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High resolution model mesh and 3D printing of the Gaudí's Porta del Drac

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Abstract. This article intends to explore the limits of scanning with the technology of 3D Laser Scanner and the 3D printing, as an approximation to its application for the survey and the study of singular elements of the architectural heritage. The case study we developed is the *Porta del Drac*, in the *Pavelló Güell*, designed by Antoni Gaudí. We divided the process in two parts, one about how to scan and optimize the survey with the Laser Scanner Technology, made with a Faro Forus3D x330 scanner. The second one, about the optimization of the survey as a high-resolution mesh to have a scaled 3D model to be printed in 3D, for the musealization of the *Verdaguer* House of Literature in *Vil.la Joana* (Barcelona), a project developed by the Museum of History of Barcelona, in tribute to Jacint Verdaguer. In the first place, we propose a methodology for the survey of this atypical model, which is of special interest for several factors: the geometric complexity in relation to the occlusions, the thickness of the metallic surfaces, the hidden internal structure partially seen from the outside, the produced noise in its interior, and the instrumental errors. These factors make the survey process complex from the data collection, having to perform several scans from different positions to cover the entire sculpture, which has a geometry composed of a variety of folds that cause occlusions. Also, the union of the positions and the average of the surfaces is of great relevance, since the elements of the sculpture are constructed by a metal plate of 2mm, therefore, the error in the union of all these many positions must be smaller than this. Moreover, optimization of the cloud has a great difficulty because of the noise created by the instrumental error as it is a metal sculpture and because of noise point clouds that are generated inside the internal folds of the wings, which are made with a welded wire mesh with little spaces between them. Finally, the added difficulty that there is an internal structure between elements of the parts of the *Drac* that are partially hidden and therefore cannot be recorded. Secondly, we expose the procedures performed to move from a point cloud to an optimal high-resolution mesh to be printed in 3D, adapting it to all the limitations that this printing technique entails. On the one hand, for the meshing process, a previous classification of the point cloud by pieces (wings, chains, mosaics, head ...) is made and an internal structure is re-assembled to avoid floating parts. On the other hand, the selection of the 3D printing technique, in this case FDM (Fused Deposition Modelling), limits the size of the model so it needs to be cut by determined maximum dimension, and also it limits the minimum thickness of the model's surface, that is to say, the model cannot be directly scaled to the desired size because the 2mm surfaces would be too thin to be printed. This research intends to advance the knowledge of data acquisition, optimization, modelling and 3D printing, with a case study of great complexity. A process that can be systematized and applied to other models.

1. Introduction

The realization of the precision model requires acquiring data, making the mesh model and the construction of the model in a format and scale so that it is printed with the maximum accuracy to the original sculpture, being a case study that comes upon the limits of the techniques of TLS, meshing and 3D printing (Figure 1). The case study is the elaboration of a 3D model of the *Drac* of the *Finca Güell* in order to be printed the *Dra*c of the *Finca Güell*, for the musealization of the Verdaguer House of Literature in Vil.la Joana, Barcelona. A project developed with the Museum of History of Barcelona

The *Drac* is a sculpture designed by Antony Gaudí in 1885 for the main gate of the *Finca Güell*. This belongs the first project that Gaudí received from Eusebi Güell, in 1884, which consisted on designing a perimeter wall with three gates, a lookout, a fountain, some decorative elements and remodeling the residential house.

The Gate consist of two pavilions: the gatekeeper residence and a stable block and indoor riding school; they both flanking a five-meter-wide gate forged in the workshops of Vallet and Piqué. This gate's figure symbolizes *Ladon*, the dragon who protects the Hesperides garden and the golden oranges tree from the *Atlantida* poem of Jacint Verdaguer. Its form and position are aligned to the situation of the stars in the dragon constellation, which can be seen at certain times of the year in from of the gate oriented to the north. Moreover, some of the details of the sculpture match the constellations Big Dipper and Little Dipper [1]. With this gate, Gaudí created perhaps the most artistic expression of the sign "private property".

Figure 1: Picture showing the complexity of the model, the level of detail it has and the concealments it can present. Source [2].

It was mentioned in the international press, and etchings of his work accompanied the critics' praise. *Correo catalán* with measured understatement said: "it has resulted in a notable combination of richness, novelty and elegance." And "the execution of the sculpture has been perfect despite of the multiple difficulties that presented the dispersion of the decorative elements which are integrated in the construction." [3]. To build the sculpture they faced many difficulties from both the scale and complexity of Gaudi's design: the birdlike claws, the writhing neck, the curling tail and the furled wing are all dramatically presented in iron, which captures the tension and strength of the beast's movement.

Nowadays, the gardens of the *Finca* are part of the gardens of the *Palau de Pedralbes*. The whole is part of the heritage of the University of Barcelona, which ceded the use of the enclosure of the pavilions to the City Council. In 1969 the *Pavilions Güell* were declared Historical-Artistic Monument of National Character.

2. High resolution survey

The sculpture of the Drac has a geometry so complex and with so many folds, that it is impossible to be scanned from a single position per side. For a good coverage of it and avoid the maximum possible occlusions, 25 positions have been made to collect all the data, distributed on the two sides of the sculpture, one that is inside the garden and another, outside; in each side the positions were equidistantly distributed in three rows with different heights: one at ground level near the sculpture, another at half height, and finally, one more distant with a tripod of 3m. In addition, a last scan was made in the middle of the door that saw on both sides of it to serve as a connection between the positions.

Given complexity of the steel grid of the wings, the model must be scanned very close to reduce the size of the pulse at a distance and thus reducing the instrumental errors.

2.1 Data collection

The data collection of the *Drac* was realized with a terrestrial laser scanner model Faro Forus3D x330 (time-of-flight laser scanner), whose range is 360º H * 305º V and has a 70Mpx camera. The scans had a resolution and angle of ¼ with 360º, and ½ with a specific angle, and x4 quality.

Tests were performed to scan the door with an optical digitizer, but this option was discarded by the impossibility of scanning the metallic framework of the wings for its fineness, the problems generated when scanning black elements, metallic elements with brightness and also because the non-existent possibility to scan the internal areas of the sculpture.

2.2 Aligning point clouds

The alignment of the point clouds was done with the software Polyworks, IMAlign extension. As it is a very complex and detailed sculpture, the clouds have to be loaded with much detail, working with a grid mesh detail from 2mm to 2cm, to obtain a connection between meshes with reverse engineering high precision processes.

For this process, we used a cloud with an overview of the door, as a reference from which to align the rest of the positions in an orderly way for each door side. It is an iterative process that looks for the surfaces that are nearer than a specified distance. Starting with an iterative process that looks for the surfaces with a distance of 5cm, then iterating repeating it with shorter distances until 1mm. In order to arrive at the level of detail that is required for the model, an overlap of more than 80% between neighboring positions is taken into account in the survey.

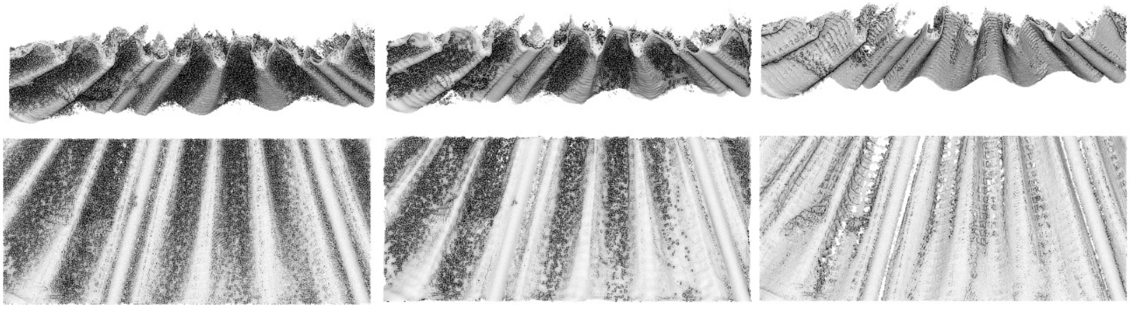
For the union of the other side of the door, the point cloud (taken from the center of the door), was joined, which sees the two sides of the door with its near surroundings (10m maximum). This alignment has more than 60% overlap with the clouds on both sides, on the floor surfaces and the pavilions attached to the door. The door elements which tend to be curved and relate the two faces of the door were included in the alignment process to ensure a continuous surface, such as spirals rotating around the support structure, which are only 1cm thick and that are scanned from both sides of the model. The floor surfaces and side walls that are scanned between the bars are eliminated, due to the instrumental errors that can be introduced.

3. Methodology used to optimize the point cloud

Given the geometric complexity of the model, the normal point cloud has to be generated by position and not as a later analysis of the model. The normal was generated in Meshlab, taking into account the position of the scanner in relation to each point of the grid (structured point cloud), which starts from a PTX format file, which maintains that structure.

The Meshlab import allows filtering the grid by angle of incidence, without altering the position of any point, only eliminating the points within a preset margin, in this case by a very high incidence angle between neighboring points (as seen in the Figure 2 C), through tests carried out on the model it was decided to use the angle of 85°, as the filtering limit. This eliminates points with mixed edge problems, which has a huge impact on the model, mainly in the wings, which are constituted by a grid on which the point is split and generates multiple returns, leaving a point cloud inside the folds. From the grids created by Meshlab from each point cloud, only the normal vectors, the colors and the intensity were exported.

In the figure 2, a point cloud, in which we applied the process of filtering by angle from a grid in Meshlab (Figure 2 c), is compared with the point cloud without filtering from the scanner (figure 2 a) and with a point cloud filtered with the process of moving least squares MLS [4] in CloudCompare (Figure 2 b). The point cloud without filters from the scanner in this case has a very high noise from the incidence angle, so much that it prevents the correct meshing of the surface (Figure 3 a), this mesh mixes the instrumental noise with the real surface and creates a smoothed organic form, which, in this case, does not represent the *Drac's* wings.



a) b) c)

Figure 2: Comparison between processes of filtering point clouds, in a wing section of the Drac, in top view and elevation. a) Point cloud without filters, b) MLS filter Meshlab, c) Filtered by position with an incidence angle limit of 85º

Since a reliable mesh from the unfiltered cloud point could not be made, it is generated a mesh from the MLS-filtered point cloud (as shown in Fig. 3b), generating a mesh that tends to be a continuous surface, but does not correspond to the real model since the surface is averaged with the instrumental error and a new surface is generated (as shown in figure 4).

a) b) c)

Figure 3: Comparison of the meshes made with poisson, based on the point clouds of Figure 2.
a) Point cloud without filters,
b) Meshlab's MLS filter, and C) Filtered by position with an incidence angle limit of 85º

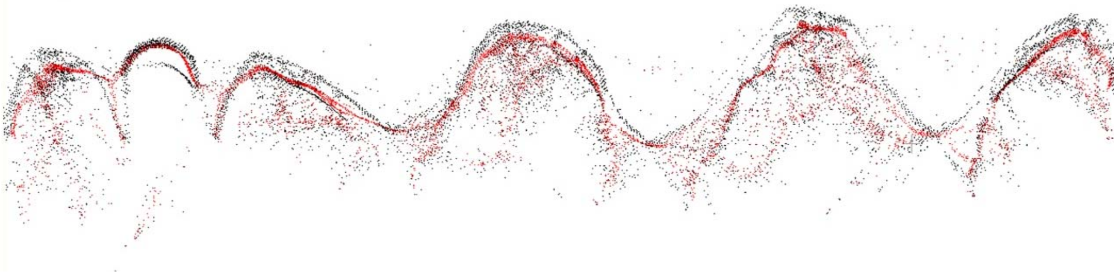


Figure 4: Wings point cloud. Without filter in dark grey and MLS filtered cloud in red

In conclusion, we emphasize the importance of filtering the point cloud by position, instead of filtering the cloud as a whole, with a grid importing filter or cloud structured in PTX format (with an incidence angle limit of 85º), which allows to reduce the instrumental errors as demonstrated in the section of the meshes of figure 5. In this figure, it is compared a mesh generated from the point cloud without filter (grey), one from the cloud filtered by MLS (red) and one filtered by angle from a grid in Meshlab (blue); between them and with the point cloud unfiltered (in the background in grey, with 5 mm of thickness). The figure 4 it's an amplified part of left figure 5.

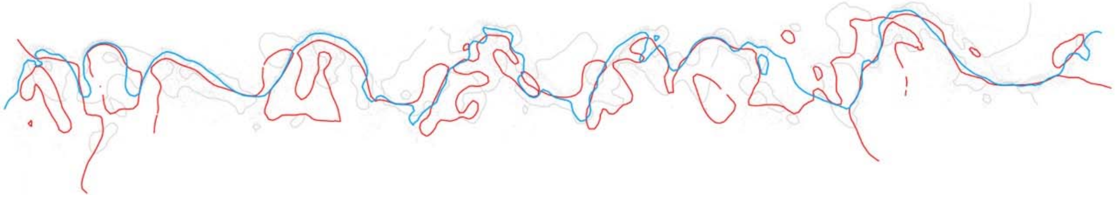
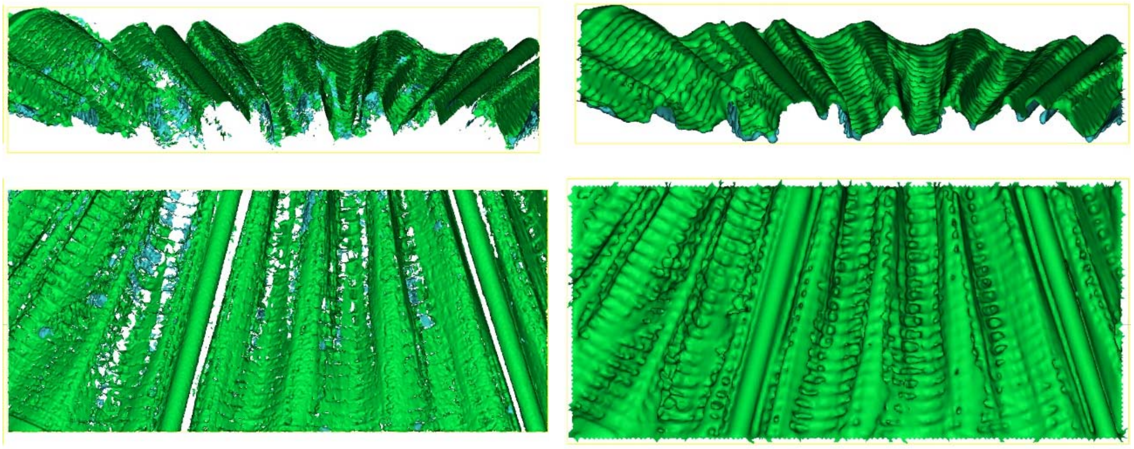


Figure 5: Comparison of the mesh in vector section.



a) b)

Figure 6: a) Meshed with Geomagic Wraps b) *Screened Poisson equation*. Both of a section of 1 million polygons.

4. Meshing with Screened Poisson equation

The results of these tests demonstrated the need to use the *Screened Poisson equation meshing process* in Meshlab [5], mainly because it allowed us to generate a continuous mesh of the surface, in circumstances under which the input data contain high instrumental noise, generating a mesh that reduces problems like polygons in the interior of the surface with inverted polygons (which present a difficulty of being closed very high). *Filled Poisson reconstruction* generates a surface that interpolates these artefacts. However, *Poisson* models tend to oversmooth the data, so it is decided to make high resolution meshes with a depth of the octree of 12, so that the mesh has the resolution and necessary detail, generating meshes of high resolution that soon have to be decimates.

5. Classification of the point cloud in relation to the modeling

The point cloud model and meshes were divided according to the difficulties of the meshing process, and by the parts that constitute the sculpture. The main points that were taken into account in this classification are:

The hidden internal structure: many parts of the *Drac* are plates that act as a case with an inner structure that supports them. This structural element may be totally or partially hidden, or visible, but with unreliable data because of the instrumental error.

The thickness of the surfaces: Some sheets, the *Drac* is made of, are 1mm thick. Those, when scaled, cannot be printed, so modeling processes are used to generate closed models, separating the clouds from each face at an appropriate distance and later editing. Having in each decision the criterion of minimally affecting the original model, closing the model by the internal faces without affecting the external appearance of the model.

Geometric complexity in relation to concealments: a reason for the occlusions and lack of data are the folds of the figure, where the sheet gets into the sculpture making it impossible to scan its interior, therefore, you cannot take data from that area.

5.1 Classification of the point cloud

The *Drac* presents different geometric topologies and textures according to the parts of the body. Thus, each zone of the sculpture involves thinking of a different strategy when it comes to making the meshing process: passing from point cloud to mesh, and its subsequent decimation. To perform this meshing process of the *Drac*, the point cloud has been divided according to the parts of the dragon they represent. First, to extract the door from its context, this means to segment the floor and the walls on which the door is anchored. Once the door is isolated, it is classified into five parts: the base of the door (consisting mainly of a mosaic), the chains, the wings, the lower trunk (including the tail and rear legs), and a group composed of the head, neck and front legs (Figure 7).

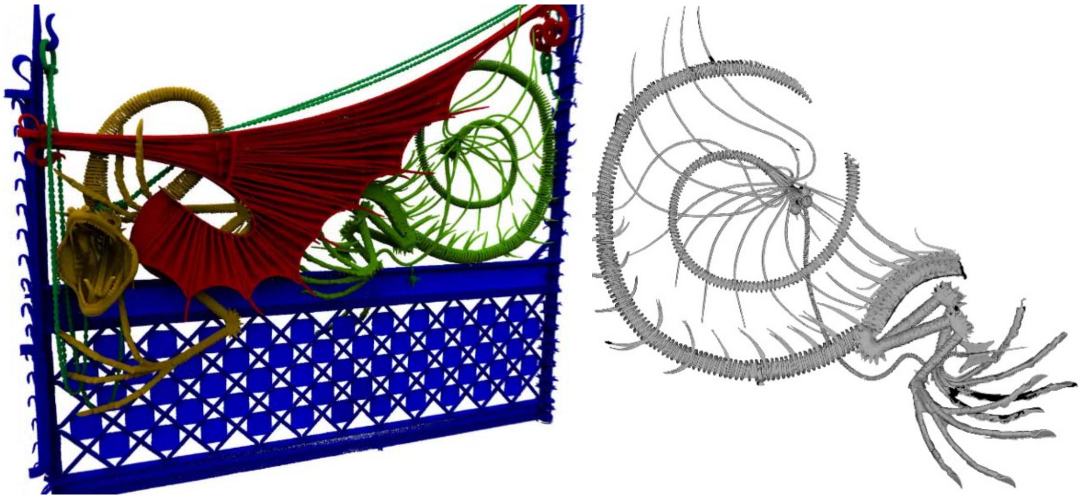


Figure 7: Division and classification of parts of the Drac: Base in blue, chains in turquoise green, wings in red, lower trunk in green (independently on the right), and head, neck and front legs in yellow.

The Base: Like the rest of the door, it has an important sculptural complexity, and includes the door frame and lower lattice. The frame at the same time presents ornaments of vegetation that wrap the vertical parts. The lower lattice presents a greater complexity, as much for the union between positions as for its later meshing, since it is constituted by a mosaic of metallic plates of 1mm of thickness (each plate has a square shape and a central embossed motif). Once meshed, the surface of the mesh was edited taking into account the direction of normal in relation to the two main faces of the door, to give it the minimum thickness required to be printed (1/5 scale), with a printer with maximum print of 0.4mm. This mesh of the mosaic was not realized by the extrusion of only one side of the plate, since it presented details towards the two sides of the door.

Chains: The chains were not able to be fully scanned, due to the internal occlusions and the lack of an upper scan to them, leaving an upper part without information. The areas with missing information require important manual modeling and since printing at 1/5 scale was not feasible because it is too fragile, it was decided to remove the chains from the model.
Removing the chains, from the point cloud model, is developed with a semi-automatic process. It performed a curvature analysis to select the intersection between the parts of the dragon and the chain, then these points of intersection are separated from the model causing a discontinuity in it. Thanks to this discontinuity, by applying the segmentation process *Label Connected Component* [6] (with a minimum of 10 points components), we can segment the cloud by isolated elements with their subsequent classification.

The wings: The surface of the wings of the *Drac* present a significant noise between their folds. There is also a lack of important information inside the sculpture because of its poor visibility from the outside. This makes that elements inside the wings cannot be registered, as for example the chest of the dragon.

On the other hand, we find the big problem that the surface that makes up the wings is a grid of thin wires spaced between them. To make a realistic model that simulates the texture of the wings and that can be printed to scale, it is chosen to make the wings a single continuous mesh without holes, instead of trying to mesh the grid like it really is. In our model, the entire wing is a single rough surface, rather than a composition of spaced rods.

Bottom trunk, tail and hind legs: the most complex of these parts are the body and tail of the *Drac*, composed of a helical element held by a plate of rectangular section inside the body. Leaving most of the interior space of the helicoid empty, with a pitch of the helix quite too narrow to see through.

This part of the model highlights the precision of the alignment, having continuous helical surfaces regardless of the side of the door on which it was scanned. It also shows the decision to perform the high number of positions that were made on the model, trying to cover all the angles of the internal faces of the model, as shown in the Figure 8.

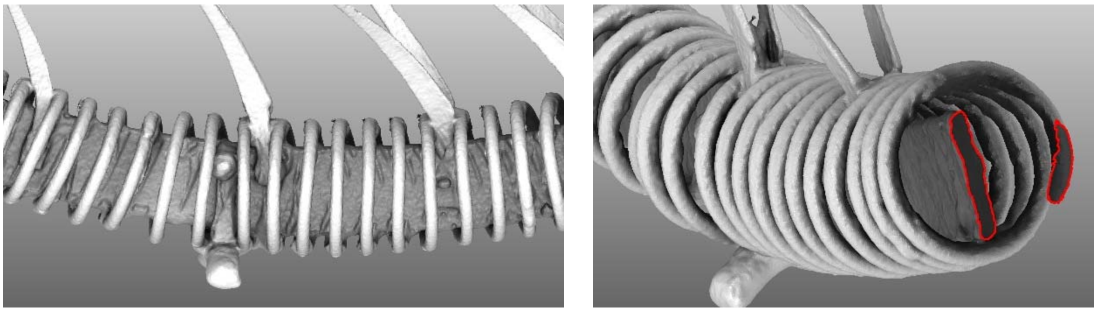


Figure 8: Internal structure of tail, orthogonal and sectioned axonometric views.

Head, neck and front legs: In this case we face the impossibility of taking data on the inner parts of the head, which is made with forged metal plates, with a thickness of millimeters. Therefore, due to the lack of data it was decided to close much of its interior.

An example of this is the detail of the eyes. These is an inner void in the dragon's head. As it is impossible to know how the interior is and, therefore, there would be an open mesh, we chose to create eyes that close the mesh. To do this the edge of the perimeter of the eyes is cleaned by tightening its edges so that it is rounded, then this circular perimeter is extruded, and at the end, a closed mesh with curvature is made in the inner edge of the created cylinder (Figure 9).

The *Drac*'s neck presents a case similar to his tail. Although, in this case the inside of the helical member is constituted by a cross-structure and fastener elements (such as riveted pins and ro-rooted bolts). Taking into account this complexity, it was decided that its interior was solid, meaning the spaces between the helical tube had to be closed. To do this, it takes 2 steps, first, to erase all the parts of the mesh inside the neck and the internal faces of the helix; and secondly, mesh bridges are created between the tube at strategic points to minimize the voids and that these new, narrower and defined voids can be automatically closed with an intermediate curvature.

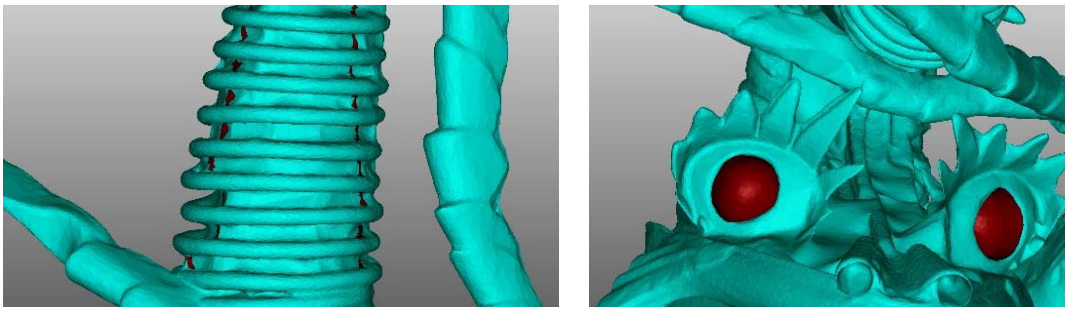


Figure 9: Left neck with bridges between the helical and meshing eyes.

As discussed above, the complexity of the geometry of the model causes a large number of occlusions, which causes the mesh to be incomplete or perforated in some areas. In general, for most voids, they are automatically filled, always having a control in which type of voids (mainly controlled by size), obtaining a high resolution final model as shown in figure 10.

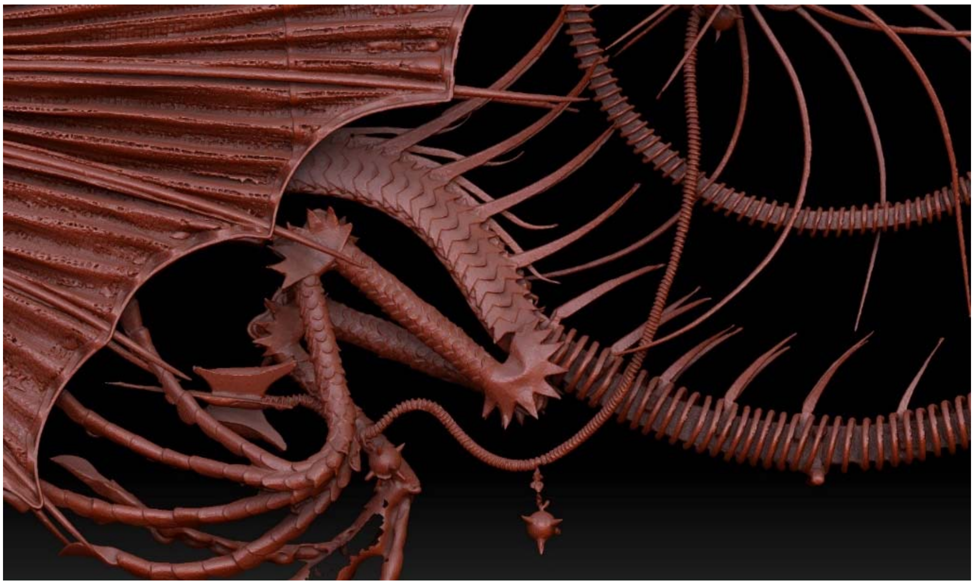


Figure 10: High resolution model without the base of the door, with a total of 150 million polygons.

6. 3D Printing by Selective Laser Sintering SLS

The mesh taken from the point cloud contains too many polygons to be exported and be read by the 3D printer software. For this reason, a method of simplifying the mesh should be applied. The simplification process applied is "Simplification: Quadric Edge Collapse Decimation" by Meshlab.

A number of constraints are applied to the polygonal reduction: a quality restriction on the formation of polygons using the default value of 0.3 (0 has no restriction, 0.5 penalizes the faces according to their quality); the preservation of the normal vectors of the faces (making the surface maintain the same orientation as the original); the optimum positioning of the simplified vertices (letting the program decide the new position of the vertices trying to minimize the quadratic error), and finally, a final cleaning of the mesh. After all this steps, a model of the Figure 11 was obtained.

Mesh optimization: Once we have the mesh simplified and scaled to the desired size, we look for and correct defects in it that may make impossible to print it. Apart from generating a closed mesh, the following process are applied: look for and erase "Non-manifold Triangle”, "redundant Triangle", "crossing Triangles" and correct "reversed Triangle".

Figure 11: Left: 3D printing grid (1.5 million polygons). Right: picture of the printed model

The SLS (Selective Laser Sintering) type 3d printer used in this case study was a model of the CIM-UPC foundation, which had the limitation in terms of detail of 0.8mm and a tolerance in the pieces of +/- 0.30mm per 100mm [7].

7. Conclusions

When you have a point cloud with noise due to instrumental error caused by scanning a wire mesh, MLS processes modify the data tending to generate new surfaces that does not represent reality in an accurate way. As shown in the article, a filtering by scan position must be applied in relation to the angle of incidence, to reduce the said instrumental error in complex elements that compose the door of the *Drac*.

In two weeks, collecting data, modeling and SLS printing were performed, demonstrating the robustness of the proposed methodology. Taking into account the complexity of the different zones that make up the model, efficient techniques of modeling and problem solving processes are proposed, as much in the internal structures, as the thicknesses of the surfaces and the geometry in relation to the concealments.

The aim of the model is to be part of the cultural heritage of a museum. Being part of an exhibition requires rigor and fidelity in the final result, which is evident in the process of generating the model for subsequent 3D printing. Taking into account the limitations of the printing processes, a scale model 1/5 of a section of the door with a high level of complexity is achieved.

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