STUDY ON DIFFERENT GRAPHIC REPRESENTATIONS IN ARCHITECTURAL HERITAGE. DIGITAL AND PHYSICAL MODELLING

GARFELLA-RUBIO, José T. [(1)]; MÁÑEZ-PITARCH, Mª Jesús [(2)]; MARTÍNEZ-MOYA, Joaquín A. [(3)]; GUAL-ORTÍ, Jaume [(4)]

(1)Departament d'Enginyeria de Sistemes Industrials i Disseny. Universitat Jaume I. Avinguda Sos Baynat s/n, CP-12071, Castellón, Spain. garfella@uji.es

(2) manez@uji.es

(3) jomoya@uji.es

(4) jgual@uji.es

ABSTRACT

In recent years, cutting-edge methods have emerged to gradually replace or be used with traditional methods to carry out graphic surveys of architectural heritage; modern topographic tools such as 3D scanners and specific software. In addition, the new technologies of additive printing and three-dimensional digital representations has made architectural heritage more accessible to the general public. The main objective of this study was to conduct an analysis of each of the methods, to determine their advantages and disadvantages, as well as to carry out a comparative study of the results obtained with each of them.

INTRODUCTION

The graphical representation of architecture has been a necessity for centuries, either as a sign of artistic expression or as a method of documentation and study. Sketches, drawings, maps, plans, engravings and paintings were the methods of graphic representation used for centuries (Garfella, Máñez, Cabeza, & Soler, 2012) The advent of photography was a technical breakthrough as a method for documenting artistic and, more particularly, architectural heritage since it made it possible to capture images that were very similar to how scenes are perceived by the human eye, as well as allowing three-dimensional images and the photogrammetric rectification of buildings, which in turn enables us to take measurements directly from them (Lerma, 2002).These systems of representation have progressed exponentially with the development of both cutting edge optical and photographic optical equipment and the development of powerful computers and highly specific and advanced graphics software.

The purpose of this paper is to analyse the use of different graphic survey methods, both traditional and advanced, in the graphic surveying of architectural heritage applied to a case study, namely, the side Portal of “Nuestra Señora de la Asunción” in Vistabella del Maestrazgo in the province of Castellón (Spain). The volume and dimensions of this *retablo*-portal (Renaissance style from the XVII century) have made it an excellent testing ground for our study.

For the study, as a first step, we located several old photographs in historical archives and various publications.

Then, we carried out surveys using traditional methods, such as freehand sketches that were dimensioned manually with measuring tapes, distance meters, levels, plumb-lines and archaeologists’ combs, and the later scaling of the façade from the field data. Anaglyph images were also created using both old scanned photographs and modern digital images.
Photogrammetric surveys were also carried out, which allowed us to rectify the item using specific software. Photogrammetric restitution of the façade was also performed using the Photomodeler program, which enabled us both to create three-dimensional images of this architectural element and to generate a cloud by spatial mesh points that define this element with precision.
Another technique used was to survey the façade by means of a 3D scanner. This was performed with the aid of topographic support equipment.

Finally, we employed SfM (Structure for Motion) systems or low-cost graphic surveying systems through the use of digital photographs and different commercial software applications that enable the user a simple way to generate, like the previous systems, and edit both three-dimensional images and meshes or point clouds.

In recent years, the physical and digital modeling of three-dimensional models has entered with some urge, all accompanied by a certain evolution of software and 3D printing equipment which have become significantly cheaper.

Data management software has experienced a breakthrough in the sense of seeking the integration of information, and through a simple and accessible interface, proceed to modelling, making presentations and even making videos of the documented object, with scarce resources and from a graphic point of view.

The 3D printing has lately become a powerful tool, not only of display and spatial conception, but its potential goes beyond allowing the creation of prototypes in a quick and effective manner and even allowing the manufacture of items or unique elements at a reasonable cost. Its field of enlargement is quite wide from de artistic creation, the industrial designs, the engineering, the architecture, the archaeology and the biomedicine, only to mention some of the most relevant ones.
Another functioning of the models is to serve as a perceptive instrument so that people with visual impairment can have access to graphical and visual information. In the architectural heritage domain, there is a great deal of visual information, which is practically inaccessible for a blind person. The models used as a tactile perception tool allow these people with visual impairment to obtain information through the sense of touch.
Within the architectural heritage domain and the museology there are different approaches of study with reference to the development of devices directed to people with blindness or visual impairment. The tactile devices are used as didactic tools of support when visiting museums or spaces for cultural dissemination. We can establish the following types:

-Embossed sheets, draws and tactile diagrams

-Scale models and embossed plans
-Models

In recent years, certain techniques have been developed for the rapid manufacturing of prototypes, in particular of additive manufacturing, commonly known as printing in 3D, which have made possible the realization of these models in a very effective manner (Gual, J., Serrano, J. & Máñez, M. J. 2015).

In the field of architecture, several studies on the use of the architectural touch models produced through 3D printing have been carried out as the ones made by Voigt and Mr Martens. From the vast amount of digitized buildings belonging to the architectural heritage, it is possible to develop tactile models oriented to everyone and especially to people with visual disabilities. Through them, it facilitates the understanding of constructed architectural space (Gual, J., Puyuelo, M., & Lloveras, J., 2014; Gual, J., Puyuelo, M., & Lloveras, J. 2015a; Gual, J., Puyuelo, M., & Lloveras, J. (2015b & Gual, J., Puyuelo, M., Lloveras, J., & Merino, L. 2012).

At the national level, there are also remarkable experiences as the one carried out from the Universitat Jaume I, in collaboration with the Universitat Politècnica de València and Universitat Politècnica de Catalunya, with diverse positive experiences in the field of tactile drawings produced by printing 3D (Voigt, A., & Martens, B., 2006). As well as other experiences that aim at the development of models and tactile plans enabling the dissemination of local architectural heritage among people with visual problems and the general public (Máñez Pitarch, M.J., et alt., 2016).

The main objective of this chapter was to conduct an analysis of each of the methods on our testing ground, to determine their advantages and disadvantages, as well as to carry out a comparative study of the results obtained with each of them. We also sought to determine the degree of error or distortion each of them has by superimposing the models obtained for the same case study with the different methods, the suitability of using each of them depending on the item to be represented, and its volumetric conditions, location, setting, and so forth. The results thus obtained may be useful in subsequent graphic surveys both in the professional field of architecture, engineering and archaeology, and in the field of teaching.

BACKGROUND

In carrying out this study, the guidelines regarding the essential tasks to be observed when studying architectural heritage were followed, i.e. previous studies and/or the architectural survey. Annex B of "The Charter of Restoration" (which sets out instructions for the execution of architectural restorations), written in 1972 (Brandi & De Angelis 1972), established that the drafting of projects involving the restoration of a piece of architecture must be preceded by a careful study of the monument. These studies, known as previous studies, should be performed from different approaches to take into account aspects such as its position within the territorial context, either in the urban or in the rural setting, its typological aspects, formal properties and appearances, and the characteristics of its construction and the systems used, etc. both of the original building and of any additions and modifications carried out in later times. Moreover, previous studies should gather bibliographic, iconographic and archival research in order to collect as much historical data as possible.

Moreover, any restoration project should be based not only on a complete planimetric and photographic survey that is also interpreted under the metrological aspect, but also on the regulating lines and systems of proportions. Likewise, it must include a careful study to verify the stability conditions.

Any restorative or rehabilitative intervention on architectural and archaeological heritage requires, from our point of view, a survey which documents and provides rigorous evidence of its current state. The technologies used in these types of surveys oriented towards the geometric documentation of all kinds of heritage objects have advanced considerably in recent years. This has occurred despite the inexistence of paradigms on which to base the decisions concerning the protocols to be followed in the surveying process or the most appropriate techniques, depending on the type of object to be studied and the degree of definition required for each purpose.

In this sense the decision regarding the technology to be used should comply with the aims defined by the nature of the documentation that is required. The level of requirement may vary depending on the agents involved in each intervention (Barrera, 2006). Yet, as a reference to that level we could take into consideration the fact that the different degrees of documentation should be proportional to the historical interest of the architectural or archaeological element under examination, as well as being appropriate to the purpose of the study.

Therefore, the methodology followed in this study, as explained below, included the following activities:

1.- Locate the building within the corresponding urban, territorial, social, historical and artistic context. For this, a thorough historical and geographical search was carried out.

2.- Bibliographical, graphical and archival data about the building have been checked.

3.- On-site collection of data about the buildings and their subsequent graphical representation, that is to say, a graphical survey. With the aim of capturing the dimensional, metric, geometric and graphic features of the construction fieldwork was conducted.

4.- Finally, the results were compared and conclusions were drawn.

With the use of active image (laser scanning) systems, and the use of passive systems (camera), it can be verified that the result of the data collection of the architectural elements has been positive. Regardless of the chosen method, we would be in a position to proceed in a simple way to the generation of digital models with texture very attractive to the eye and easy to handle. Then, we will be able to proceed to the physical printing of the model to scale with a certain degree of definition, even with the help of specific low-cost software.

In recent years, multiple data management and integration tools have been introduced, able to unite with precision, in a single model, the documentation obtained through structured point clouds (with all the points oriented according to their normals). Those clouds are obtained from scanners and models from automatic systems of photography by techniques from Structure from Motion (SFM) and later exported in a compatible format for printing.

With the evolution of 3D technology, a wide variety of 3D printers has proliferated in the market (mostly low-cost) capable of printing at a small scale and cost, models made in a simple and automatic way.

A COMPARATIVE STUDY OF DIFFERENT GRAPHIC SURVEYING METHODS APPLIED TO THE PORTAL OF “SAN MIGUEL” THE CHURCH OF “NUESTRA SEÑORA DE LA ASUNCIÓN” IN VISTABELLA

The testing ground

There is a church in the town of Vistabella del Maestrazgo, in Castellón (Spain), with two great Renaissance Portals. The one called lateral or secondary is the one taken as a testing ground, reference or model. This Portal, devoted to “San Miguel”, has been greatly studied by this group of researchers from the Universitat Jaume I.

Geographical, historical and social context

Vistabella del Maestrazgo is a small town located at the northwestern end of the province of Castellón, in the Valencian Community, Spain. The town is located about 1249 metres above sea level.

Some of the medieval walls and buildings, built after the Christian Reconquest from the Arabs by Jaime I of Aragon, are still standing in the town of Vistabella del Maestrazgo. The medieval village was developed following the city model that recalls the ancient Roman hippodamic, or grid plan cities, with rectangular roughly orthogonal blocks built upon a central cross, in the middle of which there is a square.

After the Christian reconquer, the village was owned by several lords. Until in 1303 Vistabella was sold by its lord, Guillem d'Anglesola, to the Order of the Temple. Upon the extinction of the Order of the Temple in 1312. In 1317 the Order of Montesa was created, at which point (and until the 19th century) Vistabella belonged to the Order of Montesa. In the fourteenth century a large territory in the north of Castellón took the name of Maestrazgo de Montesa, since it was under the government economic power and jurisdiction of the Order of Montesa.

In the early of the seventeenth century, a new plant temple was built in the village of Vistabella, following the Renaissance style that prevailed at that time: the Parish Church of “Nuestra Señora de la Asunción”. The building is located in the northeast of the village outside the mediaeval town walls, in the “Plaça del Dau”, which is the main square of the village. It was declared a Listed Building of Cultural Interest, classified as a monument, on 28th September 2007 (BOE, 2008).

From the outside, it can be seen to be a freestanding building with a rectangular layout, and having another small rectangle attached at the head. The main features that stand out in its southward-facing main façade are two portals and the bell tower. Particularly interesting is the Main Portal, framed by an impressive *retablo*-façade, sheltered by a pointed arch. Built of masonry and stonework, the main body is covered with a gable tile roof, the apse is covered with a five-water tile roof, and the header with a single-slope tile roof, which is lower than the previous constructions, as we can see on Figure 1.

Its interior consists of a main nave and chapels between five-section buttresses, an octagonal chancel and an ambulatory with a chapel and sacristy in the header. Both the nave and the chancel are covered with stellate ribbed vaults and the side chapels have simple ribbed vaults.

Figure 1.General view of the main façade of the Church "Nuestra Señora de la Asunción" in Vistabella del Maestrazgo.

Scope of the study

The present study aims show the results obtained in a particular study case by comparing different methods of graphic representation that are used in architectural heritage to achieve a successful graphical representation of its elements and finally the physical modelling of the building.

When intervening on heritage buildings and archaeological remains, it is fundamental to understand the state they are in today and what it was like when they were built. Either in a preliminary study or in the project phase, a rigorous and accurate process of graphic documentation needs to be carried out before making any decision or undertaking any technical work on them.

The first step, prior to any fieldwork, is to find as much documentary and historical background material as possible, whether in the form of administrative documentation resulting from the possible drafting of projects or actions carried out on the element previously or through documents from historical files, bibliographic or church fabric books, among others. Then it is necessary to search for and collect all existing graphic documentation, through old photographs, engravings, or paintings and so on, with the aim of revealing the status of the element that we want to represent or document graphically.

From then on, and depending on the conditions of the setting and those of the actual object to be represented, the most appropriate method of working can be chosen for each particular case. In this study case, we have used the Portal of "San Miguel" as a testing ground to see the possible outcomes, and thus subsequently draw conclusions about the different systems of documentation used and how they can serve as a starting point or help when it comes to undertaking new works.

For this reason, a hybrid system of data collection was used, consisting in sharing traditional system processes and more up-to-date systems, using low-cost software or applications as far as possible for the management and post-processing of the collected data.

It is therefore becoming more and more common to demand that data collection in the documentation of survey elements be performed relatively quickly and with a high level of accuracy. The current trend is to use advanced graphic and geometric documentation tools by means of the mass capture methods (3D scanner) and terrestrial photogrammetry (Yastikli, 2007), all accompanied by the additional support of classical and more advanced topographical methods. This jointed or hybrid way achieves high rates of accuracy and cost-effective processes, thereby making this process even more sustainable.

The graphic documentation that is generally obtained and required for subsequent phases (project, damage assessment, enhancement, etc.) is usually focused on the conventional orthodox planimetric, scaled and two-dimensional dihedral representation of the object that has been measured (floor layouts, sections, elevations) on paper and, in some cases, with a complete absence of colour (i.e. in black and white). At the most, in certain cases, we can observe the presence of shades of grey or a hierarchy of line thicknesses or the use of colours in reference marks or shaded areas that are completed with the inclusion of colour or black and white orthophotos. However, technological and visual advancement make it increasingly more necessary to obtain, provide and record 3D data and then use them to create a three-dimensional or virtual model that graphically represents both the geometry of the building and the appearance of its different faces, shapes and colours, and even photorealistic computer graphics of transformed reality can be created. In this sense, the application of photogrammetry has progressed over the last few decades. Recent developments include capturing point clouds using a 3D Laser Scanner or Terrestrial Laser Scanning combined with photography (Garfella et al., 2012).

Once the results from the point clouds have been obtained and the meshes created, a physical printed model at scale can be generated. These models can be made in volume conforming the three dimensions or as a bas-relief on a surface, creating a tangible image, especially suitable for the representation of surface architectural elements such as façades and hollows.

Methodology

Survey methods can be divided into three main groups: the first and most classical involves traditional techniques and the use of the simplest devices to measure the object directly. The second group consists of topographic methods and techniques. Finally, the third group includes methods based on photography (Martinez-Espejo, 2014).

- Direct measurement methods. Of all these methods, the measuring tape has been the most frequently used instrument, and it offers adequate quality if chained measurements are not performed. Metal and invar tapes generally offer better results because they are less subject to deformation due to stretching. Currently, manual laser meters are replacing measuring tapes, as they are being used increasingly more often, but the methodology is analogous. Besides the tape measures, we found other support tools that were also commonly employed, such as the plummet for defining the vertical, a water level to define the horizontal, and an archaeologist's comb for measuring mouldings.

- Topographic methods. These can be categorised in three groups according to the type of coordinates that they represent: planimetric (ordinate and abscissa referenced to a Cartesian system, triangulation and/or trilateration, or polygonation), altimetrical (using topographic levels or total stations) or the three-dimensional position directly (planimetric survey plus levelling taken by theodolites, total stations and 3D laser scanners).

- Photogrammetric methods. Depending on the data provided, these may be divided into planimetric surveys (monoscopic photogrammetric methods, stereophotogrammetric methods, simple rectification, mosaic and orthophotography) or three-dimensional surveys (monoscopic photogrammetric methods, stereophotogrammetric methods and chained rectification).

Of all these methods, we will focus on three-dimensional surveying with advanced tools, and especially on two types of surveys: “Image-based modelling” and “Range-based modelling”. These two methods were chosen as they are currently the most widely used to obtain polygonal models with a high level of detail (Lerma, Cabrelles, Navarro, & Seguí, 2011).

Those instruments that allow the generation of a 3D image of the framed scene have to be established as three-dimensional sensors. These 3D images may be either the representation of the external surface of an object or the representation of everything that is inside the volume that is enclosed by this surface. In terms of their characteristics, the three-dimensional sensors can be classified in different ways. It is worth noting a particular type of sensor that uses non-ionised light radiation to explore the surface of an object, without any physical contact. Depending on the nature of the light used to take the measurement, we can speak of passive and active three-dimensional sensors. The passive ones are those that use the natural daytime light resulting from sunlight in open spaces or in closed environments using generic illuminators located in a random fashion with respect to the object. Active ones are, however, those that need encoded light to play a role in the measurement process.

In surveying with passive sensors, data is acquired through inexpensive and easily transportable systems. The images need a mathematical model to obtain information about the spatial position of the points of the object from two-dimensional images. To obtain accurate studies, a certain amount of experience is required in data collection and in processing the recorded information.

When surveying with active sensors, distances are surveyed directly and produce three-dimensional measurements of the surveyed object. Typical examples are the laser scanner (Time of Flight or triangulation) or beam projection systems (stripe projection system). The level of detail obtained by the distance sensors varies from tenths of a micron to centimetres. Generally, they are easy to use. Some of its drawbacks are that they are costly, bulky, specific to a distance interval and volume, and present problems with some materials. However, distance sensors are a frequently used and convenient working tool, especially in the case of not very experienced users, since they allow millions of points to be surveyed in a few minutes.

For this study case, we chose to use a hybrid system of data collection, consisting of both traditional and cutting edge processes and systems. For the management and post-processing of the data collected, we used low-cost software and applications whenever possible. The traditional data collection methods allow us to obtain fast and accurate direct contact with the actual building or piece to be surveyed, thereby allowing their materials, shapes, imperfections, texture and colour (Garfella, Máñez, Martínez & Cabeza, 2013) to be felt – something we can hardly appreciate if this is not carried out in a direct sensory way (see Figure 2). However, the limits of these methods are those of human perception itself, and often have to resort to high travel costs and auxiliary means in order to endow a certain study with some degree of scientific rigour. Therefore, in this case we have used these traditional methods to make sketches and direct measurement with measuring tapes, profile combs, measuring tapes and manual laser distance meters to represent and measure the elements that are in the field of the human scale, without the need to employ unusual and expensive auxiliary media.

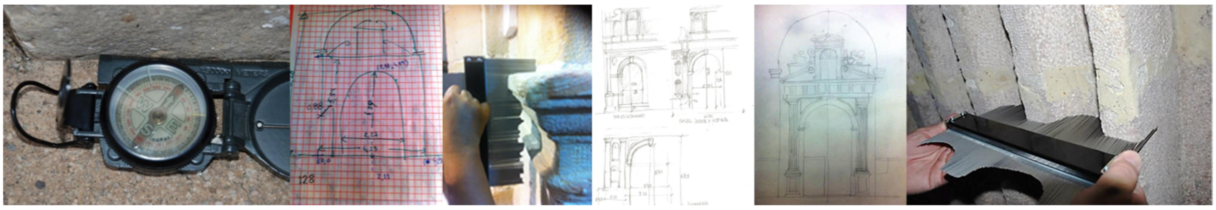

Figure 2. Examples of the traditional data collection method

Because of the technological means available to us nowadays, we did not want to miss the opportunity to improve the value of data collection by traditional and conventional methods using the topographic support based on the equipment we had. We have been able to provide topographic support to the manual fieldwork by collecting topographic data from various significant points on the model using a robotic laser-measurement calibrated total station with image and reflectorless measurement. This station includes among its main tools two Topcon iS-203 internal coaxial digital panoramic cameras with an apparent resolution equivalent to 4.8 megapixels, with an angular accuracy of ± 3" (1.0 mgon). This equipment ensured metric rigour in the measurements taken in the field. A single positioning of the equipment and a single reading by point radiation were performed in an attempt to eliminate as far as was feasible any possible errors due to the equipment or changes in position (see Figures 3 & 4). This topographic support was improved by giving the values of the local coordinates the overall position obtained by means of a Trimble model 5700, RTK GPS global positioning device, which is accurate to within centimetres.

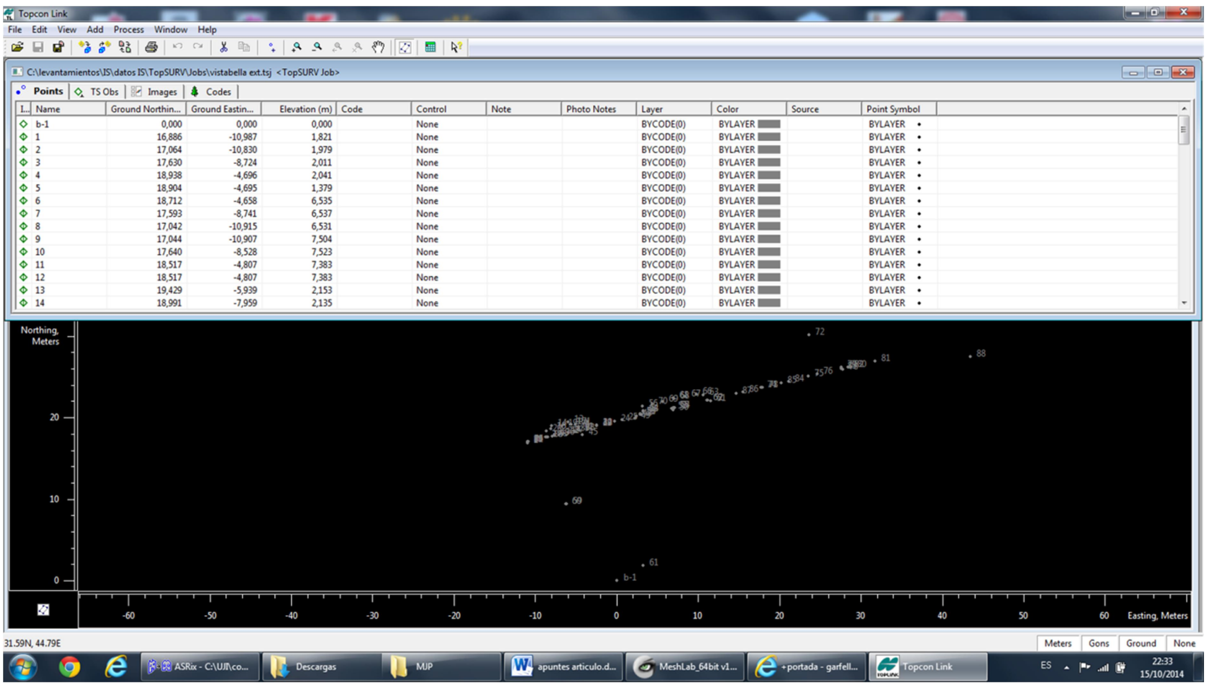

Figure 3. Topography data collection and coordinate data chart position on the floor layout as provided by Topcon Link v. 8.2. software

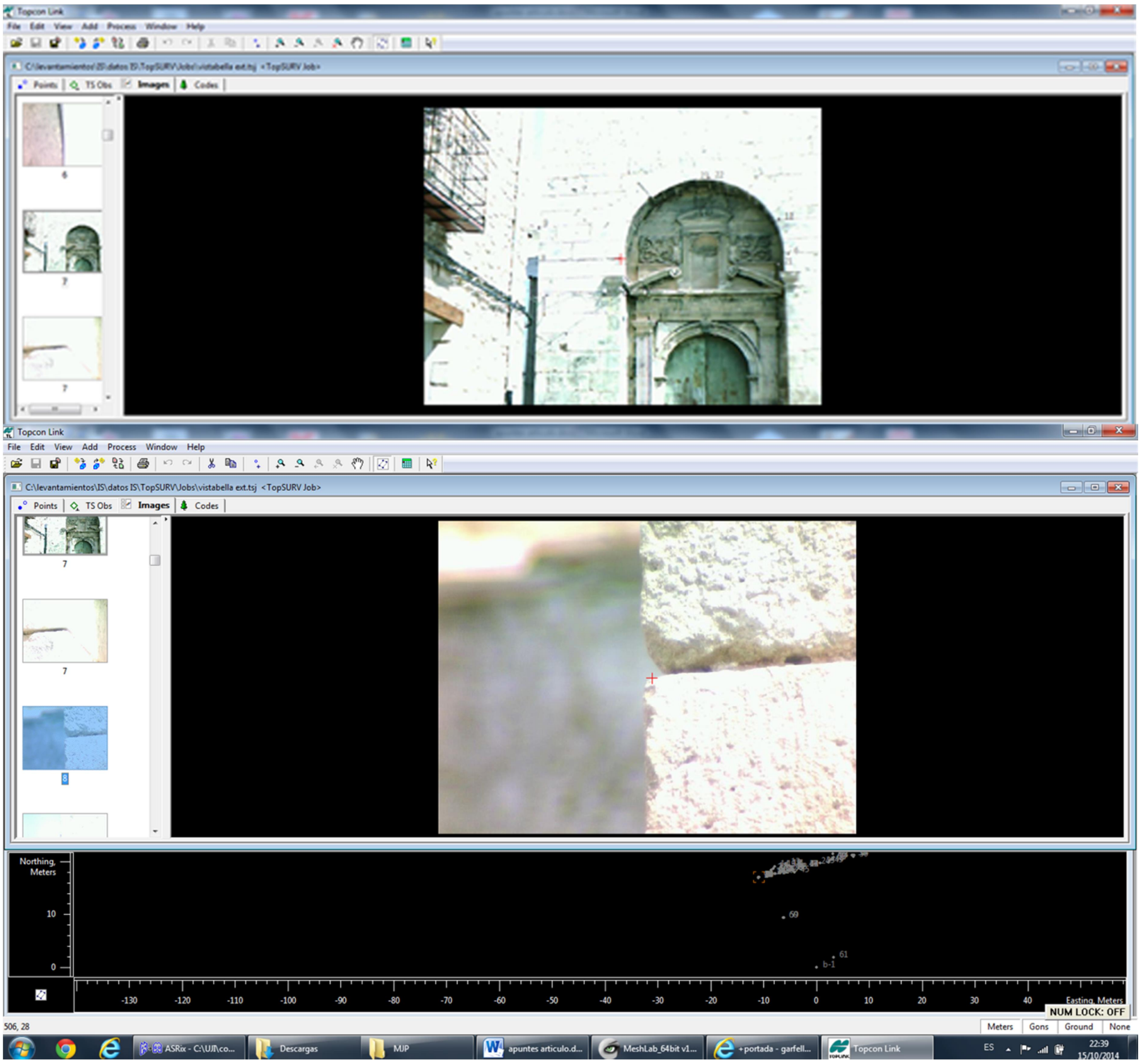

Figure 4. Image showing the collection of photographic data with two different zoom lenses, one more panoramic and the other more detailed, as shown by Topcon Link v. 8.2. software

We also documented the Portal by means of mass non-intrusive data collection using a 3D terrestrial laser scanner based on flight time or pulses with a long-range invisible class one Topcon GLS 1500 laser. The reading rate of the Topcon is 30,000 points per second and has an accuracy of 4 mm at a scan range of up to 150 m and an angular precision of 6" (2.0 mgon), associated to a 2.0-megapixel integrated coaxially aligned digital camera. A single point was established from which to perform a frontal scan of the Portal. This point was located about 15 m away and a scan resolution of 1x1 mm was set at this distance. A normal field of view of 70° (± 35°) was set in order to cover the whole surface of the Portal. The scanner referred to above gives us a densely structured cloud of points. Because we only used one station position with a local coordinate system, no registration was needed. We can then transfer the data to a georeferenced system, supported by GPS data if necessary. The scanner gives us the local coordinate system (x,y,z), along with the intensity of the refraction of the laser beam that bounces off the surface of the object to be measured. In the lab and using specific software, it becomes possible to deduce, among other things, the colour index of each point with its

RGB (Red, Green and Blue) or RYGCB (Red, Yellow, Green, Cyan and Blue) index. This is thanks to the photos taken coaxially by the equipment during data collection, in which the management software applies a colour pixel from the internal camera to each point in the cloud, since the point cloud and the photographs are linked because they have been produced at the same time during the process of measuring the piece. Therefore, we can obtain almost realistic models where the colour takes on its highest expression and, depending on the quality of the point cloud mesh and the pixel quality of the camera, we can accomplish effects with very realistic colours. This in turn will enable us to create a realistic virtual three-dimensional model that is very close to the virtual model we are looking for. The time needed to scan a surface of 6 x 10 m is 15’, which produces a dense point cloud of 677,426 points (see Figure 5). The point cloud thus obtained does not need any registration because we have only employed one station position and only one point cloud has been obtained.

In this case, point collection with both the total station and the scanner was performed without placing artificial targets with a known reflection index. Instead natural targets or support points on the building itself were chosen for use, determined by the operator’s own experience.

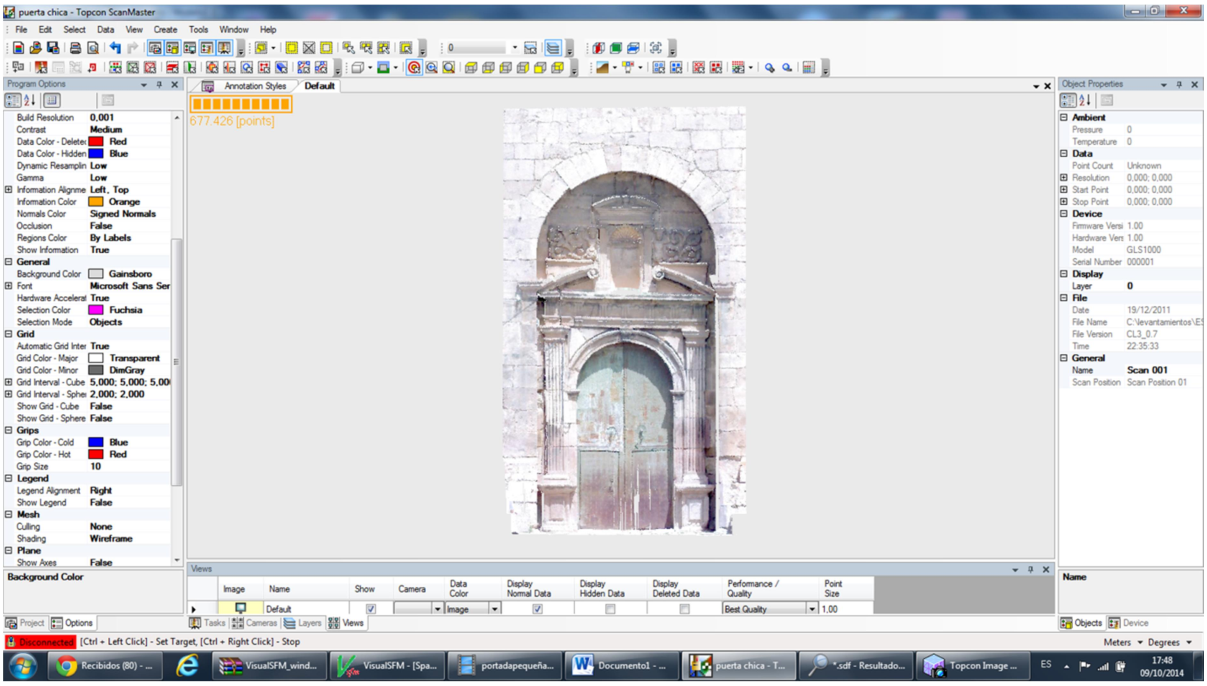

Figure 5. Ortho-image of the point cloud obtained using the scanner, grid step 1 x 1 cm and processed with Topcon Scanmaster software

The standard measurements or data collection were performed with the automatically activated two-axes angular compensator (horizontal and vertical), both for the scanner and for the total station.

The software provides us with meshes and an application with simple textures based on the construction of irregular triangular meshes, which in the case we are studying would cover about 1,272,266 units and last about three hours (see Figure 6).

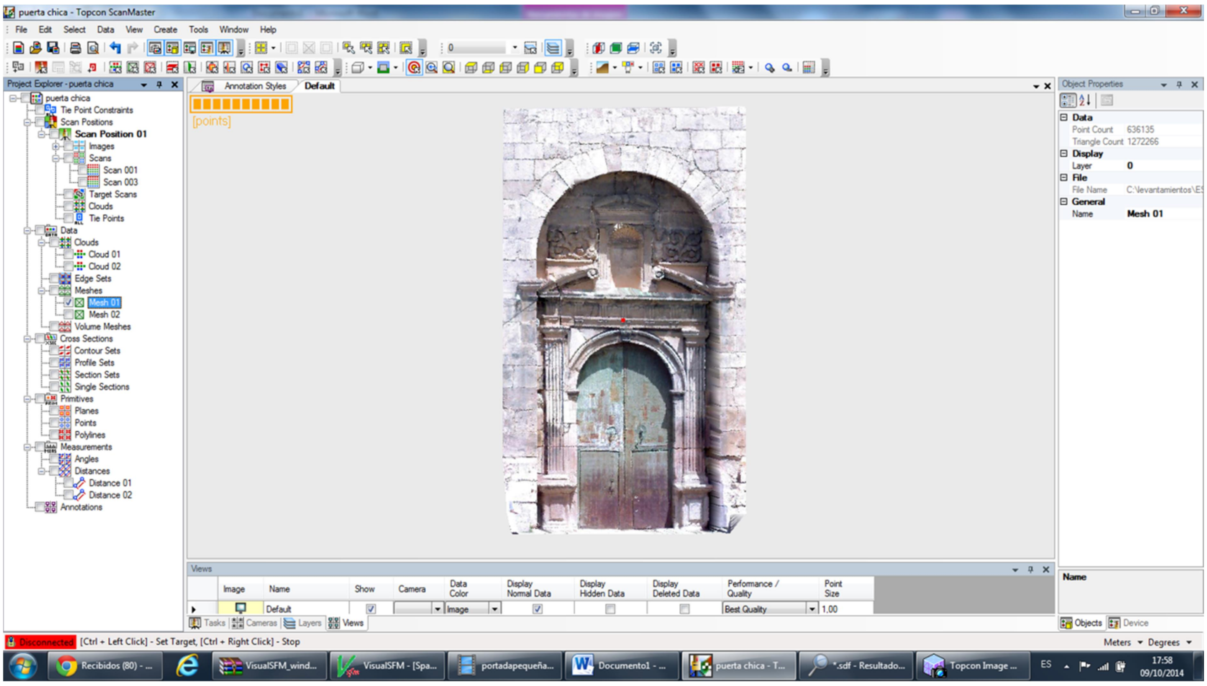

Figure 6. Ortho-image of the mesh and texture of the point cloud with an irregular triangular mesh (TIM)

Finally, the different data collections were completed with a 10.2-megapixel Nikon D-80 digital camera and a Nikon 5200 24-megapixel camera, fitted with a conventional lens between 18-135 mm, with a focal aperture of f/3.5-5.6 and Sigma wide-angle 8-16 mm lens, and focal aperture of f/4.5 to 5.6 mm.

With the photos captured with the 10.2-megapixel camera, plus the help of topography and all the notes made while performing the manual data collection, we were able to undertake the photogrammetric rectification of the façade with a certain degree of rigour. Prior to moving on to this stage, the camera and the focal opening were calibrated on graph paper, using a low-cost program. Thus, we were able to vectorise the Portal with some precision, although for the rectification work to be easily vectorisable it had to be carried out plane by plane both parallel and perpendicular to the portal (see Figure7).

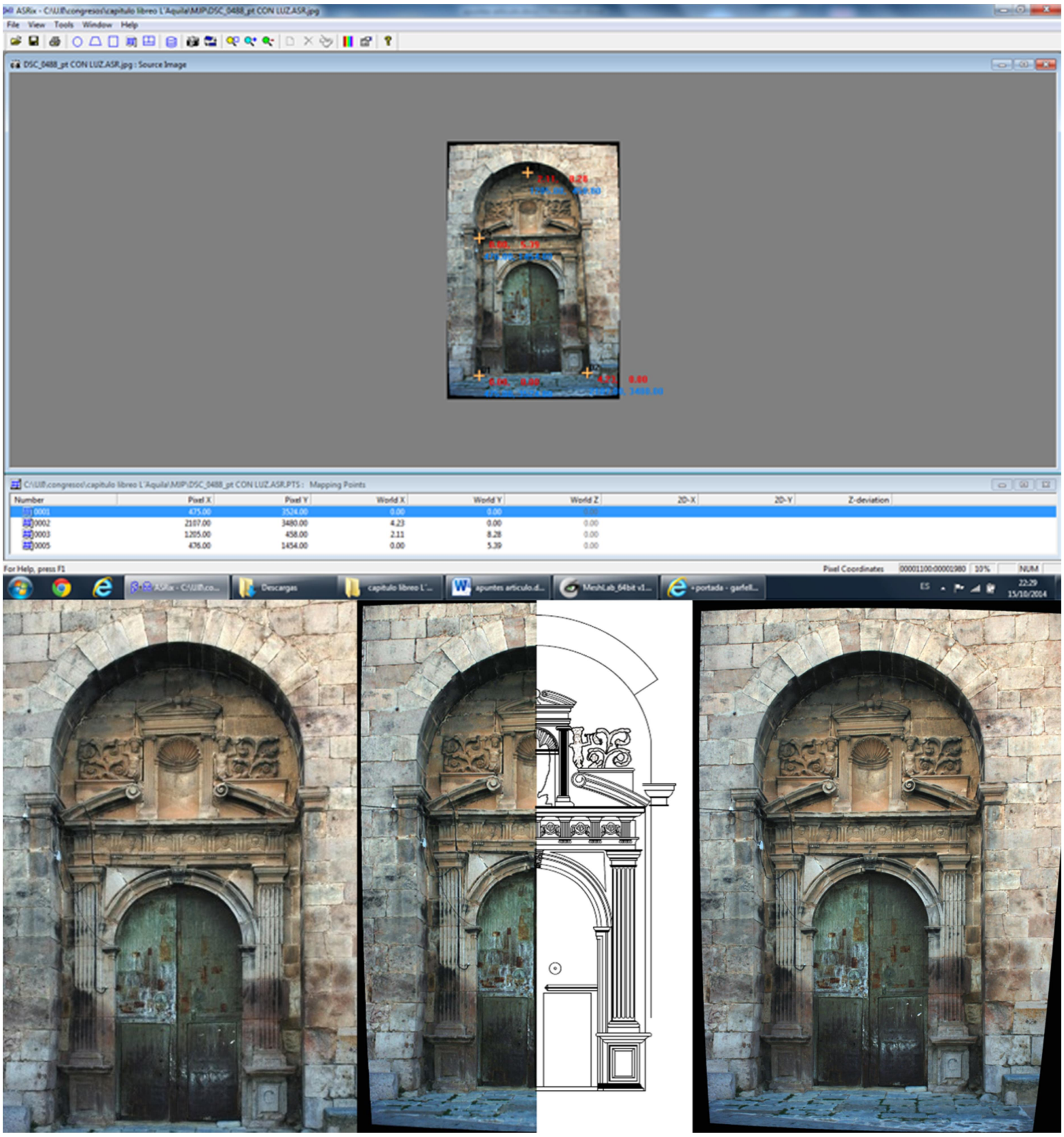

Figure 7. Ortho-image of the process of photogrammetric rectification using Axris software from the current status, its vectorisation, and rectified image

Camera calibration and image orientation are critical processes. In the calibration phase it is important to distinguish between internal and external parameters of the cameras. The internal orientation parameters consist of: the constant of the camera (or focal length, f), position of the main point (x0, y0) and several additional parameters used to model possible system errors due to, for example, lens distortion. The external orientation parameters consist of: the three spatial coordinates (position of the camera in space, generally indicated by X0, Y0, Z0) and three rotations of the prospectic centre of the camera in space (Pérez et al.,2007). Obtaining both internal and external camera parameters can generally be achieved using two images (relative orientation) or by a set of images (Bundle solution).

With at least two of the photos taken of the façade, one to the right and the other to the left, we can easily create a stereoscopic 3D view of the portal based on anaglyph images of the object aided by the free software application Anamarker (see Figure 8).

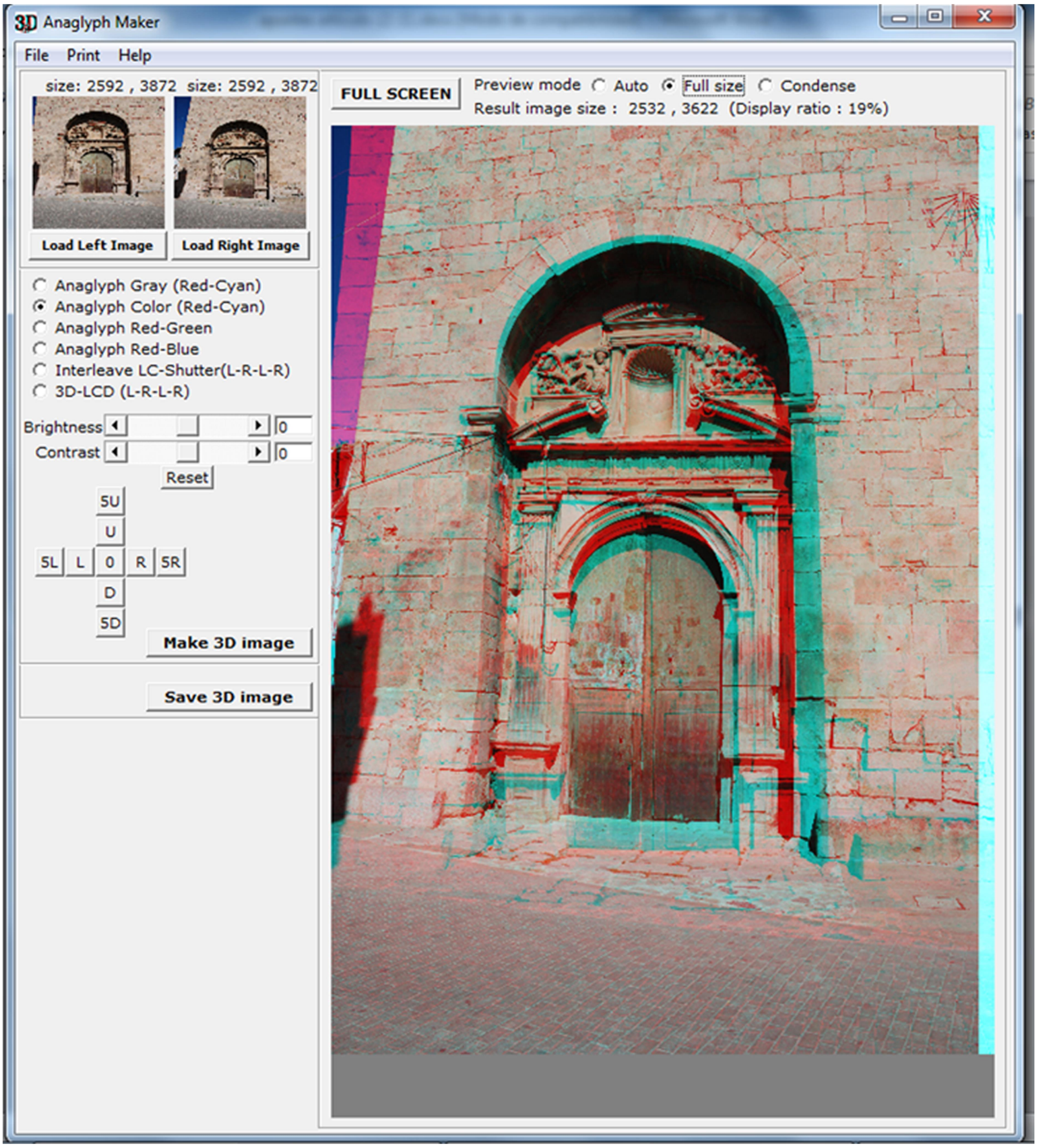

Figure 8. Anaglyph image of the façade created using Anamarker software

The next step was to document the portal by using cutting edge photographic capture systems, based on SfM (Structure for Motion), which consists in setting up point clouds or mesh models from groupings of the projections from different photographs by matching homologous points in the different exposures. In this process, no specific planning is needed, providing that the overlapping surface between the different photographs is large enough. This system is also known as Automated Digital Photogrammetry. To achieve this, we used a commercial low-cost software application called PhotoScan by Agisoft and another free one with similar features, 123 Catch by Autodesk, as a testing ground.

With this purpose in mind, we took 22 digital photos of the area around the portal, from left to right, with the Nikon D-5200 with a resolution of 24 megapixels and a separation between photographic exposures of about one metre. First we used PhotoScan to automatically orientate the 22 photographs, and then we went on to create a dense cloud of points that automatically provided us with 3,743,716 points (see Figure 9).

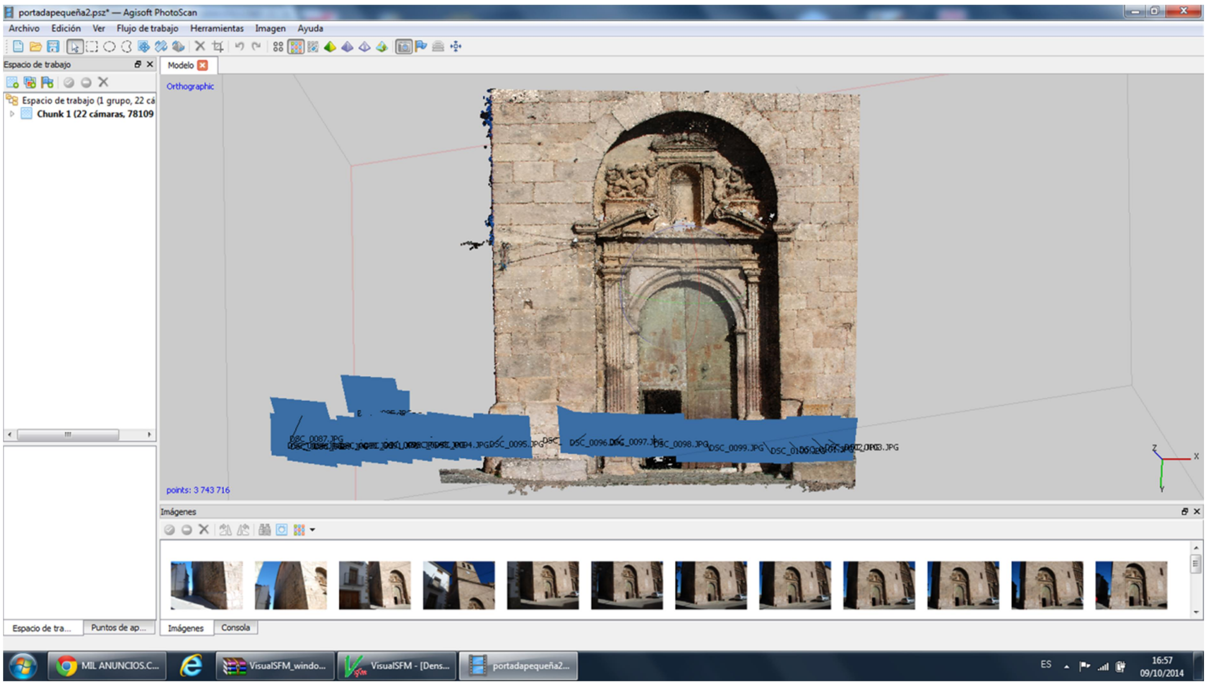

Figure 9. Orthographic view of the dense cloud of points obtained with the software Pothoscan from 22 photo captures

Once the dense cloud of points has been obtained, we can go on to carry out the structured meshing and texturing, which are also performed automatically, the result being 193,808 faces and 97,658 vertices. The software application offers the possibility of filling any holes in the mesh, although we did not make use of this feature so that subsequent comparisons among the different models would be similar and homogeneous (see Figure10).

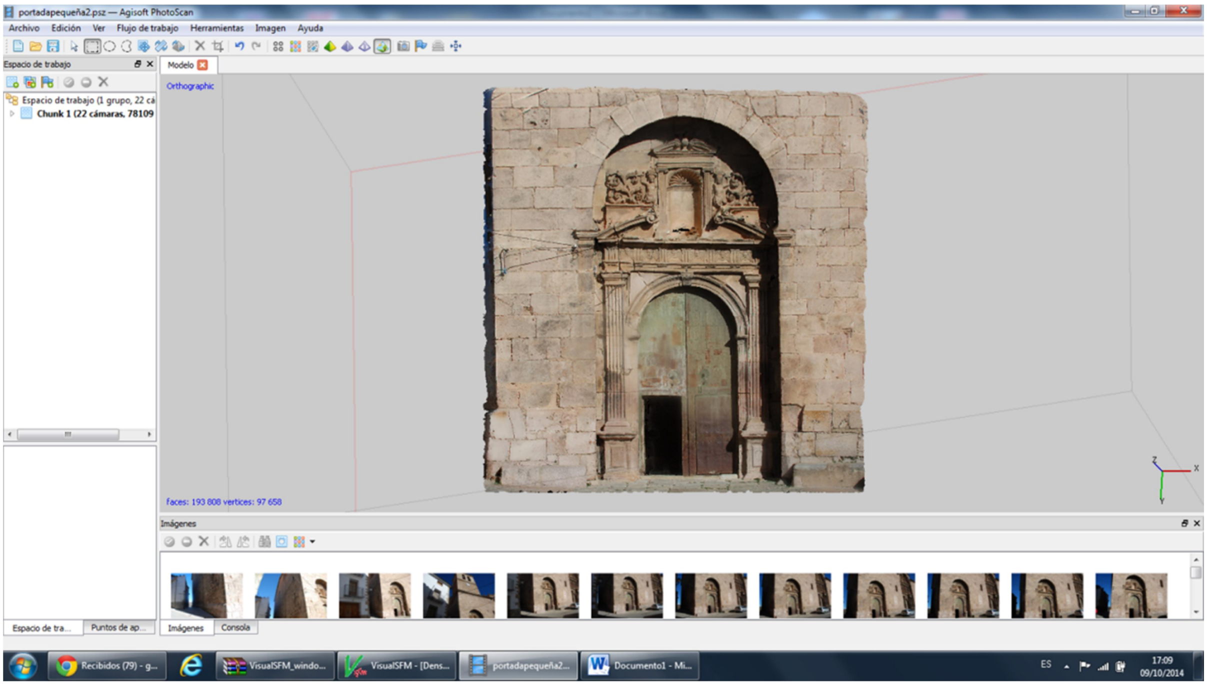

Figure 10. Orthographic image of the texture obtained

After meshing and texturing, we can automatically obtain different images of the portal by applying colour and lights (see Figure11).

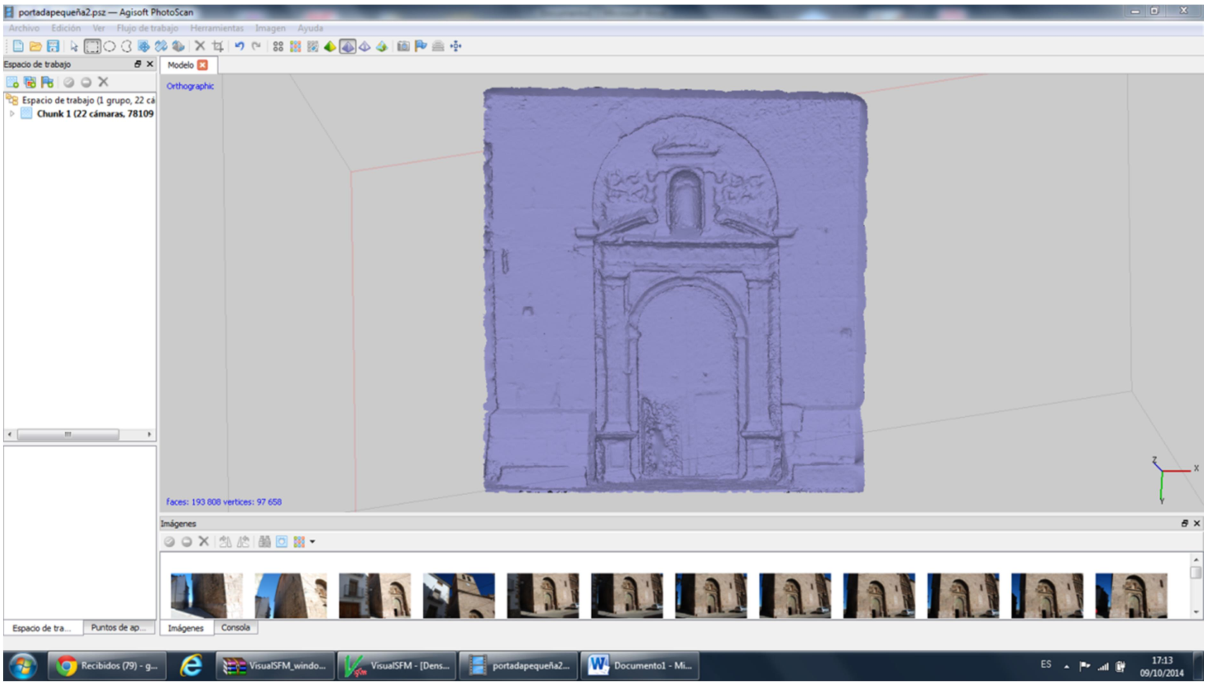

Figure 11. Orthographic image of monochrome shading

Finally, we export the point cloud obtained in (ASCII compatible) TXT format, where data include relative position (x, y, z), colour (R, G, B) and normal vectors in the three directions.
The next step is to process the same 22 photographs in the same way using 123 Catch software, which automatically aligns the photographs and creates points, meshes and textures. We have the possibility to select a working area and crop and clean it (see Figures 12 & 13).

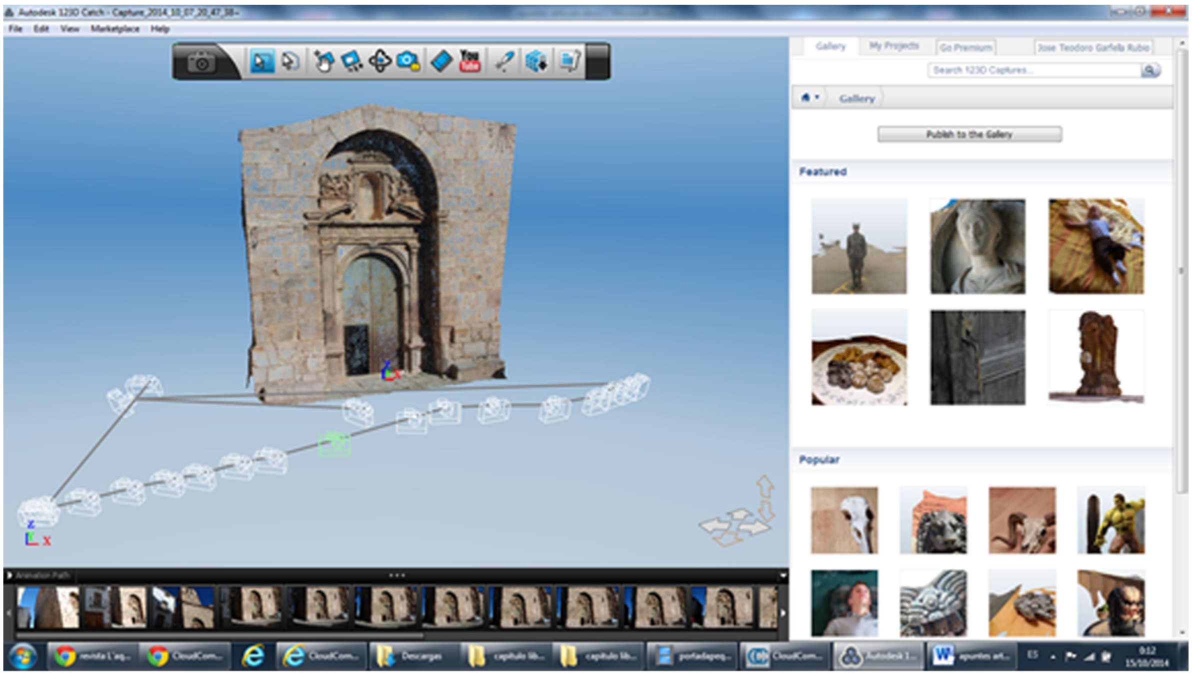

Figure 12. Image alignment and the texture obtained

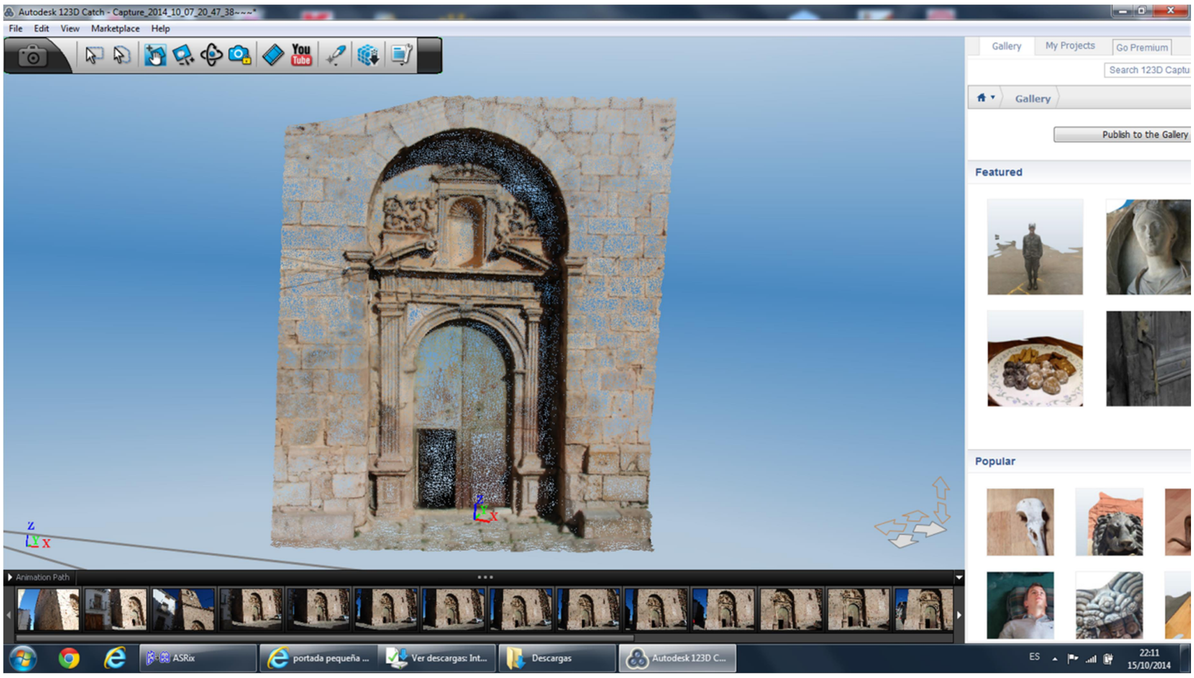

Figure 13. Image point cloud and mesh

Once the surface has been discriminated, we export the data thus obtained in OBJ format, which is compatible with many commercial mesh or solid applications such as MeshLab; on opening this free software application we checked the results and found that in this case we had obtained 73,030 points (see Figure14).

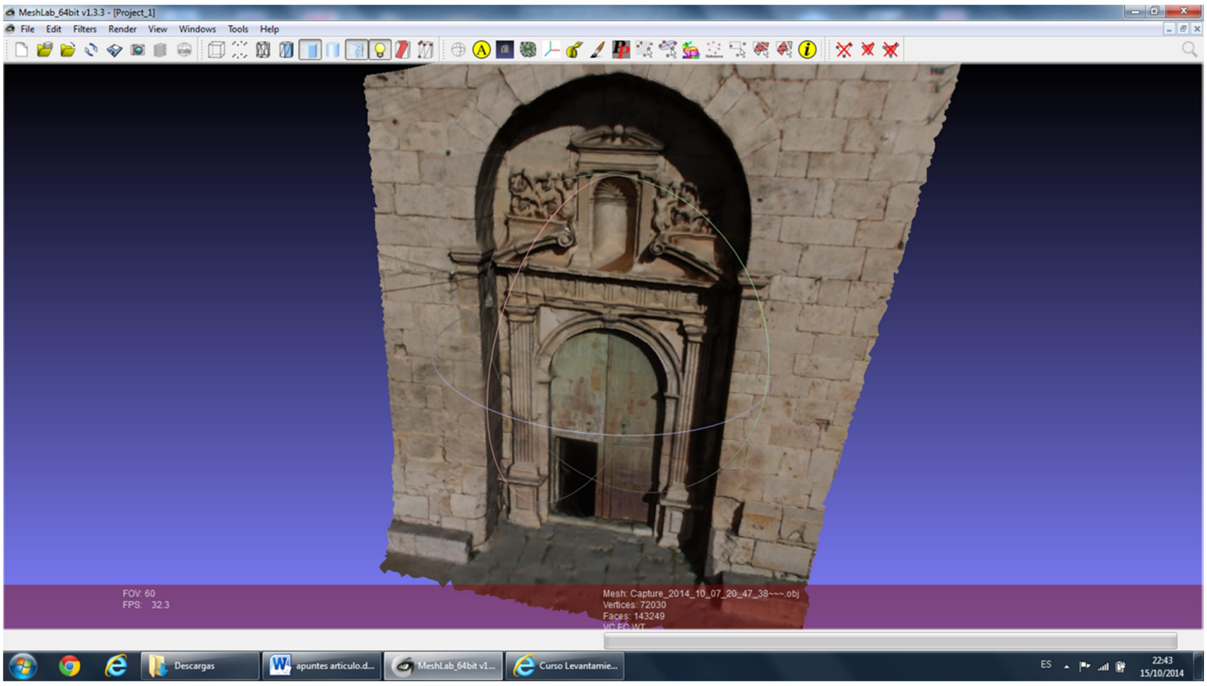

Figure 14. Point cloud and mesh obtained with 123 Catch using MeshLab software

MeshLab is a very interesting free software application that has a powerful engine for moving and managing data on the screen and is capable of moving millions of points with ease almost instantly. Likewise, this application allows us to improve, soften and light the meshes and texture obtained, thus enabling us to construct a solid model that can easily be printed on 3D printers. Another important feature of this application is the number of formats that are supported for import as well as export. We therefore employ it as an interface for improving application data that are exclusive of measuring equipment, allowing us export to more common files.

Method of graphic restitution

Modelling or 3D printing can be classified into two major groups, according to the form of creation of the model. One of them will be by addition, or Additive Manufacturing, (AM), consisting mainly in adding particles or elements to the object, to create the total volume. The other method is by subtraction; consisting in removing or shaping material to get the desired form.

The Creation of the physical models by addition has been carried out by different techniques of rapid prototyping of prototypes by the method of Additive Manufacturing, (AM), known as "3D printing". During the process of manufacture or construction of its parts, the material is deposited slowly so that it progressively creates the geometry of the piece; they are also known, as in layers manufacturing techniques (Máñez Pitarch, M.J. et alt., 2016 & Martínez-Moya, J.A., Gual-Ortí, J. & Máñez-

Pitarch, M.J., 2018). Three printing techniques have been used: printing by deposition of plastic thread plastic (FDM), stereolithography (SLA), and printing powder (3DP).

The FDM (Fused Deposition Modeling) printer is fed by rolls plastic filaments PET (polyethylene terephthalate) based, PLA (polylactic acid) or ABS (acrylonitrile butadiene styrene), which melts through an extruder head, which deposits it in its precise corresponding position, layer by layer, on the printing bed. After the machine is warmed, a strand of material 1.75 mm or 2.85 mm diameter is extruded on the platform through a nozzle that moves on 3 axes (x, y, z). The platform descends a level with each new layer applied, until the object is printed. During printing, depending on the object to print, the use of supports is required to improve the quality of the model. Its function is to support the protruding parts of the 3D model, given that, if not done, certain models can't be printed. These supports, in our case, have been built with the same material as the printed object, which once completed must be cut or removed. The used equipment has been the WANHAO Duplicator Printer i3Plus with a print speed of 50-250 mm and a thickness of 0.01 mm with strand of 1.75 mm in diameter has been used to print with wire. The maximum print size is 200 x 200 x 200 mm. The material used has been Green PLA plastic (see Fig. 15).

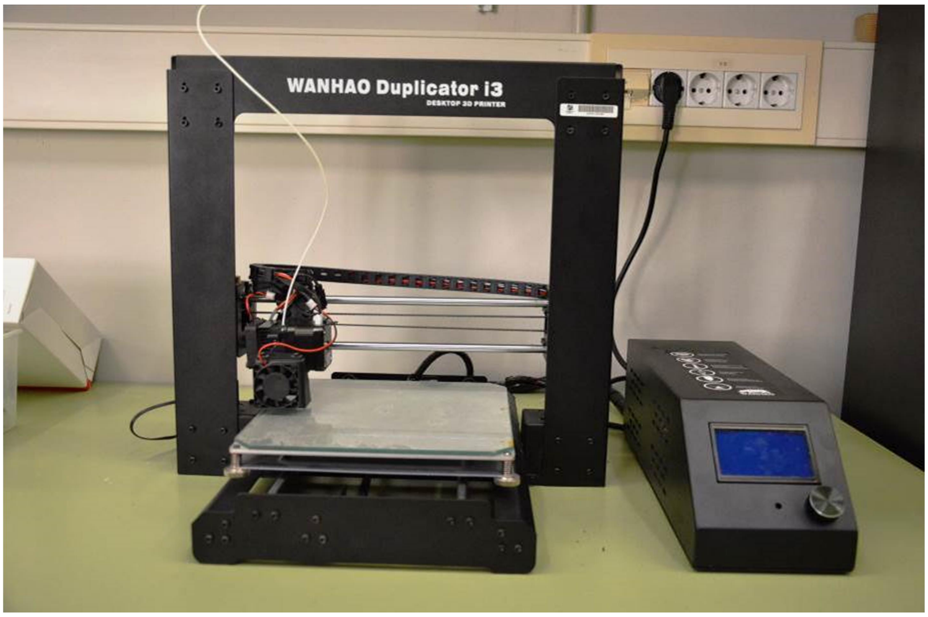

Figure 15. Image deposition printer.

The second experienced and used additive printer has been the one known as resin printer. Through the process of Stereolithography (SLA), it uses as printing material a liquid resin solidified under the effect of ultraviolet (light curing). This printer works downward, from top to bottom, in such a way that the photosensitive liquid is introduced on a base tray, which must be perfectly levelled, on which, in our case, a light beam is projected layer by layer, that by striking the photosensitive liquid solidifies and sets up the shape of the object to print. A proper arrangement of the part to be printed must be planned in order to make it freestanding during the printing process. For resin printing it has been used a 3D printer XYZprinting Nobel 1.0a with Stereolithography (SLA) technology. The printable area maximum size is 128 x 128 x 200 mm and the material used has been transparent photosensitive acrylic resin. A thickness of 0.05 mm has been used. (see Fig. 16).

Figure 16. Resin printer.

The powder printer used, as previously indicated, works creating the model through the addition of material, prior injection on a foundation of a binder material, which, pass after pass, gets attached and secured on a specific clogged dust tray. In successive passes, it forms and grows upright. These models are embedded in a block of loose powder, so at the end a removal of the material and removal of the interior of the model by manual means must be done, suction or blast of air as the case may be. These models are often designed with interior holes for the evacuation of the dust inside the model, leaving initially printed the exterior surface or the perimeter with a certain thickness, which allows optimizing the material. The used equipment has been the 3D Mod. Z 310 Printer. In this case the material is special powder printing zp® 150-caking zb® 60. The maximum print size is 280 x 220 x 200 mm and the thickness is of 0.1 mm. (see Fig. 17).

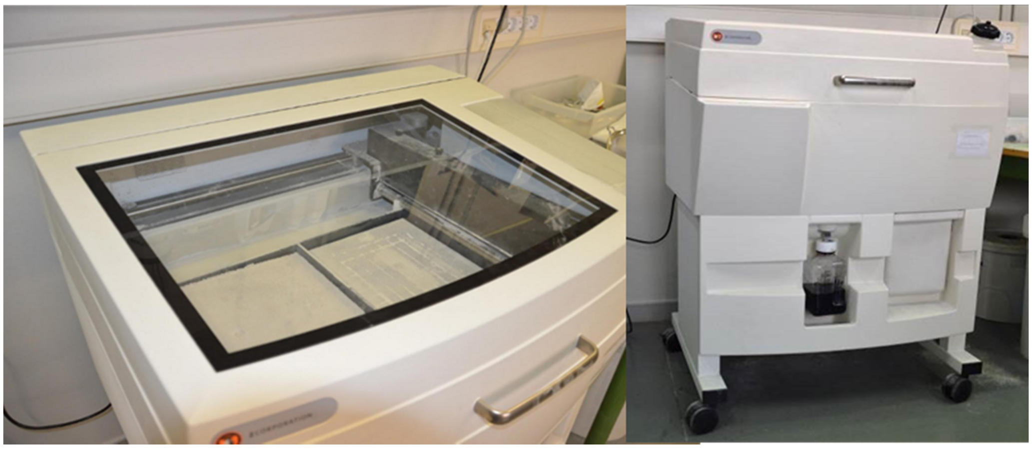

Figure 17. Image printer powder

Zprint team's own software, which transfers the digital format in STL or OBJ format to the printer, allows us to have a visualization of the part to be printed, it also allows us to move it, shift it, scale it and adjust it when necessary to the the printing platform's size. It can even simulate the reproduction of the part (see Fig. 19) and has a small rendering engine. We are currently investigating the use of atomized ceramic material.

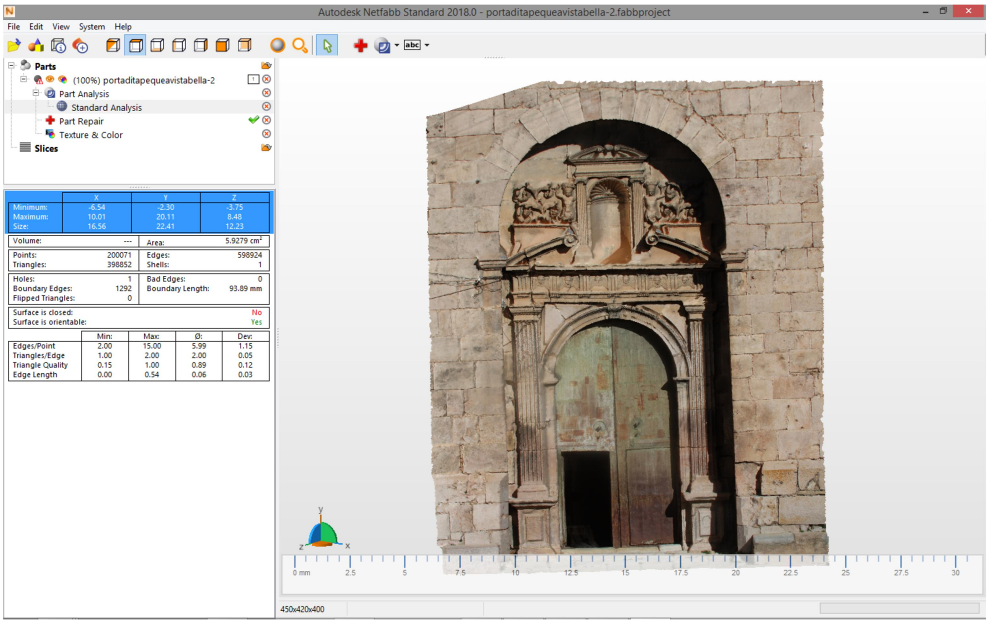

Figure 19. Image of the cover through the Netfabb program

Finally, a subtraction system has been used, consisting fundamentally in a numerically controlled table top milling machine.

With all the documentation procedures, it has been possible to generate a surface in three dimensions through the point clouds and the integration software with more or less depth. For that, before printing, a solid digital volumetric model has to be generated, able to be recognized by the various printers, usually in STL format. These models should be perimeter closed and have no holes. Depending on the printer used, those models may be completely solid on the interior or lightened only with a surface layer of finite thickness.

Prior to the printing process, it is suitable to proceed with a verification of the digital model, in order to check that there are no gaps in the surface and that the generated meshes are completely closed, as well as check that the faces of the mesh are oriented according to its normal. Otherwise, the printing process will fail. This verification process is carried out by means of specific software, in this specific case Autodesk Netfabb tool has been used. (see Fig. 20)..

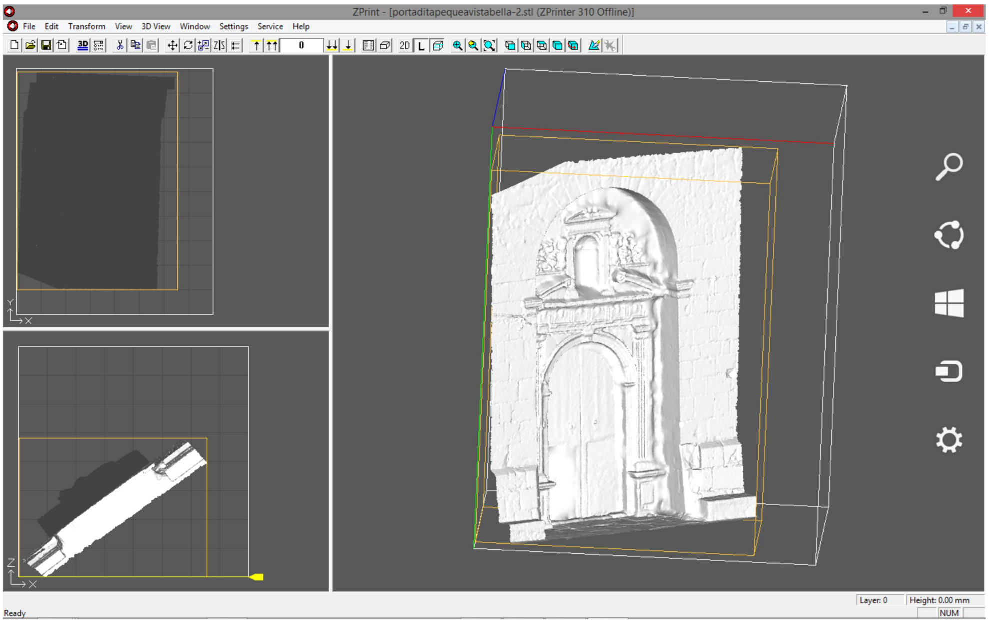

Figure 20. Image program management for the printer from dust.

The management software used to transfer the model to the printer has been the Cura (see Fig. 21).

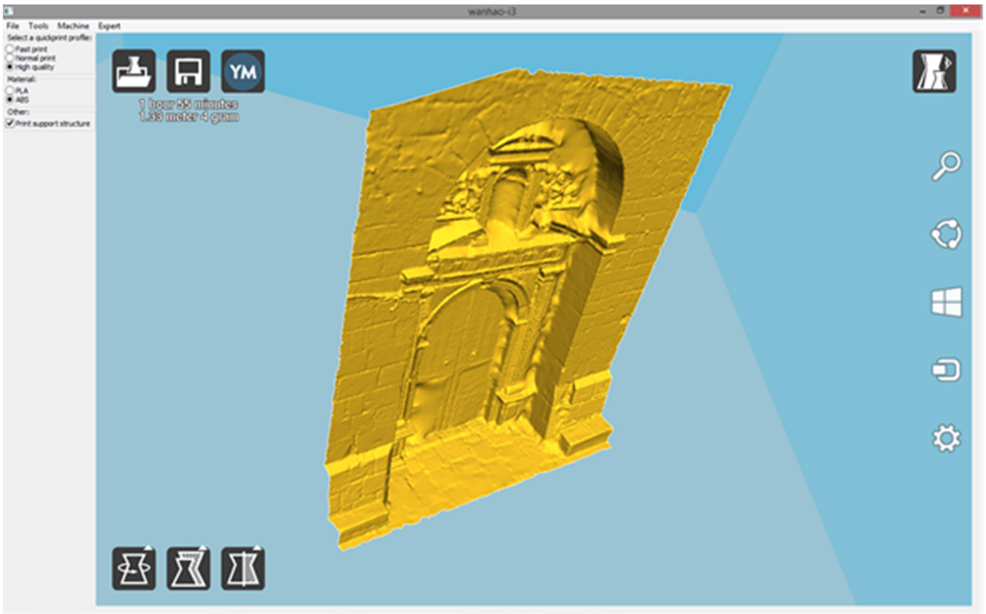

Figure 21. Screen shot of Cura software.

The management software used to transfer the model to the printer has been the Builder 3D (see Fig. 22).

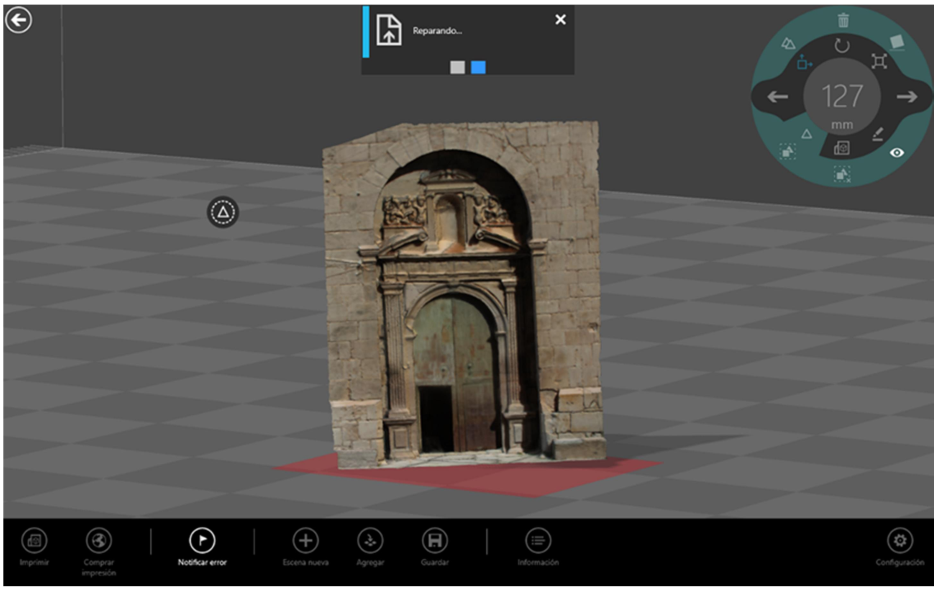

Figure 22. Management of the point cloud through the 3D Builder.

The subtractive printing, consisting of a milling cutter, directed under numerical control, that produces displacement in both horizontal directions and in depth through the drill or tool (milling cutter). From a piece of soft material, attached to the table, a series of slits are made in its interior by cutting or emptying the material in both horizontal axis and at certain depths, creating bass-reliefs with millimeter accuracy depending on the tool, it is not possible the conclusion of right angles, being all of them lightly blunt. The used equipment has been a three-axis milling machine Galileo (see Fig. 23).

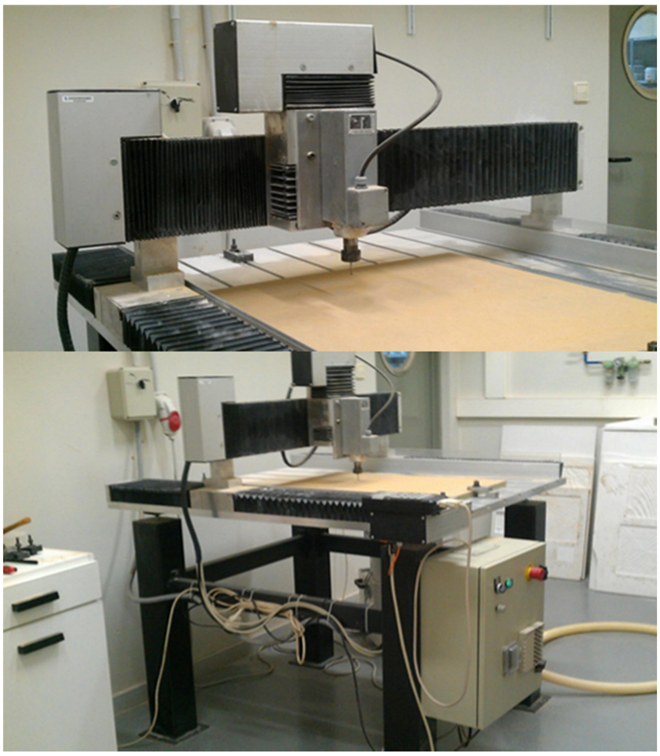

Figure 23. Printer using numerical control milling.

The software used for printing with this equipment has been FotoCam Software engineering PC, by means of a plug-in of Photoshop from a bitmap image.

With all of them, different printings have been made to check the quality, accuracy and results (see fig. 24 & table 1).

Figure 24. Result of the different impressions of resin, yarn extrusion, milled and dust.

Results	Accuracy	Quality	Durability	Size	Time printing	Cost	Overall result	Color
Powder Printer	Very good	Good	Scarce	Large format	Medium-high	Raised by Material	Positive	White Monochrome
Thread Printer	Good	Regular to good	Very good	Medium size	Reduced	Economic	Positive	Monochrome Color
Resin Printer	Very good	Regular	Good	Small	Medium	Medium	Regular	Transparent Monochrome
Numerical control	Good	Good	Very good	Very large size	Media	Economic	Very good	Depending on Base material

Table 1. Comparative data of 3D printers

NEW TRENDS

In relation to the application of new trends and once the accuracy of the procedures has been analyzed, a new system to verify the suitability of the making of the models has been employed, all of this using the same photographic resources previously used with the 22 photographs taken of the small door of the Church. This test has materialized with a commercial type platform such as is the tool Recap of Autodesk, successor and catalyst for the previous resources of the mentioned mercantile, as have been 123 Catch, Memento, and finally Remarke. This integrator software has a module to be able to collect information both through a scanner or cameras, using the module Recap Photo, also from Autodesk. The program is very complete and the point cloud management module from the laser scanner is able to automatically proceed to the automatic registration if the cloud is a structured cloud with all points oriented in their normal (see Fig. 24).

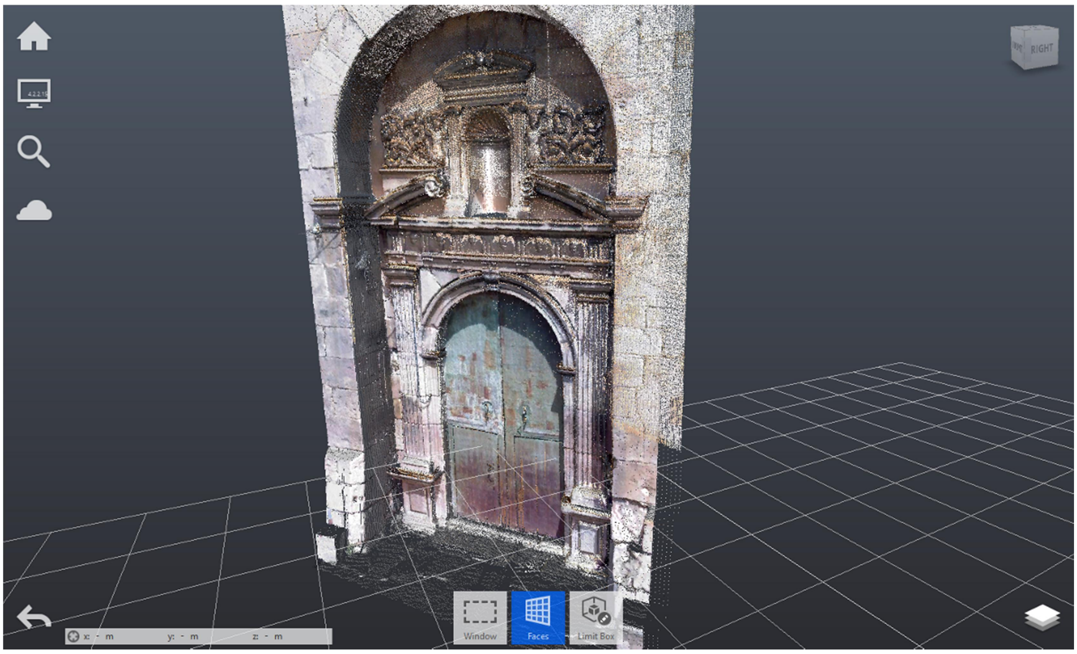

Figure 24. The cloud photo points in RGB colour of the scanner with the Recap.

The photo integration module, proceeds similarly to the Photoscan of Agisoft, given that automatically proceeds to the calibration of the camera, the orientation of the different photos and finally to the creation of a mesh of uniform triangles, to which the texture of the photo can be applied to. This way, very visually engaging virtual models are obtained (see Fig. 25& 26).

Figure 25. Model obtained with Recap Photo

Figure 26. Model of meshing retrieved with Recap Photo.

In this line of new trends, the graphic tool Sketchup Trimble Inc. has begun being used as a visualizer. For the realization of virtual reconstructions and efficient presentations (see Fig. 27).

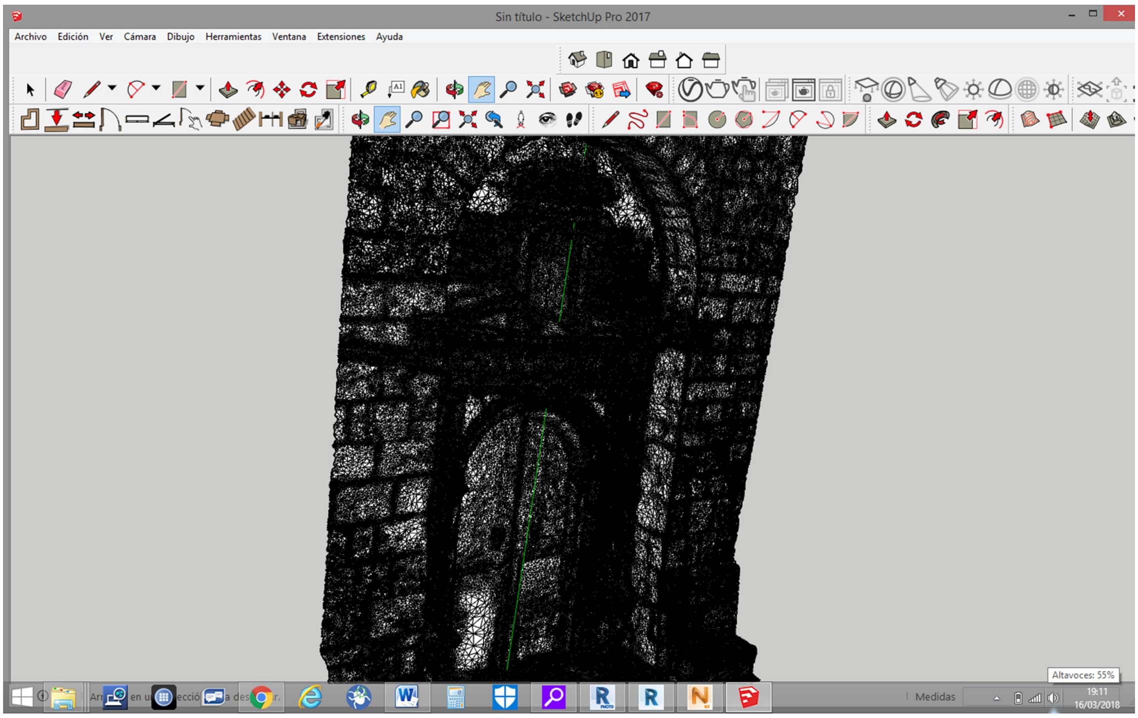

Figure 27. Model of meshing retrieved with Sketchup.

RESULTS

Finally, in this section, we will compare the differences among the various point clouds obtained through the two SfM systems and through the 3D laser scanner. We favoured the 3D laser scanner as the more reliable data as, to date, it is the most proven system. We chose CloudCompare as our reference software, which is also free.

Hence, first we will load the point cloud obtained using the 3D scanner (see Figures 28 & 29).

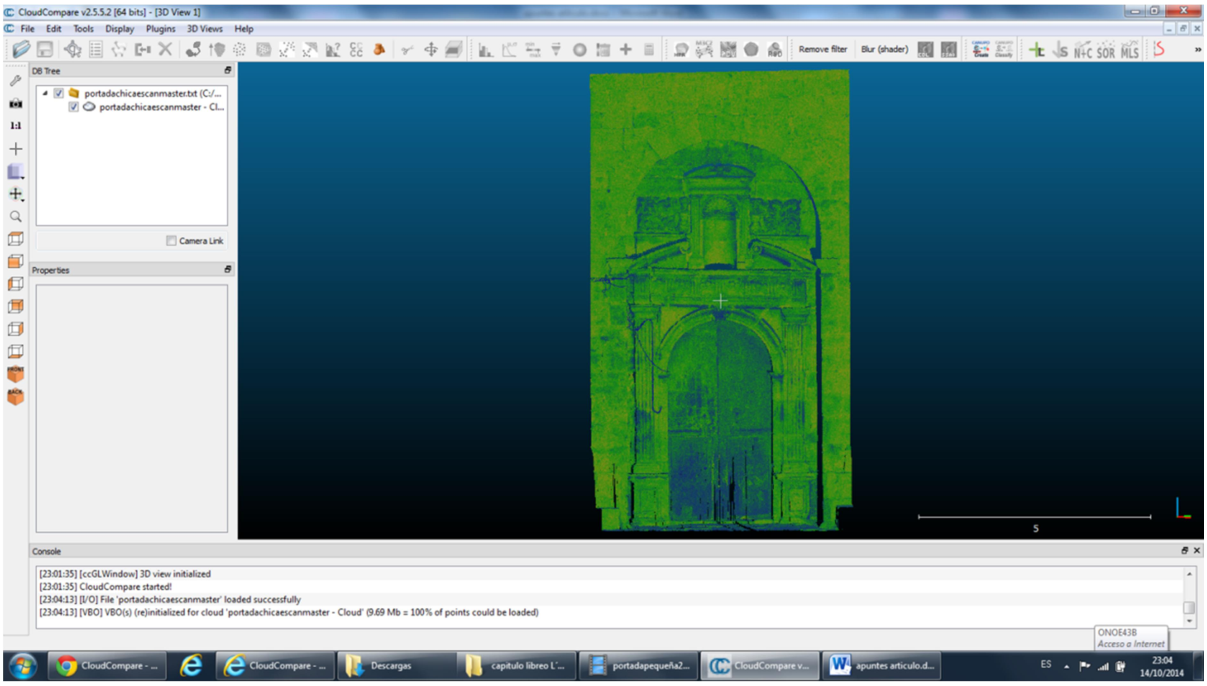

Figure 28. Point cloud image obtained with the scanner by means of CloudCompare

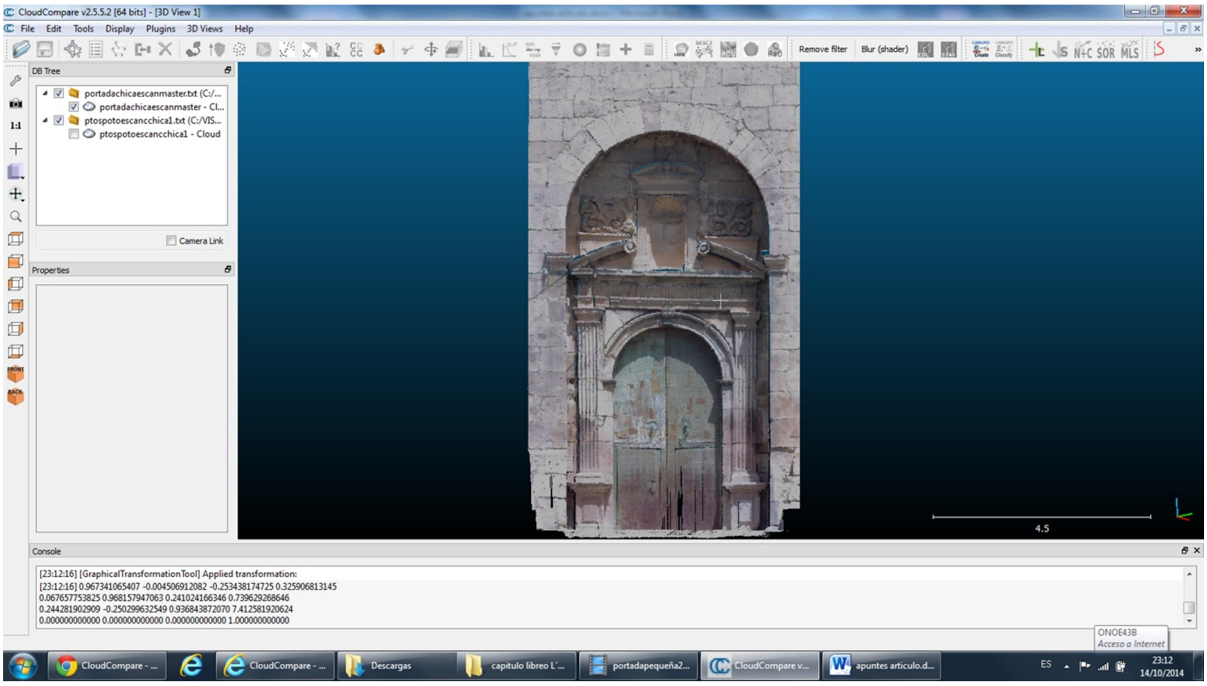

Figure 29. Image of point cloud and texture obtained with the scanner by means of CloudCompare

We then load the dense point cloud obtained using PhotoScan in the same project as can see in Figure 30.

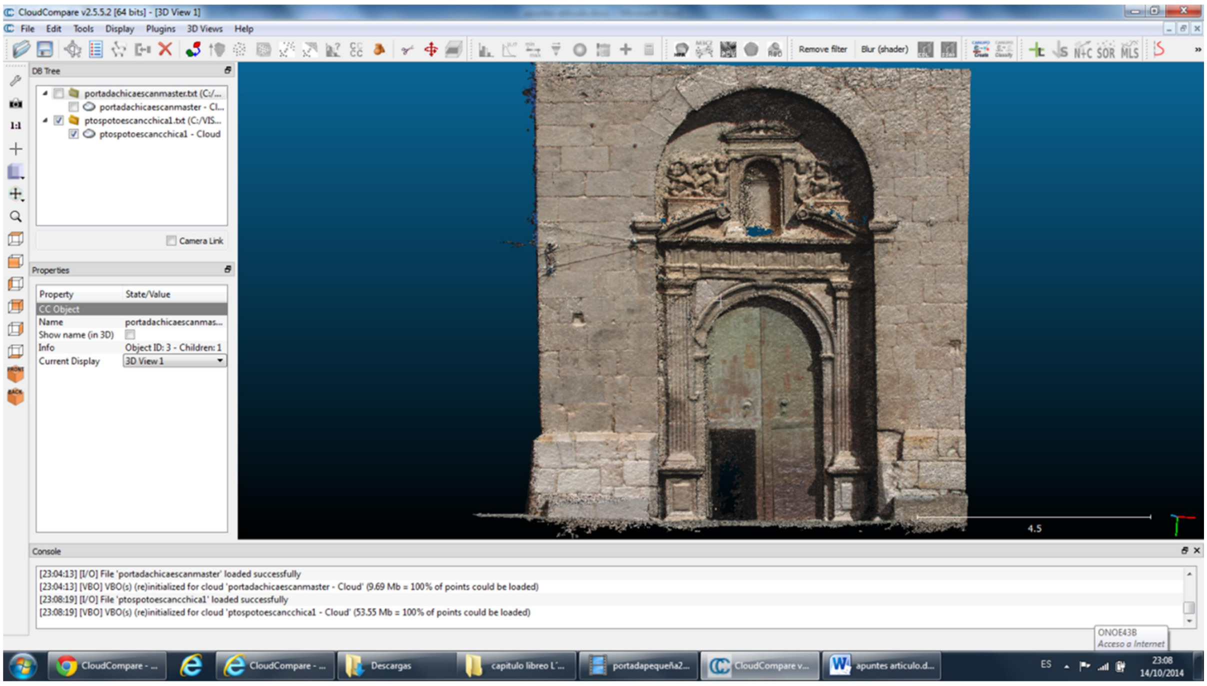

Figure 30. Point cloud image obtained with Pothoscan by means of CloudCompare

Once the two clouds of points have been loaded we compare them through the semi-automatic engine contained in the program itself in order to orient and, if necessary, scale the clouds by an automatic orientation and scaling system, an error of 1000^{e} - 20 being set as the defining parameter for all the models studied as we can see in Figures 31, 32 & 33.

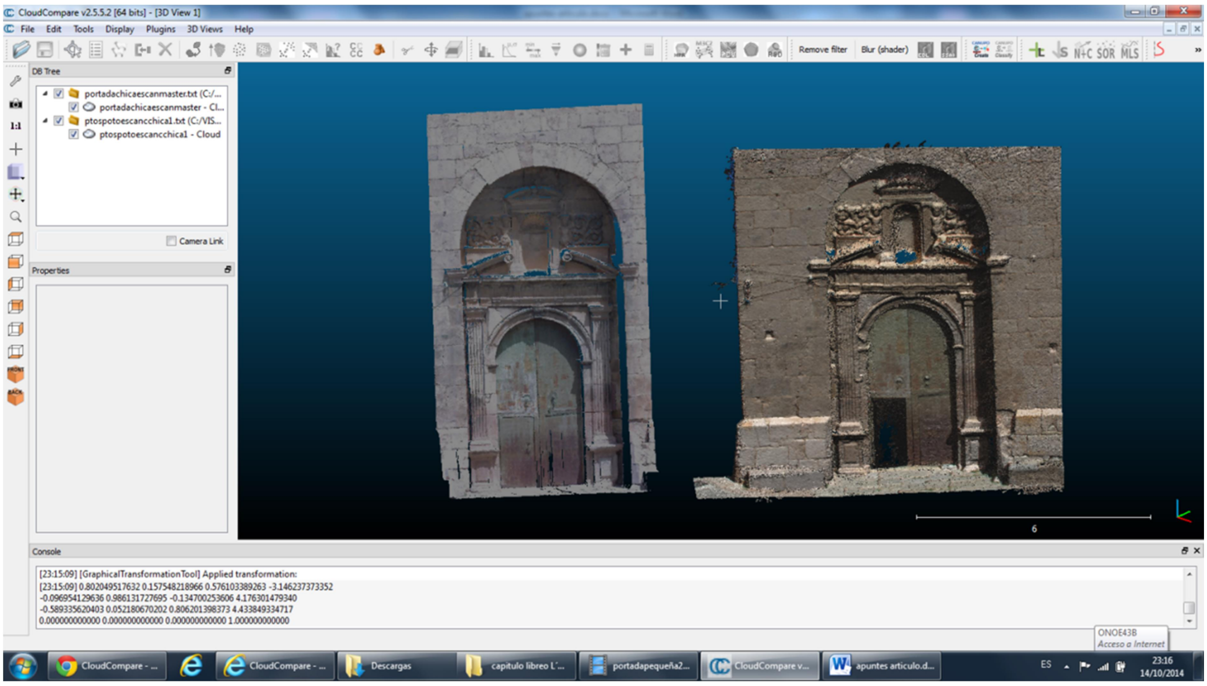

Figure 31. Frontal image of the two textured point clouds obtained with the scanner and Pothoscan using CloudCompare

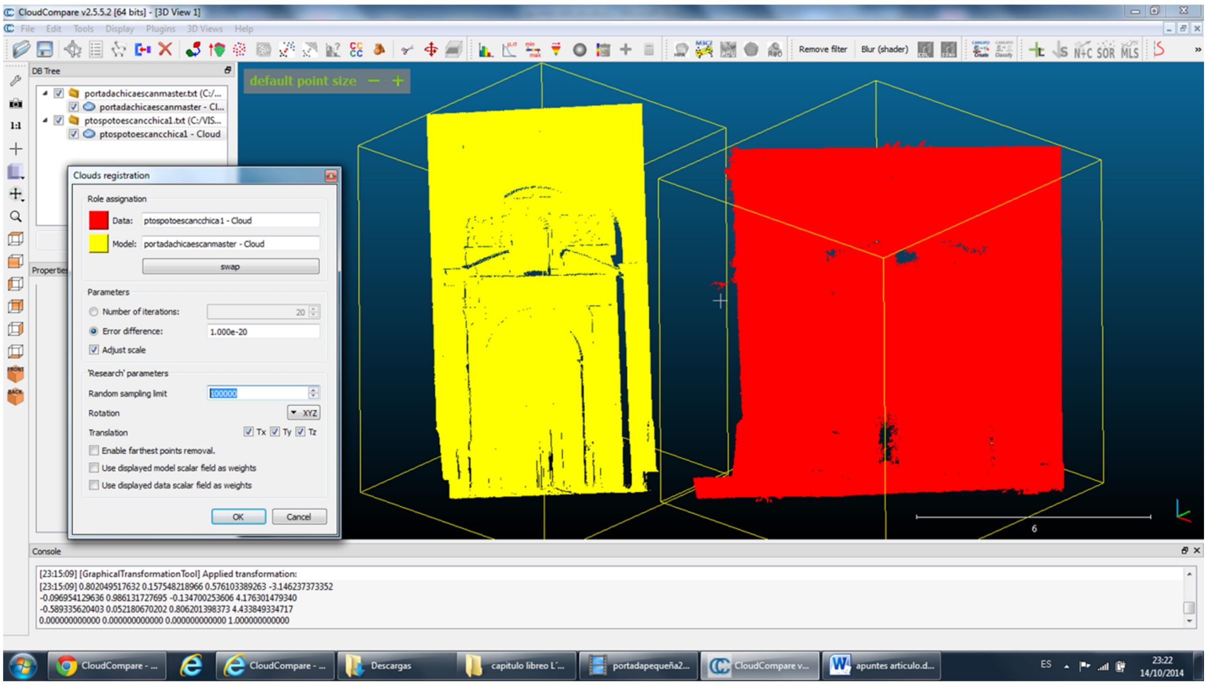

Figure 32. Frontal image of the two point clouds distinguished by yellow and red tones, before alignment and comparison using CloudCompare

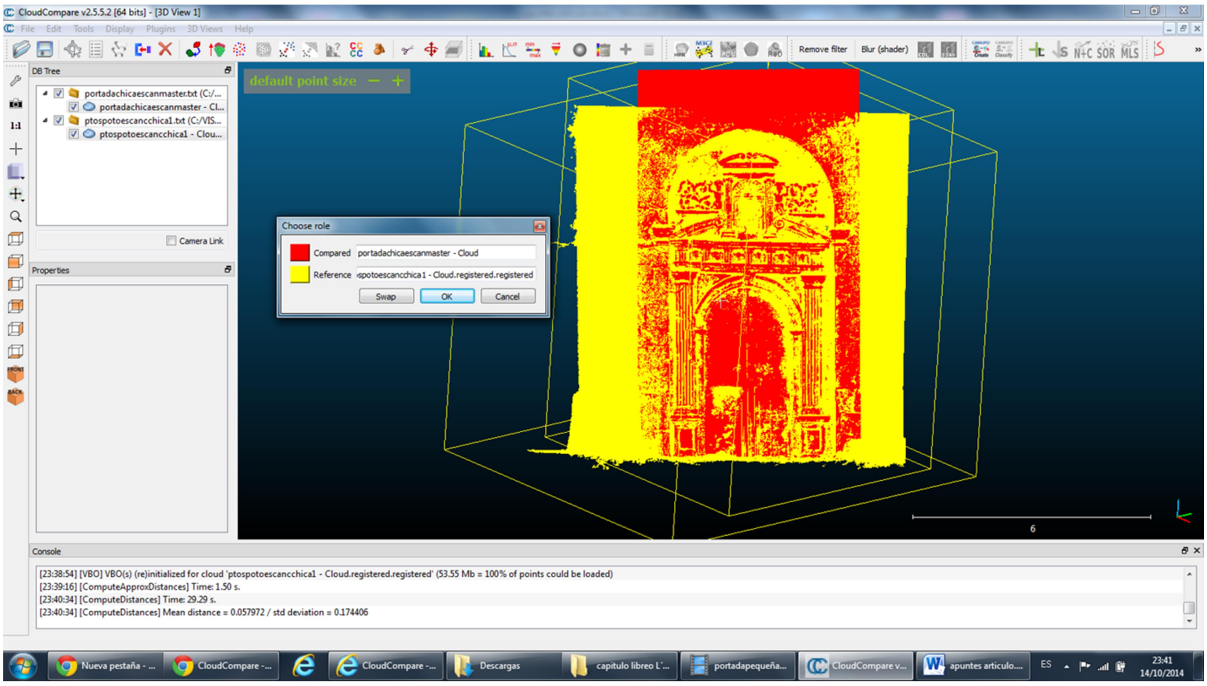

Figure 33. Frontal image of the two point clouds once they have been aligned for comparison using CloudCompare

When the two point clouds have been aligned by the software, the program itself offers us an array of data and statistics about the point clouds being compared. On examining the results, we can see that in the central part of the point clouds to be compared there is practically no difference among them, since this is the approximately 6x10m area captured with the terrestrial scanner, while in the peripheral areas of the point cloud the dispersion range is greater because no reference points can be found with which to compare their difference (see Figures 34 & 35).

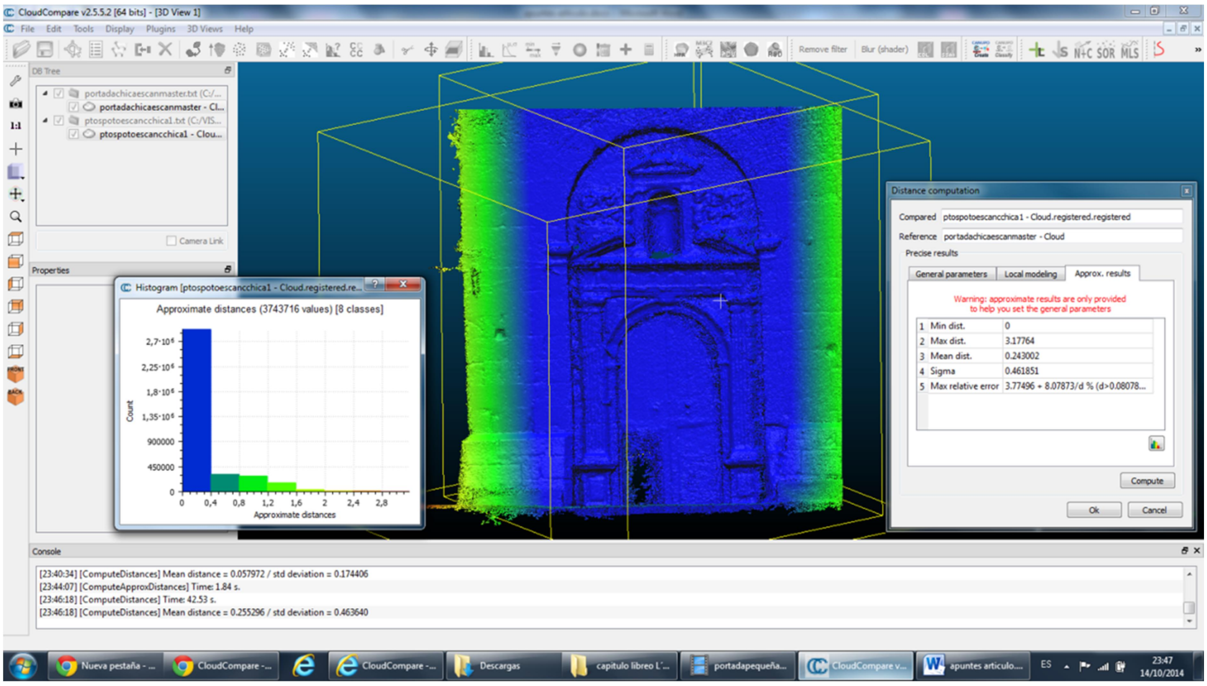

Figure 34. Frontal image of the two point clouds once they have been aligned, with the tone indicating the dispersion in terms of the distance between the two point clouds through CloudCompare

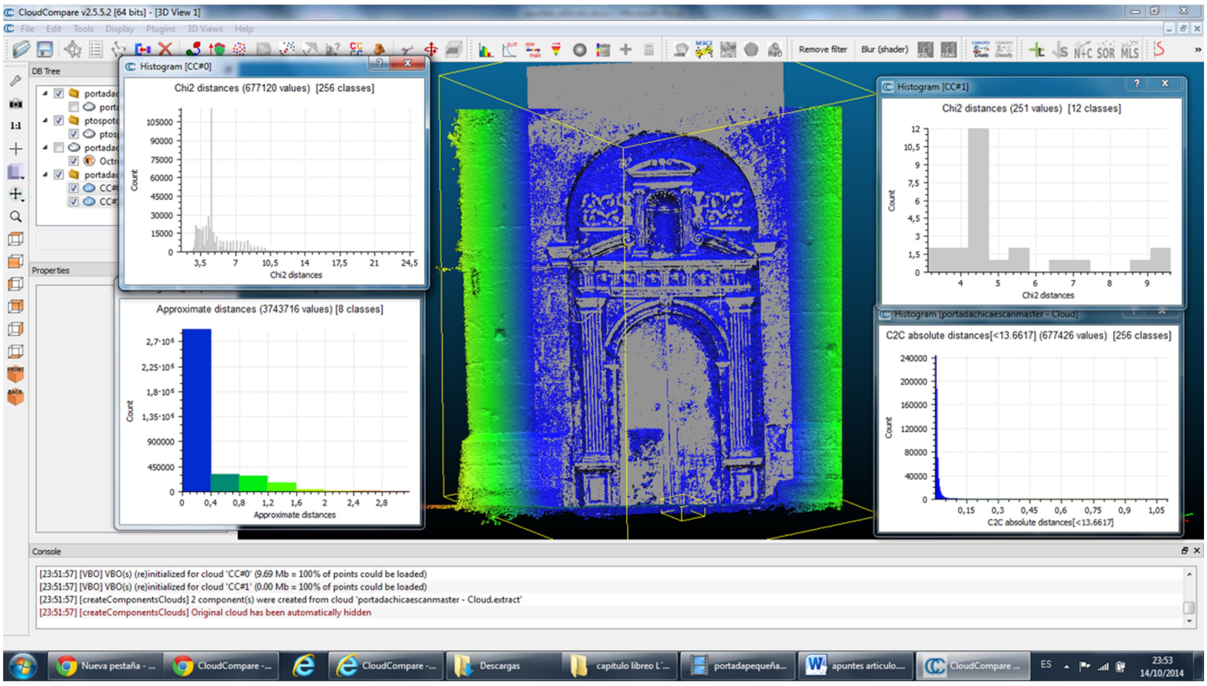

Figure 35. Image of the two clouds of points and different comparison parameters through CloudCompare

Similarly, we now load the point cloud obtained with the 3D laser scanner and the mesh obtained by the 123 Catch software application (see Figure 36) and then align or pair the two models (see Figures 37 & 38).

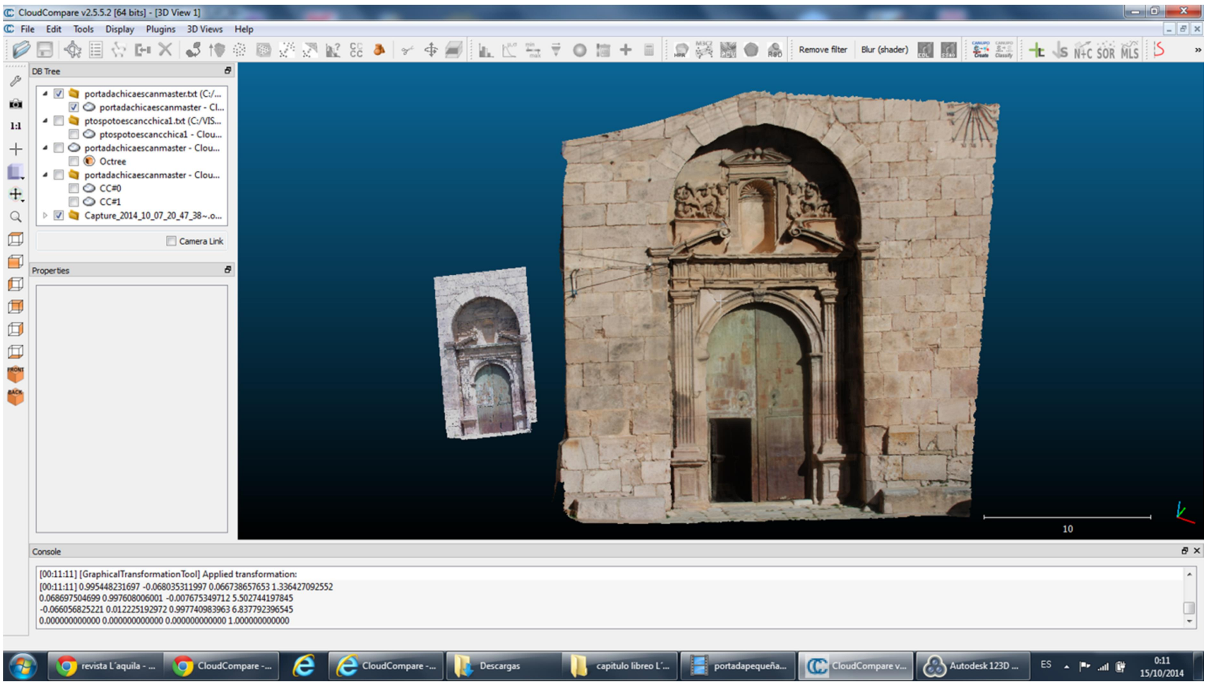

Figure 36. Frontal image of the two textured point clouds obtained with the scanner and 123 Catch using CloudCompare

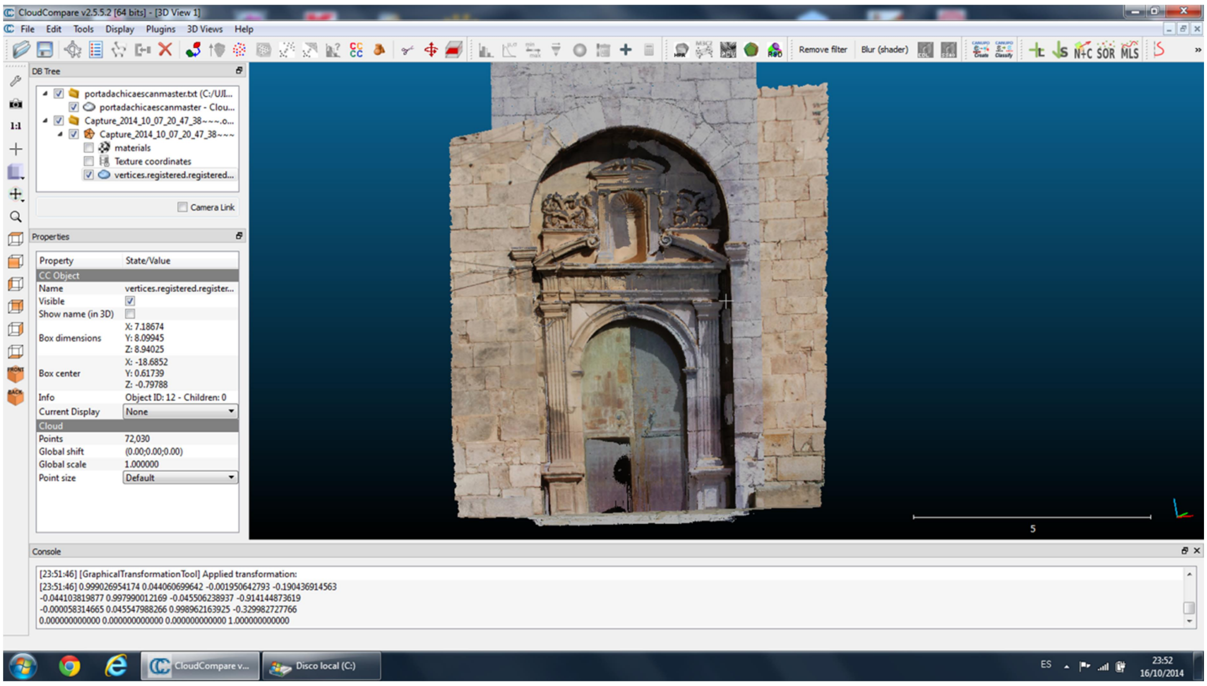

Figure 37. Frontal image of the two point clouds once they have been aligned for comparison using CloudCompare

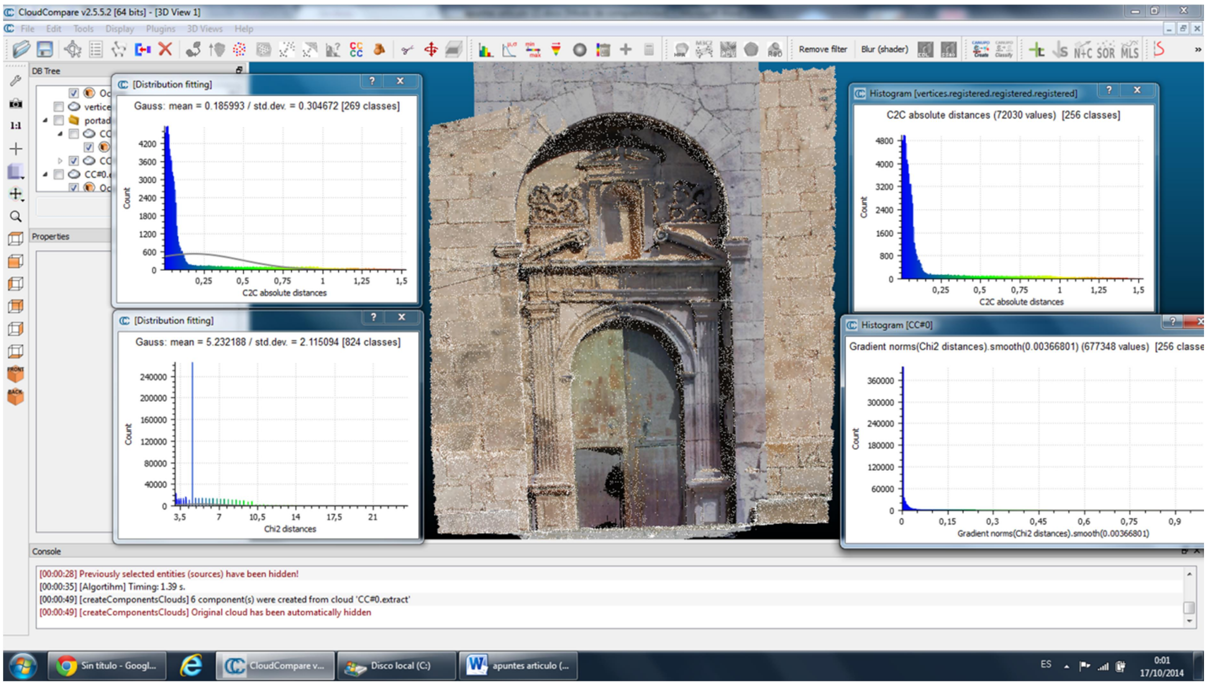

Figure 38. Image of the two clouds of points with different comparison parameters using CloudCompare

From our viewpoint, the combined use of surveying with scanner and multi-photo systems notably reduces the time and the number of operators required. As much as it becomes possible to overlap different works, taking advantage of the time intervals in which the laser is scanning to take the photographs and draw the sketches. In this particular case, we have only set up one topographical station; if different stations are employed, the time increases significantly.

Finally, and once the digital model has been developed, we can continue with one of the models or meshes obtained to produce a digital solid model, which we can reproduce on a smaller scale as an inverse architecture (Celani & Milan, 2007), by preparing a tangible physical model either by modelling on a 3D printer or with numerical control equipment or milling (Gual, Puyuelo, & Lloveras, 2004) as we can see in Figure 39. In recent times these techniques have moved towards the physical impression of an almost realistic 3D model that can even include colour.

In the case of the 3D models made with thread and photosensitive acrylic resin the results are acceptable, although the texture of the materials is not optimal for this type of architectural pieces, there also exist a great limitation on the print size. The advantage of these materials is their toughness and resistance to bumps and drops.

Another printing tests were conducted through the dust printer. In this case it is obtained a more architectural finish, with a texture closer to the original models (stone). The disadvantage of these models is its fragility. They can be treated with a consolidating, even though they lose their texture and original colour.

Figure 39. Image of two physical reproductions of the Portal made by numerical control milling. On the left: on plaster, and on the right: on wood

FUTURE RESEARCH DIRECTIONS

One possible future research line would be to study graphic methods that allow us to cover easily in the models obtained by 3D scanner, shadow areas not perceptible from the normal height, or in inaccessible places for them, by using photographic images produced by cameras installed in drones or small cranes, that allow us to raise the point of view and can view these elements (cornices, covers, bell towers) or access any area of difficult access (extrados vaults, narrow stairs, etc.).

CONCLUSIONS

According to everything outlined above, from the early steps of the architectural survey, we can conclude that all the systems are compatible with one another and that one should not necessarily exclude another. Instead, they can support or enhance each other by providing the improvements needed by another while having its own shortcomings offset, and this is why we cannot do away with the traditional collection of data even if it only involves the use of small sketches or diagrams. For a dimensional study, depending on the resources we have available to us, we will have to resort to traditional methods of direct or indirect measurement based on traditional or electronic topography, which will endow our work with a certain degree of geometric and dimensional accuracy.

As for the mass data collection systems used in this case, we must highlight the accuracy and amount of information provided by the terrestrial 3D scanner, although stationing time, travel requirements and moving equipment is rather laborious. Yet, in this case it has been cost-effective and necessary to achieve the aims of this study, because only a single station is needed. As a weak point of the system, we can highlight, for example, the high cost of both the measurement equipment and the management software.

In contrast, through the two tried and tested programs (PhotoScan and 123 Catch), multi-photo capture systems are very convenient as far as data production and subsequent processing are concerned. However, as we understand it, the weak point of this system lies in the total automation of the process without the operator being able to intervene in the process of control and data management. In contrast, their main advantage is their economy and ease of use.

On evaluating the quality of the metric results obtained, we can state that in the test conducted if we compare the different point clouds accomplished by the scanner (see Table 2), and after testing the other two point clouds from the multi-photo systems, the deviation or error is practically negligible. In consequence, the three clouds can be considered to provide adequate mass information about the object to be represented with a certain degree of accuracy and rigour.

A weakness of this kind of work is the invisibility or lack of perception of the parts of the objects to be documented. In this case, because of its size (8.5 m high), the Portal does not allow us to photograph the cornices or reliefs with standard means and equipment. Likewise, perhaps the scanner cannot scan certain areas that produce their own shadows. This is even more the case when a single station and a static system of measurement are used and there is a lack of reach in the case of the photographic cameras. This issue has been solved in recent years with the use of drones that are able to reach or access any point that cannot be appreciated from the human standpoint.

Planning carried out prior to undertaking the fieldwork is, from our point of view, of vital importance because it is not only necessary to ensure the correct and complete collection of information, as happens with each of the systems separately, but also to avoid unnecessary redundancy thereby preventing obstacles, noise and shadows. If they are combined, an appropriate programme of work can be established for each situation.

Improvements are also seen when it comes to generating graphical documentation because being able to obtain textured photogrammetric surfaces means it is no longer necessary to perform this work with the data from the laser scanner, whose point clouds are used directly for the development of geometric studies, which in turn ensures the highest accuracy of the regulating lines of the construction elements.

Furthermore, the textured surfaces generated by photogrammetry are the best instrument for studying pathologies, as the data are recorded precisely because of the values for the brightness of the surface being photographed.

	Point cloud generated with terrestrial 3D laser scanner	Cloud points obtained with PhotoScan	Cloud points obtained with 123 Catch
Collection data speed	Good	Very good	Very good
Number of shots	1 station	22 photograps	22 photograps
Economic cost of the system	Expenxive	Ecomomic	Very ecomomic
Time of process	Good	Very good	Very good
Precision	Very good	Good	Good
Point Number	677.426	3.743.716	73.030
Point Faces	1.272.266	193.808	
Results outside comparison range	Very good	Good $2,7x10^6$ points with less than 0,4	Good 4800 points with less than 0,25
Output Format	txt	txt	obj
Color	Good	Very good	Very good
Control parameters	Manual	automatic	automatic

Table 2. Table summarising relevant data

We can state although the new SfM systems cannot replace traditional systems such as 3d scanner by its rigor and precision as we can see on Table1. The data collection from these systems, through proper and controlled use of them, can provide us a sufficient degree of reliability in certain graphic surveys. Depending on the object to represent can be very useful to fill empty areas that it is not possible to document using the 3D scanner for its lack of accessibility. According to Table 1 data, PhotoScan gives us much information of the surveying object, 3.743.716 points obtain with PhotoScan versus 73.030 points of 1,2,3 Catch, although the distortion rate is lower in 1,2,3 Catch, the use of one or another tool depends on if must predominate work accuracy level or quality of the image to represent.

Powder printers often create heavy, unstable and soft models; the material used is excessively expensive.

The deposition printing, as fundamental problems, lacks proper resolution in relation to the other two printing systems by addition and needs support systems so that the printed models are freestanding. On the other hand, the models are rigid and stable.

The resin one, to be able to print correctly must be perfectly leveled, materials must be perfectly stored and protected so as not to alter the light sensitive conditions, these being very delicate and perishable. On the other hand, the models are of high quality and resolution, but large sizes cannot be achieved.

Numerical control printer (CNC) allows large format works, in material and more stable shape, but in bass-relief, very elaborate textures may be obtained, with the limitation right angles, which should be replaced by blunt ones.

The creation of physical models or mock-ups made by additive manufacturing techniques allow us to obtain physical models in a fast and effective way which enable us to be able to work in the field of inclusive design and heritage architecture, since there are numerous CAD digital information, which employed in a proper manner and, at the same time, simple and low-cost. They could serve as instrument for people with disabilities to access cultural content that otherwise would be inaccessible for them.

To complete the process, it is necessary to count with the collaboration of affected users to check at first hand the effectiveness of the models and to be able to correct or improve certain aspects such as the scale, texture, and explanatory texts among others.

In this case study case the physical mock-ups acquire special importance as a tool for the dissemination of the architectural element for the general public, as these architectural elements do not currently longer exist physically and they are difficult to interpret for the general public from simple orthogonal views due to the geometric complexity of the piece.

The new technologies of digitization in construction through additive manufacturing (3D printing), allow us to currently represent a physical and tangible model to offer it as a resource for people with visual impairments, as well as for all those interested in the architectural heritage.

REFERENCES

Barrera Vera, J. A. (2006) *Aplicación de tecnologías innovadoras en la documentación geométrica del patrimonio arquitectónico y arqueológico.* (Unpublished doctoral dissertation). Universidad de Sevilla, Sevilla, Spain.

Brandi, C. & De Angelis, G. (1972) *Carta di Restauro, 1972*
(Circolare n°117 del 6 aprile 1972). Roma, Italy: Ministero della Pubblica Istruzione

Celani, G. C. & Milan, L. F. M. (2007) Tactile scale models: three-dimensional info graphics for space orientation of the blind and visually impaired. In: Taylor & Francis Group (Eds.) *Virtual and rapid manufacturing: Advanced research in virtual and rapid prototyping* (pp. 801-805). London, UK: Taylor & Francis Group

Conselleria de Cultura i Esport (2007) *Decreto 169/2007, de 28 de septiembre, del Consell.* (BOE, jueves 24 de enero de 2008, suplemento del número 21) España: Boletín Oficial del Estado

Garfella Rubio, J. T., Máñez Pitarch, M. J., Cabeza González, M. & Soler Estrela, A. (2012, April) *La documentación gráfica a través del empleo de metodologías avanzadas de* *fotogrametría y escáner 3D*. Paper presented at the 4º Congreso de Patología y Rehabilitación de Edificios. Colexio Oficial de Arquitectos de Galicia, Santiago de Compostela, Spain

Garfella Rubio, J. T., Máñez Pitarch, M. J., Cabeza González, M. & Soler Estrela, A. (2014*) Los sistemas de fotogrametría y láser escáner, en combinación con los métodos tradicionales en la documentación del patrimonio, para la obtención de una arquitectura inversa y su preservación*. Paper presented at the Congreso Latinoamericano REHABEND. Santander, Spain: Universidad de Cantabria

Garfella Rubio, J. T., Máñez Pitarch, M. J., Martínez Moya, J. A. & Cabeza González, M. (2013, June) Aplicación del color a las nubes de puntos, las texturas y su posterior modelización mediante toma de datos avanzada a través del escáner y la fotogrametría arquitectónica. Paper presented at the X Congreso Nacional del Color. Valencia, Spain: Universitat Politècnica de Valencia

Gual, J., Puyuelo, M. & Lloveras J. (2004, November) Three-dimensional tactile symbols relief maps for the visually impaired. *4th World Conference on Design Research*. Delft, The Netherlands: International Association of Societies of Design Research (IASDR) and Delft University of Technology.

Gual, J., Puyuelo, M., Lloveras, J., & Merino, L. (2012). Visual impairment and urban orientation: pilot study with tactile maps produced through 3D printing. Psychology: Ambiental-Bilingual Journal of Environmental Psychology, 3 (2), pp. 239-250.

Gual, J., Puyuelo, M., & Lloveras, J. (2014). Three-dimensional tactile symbols produced by 3D printing: improving the process of memorizing a tactile map key. *British Journal of Visual Impairment, 32 (3)*, pp. 263-278.

Gual, J., Puyuelo, M., & Lloveras, J. (2015a). Improving tactile map usability through 3D printing techniques: An experiment with new tactile symbols. *The Cartographic Journal, 52*, pp. 51-57.

Gual, J., Puyuelo, M., & Lloveras, J. (2015b).The effect of volumetric (3D) tactile symbols within inclusive tactile maps. *Applied Ergonomics, 48*, pp. 1-10.

Gual, J., Serrano, J. & Máñez, M. J. (2015). Aplicación de la fabricación aditiva en la obtención de moldes para termoconformar gráficos tangibles orientados a personas con discapacidad visual. Tangible graphics using rapid prototyping techniques: volume as a design constituent. *The Spanish Digital Journal on Blindness and Visual Impairment, 66.*

Lerma García, J.L. (2002). *Fotogrametría moderna: analítica y digital.* Valencia, Spain: Universidad Politécnica de Valencia.

Lerma García, J. L., Cabrelles, M., Navarro, S. & Seguí, A.E. (2011) La documentación patrimonial mediante sensores de imagen o de barrido láser. In: Secretaría General técnica (Eds.) *Documentación gráfica del patrimonio* (pp. 108-117) España: Ministerio de Cultura.

Máñez Pitarch, M.J., Gual Ortí, J. Garfella Rubio, J.T. & Martinez Moya, J.A. (2016). Renaissance-Style Architecture en El Maestrazgo: From Virtual to Tactile Models. In: Giuseppe Amoruso (Ed.), Handbook of Research on Visual Computing and Emerging Geometrical Design Tools. Hershey, Pensilvania: IGI Global.

Martínez-Moya, J.A., Gual-Ortí, J. & Máñez-Pitarch, M.J. (2018). Physical scale models as diffusion tools of disappeared heritage. In: Giuseppe Amoruso (Ed.), Putting Tradition into Practice: Heritage, Place and Design. Proceedings of 5th INTBAU International Annual Event. Milano, Italy: Springer.

Martínez-Espejo Zaragoza, I. (2014*) Precisiones sobre el levantamiento 3d integrado con herramientas Avanzadas, aplicado al conocimiento y la conservación del patrimonio Arquitectónico.* (Unpublished doctoral dissertation). Universidad Politécnica de Valencia, Valencia, Spain.

Pérez, A., Lerma, J.L., Martos, A., Jordá, F., Ramos, M. & Navarro, S. (2007, February) *Generación automática de orto fotografías verdaderas en Arquitectura*. Paper presented at the Séptima Semana Geomática de Barcelona, Barcelona, Spain.

Voigt, A., & Martens, B. (2006). Development of 3D tactile models for the partially sighted to facilitate spatial orientation. In: *Communicating Space(s): 24th eCAADe Conference Proceedings*, pp. 366-370. Volos (Greece): University of Thessaly.

Yastikli, N. (2007), Documentation of cultural heritage using digital photogrammetry and laser scanning. In: Vigato, P.A. (Ed.) *Journal of Cultural Heritage, no 8* (pp. 423-427) Padova, Italy: Elsevier for Editors

ADDITIONAL READING

Herráez Boquera, J., Navarro Esteve, P. & Denia Ríos, J. L. (2010) Fundamentos y aplicaciones de la tecnología de Escáner Láser para documentación y restauración de patrimonio. In Alcántara Onofre, A. & Lara Gutiérrez A. M., (Ed.), *Implementación de nuevos métodos de documentación y registro fotogramétrico digital para la protección y puesta en valor del patrimonio monumental mexicano* (pp. 17-41). México: Universidad Politécnica de Valencia.

Máñez Pitarch, M. J. (2014) *La arquitectura religiosa renacentista en tierras del maestre: la iglesia de Nuestra Señora de la Asunción de Vistabella del Maestrazgo*. (Unpublished doctoral dissertation). Universidad Politécnica de Valencia, Valencia, Spain.

Mataix Sanjuán, J., León Robles, C. & Montes Tubío, F. de P. (2013) Fortalezas y debilidades de la técnica de levantamiento gráfico con escáner láser para la catalogación del patrimonio cultural Aplicación a la iglesia de San Francisco (Priego de Córdoba). *Revista EGA nº 21, Conversando con Cruz y Ortiz* (pp 219-225)

ACKNOWLEDGEMENTS

We wish to thank the Universitat Jaume I and the Department of Industrial Systems Engineering and Design for their collaboration and the staffing needed to carry out this work and to Cristina Fabuel for her great help and support.

KEY TERMS AND DEFINITIONS

3D Model: It is the three-dimensional representation of an object made on a computer with specialized software. It is made up of a collection of points in space connected by geometric entities such as triangles, lines, surfaces, etc. It can be obtained through the scanning of a real object or through algorithms that provide the necessary data for its creation.

3D Rendering: Computer graphics process to get 2D photorealistic effect images from 3D virtual models.

ABS: Acronym of Acrylonitrile Butadiene Styrene, it is a plastic term, used as fused filament for 3D printers.

AMF: It is a file format designed to support additive manufacturing processes, such as 3D printing. Its acronym comes from Additive Manufacturing File. Besides the model geometry, AMF files provide a lot of information about the model being printed, which does not need post processing to define data such as the model position in relation to the 3D printer, orientation, colours, material, etc.

Additive manufacturing: It consists in the formation of 3D objects by adding successive layers of material in order to form a piece with volume. It is a type of manufacturing that can be done with many different types of materials and is faster than conventional manufacturing techniques. When combined with digital production tools, high precision can be obtained. It includes, among others, the following processes: stereo lithography, fused deposition modelling (FDM), selective laser sintering, inkjet binder, light-curing resin, laminated objects manufacturing.

Blender: It is a 3D modelling software.

CAD: Acronym of Computer Aided Design. Normally drawing or virtual modelling software for 2D and 3D.

CAE: Acronym of Computer Aided Engineering. In 3D printing, it refers to the engineering aspects linked to 3D modelling from CAD. While in CAD it is a question of generating a model, in CAE the purpose is the analysis of its characteristics using engineering methods. CAE processes, thus, allows us to extract information to optimize the development and the cost of manufacturing by analysing the model characteristics, properties, material and geometry. Likewise, they allow to determine the viability and profitability, the quantity of materials, the times and costs of manufacturing.

CAM: It is the use of computer software to assist in the manufacture of a 3D design. It is an acronym for Computer Aided Manufacturing. In 3D printing we refer to CAD –computer aided design- regarding design and to CAM regarding manufacture. The design and manufacture with the help of the computer form a technology that encompasses many disciplines, such as graphic design, database management for design and manufacturing, robotics and computer vision, among others. Through the CAM, precise instructions based on G-Code are created to drive the machine and its tools.

CNC: It is the acronym of Computer Numerical Control, which is a process based on a series of coded commands, normally, on a G-Code file.

Cultural Heritage: The legacy of tangible and intangible attributes inherited by a society from past generations. In this case: buildings, monuments and landscapes.

Cura: It is a free slicer 3D software that can be used with Windows, Mac and Linux. It can open files with the extensions STL, 3MF and OBJ.

DLP: It is the acronym of Digital Light Processing. It is a type 3D printer that solidifies photosensitive resin by means of a light source that can be a projector, a halogen or LED bulb, or an LCD or UV LED plate. The DLP printing process is similar with that of the SLA but faster. As with SLA, the object can be created from the top down or from the inside of the tray upwards. In both cases, the surface of the resulting piece is smoother than with processes such as FDM or FFF, since the layers are less visible.

DXF: It is a CAD universal file format. It was developed by Autodesk and it is one of the most used in design, engineer and product development. DXF files can be imported in CAM software and, afterwards, be converted into G-Code.

Extruder: It is a part of the 3D printer that, fed by cold filament of the thermoplastic reel, extracts it in liquid state by heat, pushing it through a small nozzle.

FDM: It is the acronym of Fused Deposition Modelling. It is a 3D printing technique which consists in depositing flat layers of molten material superimposed on each other to get an object with volume. By extension, 3D printers that use this technique are called FDM printers. That is, they print from the fusion of plastic filament.

FFF: It is the acronym of Fused Filament Fabrication. It is another way of naming the FDM technique.

Focal length: The focal length of a lens refers to the distance between the lens itself and its focus point. The focal length of a lens determines the field of view of the scene. It is called wide angle lens because it captures a large part of the scene and has a very broad field of vision. A target of great focal distance is called a telephoto lens as it acts approaching a particular area of its scene.

G-Code: It is the language that the 3D printer understands. It is a programming language that is used to control automated machines and tools. In 3D printing, the code determines a trajectory from which the parts of the printer responsible for creating the piece move.

ISO: It is the index or level of sensitivity of a photographic film to light. The lower the ISO, the lower the sensitivity of the film, which requires a longer exposure, while a film with a high ISO only needs a brief exposure to light.

Laser Scanning: Data Collection of real-world objects by 3D scanner devices to construct a digital three-dimensional model.

Meshlab: It is a free mesh editing program to view, join, transform and repair STL, PLY, STL, OFF, OBJ, 3DS files. It also supports other file extensions and point clouds.

Montesa Order: Old christian military order, territorially limited to the old Kingdom of Aragon.

OBJ: It is a file format that contains 3D geometries and includes data such as the position of each vertex, and the normals and faces that make up each polygon. It is one of the main formats for the exchange of files between software and is often used as an alternative to the STL extension because it allows to incorporate information about colour, materials, etc. Its full name is Wavefront 3D Object.

Open source: It is the free distribution software that has a public code that can be downloaded, modified and redistributed by multiple developers. There is several open source software to create and modify 3D models for printing.

Orthophoto: Photograph geometrically corrected getting an orthogonal view that can be used to measure true distances.

Photogrammetry: The science of taking measurements from photographs by computational models.

Photopolymer: It is a photosensitive resin used in 3D printing by stereolithography or by DPL. That is, it is a type of liquid plastic that reacts to light solidifying. The reaction occurs under UV rays and at a certain wavelength.

Photosolidification: Also known as stereolithography, optical manufacturing, SLA or SL. It is an additive manufacturing process that is based on the solidification of resin by ultraviolet light. Three-dimensional objects are formed by the addition of superimposed layers on top of each other. Each layer is generated by directing an ultraviolet light laser to the sectors of the object where the addition of material is needed, which causes the resin to solidify creating a thin layer of solid material glued to the previous layer. As with DSL, the object can be created from the top down or from the inside of the tray up. In both cases, the surface of the resulting piece is smoother than with processes such as FDM or FFF, since the layers are less visible.

PLA: It is the acronym of Polylactic Acid. A biodegradable thermoplastic polymer used in filament form as a 3D printer material.

Point Cloud: A three-dimensional coordinate system that represent the external or internal surface of an object created by 3D scanners or photogrammetry.

Polyamide: Better known as nylon. It is a synthetic fibre used in 3D printing by laser sintering from a very fine white granular powder. The printed pieces are strong and slightly flexible, so they can withstand small impacts and withstand some pressure while bending.

Resin: It is a photopolymer compound that solidifies with light at a certain wavelength and is used as a printing material mainly used in 3D printers with SLA and DLP technology.

RGB: It means "red, green and blue". Red, green and blue are the 3 colours that monitors use to display images.

SketchUp: It is a 3D modelling software developed by the architectural company Trimble Buildings. It is available as a commercial version called SketchUp Pro and as a free version called SketchUp Make.

SLA: Also known as SL, stereolithography, optical manufacturing or photosolidification. It is an additive manufacturing process that is based on the solidification of resin by ultraviolet light. Three-dimensional objects are formed by the addition of superimposed layers on top of each other. Each layer is generated by directing an ultraviolet light laser to the sectors of the object where it is necessary to add material, which causes the resin to solidify and thus a thin layer of solid material is glued to the previous layer. As with DSL, the object can be created from the top down or from the inside of the tray up. In both cases, the surface of the resulting piece is smoother than with processes such as FDM or FFF, since the layers are less visible.

Spool: It is the support of the plastic filament roll used in 3D printers.

STL: It is the acronym of Standard Tessellation Language. It is a computer file format that defines the surface of 3D modelled objects and is used in 3D printers and numerical control machines (CNC). Most 3D modelling programs can export in this format, which does not include information about colour, textures or physical properties of the model which the OBJ format does.

Structure for Motion: Imaging technique that gets 3D structures from 2D image sequences coupled with local motion signals by specific software.

Texture: It is the term used in 3D design when referring to the colour or the image simulating a concrete texture applied on a 3D model surface.

Thermoplastic: It is a type of plastic that makes up the majority of 3D printing filaments by FDM, such as PLA, ABS, PVC, PE and nylon. When melted it becomes a fluid able to be extruded and that hardens quickly when losing temperature.

Vistabella del Maestrazgo: Municipality in the north-western end of the province of Castellon at Valencian Region, Spain.