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Filtering Surfaces in Surveys with Multiple Overlapping: *Sagrada Familia*

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Abstract. The heritage survey with the Terrestrial Laser Scanner (TLS) allows the document of the geometry of the building and to constitute a 3D point cloud as a register of its conservation state. When complex buildings with architectural and sculptural elements are scanned, there are a lot of captured data that is not valid, because of the instrumental error and foreign elements of the buildings. For that reason, the point cloud must be cleaned with the objective to obtain a final model from which different products could be created, such as plans, technical documents and 3D models to print. For this cleaning process, in this article with the case of study is Antoni Gaudi's *Sagrada Familia* (*Fachada del Nacimiento*), we propose a methodology based on applying some filers, considering the fact that more than 3000 positions were realized, 750 of them belong to the same facade with positions that have a lot of overlapping data. Therefore, in a same zone of the building there is data scanned from multiple positions in different ways, so we can find there any kind of error, such as the noise from boundary effects, glass flections and mobile objects, and scans realized from a scissor lift, that have been previously validated. Different point cloud filtering processes have been studied, through the point cloud itself (position by position and with a unitary cloud), and by meshing it. Every process requires the knowledge of how the scan was realized, what type of error dominates in each zone is analyzed. Therefore, each filtering option accomplish the requirements established after the analysis.

1. Introduction
This article proposes a methodology for the filtering of point clouds in architectural surveys of great complexity, in buildings that combine sculptural and architectural elements with multiple relationships between interior and exterior areas, taking into account the data capture at great distances with high resolution, for this, the Topography and Terrain Laser Scanner (TLS) technology are used together. For this, a workflow is developed that allows the filtering of point clouds, of surveys composed of massive data captures, with an overlap that exceeds 70% between positions, forming a single continuous point cloud. Therefore, the term surface of the point cloud is included, referring to its continuity, in which the filtering takes into account the instrumental and methodological errors and the need to have a coverage of the building without occlusions. To optimize instrumental and post-process errors, the point cloud has to pass certain filters, to obtain a cloud of points as a single surface, looking for the average of these information captures, averaging the surface captured in multiple positions.

The case study for research on filtering techniques in mass surveys is applied to the *Sagrada Familia*. A building that, due to its geometric complexity, number of sculptures and the proposed technical requirements, requires a massive data collection and a high degree of detail. The proposed methodology focuses on the last part of the filtering process, on how to filter the final point cloud. However, the previous steps that will be carried out are explained, in order to have a point cloud in conditions to be able to apply this final filtering.

This model of point clouds fulfils a series of technical requirements that guarantee that the model is generated as a single surface, allowing a useful three-dimensional model to be considered in restoration processes of the facade. The accuracy of the model is very important due to several factors, both the coating of all the surfaces of the building, and the detail that can be extracted from this model (which should allow to locate architectural pathologies for restoration work), and being sufficiently dense to take raster images and videos (that allow a clear identification, reducing instrumental and methodological errors typical of the TLS technology).

An example of this overlap between positions is the front of the *Fachada del Nacimiento* towards Marina Street. On this facade, more than 100 sculptural groups are scanned. These groups can present several grouped sculptures of different sizes, from sculptures of saints of more than three meters, to small elements of animals of less than thirty centimeters with a great wealth of details. All this integrated through an ornamentation that ends up defining each of the three portals, *Portal de la Esperanza*, the *Portal de la Fe,* and the *Portal de la Caridad* (or *Portal del amor*) in the center, the *Portal de la Caridad* ends with the Tree of Life that starts at 42.5 m, reaching 63.2 m. These portals present so many sculptural and decorative elements that come to merge with the architecture itself. These portals have symbolic elements that intertwine with the ornamentation, such as rosaries interlaced with the sculptures, or for example clusters of fruits interspersed with balconies.

This complexity generates several restrictions, especially in the process of delimitation of elements in the documentation process, understanding the difficulty of scanning the sculptures individually and maintaining homogeneity with the rest of the building. Contrary to this, a methodology is proposed that seeks to encompass all the survey as an integral model, that does not generate contradictions in the models generated.

With the purpose of documenting, the Technical Office of the *Sagrada Familia* established technical specifications for the elaboration of a 3D point cloud obtained by techniques of massive capture of spatial data. These general objectives at the beginning of the project have the following basic requirements:

- Digitization greater than 95% of the facade surface.
- The union between general positions with resolution of 20 mm, will not exceed an error greater than 15 mm in 3D and 25 mm with respect to the georeferencing with the support points (topography).
- The union of model positions in detail with a resolution of 2 mm, will not exceed 5 mm error in 3D and 10 mm in georeferencing with support points.

These requirements are met, in some cases exceeding expectations, since a facade covering greater than 95% is obtained, but with a homogeneous 5mm model. A unique model is generated that does not divide sculptures and architecture, in the construction of the model, in which a resolution of a single model is guaranteed, of 2 mm distance between points of the 3D point cloud, in the areas of sculptures, both in the exterior and interior (understanding its difficulty to be at high altitude). In terms of quality control, in relation to topography, an average error of 7.6 mm is obtained, in the overall project, with 140 spheres for TLS, which are controlled by replacing them with topographic prisms. In this project, 4530 scanning positions are performed. Positions are ruled out due to poor quality in terms of color and for not passing the quality control filters, reaching a total of 2032 useful positions.

1.1. Case study

The Expiatory Temple of the *Sagrada Familia*, located in the city of Barcelona, was declared a monument of humanity by UNESCO at the meeting held in Durban on July 17, 2005. Specifically, the *Fachada del Nacimiento*, the apse and the crypt, elements started by Antoni Gaudí and finished by his immediate disciples. The facade is composed of four towers: Bernabé, Simón, Judas and Matías (Bernabé is the only one who saw Antoni Gaudí himself finish), topped by a sculptural terminal more than 107 m above ground level.

The difficulty of making a survey that distinguishes the architectural and sculptural elements and the high demands of technical requirements, make rethink how to make the data collection, reaching the point of considering working the entire facade with the resolution of sculptural model. This entails carrying out a large number of scans from the ground, from the facade itself, terraces of adjoining buildings and scissor lift platform up to 26 m high. The fact of using the 26 m platform allows filling parts that the scan from the ground cannot reach (figure 1).

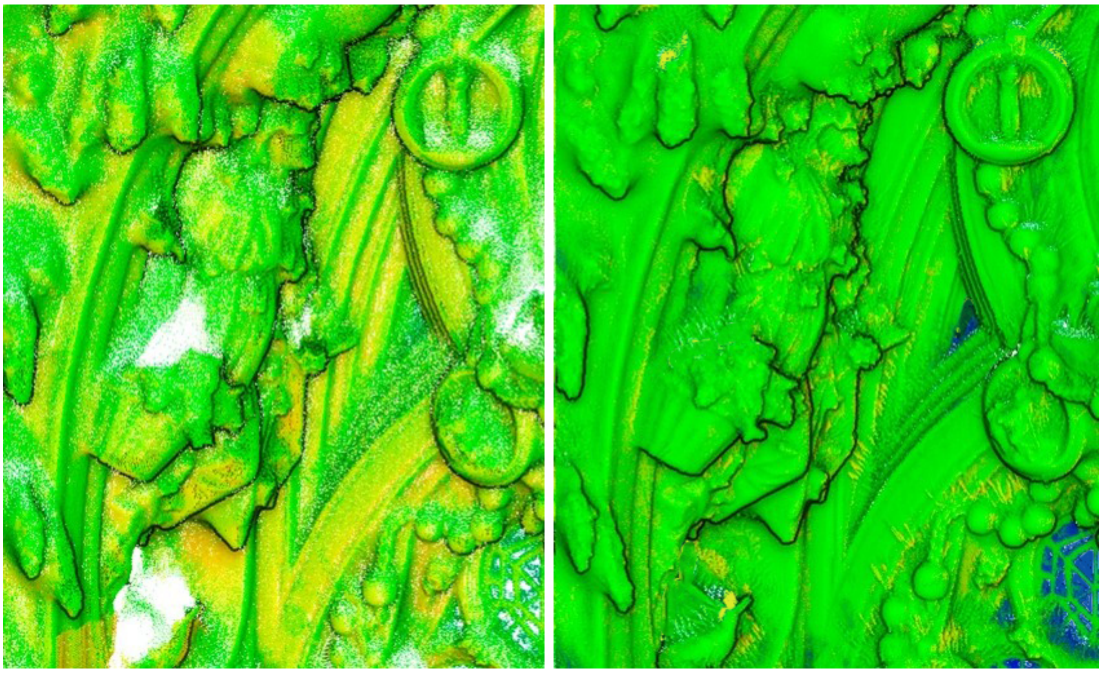


Figure 1. Detail of the cloud of points from the ground (left), and final survey with scanners from the platform (right)

In order to obtain a single cloud, minimizing the possible errors due to the large number of positions and the different reliabilities of the methodologies used, there is a need to study a filtering methodology that allows the cloud to be cleaned without losing detail. This methodology allows to perform a rigorous quality control.

Although the object of study is the *Fachada del Nacimiento* of the Expiatory Temple of the *Sagrada Familia* in Barcelona, the need to establish a filtering methodology means that first work is done with a smaller scale environment. A space of difficult access is chosen behind the sculptural set of the Coronation of the Virgin. The fact of being outside the access to the public and having a sculpture of 10 m located at 6 m of height, allows to work during all the day and find some of the difficulties of scan that appear later for the documentation of the set of the facade. For the identification of the filtering processes, initial tests are first performed in the *Coronación de la Virgen* and then applied to the rest of the facade.

Coronación de la virgen. To make data from this space of 50 m2 and about 20 meters high, 81 scans are made from a tripod. A giraffe is added to the tripod for inverted scanners and to take out the scanner through windows. In addition, a 6 m pneumatic mast with an additional extension of 2 m is used to have a greater coverage of this area.

Exterior *Fachada del Nacimiento* street Marina. To take data from all the exterior of the façade on a sculptural scale, 750 scanning positions are made from a tripod, with a tripod of giraffe and with a hydraulic scissor lift platform, out of a total of 4530 scan positions made for the lifting of all the facade of the Nativity, interior and exterior.

1.2. Antecedents

There are a lot of topographic surveys through the massive capture of TLS data. A recent case is the Documentation Project of the Cologne Cathedral [1], or the survey of Mount Saint Michel [2] in which about 700 scans were made to survey the entire building. In our case about 4530 captures are made to raise a single façade, 750 of which, to lift the exterior of the façade creating a large amount of overlap between them. Other cases such as the Aiguilles hospital [3] with more than 20,000 m2, or the large sports stadiums surpass a thousand scans, but in these large cases the overlap between positions is much lower than in the case studied.

2. Union method at the sculptural level

The union of the entire façade (architecture and sculptures) at the sculptural level is carried out in three phases: first stage consisting of a general union validated with a survey of high precision topography (as a reference for the whole survey), a second stage of survey including all the internal and construction spaces, and the third stage, the last phase of the sculptural scale survey in which all the sculptural elements are completed (surpassing a 95% covering of the surfaces).

In this article, the third stage of surveys is prioritized. In the planning of this stage, a regular plot of scanning positions is established at different heights (Figure 2, left), reaching up to 32 m in height. For the first 1.5 meters high strip, a standard tripod is used, for the second up to 6 meters, an extendable pneumatic mast is used, and for the following, several hydraulic scissor lift platforms of 16, 20 and 26 m are used. To this last one, the 6 m extensible pneumatic mast is implemented, allowing to reach 32 m in height.

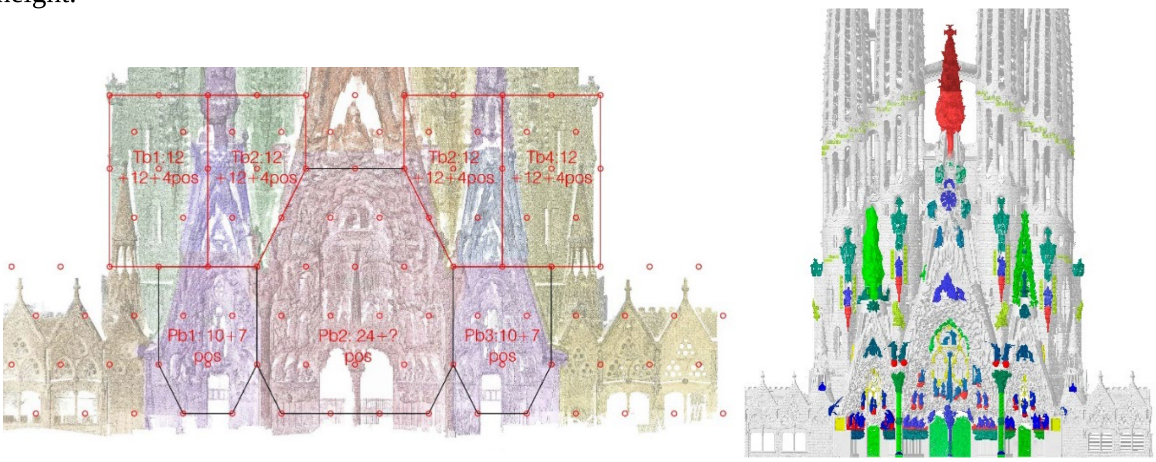


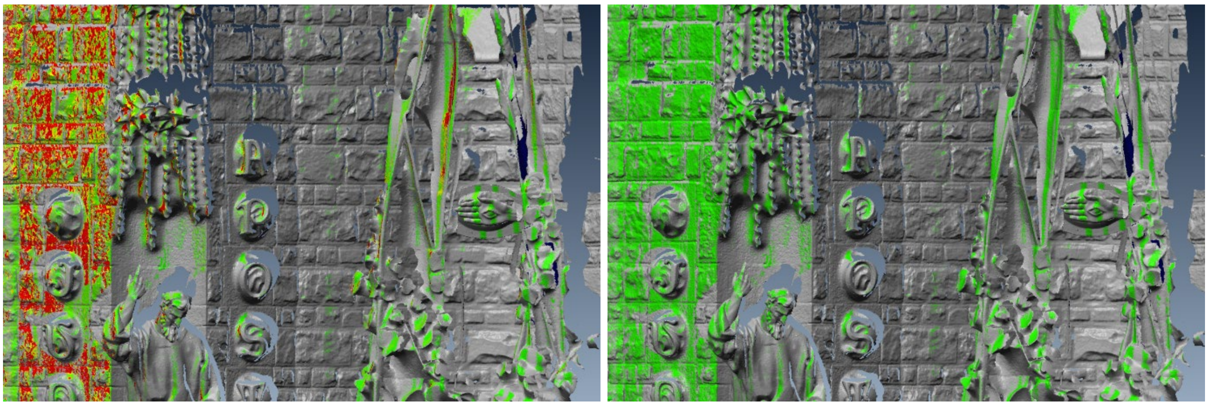
Figure 2. Distribution and zoning of the façade for the taking of data in detail, Left planning of data collection on the façade, right classification of sculptures in the planning of auxiliary positions

Althou the data collection is performed in a unified manner, for the joining process, by means of a Grid comparison method, groupings are established by zones (Figure 2, right), to validate the union of these to the general reference model individually. The registration of each zone is done taking into account the reliability of the data, depending on the stability of the accessory used in the scan. Thus, each zone joins the reference model from bottom to top.

The fact of capturing data from elements that are influenced in their stability by the effect of the wind, requires an exhaustive quality control, position by position. In the case of scans from platform, with the help of a gyroscope, a first initial validation is performed. Subsequently, a quality control is carried out based on the topographic survey and a comparative analysis between positions from the ground and positions from platforms.

Subsequently, a validation is carried out in three phases. The first consists of the detection of the spheres distributed by the facade and the verification of these in relation to the topographic coordinates. Due to the dimensions of the facade, many of positions do not see the three minimum spheres to check the correct union, for that reason the check is made position by position and for the whole area as a whole.

In the second phase, each position is compared by distance (grid to grid) with respect to the general reference model, with which the union is not validated until all the points are less than 2 mm apart. In Figure 3, we see a comparison of a position from platform against positions from the ground, to the left in red, vertices a distance greater than 2 mm. In figure 3 B, quality control is passed in the joining process, the grid is colored green, if the distance between vertices is less than 2 mm. This process is done with the PolyWorks program (PolyWorks | InspectorTM Standard, from the company InnovMetric). Finally, even when in its correct position, the continuity of the normal has been checked, which does not contain undulations due to the movement of the support.



a) b)

Figure 3. Comparative quality control of Grid between position from ground and from platform 26m, a) Distance between vertices of the grid greater than 2 mm, b) Distance between vertices less than 2 mm

Once all the scans are referenced and before proceeding to the union of all of them, a filtering methodology is developed position by position in order to minimize the noise produced by instrumental errors, reflective or translucent elements and colour.

The joining process is also done by zones, and to keep the data organized we work with a factor scale per zone that allows us to undo some step (in case of error), without the need to start over from the beginning, which is not possible, for the duration of the project, a job that has required two years of dedication. For each zone, the different existing filters are studied, without obtaining the desired results. Finally, we opt for the methodology developed in this article, which consists of making a mesh from the point cloud and then filtering the cloud of points in relation to the proximity of the mesh. This process allows to reject groups of points of objects that are not part of the façade as such, whether they are birds or elements of temple construction.

3. Advantages of the filtering method

As in any scanning project, the filtering starts with a manual cleaning of all the mobile elements (tourists, construction elements and modifications of perimeter elements to the facade that are moved along the construction). After cleaning, the scanners are filtered position by position, in order to eliminate the problem of the split border produced by instrumental error by the angle of incidence. The noise produced by the reflections is also eliminated, discarding the points with low intensity. Finally, the overexposed areas are discarded by eliminating the points with a high *composite* (average of the RGB values). Once corrected, all the positions were joined by groups, and some noise point cloud cleaning filters were studied. These filters are not adapted to the requirements of the project, since they can be so aggressive that they eliminate the areas of interest in which, due to their difficult access, they have a low density of points.

In the exterior facade, due to its magnitude cannot be eliminate elements that are confused with the ornamentation and sculptures (for example, the birds that rest on the facade and the quills that try to repel them, which are not belong to the heritage building). The proposed filtering allows to eliminate these elements in an automatic way.

With all the described, the proposed methodology consists in mesh the complete point cloud with the method of Screened Poisson Surface Reconstruction [4], obtaining a unique model that ensures the continuity between the architecture and the sculptural elements, to later compare mesh by distance with the same point cloud and discard those points that are more than 3 mm.

3.1. Pre-filter by position

The sculptural set of the facade monopolizes practically the entire surface. The fact of having so many individual sculptures linked between them by surfaces that in turn behave like an ornamented canvas, generates a problematic of a split border [5] from the sculptures towards that ornamented surface.

This error becomes a priority due to the fact that the facade is practically a sculpture in its entirety. By knowing the position of each scan with respect to its angle of incidence, the points between 85º and 90º are eliminated, and this edge error is eliminated. This process is done with the Meshlab program, by importing PLY format files, modifying the angle parameter.

In relation to the capture of the colour of an exterior facade of great height, with an intense tourist activity from 9:00 in the morning until the last sunset, the lighting conditions of the most notable scanners from the sunrise to the start of tourism activity. We find a variety of light situations, from a dawn of intense reddish tones during an important time slot, a cloudy dawn that grants a homogeneity of colour, even from the beginning of the day that burns the image of the scanner in part of the facade and generates strong shadows in others. Regarding the overexposure of the lighting at the height of the building, at different times of the day, to the conversion of the RGB into an average called composite. Following this value, the cloud is divided into two, taking as a reference the value 220. For values lower than 220 the colour is accepted as valid, and between 220 and 256 (whites and colours that approach) these areas are considered as overexposed. As I said, the fact of indirectly scanning the same areas on different days, has allowed to complement these parts with other scanners that improve colour because they have clear or better natural conditions.

3.2. Filters by point groups and isolated points

The meshing process of such a complex point cloud requires its optimization and filtering. That the point cloud does not have errors that are later transferred to the mesh. The union of all positions generates noise, isolated points or isolated groups of points that come from instrumental errors. All these elements complicate the meshing process. To eliminate this noise or isolated points, filters are used in the point cloud. To do this, choose which type of filters are used and which ones are discarded.

To reduce the isolated noise of the cloud, the neighbourhood noise filters are discarded. These filters are based on calculating the average distance of each point to its neighbours (the number of points that must be considered neighbours is first established), and then rejects those points that are farther than the average distance plus a minimum of the standard deviation times (second parameter to enter).

Due to the requirements of the *Sagrada Familia* technical specifications, the condition of having at least one point every 20 mm on all surfaces is fixed. As explained, the volumetric complexity requires a large number of scanners, to cover the highest percentage of surface. Despite this, areas of difficult access have or may have a lower density of points. As we see in the example of Figure 4 (A and B), when applying a filter of this type, in this case the SOR (Statistical Outlier Removal) filter [6], In this example, this loss of information is identified, having less density of points in the marked area, in addition to eliminating the noise of the cloud, disappears practically in its entirety the entire area. Therefore, this type of filters is discarded so as not to lose information.

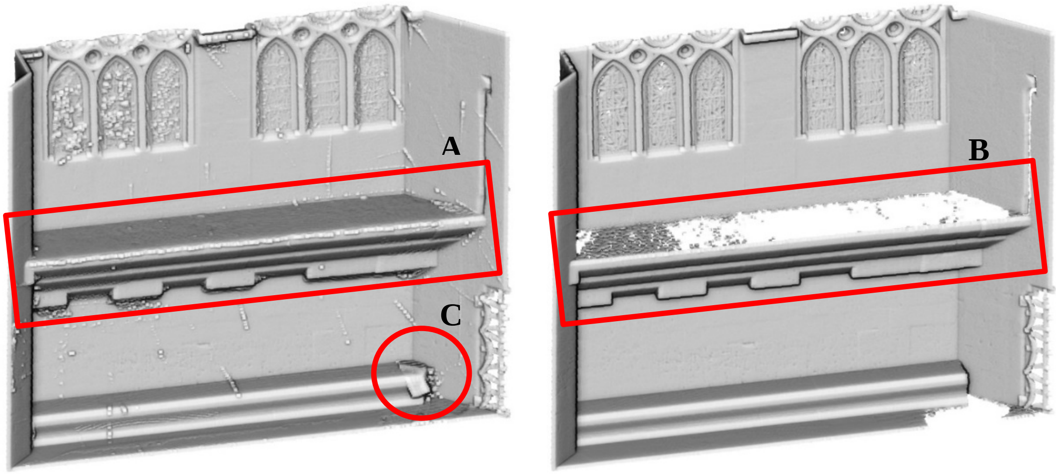


Figure 4. SOR filter. A) isolated points in the cloud, B) when applying the SOR filter, information with low point density disappears, C) Registration error from a balcony at 20 m, crossing a glass railing

On the other hand, the type of filters from isolated groups to the surface are used, specifically the Label Connected Components CC filter [7], in the CloudCompare 2.9 program. These filters are based on segmenting clouds from a subdivision of octrees, allowing to determine if point clouds are connected or separated by a minimum distance. As in the case of the study there can be no concealment, with a record greater than 95% of the surface, there should be no element that is not connected to the rest of the building. Therefore, the CC filter is applied, in which isolated points are eliminated and groups of points connected between them are grouped. In the case of the exterior facade, a single group is generated, the facade itself, and 150 groups of isolated points, which are identified manually and eliminated because they have no connection to the facade.

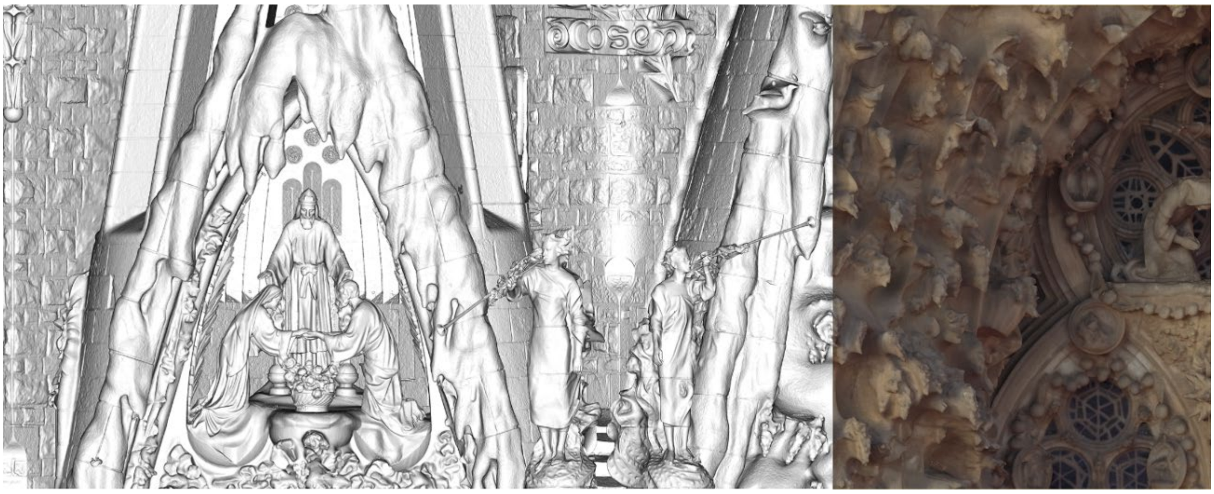


Figure 5. Example of mesh from 14 to 20 m in height, with a width -15 to 0 m, with respect to the topographic center of the cruise

3.3. Meshing and filtering

The basic idea to generate the mesh (figure 5) is to use the mesh as a method to filter the final point cloud. For this, the meshing process must create a single continuous mesh. Therefore, mesh techniques based on relating the points in the construction of polygons, are discarded, because they do not prioritize the continuity of the surface, but their union or their relationship, in most cases with respect to a curvature analysis. In this project, a meshing technique is necessary to reduce the noise of the point cloud, in the search for the best approximation to the surface.

For this reason, the Sreened Poisson equation process in Meshlab is used for the meshing process, when generating a single surface, being the average of the data, to be a meshing process that starts from a single mesh, projects a closed grid over the point cloud, which through Dirichlet and Neumann [4] restrictions allows the surface to extend to the edge of the elements of the point cloud. Obtaining three fundamental points for this process: first, the continuity of the surface, second, the pre-cleaning of noise from the point cloud without altering areas with low information, and third, generating a closed mesh.

The closed mesh is fundamental for a survey with a coverage greater than 95%, since elements such as birds (Figure 6) are only scanned momentarily on one side, and when moving between positions they are incomplete information that is eliminated directly by mesh. Complementary to this case, there are also mobile objects in various positions of data points, in the same place, generating a disconnected closed mesh, which is not connected to the mesh that describes the rest of the building. This disconnected mesh can be removed with a filter to remove smaller 50 cm elements in Meshlab or be removed in CloudCompare with the CC filter described above.

Complementary to this, this process of meshing from the projection of a Grid, allows to eliminate the problems of polygons with inverted normals. When the spikes of the meshes are reduced, the interior polygons of the mesh (product of instrumental errors) are reduced, thanks to the Poisson reconstruction, which generates a surface that interpolates these artefacts. On the other hand, Poisson models tend to oversmooth the data, for this reason, high resolution meshes are made, with a depth of the octree of 12, so that the mesh has the resolution and necessary detail, which then have to be decimated.

Due to the size of the project of the birth facade, the mesh is generated by zones. Areas of 15 m wide and variable heights, between 3 to 6 m. They are generated (only for the facade of the street Marina), about 44 meshes. Each one between 30 to 105 million polygons. Currently these mesh boxes cannot be opened all at the same time without being previously decimated, reducing the information they contain, so they are used only as a basis to optimize point clouds (which are a consolidated standard of work for large databases, both in industry and in heritage).

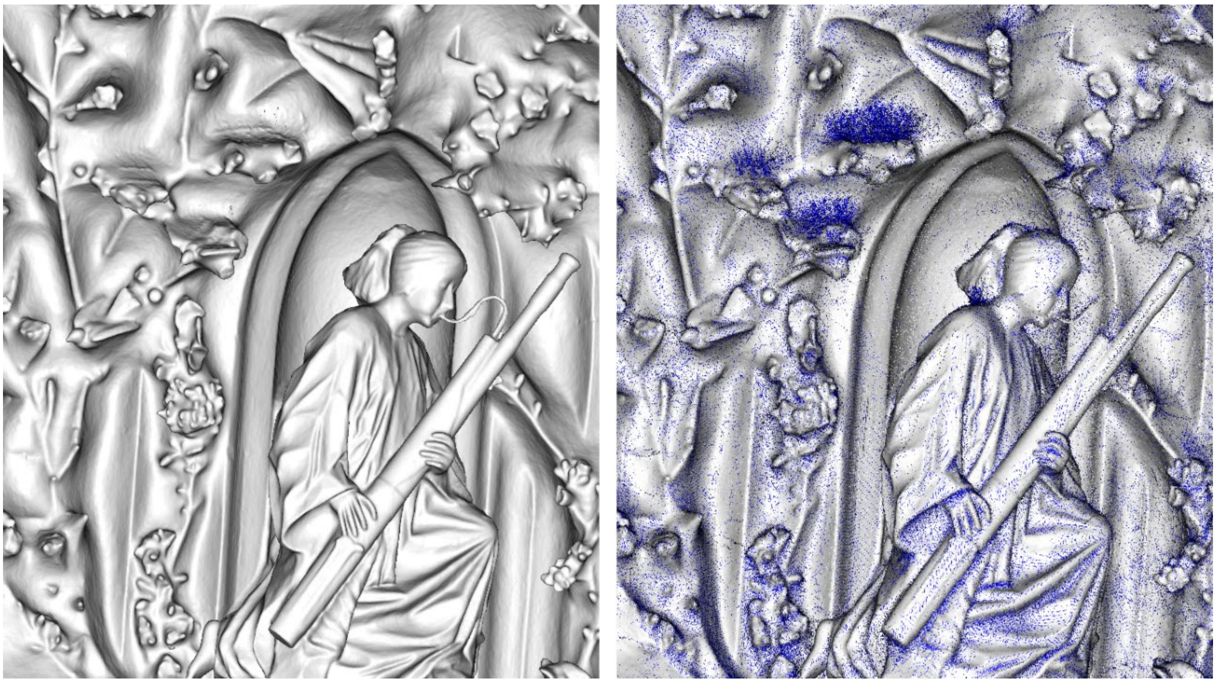


Figure 6. Example of filtering by comparison to the mesh, left detail of the mesh and right point cloud, in blue the points filtered by distance to the mesh before being eliminated.

These meshes include a scalar factor, which allows to identify the quality of the mesh, mainly in areas with little information. Since there is a continuous mesh, in some of these boxes errors are identified in the process of joining the point clouds. To detect where the error comes from, the scanner's coding by zone is used. With this coding is simple to be able to isolate which scanners are the ones that damage that area and proceed to correct it. With this process these errors are found, isolate them and fix them without major setbacks. An example of this can be seen in Figure 4 (C), where a piece of bank contains a binding error. This error is given by the scan of level 20. On that level there is a corridor with a glass railing, therefore, the entire lower part of the basilica that comes from these scanners have been captured through a glazed surface, with the error that derives from it. With the coding of level 20 scanners, in the final point cloud we can remove those scanners when they come through the aforementioned glass surface.

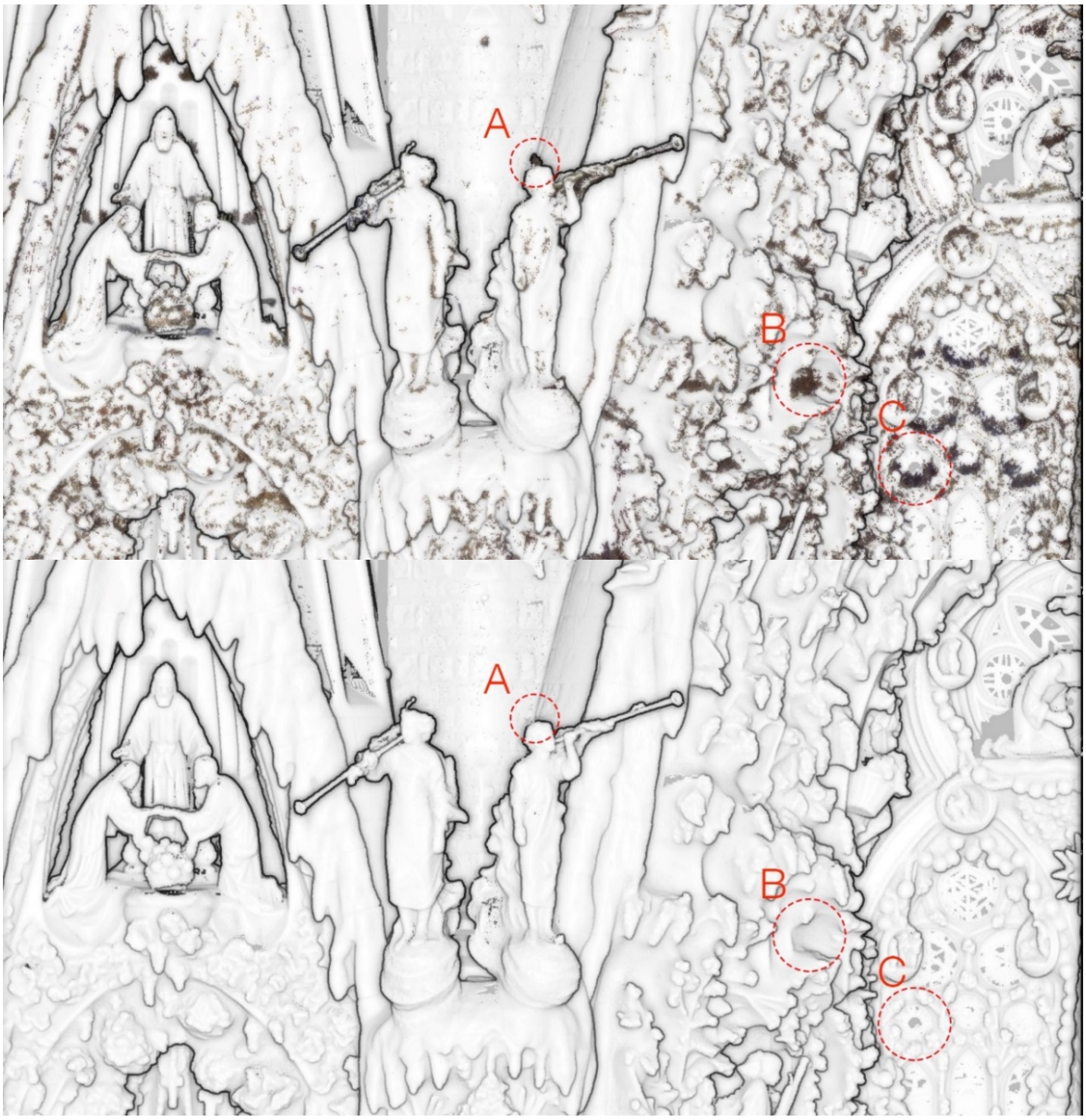


Figure 7. Point cloud with elements outside the facade in colour (upper): A, pigeons, B anti bird's tines and C instrumental errors. Final filtered cloud (lower)

Each of these meshes is compared with its cloud point counterpart by distance, storing the distance to the mesh at each point of the point cloud. From this information included in the cloud of points in a scalar factor, the cloud is divided into two, the information between -3 to 3 mm (4.140 million points) and the rest of the point cloud, being 20% of the total point cloud on the facade overlooking Marina Street (831 million points). That means that the range of -3 to 3 mm is a 6 mm point cloud that stores the best information that defines the surface of the point cloud. An example of this can be seen in figure 7, which shows the mesh and the classification of the point cloud in white colour of -3 to 3 mm and in blue colour the noise generated by instrumental errors and the anti-bird tines.

4. Conclusions

A building of patrimonial importance such as the *Sagrada Familia* requires a high level of precision, in the documentation, analysis or creation of dissemination material. Achieving a three-dimensional model true to reality is essential for analysis, planning and restoration work. As shown in the article, the requirements require a method of property surveying that is capable of assuming a 95% coverage of the facade surface. For this reason, classification by areas is essential, in relation to the different scanning positions, in projects with several thousand positions, in long-term projects, in this case more than two years of work. Having a very strict quality control, since a single position can harm the whole project, in the case of presenting significant instrumental or methodological errors, analyzed position by position.

The optimization process position by position and the first quality control, before defining the union of all the positions, the debugging of instrumental errors, the colour corrections and the elimination of duplications of groups of points, is a fundamental first step, that cannot be done with groups of positions already joined. Generating a rigorous model, for the construction of a precise and solid model to define a complete cloud of points, with which to arrive at a three-dimensional model faithful to reality. The filtering of the preliminary point cloud has facilitated the reduction of errors, which shows the final classification of the sculptures, without errors in joints (errors like split edges), or double surfaces, which is demonstrated in the comparison with a mesh of the same surface and by processes of analysis by curvature, with results that facilitates identifying changes in the geometry for its classification. This allows to generate a catalogue of sculptures for future conservation or rehabilitation.

A cloud of points is obtained, from which general plans of the building can be drawn at scales 1/50 and 1/25 for sculptural areas, allowing the generation of detail plans for studies of pathologies in restoration and for geometric studies of the building. A model that allows to make relationships of elements in heights higher than 100 m with the same resolution as the elements in the ground floor.

The volumetric complexity of the building can be understood thanks to a 3D model of point clouds, which allows studying alterations of the building, its state of preservation, relations between interior and exterior and getting to better understand how the *Sagrada Familia* was designed and built. In this article a methodology is proposed that allows to document the current real state of the building with a high resolution. A three-dimensional model that allows us to understand the relationships of the interior spaces with the façade and its connections in height with the towers.

With the filtering parameters developed in the workflow described, even defining pathologies of the building that could not be identified with other processes of scanning or meshing. The support of the final point cloud in the continuous mesh, provides a rigor that allows to generate diffusion material in the form of documentation, video or even model with a high level of resolution and precision.

References

[1] D. Pritchard, J. Sperner, S. Hoepner and R. Tenschert, “Terrestrial laser scanning for heritage conservation: The Cologne Cathedral documentation project,” *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. IV-2/W2, pp. 213-220, 2017

[2] FARO , “Los escáneres FARO se adaptan a las restricciones de acceso del Monte Saint Michel” Art Graphique & Patrimoine, recuperado el 23 de marzo de 2013 de:

https://www.faro.com/download-center/download-centre/escenado-laser-montsaintmichel.pdf?sfvrsn=12
[3] FARO , “El tamaño de estructuras a digitalizar no es un inconveniente para el escáner Focus3D X 130” ATFF, recuperado el 23 de marzo de 2013 de: https://www.faro.com/download-center/download-centre/es_us_ls_atff_2016_fr.pdf?sfvrsn=6
[4] Kazhdan, M. and Hoppe, H. 2013. “Screened Poisson surface reconstruction.” *ACM Transactions on Graphics*, vol. 32 num. 3, pp. 29.1-29.13,2013
[5] Leonardo Da Vinci European Program. (2006-2008). Theory and practice of terrestrial laser scanning. 3D RiskMapping)
[6] R.B. Rusu, S. Cousins, “3D is here: Point Cloud Library (PCL), IEEE International Conference on Robotics and Automation (ICRA).” IEEE, China, pp. 1-4, 2011
[7] A. Börcs, B. Nagy and C. Benedek, “Fast 3-D Urban Object Detection on Streaming Point Clouds” Computer Vision - ECCV 2014 Workshops, vol. 8926, pp. 628-639, 2015