with the 3D mock-up by printing show high-level results in. Despite the small size of the printed model, the additive manufacturing has printed almost all the most important details, with a minimum feature less than 1 mm. 3D printing is an accurate copy of the virtual reconstruction that have to be modeled in a perfect way. We have constructed and realized the entire digital reconstruction procedure with a clear pipeline.

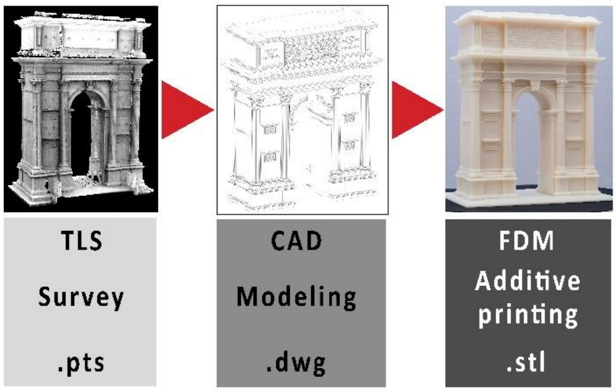

Fig. 13: 3d model construction pipeline

Weak points about these methodologies are, above all:

a) the great accuracy necessary for modeling, that is a time-consuming procedure and integration with different programs;
b) the filament deposition is evident, so the surface is not completely smooth. In the architectural heritage domain considering the need of models full of decorations and mouldings, this aspect could generate confusion.

As further development and assessment o f the presented procedure we are planning to print the same model with a different 3D printing technology, more accurate but also more expensive than the FDM one.

Additive manufacturing is the new evolution field; it is growing and enhancing so fast and it can offers a lot of applications and purposes, as the museum merchandising, the accessibility of cultural heritage especially for people with learning difficulties, for children, the elderly, for blind or visually impaired visitors, the rapid prototyping of an artwork for make it accessible also where it is not physically present and to appreciate the original status of the artwork.

Museum fruition is one of the most important development nowadays. It is possible to integrate 3D printing with augmented reality (AR). In our case, we could project on the 3D printing model the sematic characterization as well as the ornamental part, which no longer exist.

These applications and technologies can make the difference for cultural and archaeological heritage, above all nowadays that all the world suffer from wars, natural disasters and weather changes. Just think of the entire cultural heritage that the centre of Italy has lost with the series of strong earthquakes in 2016. Preservation, protection, safeguard, accessibility, research and fruition are all fundamental aspects, and we have to invest a lot in this new field, in the new technologies, for their development, to preserve our cultural heritage.

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