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of

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**FROM LASER SCANNER POINT CLOUDS TO 3D MODELING
OF THE VALENCIAN SILO-YARD IN BURJASSOT**

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Introduction

1. Introduction

This Master-Thesis Project is named “From Laser Scanner point clouds to 3D modeling of the Valencian Silo-Yard in Burjassot”. The principal objective is promoting the cultural heritage through geomatics. In this way, the 3D model will be established in the Valencian Silo-Yard.

The topic of this thesis is to give significance to the responsibility of cultural heritage through geomatics. This is within the “Tri-national Cultural Heritage Documentation projects (2015-2018)”. Taken part in the framework of the Baden-Württemberg-STIPENDIUM for university students – BWS plus, a program of the Baden-Württemberg Stiftung. In addition, this thesis supports the importance of proceeding to updating the data processing.

The purpose or finality of this Master Thesis is to create a virtual reality of the 3D model of the Valencian Silo-Yard, using the data obtained in April of 2016 from the Laser Scanner and the pictures to take the color for the 3D model.

2. Justification

This project is carried out to transfer the great importance of the implementation of Geomatics non-destructive techniques, in order to define the characteristics and help to analyze the Valencian Silo-Yard. Including the use of non-destructive techniques, the historical constructions are preserved. In addition, this project is carried out to transfer what has been learned, explaining how a real project can be developed under normal conditions.

The contribution of this document is to transfer exactly how it might be constructing a 3D model. Additionally, with this task, my double degree studies will be completed in the “International Master Program of Geomatics” of the University of Applied Sciences (Hochschule Karlsruhe), and in turn, in the “Master in Geomatic and Geographic information engineering” of the University Polytechnic of Valencia.

It is hoped that with this type of projects more people in the community can benefit and this also could help to generate new 3D models by other professionals.

In this kind of projects it is possible that there are limitations with the software, because it will need to process many point clouds of all the Scans of the work. For example, this project had around 70 scans. However, the common possibility is that the hardware has not enough memory.

Main part

3. Theoretical basis

This section explains the theoretical background of this project in different areas of interest.

3.1. 3D Laser scanning

3D laser scanners are being considered in many application areas ranging from cultural heritage documentation, industry and manufacturing, surveying to medicine. Terrestrial Laser Scanning (TLS) is a non-invasive measurements that works on basic principles of measuring the distance from the sensor to the surface of an object. This is the same principle as LIDAR (Light Detection and Ranging) system.

From a 3D point cloud measured with TLS, it allows to make a complex and accurate 3D model of an object in relatively short time. If the TLS isn't equipped with high-resolution digital camera, it must take precisely photographs, to obtain a model of an object with true color representation.

Some advantages from the 3D Laser Scanning are that a dense point cloud is faster obtained with precision and accuracy. And some disadvantages of large areas are inefficiency when captured and time-consuming work (Setkowicz, 2014).

3.2. Point cloud processing

A point cloud is a representation in three dimensions of an object or environment. Registration is the process where two or more point clouds are aligned into one single cloud, it is required that some common features are shared by multiple scans.

In order to avoid incomplete point clouds, several scans are required and registered to obtain an acceptable point cloud.

It depends on the registration software if it requires or not specific reference targets. If the software has a target-free registration process, it relies on surfaces and corners captured in multiple scans. Two common specific reference target types are spheres and checkerboards placed in the scanned environment.

The spheres have a highly reflective surface, a known diameter and precise roundness. The spherical shape allows the target to be scanned from any direction and accurate localization of the sphere centre point which is then used as reference point.

The checkerboard target consists of two black squares in checkerboard formation printed. This target is not properly acquired when placed in a steep angle in reference to the scanner, for this reason, the targets placement require careful planning in order to achieve good results. The centre intersection point is used as a reference point by the registration software.

In the scanned area invalid artifacts and invalid data points are usually found. These disturbances generated error in the point clouds measured by a 3D laser scanner. Also, spatial data from adjacent areas is considered to be present in the scanned area as defective points.

With the use of filters erroneous points are eliminated and it is complemented by manual deletion of incorrect points.

Point clouds usually are vast which in turn requires large amounts of RAM, a powerful CPU and adequate GPU for a smooth handling process. Depending on the data set, this process can be extremely taxing for computer hardware (Rex & Stoli, 2014).

3.3. 3D modeling

This section focuses mostly on the generation of the polygonal surface, triangulation or mesh generation. It is the core part of almost all reconstruction programs.

The triangulation based on a conversion of a set of points into a polygonal model (mesh). This operation usually generates vertices, edges and faces. These components together make up the small elements, in two dimensions they are triangles or quadrilaterals and in the three dimensions they are tetrahedrons. Therefore, the triangulation can be performed in 2D or in 3D, according to the geometry of the input data. However, this project is only focus in the 3D.

The results of 3D triangulation are much more complicated than a 2D triangulation. The input data could be simple polyhedron (sphere), non-simple polyhedron (torus) or point clouds. In this case point clouds are used.

Usually the polygons created need some post-processing operations mainly manually, for example, refinements to correct imperfections or errors in the surface and single triangles editing.

Certain operations consist in edges correction, triangle insertion or polygons editing. The **edges correction** process allows that the faces can be split, contracted or moved to another location. The **triangles insertion** method allows that the holes can be filled constructing polygonal structures that respect the area around. Also, this method through radial basis function or volumetric approach can be repaired incomplete meshes. The **polygons editing** operation allows that the number of polygons can be reduced, preserving the shape of the object or fixing boundary points. Also, the polygonal model can be improved adding new vertices and adjusting the coordinates of existing vertices. Moreover spikes can be removed with smooth functions.

Generally these editing operations to refine and perfect the polygonal surface when the model was created where applied (Remondino, 2003).

4. Location of research

The study site is in the Valencian Silo-Yard, which is located in the Burjassot municipality, in Valencia province, Spain. This can be seen in Figure 4.1.



Figure 4.1. Location map of the Burjassot municipality (Valencia-loc.svg 2010)

The bird eye view of the Valencian Silo-Yard can be seen in Figure 4.2.



Figure 4.2. Bird's-eye-view of the Valencian Silo-Yard (Bing maps 2017)

It is located in the centre of the town and it is very accessible by public transport from Valencia, for example, tram or metro (Figure 4.3). The tram stations of line 4 near the Valencian Silo-Yard are “La Granja”, “Sant Joan” or “Campus”. And the closest metro station is “Burjassot (line 1)”.

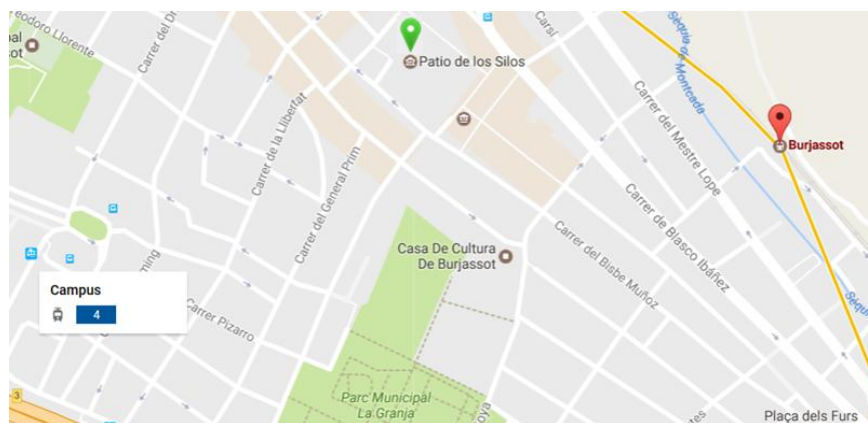


Figure 4.3. Public transport near the Valencian Silo-Yard (Google Maps 2017).

The position of the Valencian Silo-Yard in EPSG 25830, that is, ETRS89 UTM Zone 30N, the North coordinate is “722514”, and the East coordinate is “4376472”. Furthermore, geographic coordinates in geodetic system WGS-84, on the one hand, as decimal degrees the latitude is “39°.5090” and the longitude is “-0°.4118”. On the other hand, expressed in degrees, minutes and seconds, the latitude is 39°30'32"N and the longitude is 00°24'42"W.

4.1. Meaning of “Silo”

“Silo” according to “Real Academia Española” has the following three meanings. The first meaning says dry place where wheat or other grains, seeds or fodder are stored. The second meaning says underground, deep and dark. And the thirdly meaning says it is an underground missile tank.

In this project the meaning of “Silo” is combination of the first and second meaning. Therefore, in this case “Silo” means that it is a dry, underground, deep and dark place where wheat are stored.

4.2. Cultural and historical significance of Valencian Silo-Yard

The “Silos” are subterranean granaries excavated on the top of a hill for cereal preservation, in this case wheat in order to prevent rainwater accumulation and hydrothermal conditions for wheat preservation.

The following description presents the standard silo morphology in the Valencian Silo-Yard. The shape is similar to a bottle with a wide chamber and a narrow cylindrical neck at the top. The entrance of the underground space consists of a small circular mouth of 60-70 cm diameter, after that, the neck is a small narrow downward of 0.80 – 1.00 m deep. The diameter is 4 – 8 m and 5.5 – 12 m deep, including the neck, in a clay soil. In these underground barns there was capacity from 30 m³ to 260 m³. The Figure 4.4 can help us understand the meaning of “Silo” of Valencian Silo-Yard.

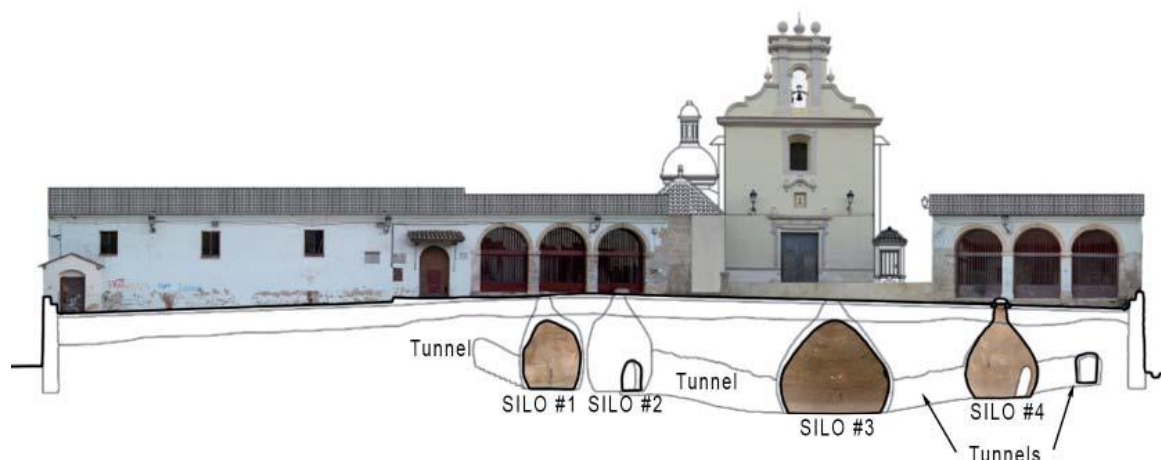


Figure 4.4. Cross section of the Valencian Silo-Yard, where underground granaries and buildings are depicted (Valls, 2014).

The underground grain storage for wheat preservation was very important for the population subsistence. In 1573, following this purpose, it was constructed in Burjassot a region that was selected owing to favorable economic, geographical, topographic and geological aspects; it is 5 km away from Valencia downtown. The wheat stored in the Middle Ages was brought in from Castile (Central-Spain) using terrestrial transport, as well as from Sicily through shipment.

Throughout history, the total number of former excavated silos in the Valencian Silo-Yard could have reached 49 silos, but some of these ruined silos were buried.

The Valencian silos fell in disuse because of the 1936-39 Spanish Civil War and the introduction of new industrial techniques. Since then, the architectural underground ensemble completely lost its original use and it led to evolutionary deterioration (Valls, 2014).

5. Material resources and technical equipment

This section presents the resources used in the development of the project, differentiating the resources used in field work that the resources used in cabinet work.

During the period of field work it was necessary to take the data:

- **Laser Scanner:** FARO Focus 3D X130 (Table 5.1)

Table 5.1. Features of Focus 3D X 130 (FARO n.d.).

<i>Range Focus^{3D} X 130</i>	0.6 – 130 m
<i>Measurement speed</i>	Up to 976,000 points / second
<i>Ranging error</i>	± 2 mm
<i>Integr. colour camera</i>	Up to 70 mio. pixel
<i>Laser class</i>	Laser class 1
<i>Weight</i>	5,2 kg
<i>Multi-Sensor</i>	GPS, Compass, Height Sensor, Dual Axis Compensator
<i>Size</i>	240 x 200 x 100 mm
<i>Scanner control</i>	Via touch-screen display and WLAN

- **Tripod**
- **Targets check-board**
- **Polyester spheres**
- **Second battery**

During the period of cabinet in this type of project, it is usually required to have a software to process the raw data from the Laser Scanner, in this project SCENE was used. But also, there exist other software for processing the scans, for example, Cyclone (Leica Cyclone 3D Point Cloud Processing Software), or CloudCompare that is a free software.

The software required in terms of modeling the data is 3DReshaper, Geomagic or Polyworks. And the free software for 3D animation is Blender or Unit.

Therefore, in this master thesis the necessary software that will be used in this project is SCENE, CloudCompare, Agisoft PhotoScan, 3DReshaper, Blender and Notepad ++, among other.

6. Description of the primary data collection process

This section presents some process to collect the primary data. The following is a short description of the main points to think before starting out in the field. These are:

- Strategy planning about the places where it is necessary to put the Laser Scanner to take measurements, using orthophotos from official agency. In this case “Valencian Cartographic Institute” (<http://www.icv.gva.es/va/inicio>).
- Also, it is necessary to visit the object of study place. To know their characteristics and the real situation. For instance, inside of the Silos, because it is impossible to see in the orthophotos.
- It should be noted that the scans will have a minimum overlapping with each other. To be obtained an aligned effective.

After that, the work could be executed in the field. In general, the first task is to review if the planned positions of the Laser Scanner in the previous study are fine. And put the targets in the place of the measurement.

Finally, outside of the building about 50 scans are registered with GPS position integrated in the FARO Laser Scanner. And inside of the building about 23 scans are registered without GPS position.

This project took part in the “Tri-national Cultural Heritage Documentation projects (2015-2018)”, the work in the field was made by the students that participated in the program the last year. These data were used to do the 3D model this year. In addition, this year we will did the measurements in the archaeological excavation area in Vergina (Greece), this is the next step in the "Tri-national Cultural Heritage Documentation projects (2015-2018).

In this case, the data collection took place in Burjassot, from 14th to 15th April 2016.

6.1. Primary data collection

The primary data used in this project are the registered 22 inside scans (Figure 6.1, left), 51 outside scans (Figure 6.1, right) at the Valencian Silo-Yard (Burjassot), and the images inside the silos.

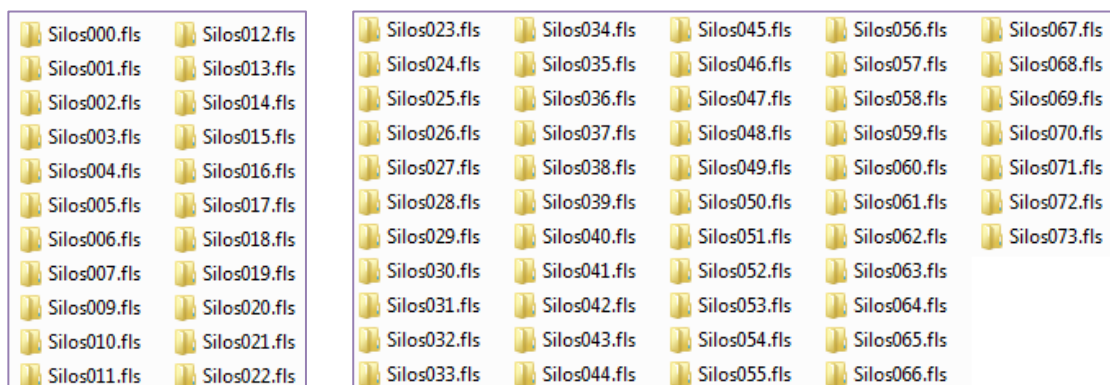


Figure 6.1. Inside Scans (22 scans, left) and outside Scans (51 scans, right) of the Valencia Silo-Yard

7. Methodology

This section explains the methodology of how to perform the processes to create the 3D model using the Laser Scanner data. The methodological framework is defined in the following sections through the process with different software. For example, SCENE software is for processing Laser Scan data,

7.1. Model of data analysis

This section presents the model analysis using the primary data (Figure 7.1).

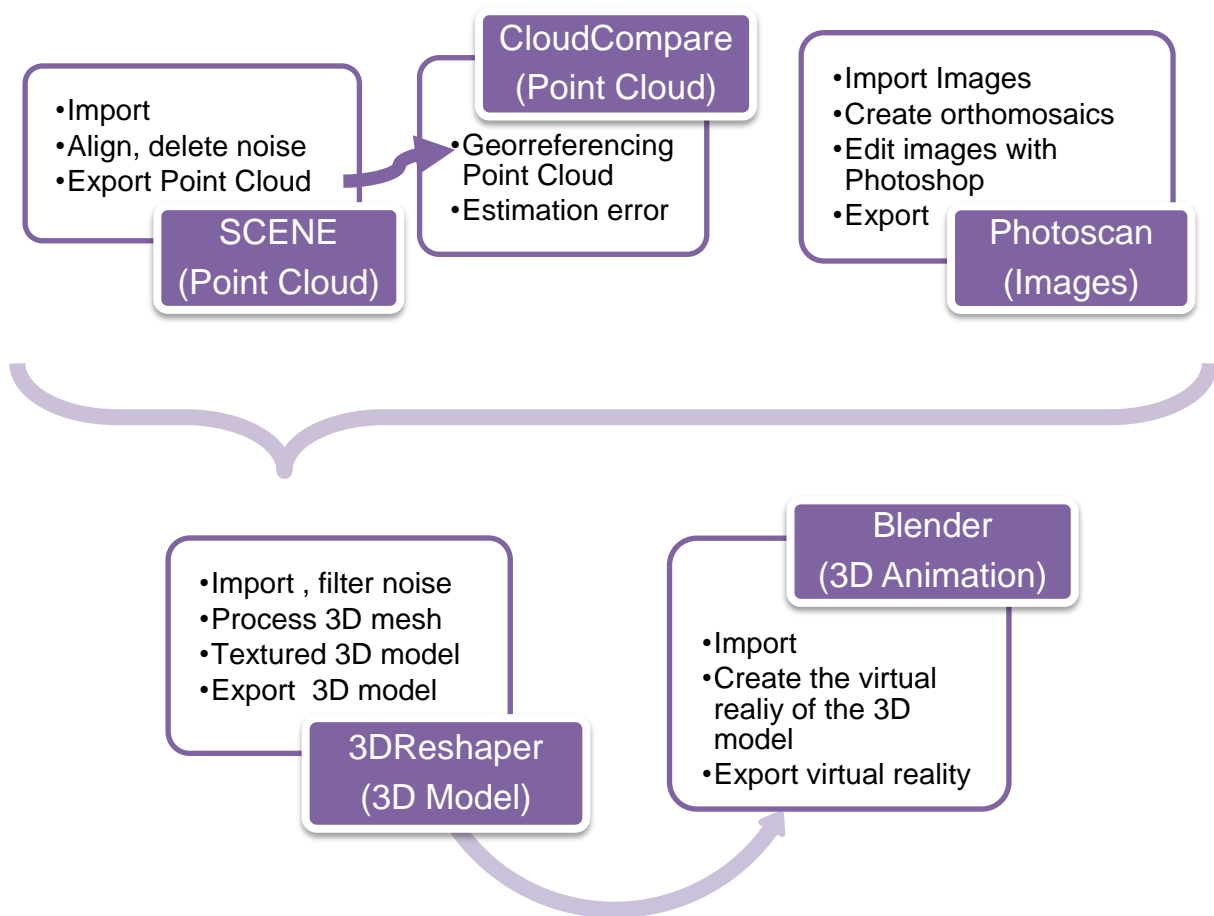


Figure 7.1. Processing scheme to obtain the 3D model

7.2. Schedule of activities

This section presents the schedule of activities thought Gantt diagram. In this diagram (Figure 7.2), specifying the activities in function of the time, sequentially, from the starting date until the finish date.

Starting date	Finish date	P1			P2			P3			P4			
		feb	mar	abr	may	jun	jul	ago	sep	oct	nov	dic	ene	feb
15/03/17	18/04/17													
15/03/17	24/03/17													
27/03/17	31/03/17													
30/03/17	30/03/17													
03/04/17	18/04/17													
19/04/17	22/08/17													
19/04/17	08/05/17													
20/04/17	22/05/17													
20/04/17	21/04/17													
24/04/17	28/04/17													
02/05/17	08/05/17													
09/05/17	09/05/17													
10/05/17	10/05/17													
11/05/17	17/05/17													
18/05/17	22/05/17													
23/05/17	12/07/17													
23/05/17	24/05/17													
25/05/17	30/05/17													
31/05/17	01/06/17													
02/06/17	05/06/17													
06/06/17	08/06/17													
09/06/17	13/06/17													
14/06/17	22/06/17													
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17/07/17	20/07/17													
21/07/17	28/07/17													
31/07/17	31/07/17													
01/08/17	07/08/17													
08/08/17	10/08/17													
11/08/17	22/08/17													
23/08/17	12/09/17													
23/08/17	28/08/17													
29/08/17	04/09/17													
12/09/17	12/09/17													

Figure 7.2. Gantt diagram of the 3D Modeling in Valencian Silo-Yard (Smartsheet 2016).

7.3. Processing with SCENE to align the raw point clouds

This section presents the point clouds processing in SCENE software. The most important task is to align the scans, and prepare this data to be georeferenced with the CloudCompare software.

7.3.1. Description of the SCENE software

SCENE is a point cloud software for FARO scans. In this project the version used was SCENE 5.5.3.16.

SCENE is the FARO Laser Scanner Software, user-friendly and generates high-quality data in next to no time, you can see more information in the next web site <http://www.faro.com/es-es/productos/software-de-faro/scene/>. This software is specifically aimed at all FARO Focus Laser Scanners. For this reason, it is efficiently and easily to processes and manages the scanned data, for example, with the automatic object recognition, scan registration or positioning.

Once SCENE has prepared the scan data, you can commence evaluation and further processing right away. With this program it is possible to place the scan (registration) and colorize them. Also, it offers functions from simple measuring to 3D visualization through meshing and exporting your scan data into various point cloud and CAD formats.

The file formats supported by SCENE can be seen in Table 7.1. The highlighted formats will be used in this project.

Table 7.1. File formats supported by SCENE.

EXPORT	IMPORT
E57 Files (*.e57)	Laser Scans (*.fls)
VRML Files (*.wrl)	VRML 2.0 (*.wrl, *.wrl.gz)
DXF Files (*.dxf)	Image Files (*.bmp, *.jpg, *.png, *.tif)
XYZ Ascii Files (*.xyb)	Workspace (*.lsproj, *.fws)
IGES Files (*.igs)	Surveyed Points (*.cor, *.csv)
PTS Files (*.pts)	PTX Scan Files (*.ptx)
PTX Files (*.ptx)	PTZ Scan Files (*.ptz)
Pointools POD (*.pod)	XYZ Scan Files (*.xyz)
SCENE Scan File (*.fls)	E57 Scan Data Files (*.e57)

7.3.2. Align Scans

The first task was to import the raw data measured from April 2016, in the SCENE software. This project was subdivided into two parts, within Silos and outside of Silos (Silos-Yard).

Once the data was analyzed, it was checked that the scans measured inside of the Silos didn't have GPS Position. Therefore, it was necessary to find some scans that had measurements within the Silos inlet and in the street with GPS position. The scans did not meet both conditions.

The scan that had measurements inside and outside was "Silos022", and the scan that had overlapping with "Silos022" and it had GPS position was the "Silos028" scan among others (Figure 7.3). Therefore, the scans that connected both parts of the project were "Silos022" and "Silos028" (Figure 7.4).

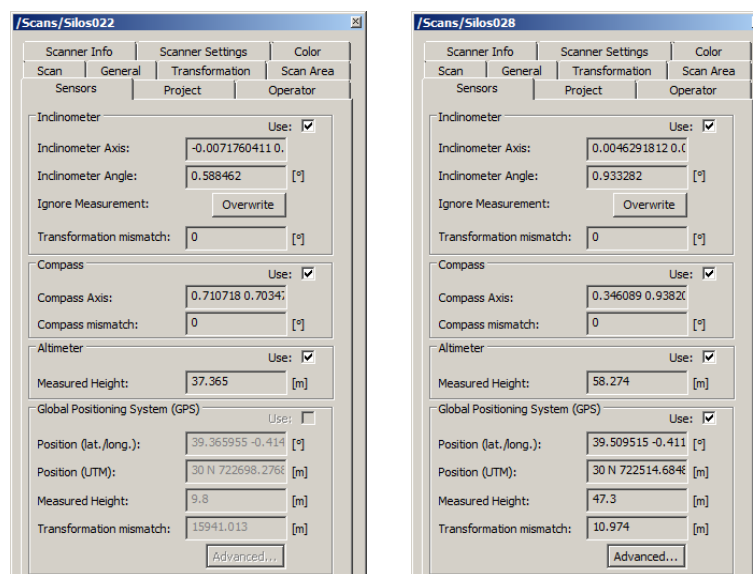


Figure 7.3. Sensors properties "Silos022" (left) and "Silos028" (right) with measure of GPS (SCENE)

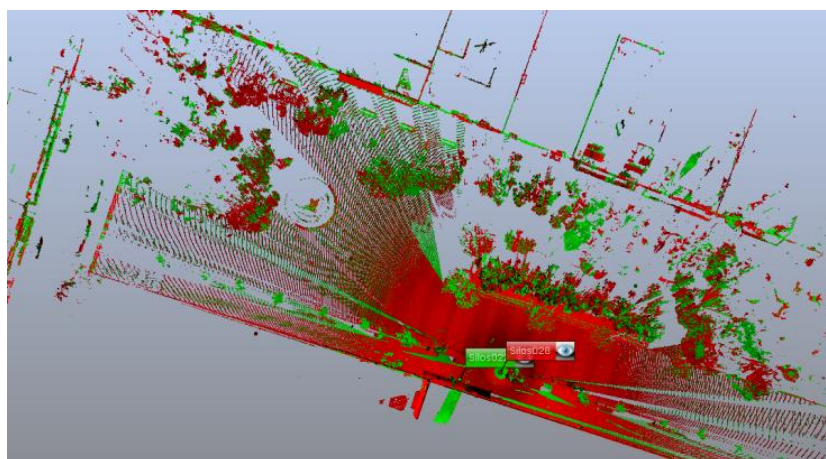



Figure 7.4. Correspondence view of "Silos 022" (green) and "Silos028" (red) (SCENE)

Then, it was decided to take the "Silos028" scan to reference (right click on the scan > Operations > Registration > Reference Scan). Because, this scan had GPS position and between this scan and the "Silos022" scan there were connection points. The "Silos022" scan was the connection to the interior of the Silos. The methodology used for aligning scans is explained below for each zone.

7.3.2.1. Inside “Place scans” one by one

To begin the alignment scans, the "place scan by target" methodology was used, adding the scans one by one. This is explained below.

Firstly, It was necessary to identify the target (checkerboards, spheres, ...) manually or automatically (automatic process, right click on the scan > Operations > Find Objects> Checkerboards, Spheres). As soon as the process of finding objects was finished, it was sometimes necessary to find the landmarks that the program could not find or insert new points.

The following button  was used to force the correspondence of targets between two scans (Figure 7.5).

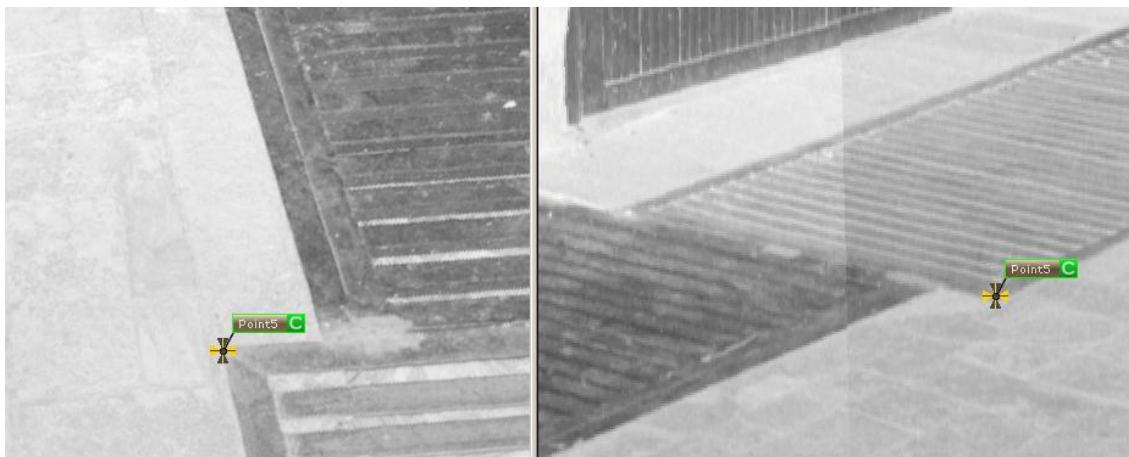


Figure 7.5. Incorporate new points and force correspondences between shown scans” by hand (SCENE)

Once the correspondence was completed, the “place scans” by the targets must be done (Operations> Registration > Place Scan > Target Based) with the parameters that appear in Figure 7.6. The “Silos028” scan was used as reference scan.

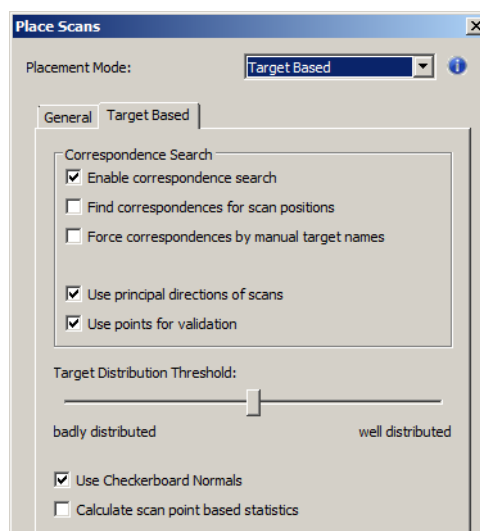


Figure 7.6. Place scan by Target Based (SCENE)

Then, when the last one "Place Scans" had a correct error, the following scan inside the corridor was continued incorporate and processing one by one. To summarize the process, the main points are:

- Import the next scan inside of the Silos (Figure 7.7).

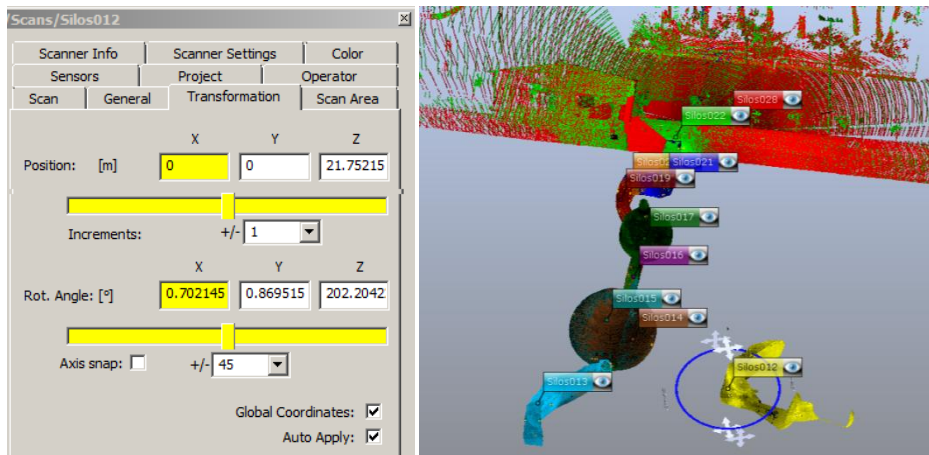


Figure 7.7. Transformation and correspondence view, before place scan “Silos012” (SCENE)

- Find targets automatic (spheres and checkerboards) (Figure 7.8).



Figure 7.8. Target common between two scans (“Silos022” – “Silos021”) (SCENE)

- Place scans by target with the new scan.
 - If the place scan was correct, incorporate a new scan.
 - If it was not correct, more points were searched that exist in both scans. Also, it was possible to apply “place scans - cloud to cloud”.
- Update “Scan Manager”, With “Apply”, to include the new data in the global adjustment.

Continuing the process, between the “Silos004” and “Silos005” scan there were no connection points. Therefore, with the use of “Quick view” the Silos005” scan had continuity with “Silos003”. The continuation of the “Silos003” scan was “Silos002” scan. The continuation of the “Silos002” scan was “Silos004” scan. The continuation of the “Silos004” scan was “Silos001” scan.

When the whole process was finished (Figure 7.9), the mean error of place scans inside was 2.7 mm.

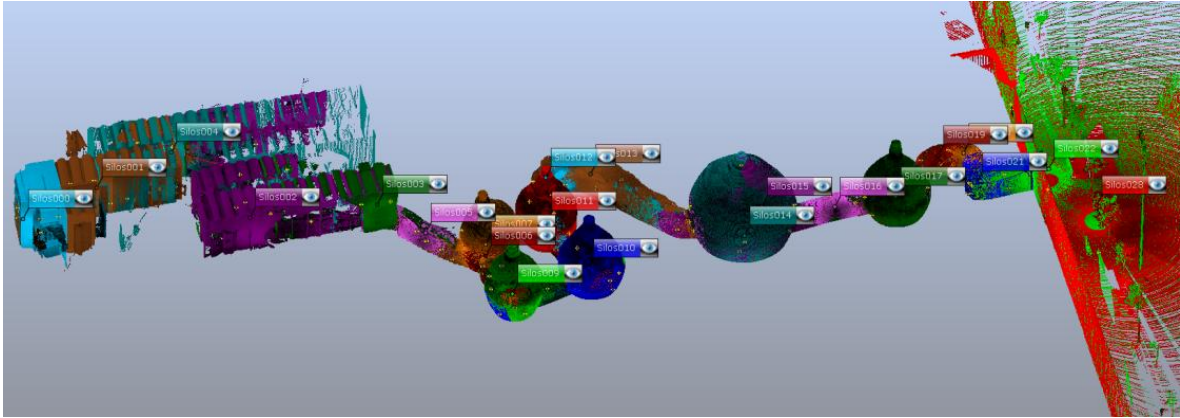


Figure 7.9. Correspondence view all scans inside (SCENE)

7.3.2.2. Outside “Place scans”

In order to start the outside alignment scans, the “Place scans” processing outside of the scans had been started in new cluster from “Silos023” scan until “Silos040” scan, the reference scan was the “Silos028” scan. And added in the cluster the scans from the “Silos040” to the “Silos060” (Figure 7.10), to make the “Place scans - cloud to cloud”. Then, it did the same process with the next scans (“Silos061” – “Silos073”).

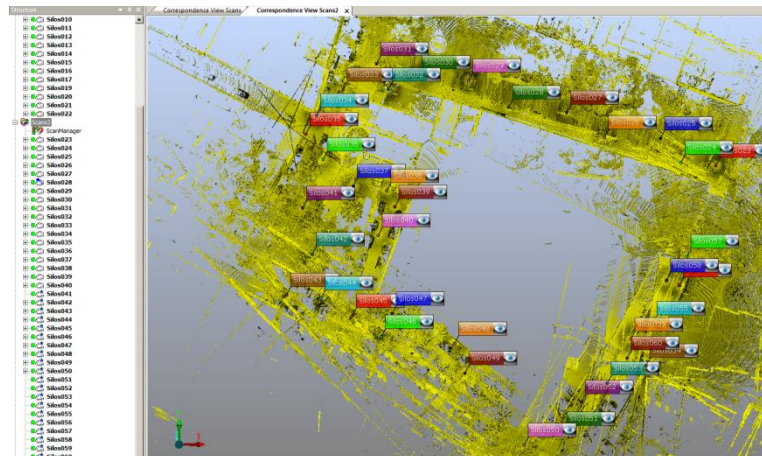


Figure 7.10. Correspondence view, place scans between 023 and 039, added the new scans between 041 and 060 (SCENE)

When the “Place scans” process had some error, as in Figure 7.11, in this case the first three scans had position error; it had been moved to the correct position and updated the process.

Fit Object	Mean Target Tension	Mean Scan Point Ten...	Scan/Cluster
✘ ScanFit	0.0002	0.0033	Silos058
✘ ScanFit	0.0001	0.0019	Silos054
✘ ScanFit	0.0001	0.0026	Silos060
✔ ScanFit	0.0002	0.0017	Silos035
✔ ScanFit	0.0002	0.0017	Silos035
✔ ScanFit	0.0002	0.0028	Silos056
✔ ScanFit	0.0002	0.0017	Silos042
✔ ScanFit	0.0002	0.0024	Silos057

Figure 7.11. Error in the “Place Scans” with “Silos058”, “Silos054” and “Silos060” (SCENE)

7.3.2.3. “Place scans” with all scans

To place all scans, in the first place all scans were moved to one cluster and updated the “Place scans”; the first results obtained can be seen in Figure 7.12.

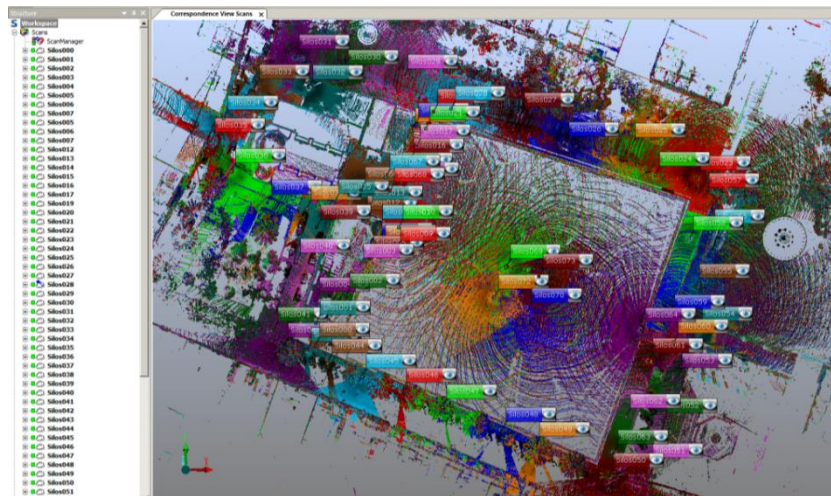


Figure 7.12. Correspondence view after finished the place scan (SCENE)

The final mean error in the adjustment results was 2.1 mm, see Figure 7.13.

Cluster/Scan 1	Cluster/Scan 2	Mean [mm]	< 4 mm [%]	Overlap [%]	Used Points	Details
Silos025	Silos023	5.138	40.9	60.7	33130	
Silos065	Scans	4.721	47.5	43.2	57756	
Silos059	Silos058	4.424	46.4	76.1	37480	
Silos049	Silos050	3.98	50.2	62.2	33608	
Silos061	Silos060	3.668	53.6	52.3	57976	
Silos030	Silos029	3.135	59.5	67.1	44754	

Overall Statistics	
Mean:	2.1029 [mm]
< 4 mm:	74.6 [%]

Figure 7.13. Results of the final place scan by top view (SCENE)

7.3.3. Colorize scans

In this project, there was only color in some scans, because they had to optimize the time to complete all the measurements with the laser scanner in one day. Therefore, the camera images were used in order to give the color to the 3D model wherever possible.

The scans having color in this project were some scans of Silos inside and one zone in the street, the name of the scans were: “Silos007”, “Silos009”, “Silos010”, “Silos011”, “Silos012”, “Silos014”, “Silos015”, “Silos017”, “Silos042”, “Silos043”, “Silos044”, “Silos045”, “Silos046”, “Silos047”, “Silos048”, “Silos049”, “Silos050”. I only applied the pictures in the scans that had color, (right-click on the cluster > Operations > Color/Pictures > Apply Pictures).

7.3.4. Deleted points which not belong to the model

The deleting process can be performed in this step prior to exporting data or later in the modeling software.

To eliminate the incorrect points it was possible to use “SCENE”, “Pointools Edit” or “3DReshaper” software. Considering the advantages and disadvantages of SCENE, the two last software were rejected. SCENE was used because it was not necessary to export new data (this data was non-georeferenced). To begin, the scattered points out of the principal area were removed, see Figure 7.14.

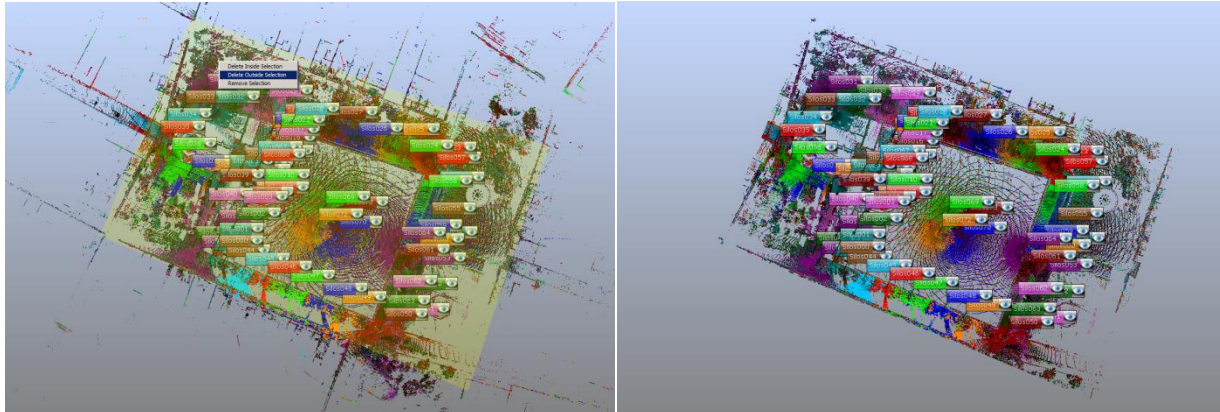


Figure 7.14. Before and after of delete the scattered points outside (SCENE)

Then, the spheres, people or wrong points were deleted, the methodology used is described below. Firstly, the “Planar view” of a scan was opened (right click in the scan >View > Planar View) to identify objects to be deleted (Figure 7.15).



Figure 7.15. Planar View outside (left) and inside (right) the Valencian Silo-Yard (SCENE)

Secondly, the selection zone was opened in “3D View” to clean the points which didn’t belong to the model (right click on the selected zone (yellow zone) > View > 3D View), see Figure 7.16. And the 3D view of the selected zone can be seen in Figure 7.17.

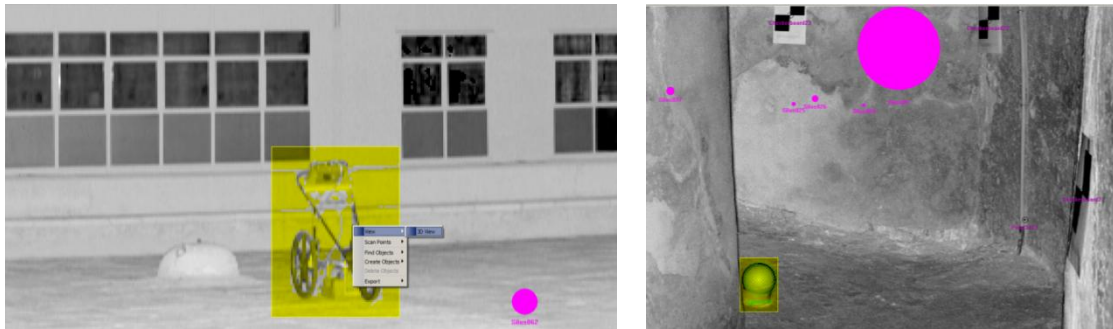


Figure 7.16. Selection zone in planar view outside (left) and inside (right) the Valencian Silo-Yard (SCENE)

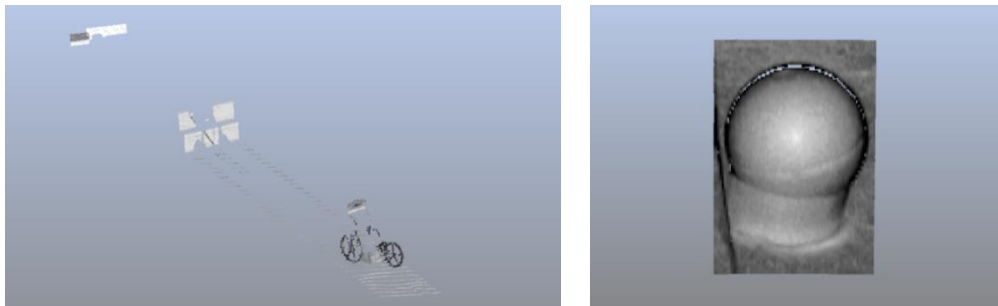


Figure 7.17. 3D View of the selected zone of the scan outside (left) and inside (right) the Valencian Silo-Yard (SCENE)

Thirdly, a selected polygon with wrong points was created to erase the selection (right click > Delete Inside Selection), see Figure 7.18. An example of incorrect points from the laser scanner is shown in Figure 7.19.

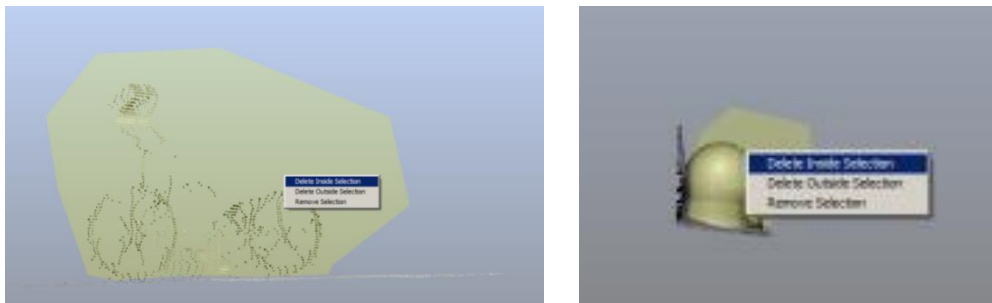


Figure 7.18. Selection polygon with the invalid data points outside (left) and inside (right) the Valencian Silo-Yard (SCENE)



Figure 7.19. Selection polygon with the incorrect points from the scanner (SCENE)

This process was performed in each sphere, object, person, or points which didn't belong to the model in the scans, one by one.

7.3.5. Create the Point Cloud from Scans

The dense point cloud was created with the process “Project Point Cloud / Scan Point Cloud Settings”. The result of the 3D view of the point cloud can be seen in Figure 7.20.

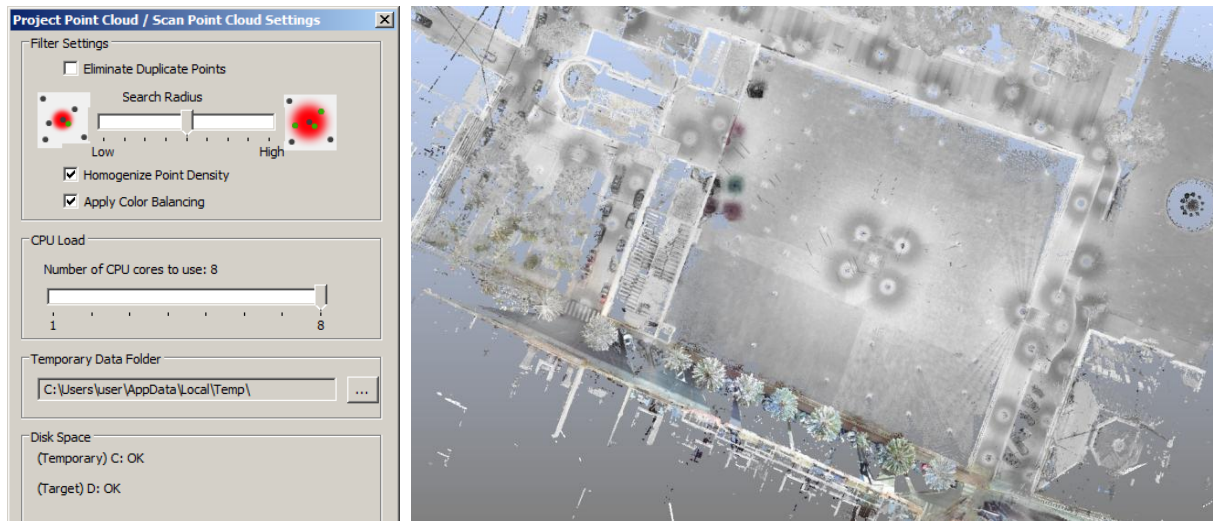


Figure 7.20. Create Point Cloud and 3D view (SCENE)

7.3.6. Export final data

Before the export of the final data, it was very important to know which format can read the software of the following step. Also, it was a good idea to try to open an exported file in the following software, because sometimes the software could not open the new information correctly and it was necessary to make changes.

In this case, the export format was PTS, since this was the best format for 3DReshaper software. SCENE allowed exporting all the data in the same file or scan to scan. As this was a large project, the last option was selected. In addition, it was possible to choose the grid spacing to reduce the point clouds, this is subsampling (Figure 7.21).

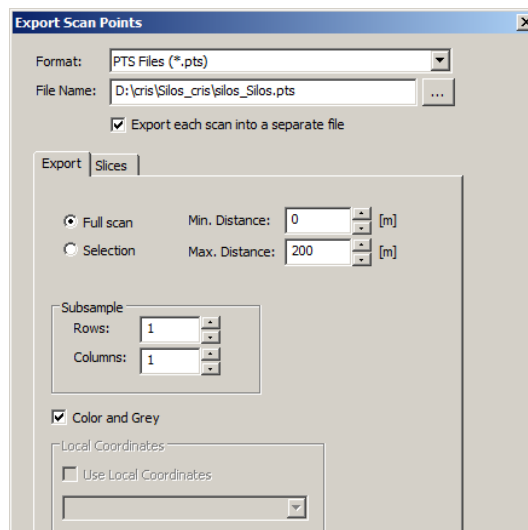


Figure 7.21. Export scans in PTS file (SCENE)

7.4. Processing with CloudCompare to georeferencing the point clouds

This section explains how CloudCompare can be used to georeference the scans. For this, it is necessary to know the rotation degrees and the translation meters of the data. These parameters are obtained with this program.

7.4.1. Description of the CloudCompare software

The version used in this project was CloudCompare version 2.8 beta.

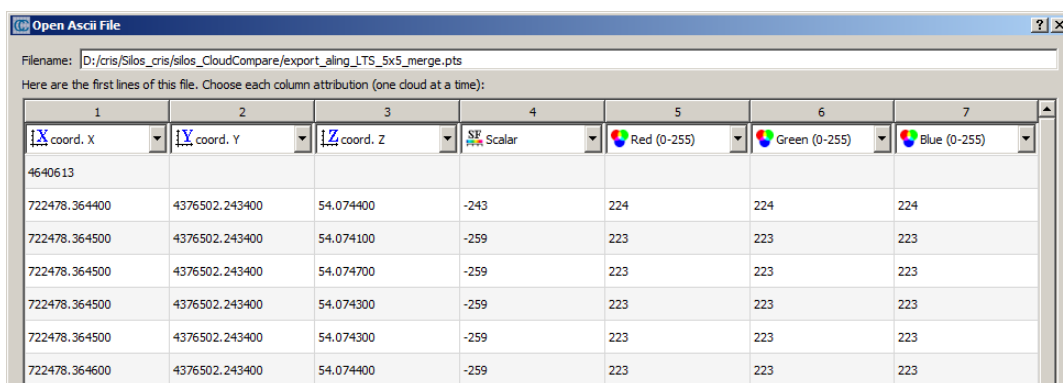
CloudCompare is an Open Source Software. This software can be used to treat 3D point clouds and meshes. At the origin, this software was designed to compare between two dense 3D point clouds. Nowadays, this software allows more generic processing of the point cloud and other advanced algorithms (CloudCompare 2017).

7.4.2. Register between two clouds

The purpose of the registration between two clouds was to align the Terrestrial Laser Scanner (TLS) cloud with the UAV cloud which had the correct position.


In order to align the scans, it was necessary to use only the coincidental part between both clouds. In this case, the corresponding zone to fitting was the Silos square without the part of the cross. The information of the Laser Scanner was reduced by a filter of a 5x5 grid spacing in SCENE, due to the fact that CloudCompare could not handle the large point clouds. As soon as both clouds were successfully adjusted, the processing of point clouds began.

First of all, both point clouds were loaded in CloudCompare (Figure 7.22). The cloud coordinates were automatically reduced 722400 m in North, and 4376500 m in East, because these coordinates were very large.



1	2	3	4	5	6	7
iX coord. X	iY coord. Y	iZ coord. Z	SE Scalar	Red (0-255)	Green (0-255)	Blue (0-255)
4640613						
722478.364400	4376502.243400	54.074400	-243	224	224	224
722478.364500	4376502.243400	54.074100	-259	223	223	223
722478.364500	4376502.243400	54.074700	-259	223	223	223
722478.364500	4376502.243400	54.074300	-259	223	223	223
722478.364500	4376502.243400	54.074300	-259	223	223	223
722478.364600	4376502.243400	54.074400	-259	223	223	223

Figure 7.22. Open point clouds in PTS format (CloudCompare)

Once both clouds were selected, click on the  “Finely registers already (roughly) aligned entities (clouds or meshes)” tool, (this tool is in the top menu, Tools > Registration > Fine registration (ICP)) (Figure 7.23). This tool uses the Interactive Closest Point (ICP) algorithm to minimize the difference between two point clouds.

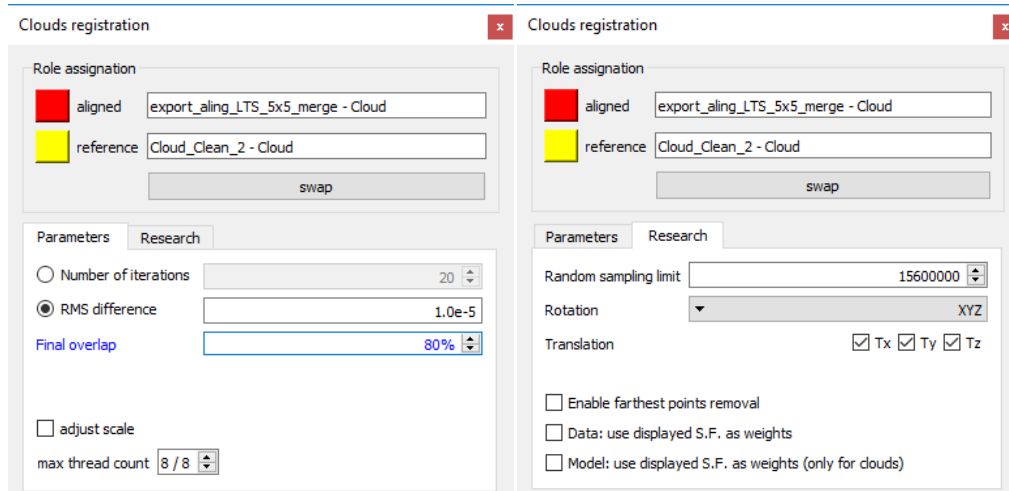


Figure 7.23. Registration values of UAV cloud (reference) and TLS cloud (CloudCompare)

This process returned a transformation matrix TLS to UAV, which can be seen in Figure 7.24. Also, it was possible to export the matrix in TXT format with more decimal digits, see Figure 7.25.

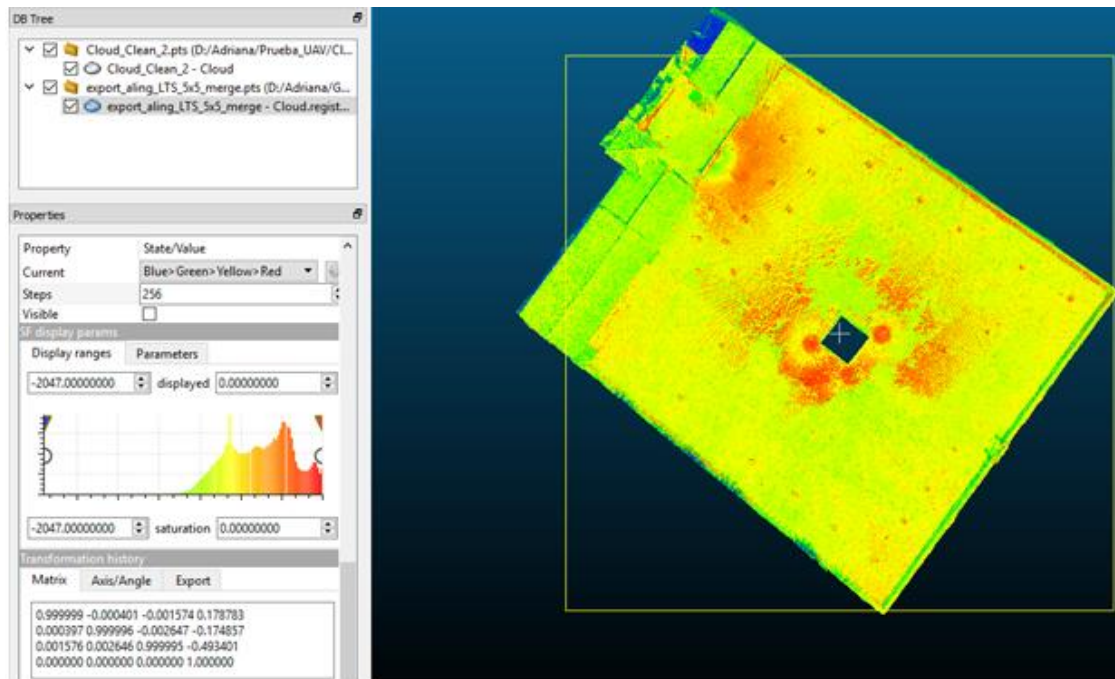


Figure 7.24. Transformation matrix TLS to UAV (CloudCompare)

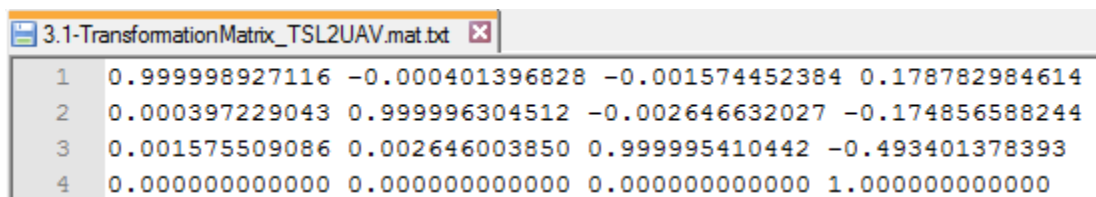
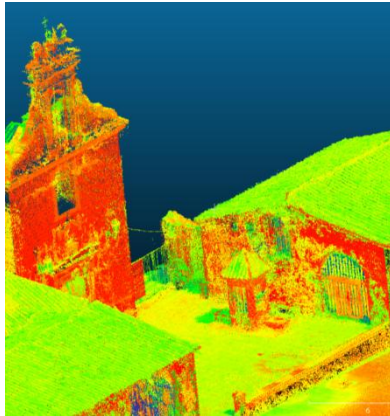
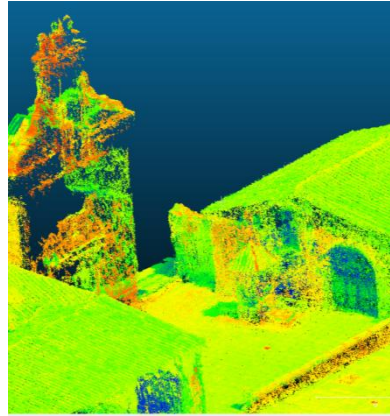
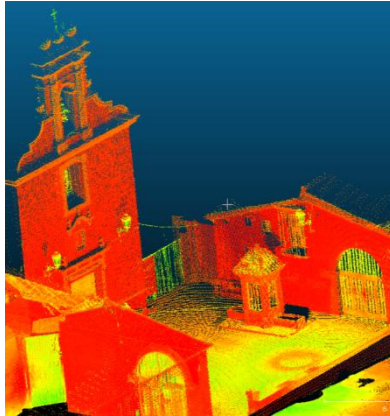
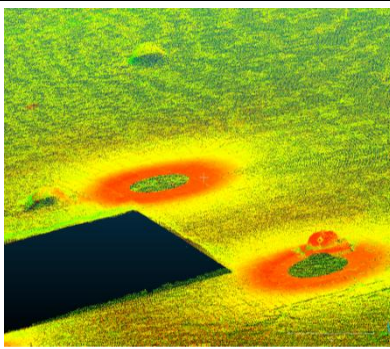
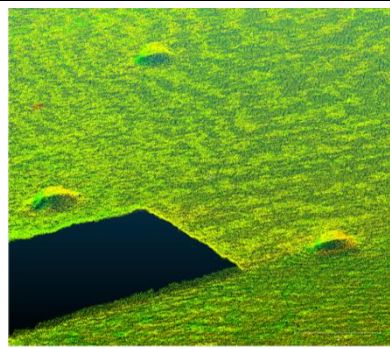
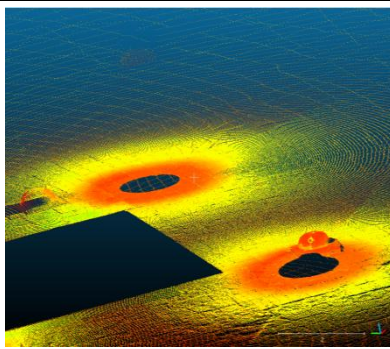
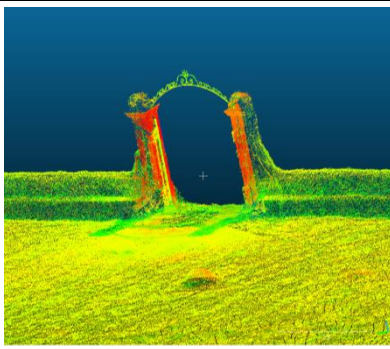
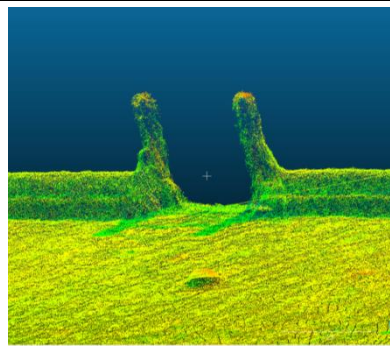
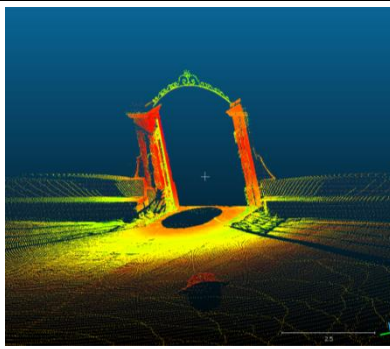


Figure 7.25. Transformation matrix TLS to UAV in TXT file (Notepad++)

The position of the point cloud was checked visually after the transformation (Table 7.2).

Table 7.2. View of the point cloud aligned in three points distributed on the square (CloudCompare)

Combined Clouds	UAV Cloud	TLS Cloud
		
		
		

7.4.3. Estimation error after transformation

The tool “Distance computation” was used in order to obtain the estimation error that is the distance between two clouds. To open this tool, in the top menu “Tools > Distance > Cloud/Cloud Dist.”

In this case the reference cloud was from the UAV and the compared cloud was from the TLS, the result obtained was **0.033 m** of mean distance and a standard deviation of 0.024. These results indicate that the aligned between both clouds was correct, see Figure 7.26. Therefore, it was possible to continue with the georeferencing of the TLS scans.

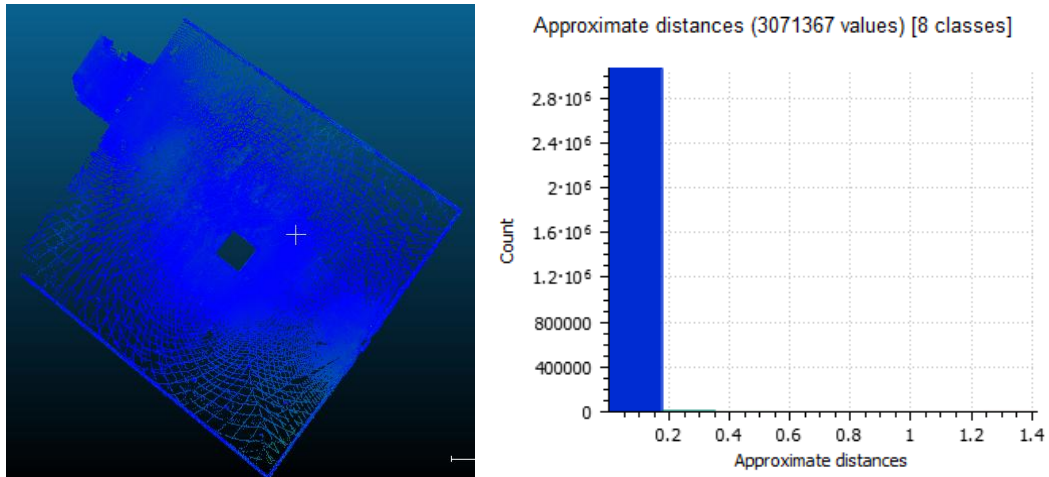


Figure 7.26. View of the TLS point cloud colorize by distance and histogram by approximate distances (CloudCompare)

7.4.4. TLS Scans Georeferenced

After doing some test with different scans, it was necessary to move the scans one by one in CloudCompare. The best way of applying the transformation matrix was loading the point clouds which were used for the acquisition of the matrix, and then loading the scan to georeference (exported from SCENE). As the coordinates of the point clouds were too large, CloudCompare translated the data near the origin (0, 0). When the point cloud was loaded, the tool that was executed was “Apply transformation” (this instrument is in the top menu “Edit > Apply transformation (Ctrl+T)”), using the transformation matrix TLS to UAV (Figure 7.25).

7.4.5. Export final data

When the point cloud was georeferenced, it was saved as an ASCII file, PTS format. It was necessary to select the parameters that appear in Figure 7.27, because if not, 3DReshaper didn't open the data correctly. The georeferenced data was renamed as “CC_” + “scan name”.

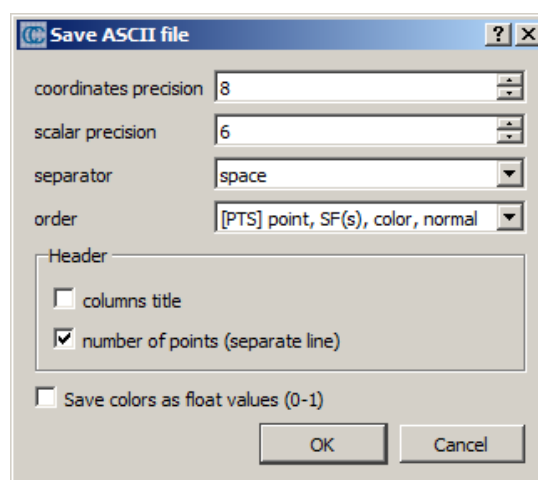


Figure 7.27. Parameters to export the PTS format compatible with 3DReshaper (CloudCompare)

7.5. Processing with 3DReshaper to generate the 3D model

This section presents the 3D model processing in 3DReshaper software. The most important task is cleaning the point clouds, creating the mesh and texturing the model.

7.5.1. Description of the 3DReshaper software

In this project the version used of 3DReshaper was 17.0.6.24515, version of April 28th, 2017.

3DReshaper is an easy-to-use dedicated to point cloud processing for various applications, like Cultural Heritage, Architecture, Geology, Mine, Quarry, Digital Terrain Modeling, Civil Engineering or Shipbuilding.

It includes a wide range of features, see Figure 7.28.

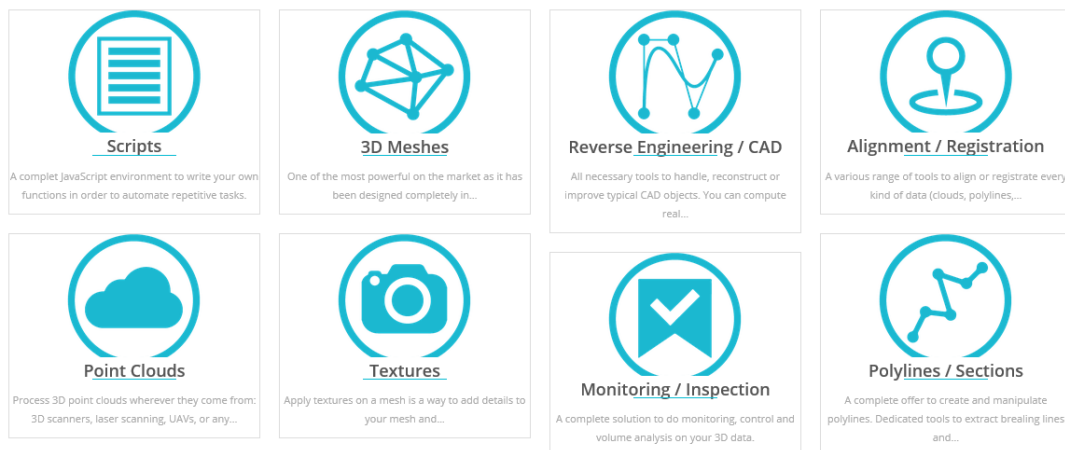


Figure 7.28. Range of features include in the software 3DReshaper (3D Reshaper 2015).

The following is a more detailed explanation of these features that we will use in this project. These are Scripts, Point Clouds, 3D Meshes and Textures.

Scripts: (Scripting, JavaScript, Automation)

In this project we will use this JavaScript environment to write own functions in order to automate repetitive tasks. For instance, erase the noise, save the point cloud in different steps of the process. Because if at any time it is necessary to compare with the old data, this is possible.

3DReshape gives us some scripts and documentation free when we install the software or in the web site in the download section. This information is inside of the program folder, it has a file “Help for script” where you can find all information about the library of 3DReshaper. And three folders: “Samples” with the project examples, “Script-Samples” and “Script-Tutorials” with the code samples of some tasks usually made with 3DReshaper.

These custom commands can be run inside of 3DReshaper, also in silent mode if neither input nor display is required, or with a dialog box containing parameters to set.

Point Cloud Processing: (segmentation, noise detection, regular sampling, smart reduction)
This module is a tool to process 3D point clouds, it is possible to import one or several point clouds whatever their origin and size. The file formats supported by 3DReshaper can be seen in the Table 7.3. The highlighted formats will be used in this project.

Table 7.3. File formats of Point Cloud supported by 3DReshaper (3D Reshaper 2015).

EXPORT	IMPORT
<p>ASCII FILES (*.asc / *.csv ...) Binary files (*.nsd) Leica Geosystems (*.pts, *.ptx) IGES (*.igs) LAS (*.las) AutoDesk DXF (*.dxf)</p>	<p>Fichiers ASCII (asc / csv / xyz / yxz– raw...) Leica Geosystems (*.pts - .pcs - .pcst - .pcg - .pcsx - .pcix - .pci - .pci - .ptx) Leica Nova MS50 (*.sdb / *.xml) ShapeGrabber (*.3pi) STL file Binary (*.nsd) Tool path (*.iso) AutoDesk DXF (*.dxf) STL (*.stl) DMIS file (*.dms) DMIS ASCII files - only the section "SET of POINT (*.rnr) GSCAN file (*.gsn) Confocal Scanning Laser Microscope (*.csv) NIKON Nexiv video measuring system (*.csv) Perceptron SWB/SWL (*.swb / *.swl) Polyworks (*.psl) Leica T-Scan + Steinbichler (*.ac) LIDAR data (*.las) Autres ASCII (*.*) Zoller and Fröhlich (*.zfs - *.zfc) PLY points without triangles (*.ply) ESRI ASCII (raster format *.asc) FARO (*.fls - *.fws) POLYWORKS (*.psl) Coreview (*.atr / *.ftr) E57 (*.E57 files) LandXML files (*.xml)</p>

The most important step in this project is to process or prepare the Point Cloud. These will be implemented through noise detection, segmentation, regular sampling, smart reduction ... in order to save time with the subsequent step (meshing).

Some of the functions that provide 3DReshaper are for processing the point clouds. For instance, it is possible to import point clouds without limit of the imported number of points. There is “Clever reduction” to keep best points and remove points only where density is the highest. Also exists “Automatic segmentation”, automatic or manual separation and cleaning, “Density homogenization” for extract the best points evenly spaced, automatic “noise measurement reduction”. Others tools allow change the colors according to a given direction. Fusion. Registration, Alignment and Best Fit. It is possible to make a 3D comparison with a mesh or a CAD model, Planar sections. 3DReshaper give the opportunity to representation in several modes: textured, shaded, intensity (information depending on the imported data). These are some of the most important tools of 3DReshaper for point clouds.

3d Meshing: (3d Meshing, 3D Modeling, Ground Extraction, Mesh Improvement)

This module is one of the most powerful, because the process of large point clouds obtains light-weight, accurate and aesthetic models quickly.

The software provides different strategies to give the best meshing in accordance with the quality of the original point cloud and the expectations that we want to obtain.

The software developers recommend in case of noisy point clouds **two steps** to be made to get a perfect solution. In a first step, a very rough mesh is created in order to have quickly the global shape. And in a second step, this rough mesh is refined with the point cloud by adding triangles where we have the details.

Another suggestions or recommendations are using specific **triangle reorganization**. This consists of meshing along curvatures is a 3DReshaper feature that enables to organize triangles according to local curvature. The triangle reorganization follows the "flow" of the shape so that sharp angles and small radii are better respected.

This powerful technique of "specific triangle reorganization" significantly improves the quality of the 3D meshed models, with greater accuracy of the shape, especially in sharp angles and small radius areas, with better aesthetics and smoothing of the shapes and lower number of triangles needed to reach final tolerance of the model.

When the meshes are created, this software offers many tools to improve the mesh, for example, the tool "Smoothing" to keep details but improve the general aspect, "Holes filling" is used to treat a zone that could not be scanned or to obtain a closed model. The tool "Decimation" is order to reduce the size of your meshes. The tool "Sharp Edges Reconstruction" is to obtain perfect edges even if they are not scanned with a very high density. The tool "Constraint Meshing" is to use a poly-line as a break-line in the mesh. These are some tool of many others.

This software also has two other tools that are not used in this project but are important to know that exist. One of these tools is "Ground Extractor" dedicated to creating a DTM. And another tool is "Building Extractor" which is used to create simplified meshes.

The file formats supported by 3DReshaper can be seen in the Table 7.4.

Table 7.4. File formats of Mesh supported by 3DReshaper (3D Reshaper 2015).

EXPORT	IMPORT
Ascii and binary STL format (*.stl) Binary PBI format (*.pbi) DXF 3Dface format (*.dxf) Ascii POLY format (*.poly) Vertices only (*.asc) DXF polyline (*.dxf) Universal IDEAS (*.unv) OBJ formats (*.obj) STEP file (*.stp) Ascii Leica format (*.msh) VRML 2 (*.wrl / *.vml / *.iv) PLY (*.ply)	STL format (*.stl) Binary PBI format (*.pbi) DXF 3Dface format (*.dxf) Ascii POLY format (*.poly) OBJ format (*.obj) Ascii Leica format (*.msh) MDL format (*.mdl) VRML files (*.wrl / *.vrml / *.iv) OFF files (*.off) PLY (*.ply)

Camera & Textures: (Texture Mapping, Ortho-Photo, Mesh Coloration, Camera Calibration, Texture Atlas)

This module is very important for obtaining a realistic product, because it is a manager to apply textures on a mesh and a way to add details.

The software providers recommended three ways to map the texture. The first way, it is use the camera internal parameters (focal length or sensor size) and the external parameters (position and orientation) to precede an automatic mapping. The second way, it is use couples of points (point on the mesh and point on the picture) to compute automatically the camera parameters. And the last way is use both some camera parameters and couples of points if some information is missing. Also, it is possible to use ortho-photos or ortho-images to textured meshes or exported through several formats (as OBJ or VRML) in order to be used in other softwares.

This software also has three others functions: “Fully Automatic Texture Mapping”, “Camera Calibration”, “Simply apply Color on Meshes”.

7.5.2. Merge data by zones

In order to optimize the work in this large-project, it was necessary to subdivide the heritage area into seven big zones, see Figure 7.29. Also, some of these zones were subdivided again to make the 3D model.

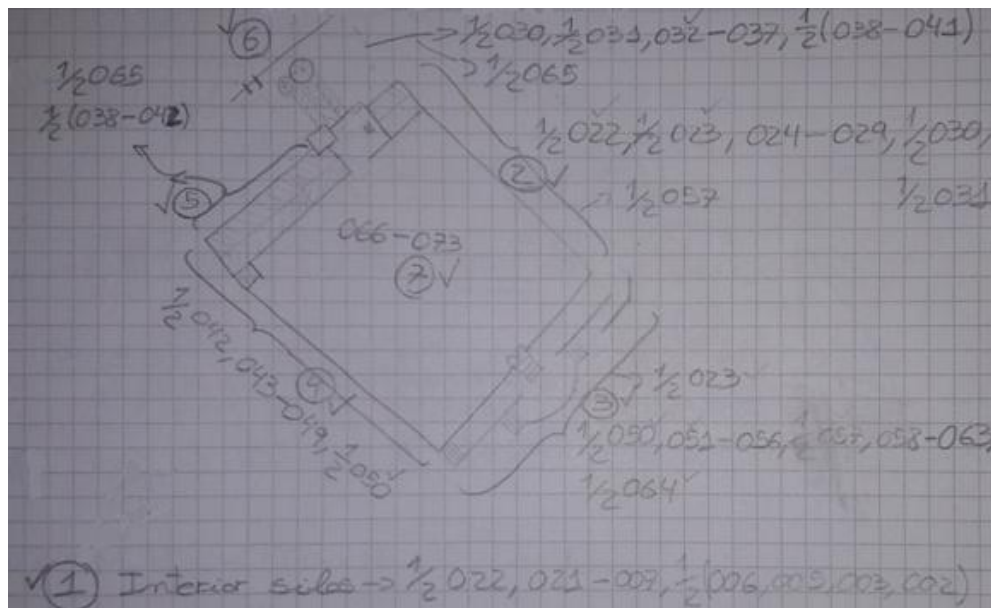


Figure 7.29. Schema about which scan belongs to each zone

The first zone alludes to the inside of the Silos, this was composed by scan numbers 002, 003, 005, 006, 007, 008, 009, 010, 011, 012, 013, 014, 015, 016, 017, 018, 019, 020, 021 and 022. Some of these scans have color.

The rest of the zones allude outside of the Silos, the second zone was the north - east wall which gave access inside of the silos. This zone was composed of the scans 021 - 031 and 057. The third zone was the stairs which gave access to the Silos square, this was composed by the scan numbers 023, 050 - 064. The fourth zone referred to the south - west wall, the scans of

this wall had color, and the numbers of scans were from scan 042 until scan 050. The fifth zone corresponds with the north - west wall, this zone was composed by scans number 038-042 and 065. The sixth zone corresponded with the building of the church, the numbers of the scans were 030-041 and 065. And the last part was the seventh zone, which corresponded with the Silos square, these numbers of scans were from the scan 066 up to the scan 073.

Finally, this project explains the 3D modeling inside the Silos, the diagram of the processes can be seen in Figure 7.30. And outside the Silos, it was explained by another participant (Yepes 2017). In order to separate the project for each student, at this point the scans which had one part inside and another outside were separated in two parts; these scans were “CC_silos_Silos022” and “CC_silos_Silos021”. The obtained results were renamed as “CC_silos_Silos022_inside”, “CC_silos_Silos022_outside”, “CC_silos_Silos021_inside” and “CC_silos_Silos021_outside”.

This separate work was merged in the last part to visualize the complete Valencian Silo-Yard in virtual reality.

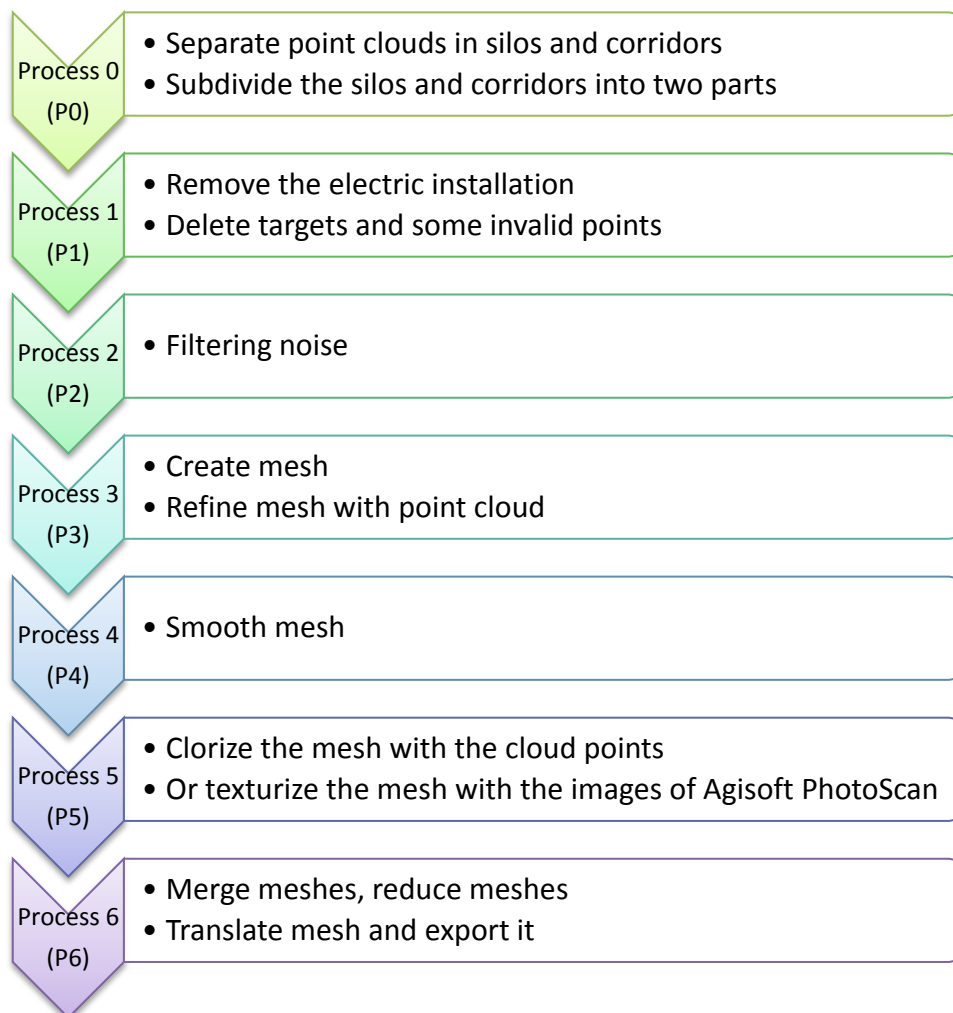


Figure 7.30. Diagram of the processes in 3DReshaper

7.5.3. Subdivide the point clouds in Silos and corridors (P0)

At the beginning, the noise reduction was tested, but the points which appeared in pink (Figure 7.31) in the preview will be deleted. At that moment, the process was not applicable, because these points defined the corridor. The same situation happened in other scans. Therefore, the filter noise will be applied later, once the clouds will be combined and separated by corridors and silos, and the illumination deleted.

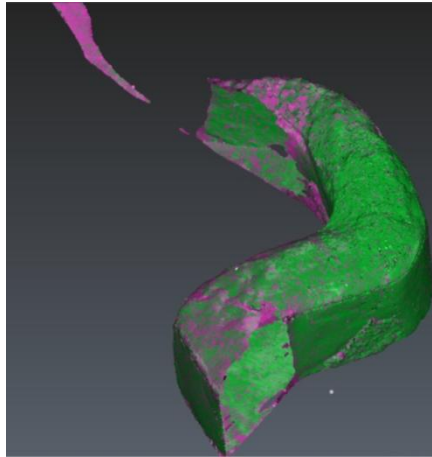


Figure 7.31. Filter clouds, noise reduction (3DReshaper 17.0.6.24515)

Seven corridors and six silos that composed the study are inside the Valencian Silo-Yard, all the interior scans were measured in high resolution. The silos and corridors are catalogued in the scheme of the Figure 7.32.

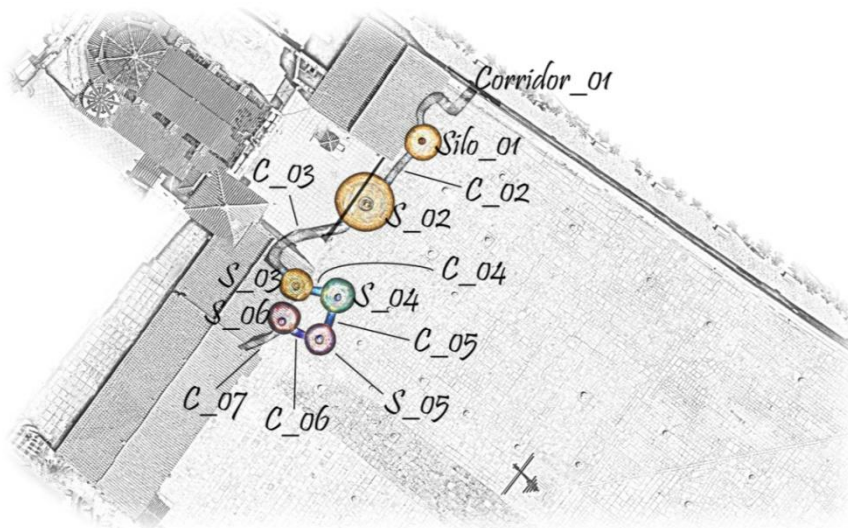


Figure 7.32. Schema of the location and numbering of each silo and corridor (orthophoto (Souby 2016))

The methodology to subdivide the point clouds in 3DReshaper is described below. This process was done in every silo and corridor, one by one. It consisted of separating out the point clouds, afterward grouping parts of point clouds in a cloud and renaming this point cloud.

Firstly, it was necessary to load all the scans that had some data of this corridor or this Silos, (3D > Import > Point Cloud). Secondly, all point clouds were selected, then it was to click on the "Clear / Separate Cloud(s)" tool (this instrument is in the top menu, Cloud > Clean / Separate Cloud(s) > Keep the two parts), and the points were inserted around the corridor or silo to

separate them from the others clouds. Each selected cloud was painted in a different color, these fragments of clouds were very important to complete the corridors (Figure 7.33).

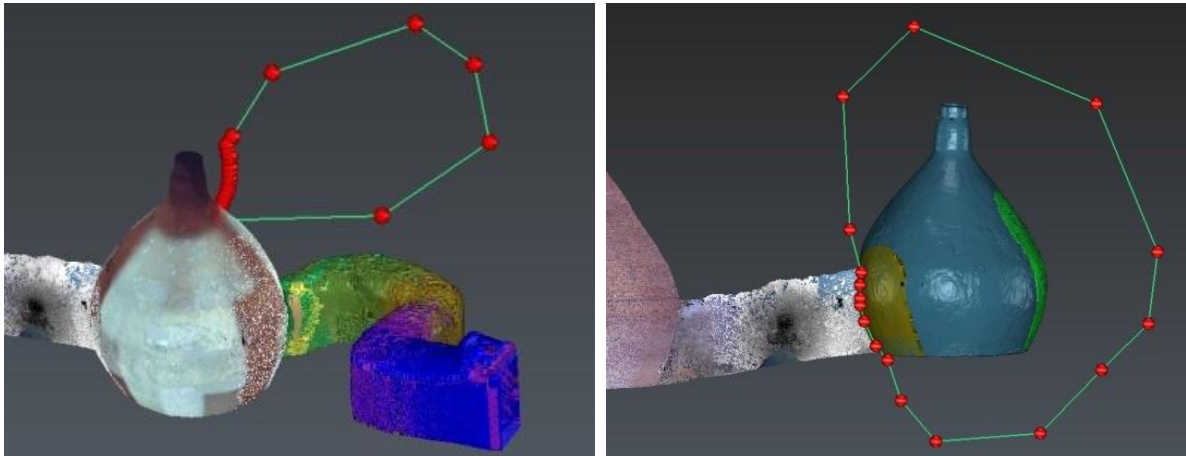


Figure 7.33. Selected cloud to separate Corridor_01 (left) and Silo_01 (right) (3DReshaper)

Thirdly, some noise was erased which was not detected in SCENE. This process was done before merging the clouds, because it was easier to eliminate noise from a scan. Some examples can be seen in Figure 7.34.

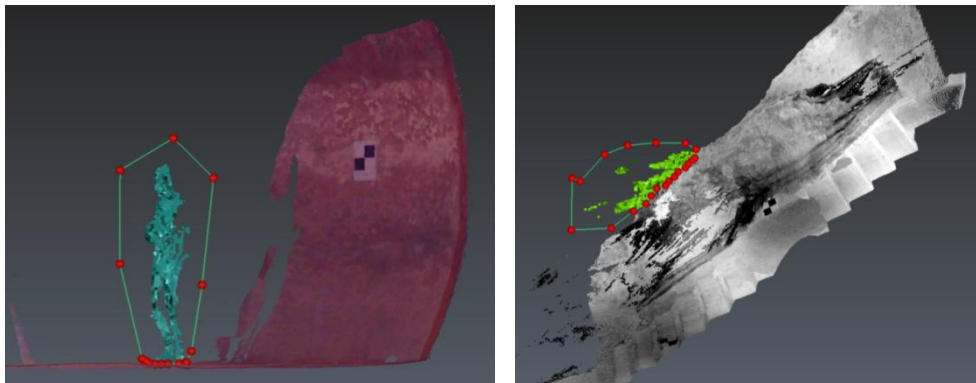


Figure 7.34. Example of noise elimination in 3DReshaper (3DReshaper)

Finally, the separated clouds were selected and then executing the “Merge Clouds” tool (this instrument is in the top menu, Cloud > Merge Clouds), see in Figure 7.35. Then the combined cloud was renamed following the nomenclature of the Figure 7.32.

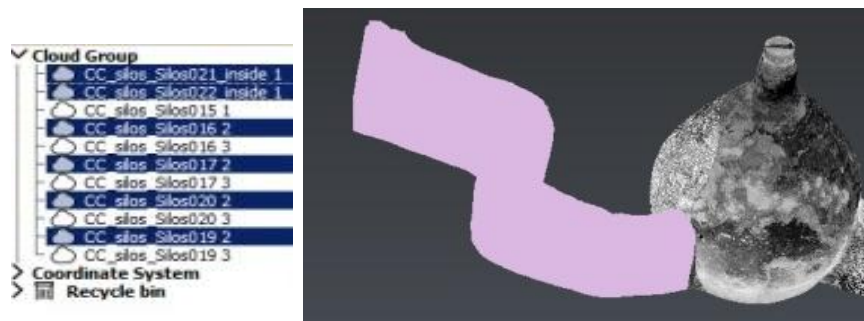


Figure 7.35. Selected clouds to merge in a cloud “Corridor_01” (3DReshaper)

The 3D model inside the building was not done, because there were not sufficient scans in this area and this part was not very important (Figure 7.36).

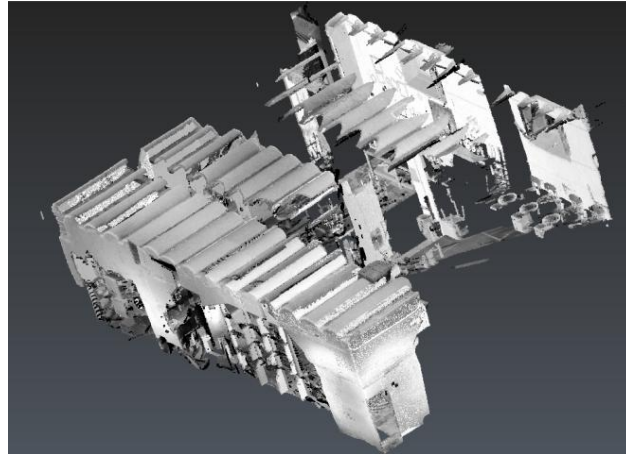


Figure 7.36. Scans inside of the building (3DReshaper)

When all the clouds were classified between corridors and silos, it was the moment to erase the electrical installation and the targets. Due to the morphology of the Silo, this one was measured from the interior. Therefore, some planes were created to divide the silos in two parts to see inside.

7.5.3.1. Separate the silo into two parts

The methodology to separate the silo into two parts in 3DReshaper is described below. Firstly, it was necessary to create the plane into the Silo (the tool is in the top menu, Construct > Plane > Plane / Draw). In order to do the plane perpendicular, it was necessary to inset zero in the z axis, which fixed the normal and in the z axis which fixed the second axis. A plane was created in each silo, see Figure 7.37.

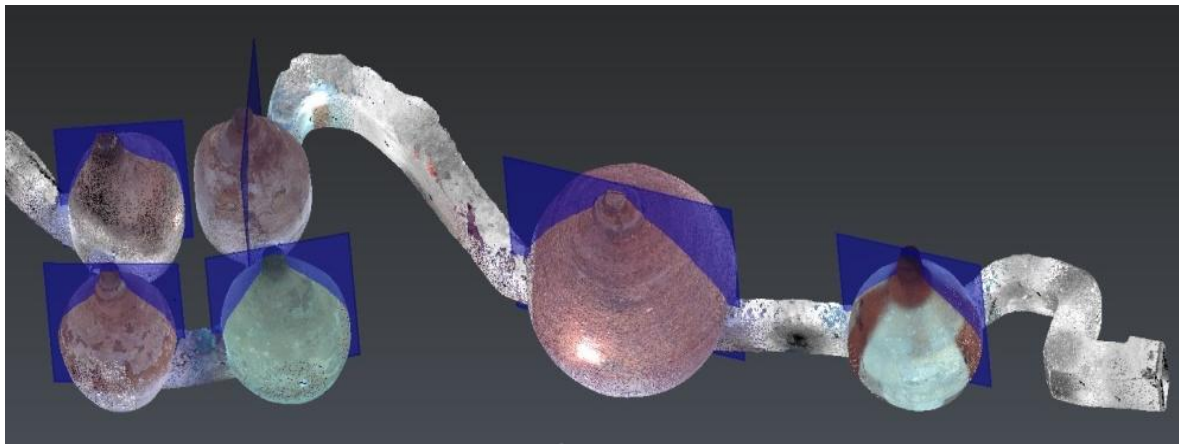


Figure 7.37. Planes perpendicular to every silo (3DReshaper)

Secondly, the silo cloud and its plane was selected and then the “Separate with object” tool was executed (this instrument is in the top menu, Cloud > Separate with object). Finally, the two clouds obtained for each silo was renamed with *the name of the cloud + “_1” or “_2”*. This process was performed for each Silo.

7.5.3.2. Separate the corridor into two parts

Also, the corridors were separated, but the “Clear / Separate Cloud(s)” tool was executed (this instrument is in the top menu, Cloud > Clean / Separate Cloud(s) > Keep the two parts), see Figure 7.38 . Finally, the two clouds obtained for each corridor were renamed with the name of the cloud + “_1” or “_2”. This process was performed for every corridor.

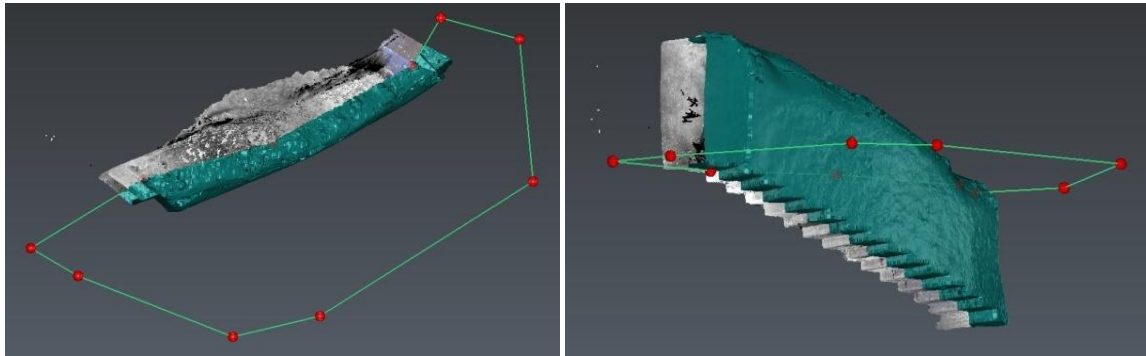


Figure 7.38. Separating the corridor into two parts (3DReshaper)

7.5.4. Delete the electrical installation and targets (P1)

This process of separating the electrical installation and targets of the point cloud was the most important step to obtain a correct 3D model.

Depending on the point cloud, it was sometimes possible to use the data segmentation to separate the electrical installation, but in other cases this was not useful. Both methods are explained below. An example of the electrical installation and the target to be cleaned can be seen in Figure 7.39.



Figure 7.39. Example of the electrical installation and targets to be deleted (3DReshaper)

7.5.4.1. Data segmentation for deleting the electrical installation

The following is a description of the methodology to delete the electrical installation through the data segmentation in silos and corridors. Firstly, it was necessary to load half -silo point cloud or half -corridor point cloud, (3D > Import > Point Cloud). It was selected and afterwards the “Filter / Explode Cloud(s)” tool was executed (this instrument is in the top menu, Cloud > Filter / Explode Cloud(s) > Explode with distance). With this tool, it was necessary to change the value

of the distance and check the preview to obtain the result expected (Figure 7.40). The different colors will be separated into different point clouds.

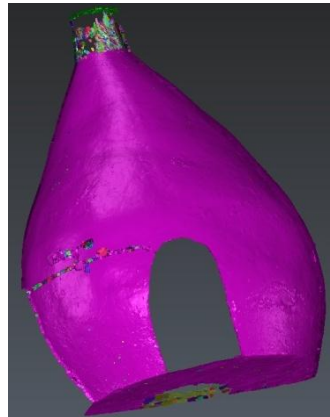


Figure 7.40. Data segmentation with default value (3DReshaper)

Due to the result of Figure 7.40, it was not possible to apply the segmentation to a half -silo. Therefore, the part around the electrical installation was extracted and then the segmentation was applied to this fragment (Figure 7.41). In this case, the optimal result was obtained using 5mm in the segmentation distance.

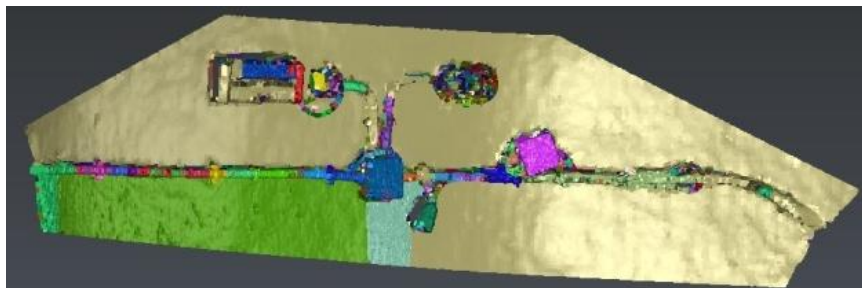


Figure 7.41. Fragment segmentation 5mm (3DReshaper)

Secondly, all point clouds that belong to the wall were merged into a point cloud. And the other point clouds that belong to the electrical installation were merged into another point cloud (Figure 7.42). Usually, some parts of the electrical installation appeared on the wall cloud. In order to delete these parts it was possible to use another segmentation or to manually separate these parts (Cloud > Clean / Separate Cloud(s) > Keep the two parts).

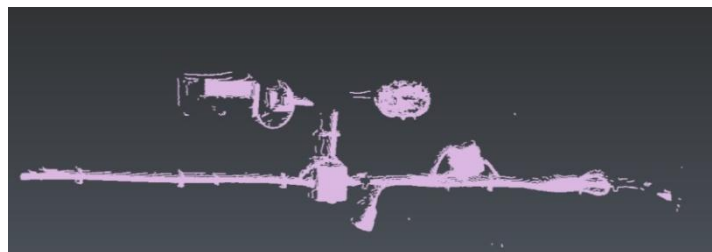
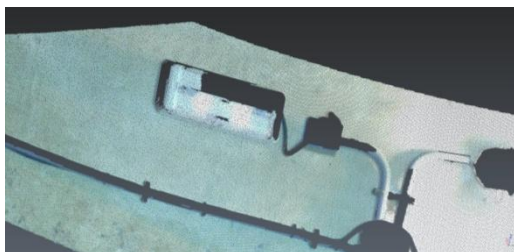


Figure 7.42. First point cloud of wall (left) and first point cloud of electrical installation (right) (3DReshaper)

Finally, when the electrical installation was separated from the fragment of the point cloud, this fragment was combined with the half -silo or half -corridor and renamed like “p1_”+ cloud name. This process was realized for each half -silo and each half -corridor.

7.5.4.2. Delete the electrical installation without segmentation

The obtained results of the segmentation of point clouds sometimes were not useful to separate the electrical installation (Figure 7.43). Therefore, in these cases, the electrical installation was separated by hand.

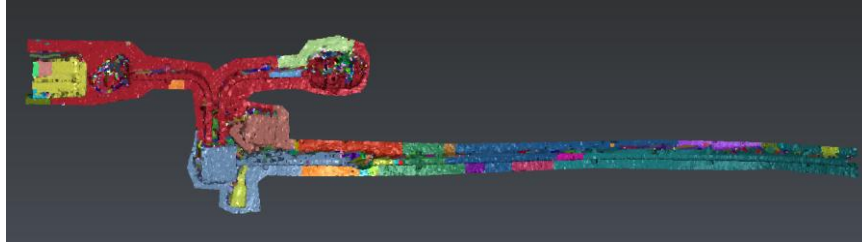


Figure 7.43. Non-optimal segmentation (3DReshaper)

The methodology to separate manually the electrical installation is described below. Firstly, the half of the point cloud was selected and the “Clear / Separate Cloud(s)” tool was executed, later points were inserted around the object to separate it (Figure 7.44). As soon as the electrical installation was separated, the final step was the same that the final step of data segmentation.

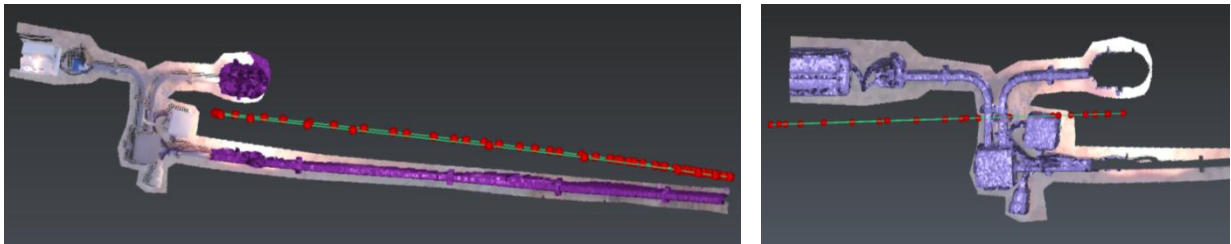


Figure 7.44. Manually separating of electrical installation (3DReshaper)

7.5.4.3. Delete targets

The following is a description of the methodology to remove manually the parts of the targets in the half -silos and in the half –corridors due to the fact that some targets were changing the morphology of the silo or the corridor, because these targets were not completely pasted to the wall. This process was very similar to the manual separation of the electrical installation. The “Clear / Separate Cloud(s)” tool was used only to separate the parts which were not preserving the geometry of the silo wall (Figure 7.45), it was performed for every target.

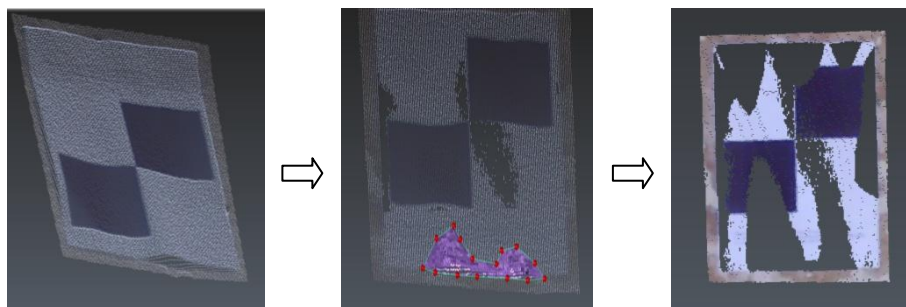


Figure 7.45. Process of removing parts of the targets (3DReshaper)

The points that are conserved of the target were used to generate the 3D model, but not to give the color to the model on the place that did not have photos.

7.5.4.4. Delete points in some zones

Sometimes, the mistake of overlapping was taking place when the different scans were superposed. For example, the overlap error appears on the stairs, this can be seen in Figure 7.46, which was deleted to avoid the noise in the mesh.

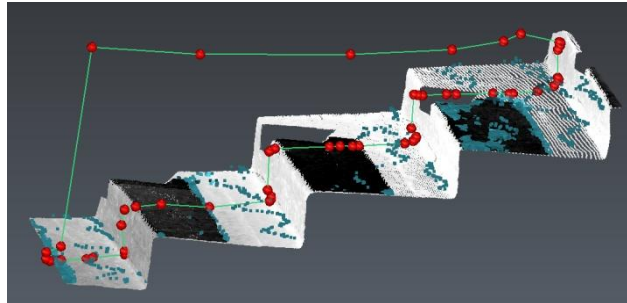


Figure 7.46. Delete noise from the stairs (3DReshaper)

The atypical case also occurs in the stairs (Corridor_07), due to a plastic cover or something similar that covers the ruined wall. The Laser Scanner could measure the wall behind the plastic cover, but also some parts of the plastic cover. These wrong points were very difficult to erase, see Figure 7.47.

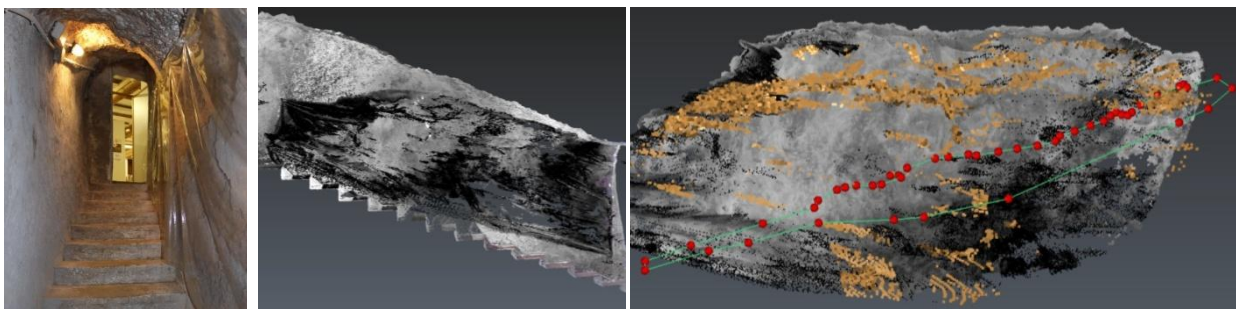


Figure 7.47. RGB picture of the plastic cover (Valenciabonita 2017), before to deleting the noise (left), and deleting the noise of the plastic cover (right) (3DReshaper)

7.5.5. Automatically filter data noise (P2)

The noise filtering process was performed, when the electrical installation and targets were deleted. This process deleted some random noise points, and also the intensity was chosen to be applied.

The following describes the methodology to filter the noise of the point cloud obtained in the previous process (Process 1 - Delete the electrical installation and targets) in 3DReshaper. Firstly, the scans with half -corridor or half -silo were loaded, (3D > Import > Point Cloud). Afterwards, the point cloud was selected and the “Noise reduction” tool was executed (this instrument is in the top menu, Cloud > Filter / Explode Cloud(s) > Noise reduction), the “intensity 0” was normally used (Figure 7.48), because otherwise, the points which had no noise were deleted. Usually, this process was executed in three iterations. For each iteration, it sometimes deleted around a maximum of 0.1% of the total number of points. In some cases, this percentage might be higher, it revised that the points to delete of blue color were noise points. This process was done for each half -corridor and each half -silo, which was renamed as “p2_”+ cloud name.

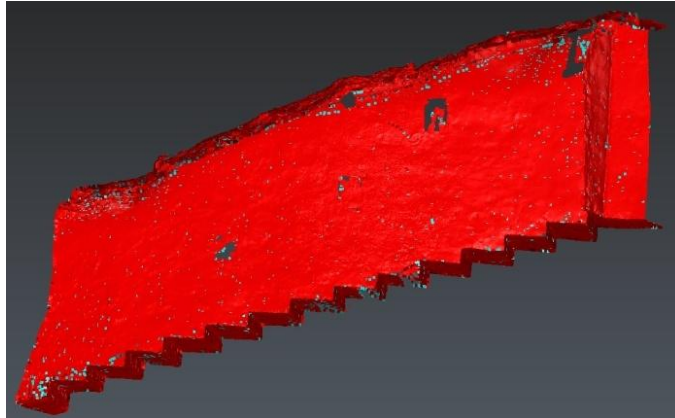


Figure 7.48. Noise reduction iteration 1, points to delete (blue) (3DReshaper)

Secondly, every half -cloud was merged with the other half -cloud in the same zone. Both point clouds were selected, afterwards the “Merged Clouds” tool was executed (this instrument is in the top menu, Cloud > Merged Clouds). Then, the noise reduction was applied once again and it was renamed as “p2_”+ cloud name of the zone+ “_3”.

7.5.6. Create 3D mesh (P3)

In order to create a realistic 3D mesh, it was created in two steps. The first step was creating a gross 3D mesh without details to fill the holes, and the second step was creating a refined mesh to visualize the bricks and details on the walls. The following is a description of the methodology of the 3D mesh creation of silos and corridors of the last process (Process 2 - Automatically filter data noise).

Firstly, the point cloud was selected and the “3D mesh” tool was executed, (the instrument is in the top menu, Mesh > 3D Mesh). Normally, in this step it is appropriate to use approximately three centimeters, this means that the mesh had a 3 cm of precision.

Secondly, the 3D mesh was checked, sometimes it was necessary to fill some small holes. In order to do this, the mesh was selected and then the “Fill holes” tool was executed, (the instrument is in the top menu, Mesh > Fill holes), see Figure 7.49.

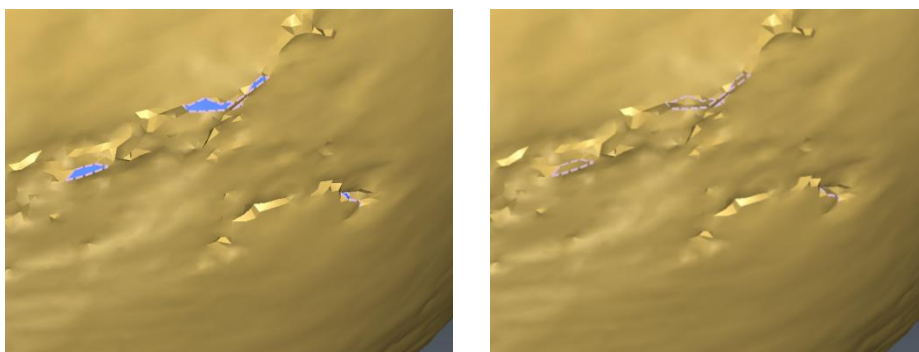


Figure 7.49. Filled holes before (left) and after (right) (3DReshaper)

Thirdly, when all holes were filled, it was time to refine the mesh with the corresponding point cloud obtained in the process 2 (P2). The mesh and the point cloud were selected and then the “Refine Mesh / From a point cloud” tool was executed (this instrument is in the top menu, Mesh > Refine Mesh > From a point cloud). Normally the mesh was refined to three millimeters

(Figure 7.50), this means that the model had a 3 mm of precision. Only in the “Silo_02” was refined to 1 mm to see the bricks in the model. In this step the 3D mesh was improved.

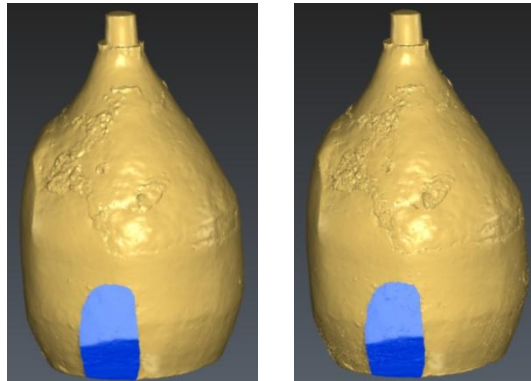


Figure 7.50. Refined mesh to 3mm before (left) and after (right) (3DReshaper)

Fourthly, once the 3D mesh was checked, sometimes it was necessary to eliminate some spikes. To do this, the mesh was selected and then the “Eliminate Spikes” tool was executed, (the instrument is in the top menu, Mesh > Eliminate Spikes). Finally, the obtained mesh was renamed with “p3_”+cloud name of the zone. This process was performed for each silo and each corridor.

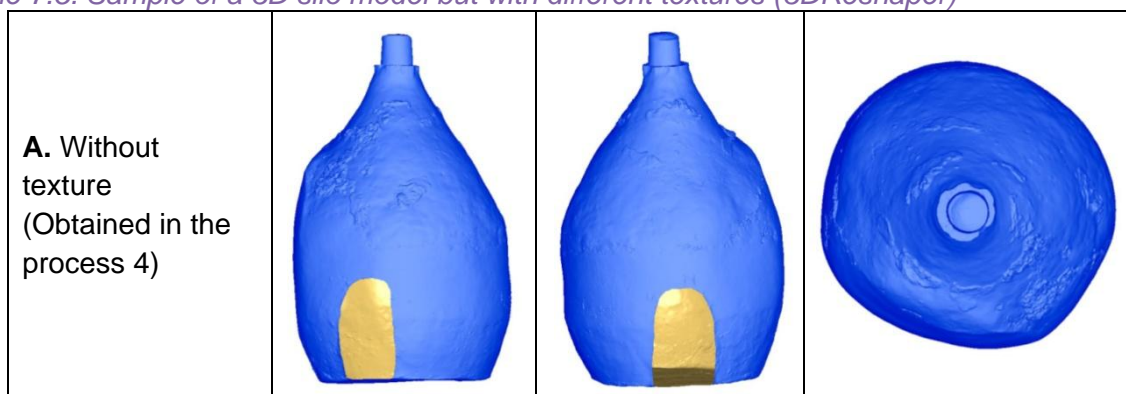
7.5.7. Smooth the mesh (P4)



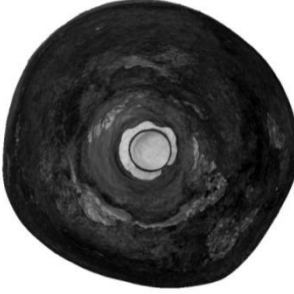






The next step was to smooth the mesh, which was obtained from the last process (Process 3 - Create 3D mesh). In order to smooth the mesh, it was selected and the “Regular Smoothing” tool was executed, (the instrument is in the top menu, Mesh > Smooth mesh > Regular Smoothing). Normally, in this step the “keep details” property was used in the mesh in order not to lose detail. Finally, the mesh obtained was renamed with “p4_”+ cloud name of the zone, for example, “p4_Silo_03.ply”. This process was performed for every silo and corridor.

7.5.8. Colorize or texturing the mesh (P5)

The following is a description of how the silos meshes and corridors meshes of the last process (Process 4 - Smooth the mesh) were colorized. Some samples of a silo with different textures can be seen in the Table 7.5. The texture of the 3D mesh was applied through two different methodologies (using color images or color of the Laser Scanner), with different results.

Table 7.5. Sample of a 3D silo model but with different textures (3DReshaper)



<p>B. Texture with intensity value of the Scanner</p>			
<p>C. Texture with Scanner color</p>			
<p>D. Texture with orthomosaic (only available in 3 of 6 Silos), obtained with Agisoft PhotoScan</p>			

With the intensity value of the Scanner, the corridors meshes were colored, because in the measurements the color was not taken. The texture with the color of the Scanner was used to color the silos meshes, where they were not photographed. And the texture with the orthomosaic obtained with Agisoft PhotoScan was used to texture the first three silos of the entrance. The methodology of these options is explained below.

7.5.8.1. Colorize the mesh

This process was used in corridors and silos without images. To color the mesh, it was selected and the “Take Color from Cloud” tool was executed, (the instrument is in the top menu, Mesh > Take Color from Cloud), (Table 7.5 – B, Table 7.5 – C.). Normally, in areas where there were no color points, the average color was taken from the closest points. Also, it was possible to choose the distance and the default color to paint the mesh when that distance was exceeded. Finally, the mesh obtained was renamed with “p5_”+ cloud name of the zone. This process was performed for each silo and each corridor. This mesh was exported in PLY format, in order to store the colored mesh.

7.5.8.2. Texturing the mesh

This process was used in the first three silos from the street access, in these silos there were images and thermal images. In this method, mosaics were used (Figure 7.51) from Agisoft PhotoScan generated with normal images. It is explained in the next chapter.



Figure 7.51. Mosaics of Silo_01

The methodology to texture the mesh is described below. Firstly, the mesh was selected and afterwards the “Texture From Pictures - From Reference Points” tool was executed (the instrument is in the top menu, Image > Texture From Pictures > From Reference Points). It was very difficult to insert the reference points, due to, there were no regular objects as windows in this place. The point cloud was used to place the reference points, see Figure 7.52. When the image was fixed in the mesh, the reference points were exported into a TXT file with the name of the image and the silo, this file will be necessary later.



Figure 7.52. Insert reference points to texturing the mesh (3DReshaper)

Secondly, the images were edited in Photoshop software to eliminate the targets and the electrical installation, as these objects were not in the mesh. Thirdly, the new images modified in Photoshop and the reference points of every image were imported. Since the images had the same dimension as the images used in the first step, all the images were located in the correct place.

Fourthly, in this software we had the opportunity to choose manually which triangle was texture by each image, this allowed to give a realistic result. The mesh was selected, afterwards the “Adjust Textures” tool was executed (this instrument is in the top menu, Image > Adjust Textures), see Figure 7.53.

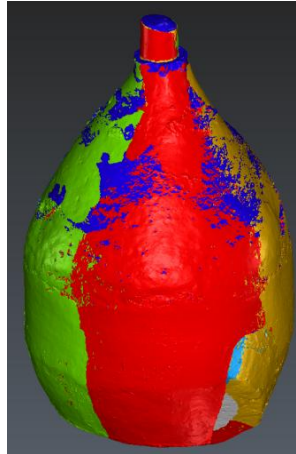


Figure 7.53. Adjusting the textures in the silo (3DReshaper)

Finally, the mesh obtained was renamed with “p5_” + cloud name of the zone. This process was performed only in the first three silos. This mesh was exported in OBJ format which stored the mesh and the images that were used to texturing the mesh.

7.5.9. Merging all the meshes

The following is a description of the methodology for combining all meshes in one mesh. The “Merge Common Borders” tool was executed, as it was not maintaining the color of the mesh, the topology was recreated to combine common boundaries, due to this, it was necessary to use another tool. To do this, the two meshes were selected and the “Join 2 Contours” tool was executed (this tool is in the top menu, Mesh > Join 2 Contours), this tool joined two meshes on a surface, see Figure 7.54. This process was necessary to avoid holes between silos and corridors.

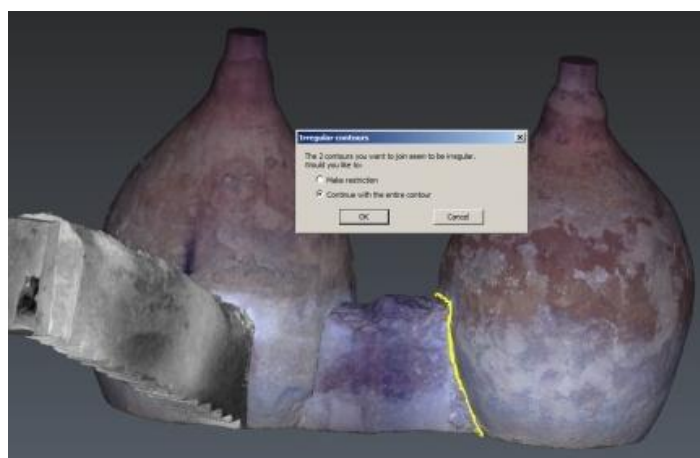


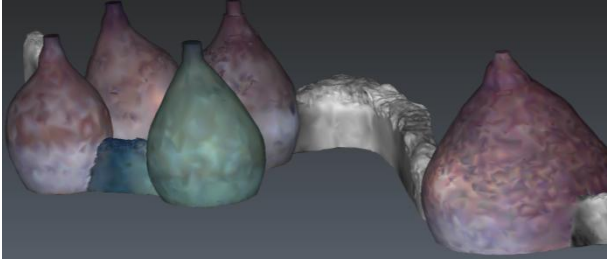

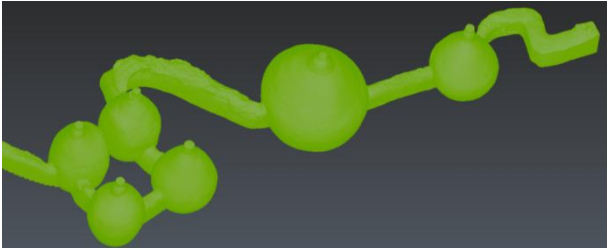
Figure 7.54. Joined two mesh (3DReshaper)

7.5.10.Reduced mesh

The goal to reduce the mesh was that the model was represented by fewer triangles, but with the same range of quality. This was achieved so that the software could run more rapid and storage less space on the disc. Depending on the purpose of the model it was possible to be reduced more or less. In other words, the model could maintain more or less detail, but for the cultural heritage aim it was necessary to have high resolution. For example, in the plane surfaces not so many triangles were necessary.

In this case the morphology of the silos and the corridors had the same characteristics, for this reason the reduction was applied to the fused mesh. To do this, the mesh was selected and the “Reduce” tool was executed (this instrument is in the top menu, Mesh > Reduce). In order to analyze if this reduction had many changes in the model, it was necessary to check the model with the next tool, so that the original mesh and the reduced mesh was selected, afterwards the “Compare / Inspect” tool was executed (this instrument is in the top menu, Measure > Compare / Inspect). Some samples with different deviation values can be seen in Table 7.6, the first reduction of Table 7.6, the reduction ratio was very high, but it was not appropriate in this case because all details disappeared. In this project, it was very important to conserve the bricks or other details. Therefore, between the second and third reduction the reduction rate was similar, the third reduction was chosen, maximal deviation of 1 mm, because the model was not distorted and the morphology of the silos and corridors was maintained.

Table 7.6. Samples of different grade of reduction (3DReshaper)

<p>A. Information about the first reduction</p>	<p>Average deviation: 0.00380 m Maximal deviation: 0.01000 m Reduction rate: 98.4%</p>	
<p>B. Information about the second reduction</p>	<p>Average deviation: 0.00074 m Maximal deviation: 0.00300 m Reduction rate: 68.3%</p>	
<p>C. Information about the third reduction</p>	<p>Average deviation: 0.00048 m Maximal deviation: 0.00100 m Reduction rate: 65.8%</p>	

The characteristic of the reduction chosen (Table 7.6 – C.) had a maximal deviation of 1 mm, and the reduction rate is 65.8% respect of the original mesh, more than 90% of the surface changes its position less than 1 mm. Looking at the Figure 7.55, the maximal change in the reduced mesh with regard to the original mesh was 3.7 mm in less than 0.01% of the total

surface. The original mesh had about three million triangles and the reduced mesh to 1 mm had about one million triangles, the difference in the number of triangles was high, the model was reduced two million triangles. This reduction was very important.

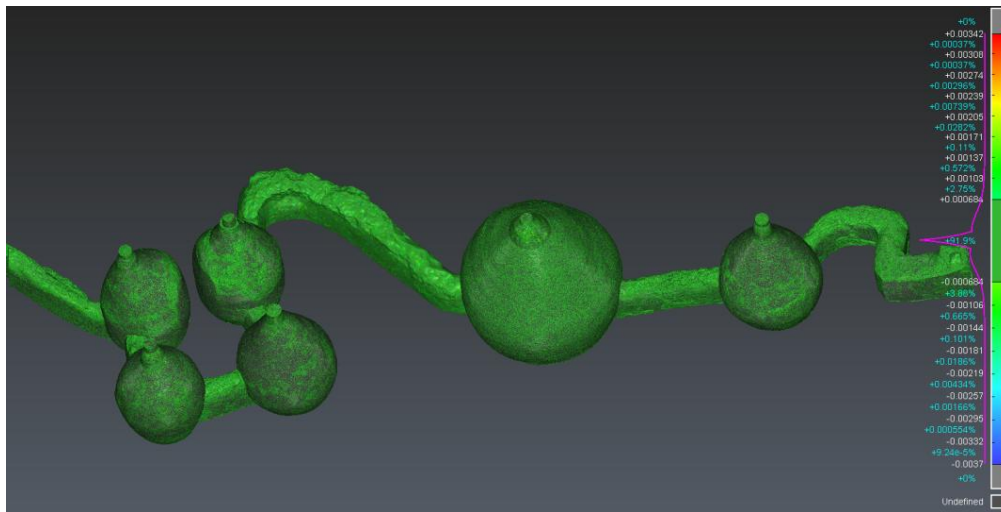


Figure 7.55. Comparing between the original mesh and the reduced mesh 1mm (3DReshaper)

Then, the first three silos were separated, as the RGB or thermal texture was changed. These silos were separated in this step, since the clean cut between the silos and corridors was perfect. There were no holes when the texture was changed, see Figure 7.56. These silos were colored with the texture, the process can be seen in section “7.5.8.2 Texturing the mesh”.

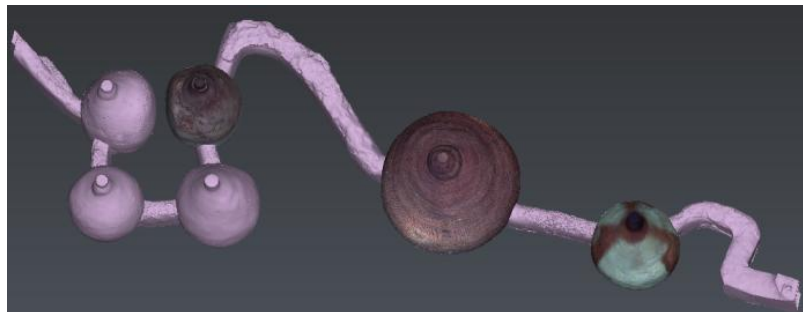


Figure 7.56. Separate the first three silos of the reduced mesh of 1 mm (3DReshaper)

7.5.11. Translated mesh

When all the processes were done, it was time to apply the translation to the model. To do this, the final meshes were selected and the “Translation” tool was used (this instrument is in the top menu, Construct > Translation), in order to create a new object translated.

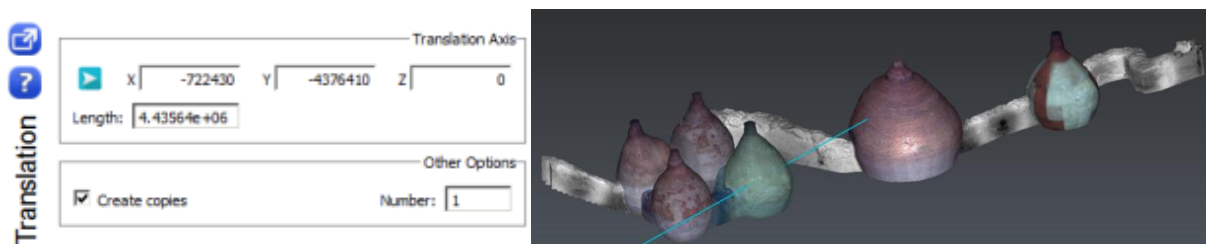


Figure 7.57. Translated mesh (3DReshaper)

In order to know the distance to be translated, it was consulted on the official website of the Valencian community (ICV – Terrasit), to obtain the coordinates of the point where the coordinate origin was near the Valencian Silo-Yard. Therefore, the translated values were “-722430 m” in North and “- 4376410 m” in East, this translation was done not to have problems when using this data in another software and not 3DReshaper, because another software cannot open the project in the original coordinates.

The colored meshes were exported to the PLY format, and the textured meshes were exported to the OBJ format. In addition, with this program, it was possible to obtain the volume of the meshes, which can be seen in “Appendix I”.

7.5.12. Scripts with 3DReshaper

The programming in JavaScript language was used with the “Script > Run” tool, the example of the code can be seen in Table 7.7. This script was developed to save the loaded point clouds in the 3DReshaper software (“.rsh”).

Table 7.7. Script to save the point clouds (3DReshaper)

```
p0_Save_Clouds_load_in_rsh.js
// Set the current directory to our containing folder
var curDir = CurrentScriptPath();
print(curDir);
// Load all the clouds of the rsh file
var clouds = SCloud.All(2);
print('clouds: '+clouds);
for( var num_cloud=0 ; num_cloud < clouds.length ; num_cloud++){
    cloud = clouds[num_cloud];
    print('nube: '+cloud);
    var name =cloud.GetName();
    var res = cloud.Save(curDir+'/save/'+name+'.pts');
    if (res.ErrorCode != 0)
        throw new Error('Save cloud failed : '+num_cloud);
}
print('Finished, save cloud.');
```

7.5.13. Some problems or errors detected

7.5.13.1. Errors in Scanner measurements

In the measurements that were taken inside the silos, there was some error in the upper part, due to this the Laser Scanner measured twice the same zone. The points were very close to each other but in a different position. Therefore, it made noise in the model. The problem can be seen in Figure 7.58. To do this, one of the repeated parts was deleted manually so that no noise appears in the model. The erasing process can be seen in Figure 7.59.

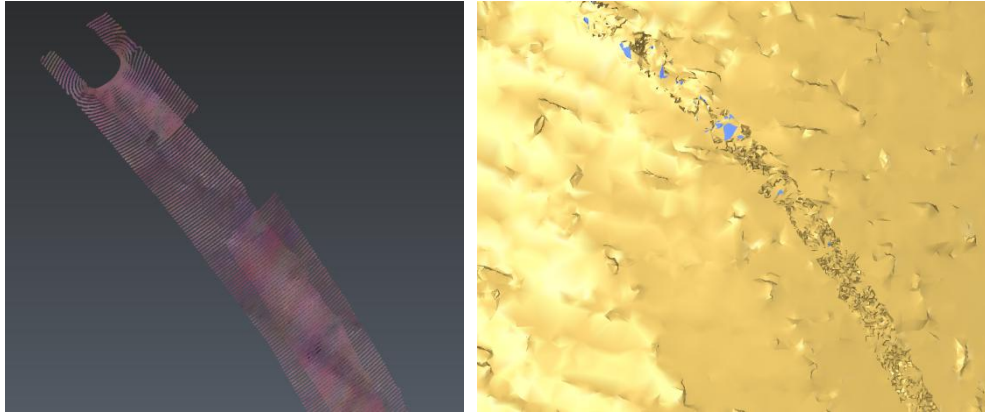


Figure 7.58. Scanner error (3DReshaper)

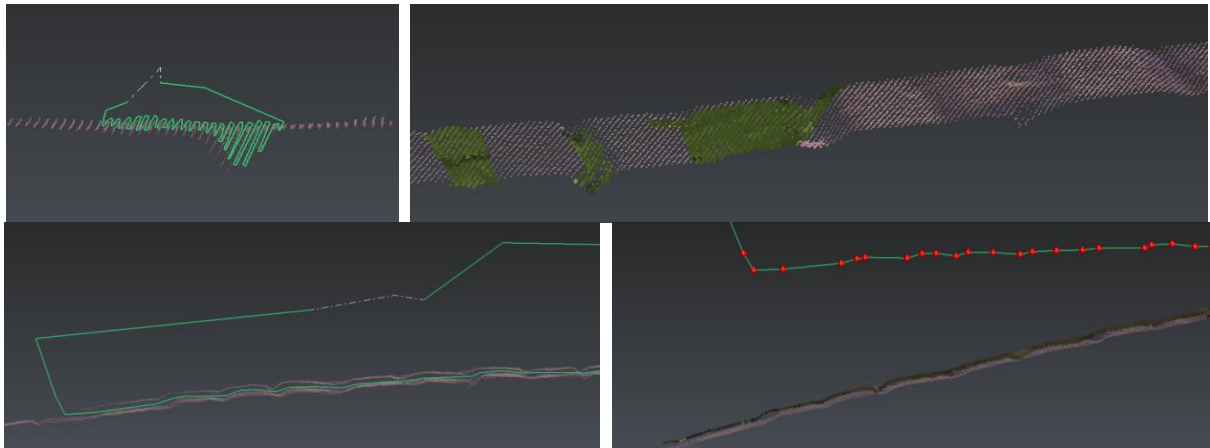


Figure 7.59. Removed the Scanner error (3DReshaper)

7.5.13.2. Problems with texture in some software

When the exported OBJ file was opened in the Geomagic software, the images were not interpreted correctly in this program. However, the same file was imported into Blender and the result was correct, see Figure 7.60.

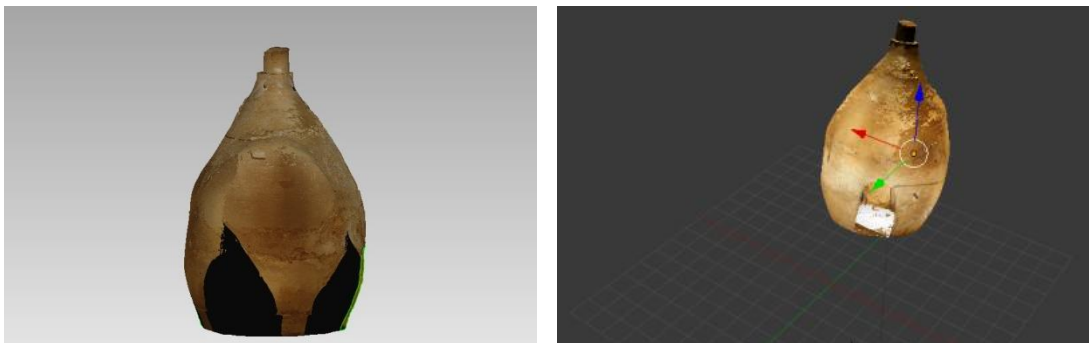


Figure 7.60. OBJ file imported into Geomagic (left) and imported into Blender (right) (Geomagic Studio 2014, Blender v2.78)

7.6. Processing with Agisoft PhotoScan to create the texture

This section presents the image processing in Agisoft PhotoScan software. The most important task is to create the orthomosaics with the RGB images and to texture the model with the thermal images.

7.6.1. Description of the Agisoft PhotoScan

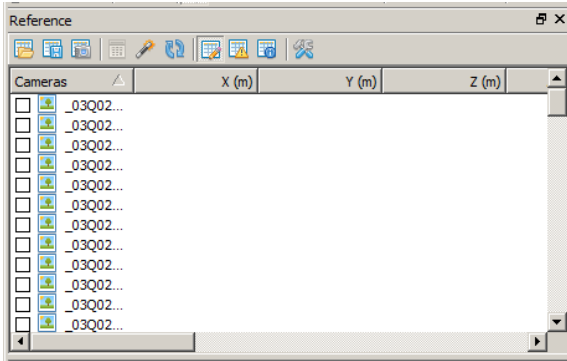
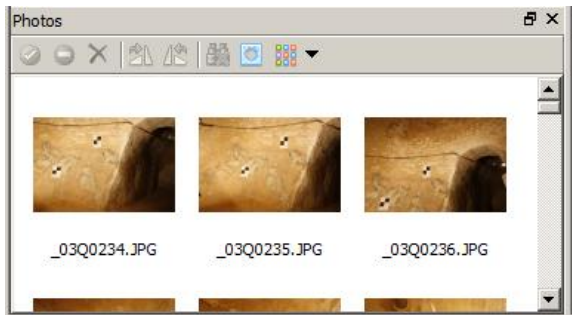
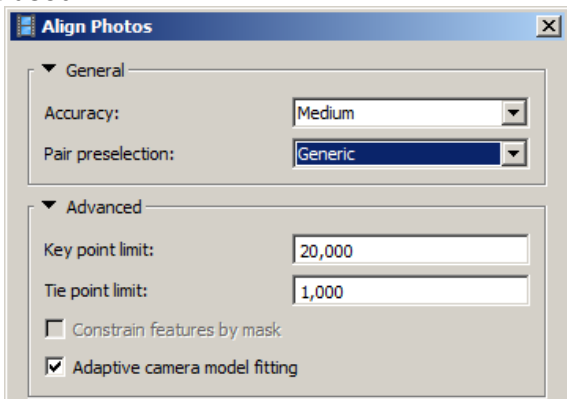
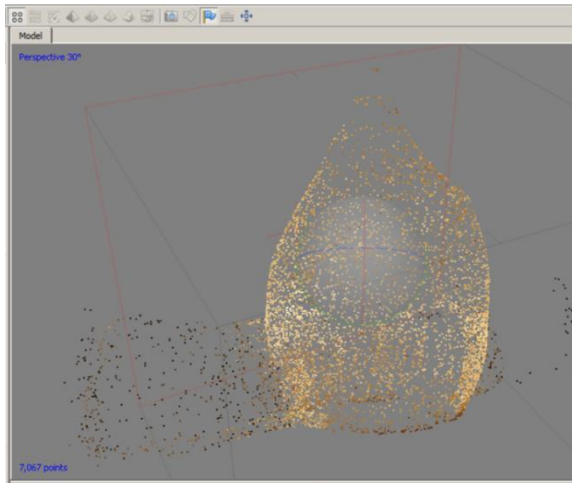
In this project the version that we use is Agisoft PhotoScan, version 1.2.6.2834.

Agisoft PhotoScan is a photogrammetric image processing product and generates 3D spatial data. Mainly this software is used for documentation of cultural heritage and GIS applications (Agisoft 2017).

7.6.2. Generated the orthomosaic in RGB

In order to generate the interior texture of the silos it was necessary to follow the steps of the Table 7.8.

Table 7.8. Process of generating the interior texture in RGB (Agisoft PhotoScan)

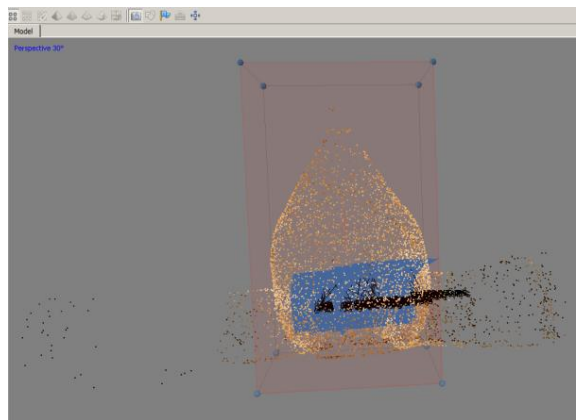
<p>1. Add the Photos</p>		
<p>2. Align the photos, where the “pair preselection” was chosen “generic”, the paired search of points before and after the image was not used.</p>		

3. Insert markers to have the model in the correct coordinates

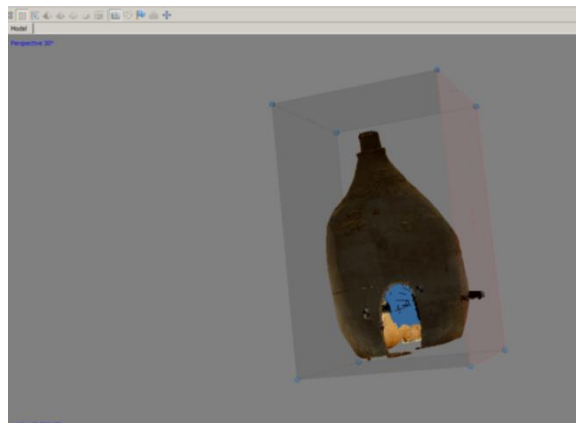
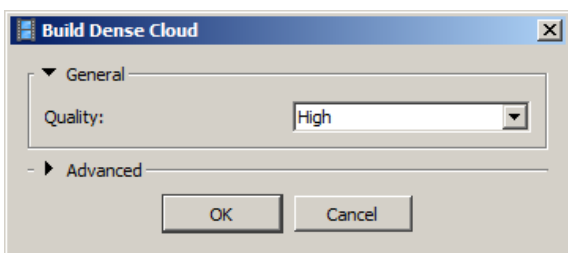
Marker	Easting (m)	Northing (m)	Altitude (m)	Accuracy (m)	Error (m)	Projections	Error (pix)
4	722489.668587	4376492.1698...	45.679226	0.005000	0.003464	7	1.282
3	722489.049416	4376490.7773...	45.313564	0.005000	0.001425	7	3.628
2	722485.804748	4376491.7608...	44.856357	0.005000	0.007705	7	6.563
1	722485.675072	4376492.7278...	45.613613	0.005000	0.007926	9	5.158
Total E...							
Contr...					0.005836		4.636
Check...							



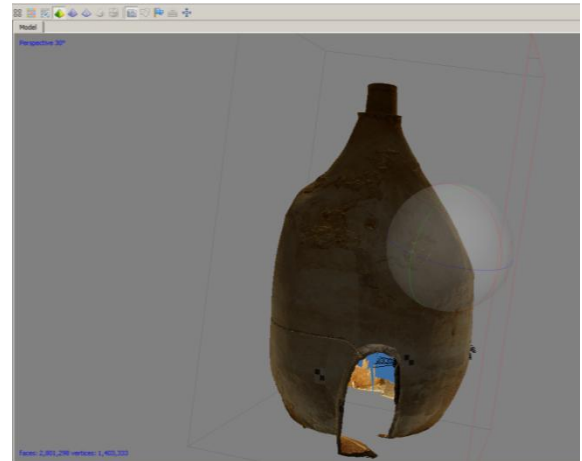
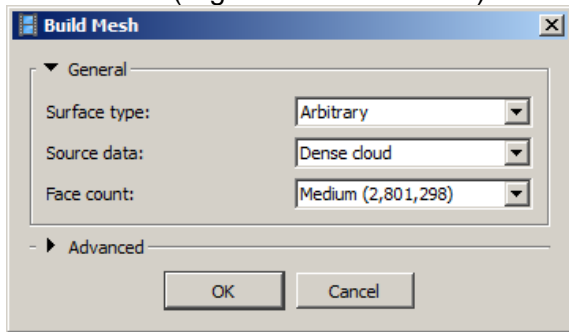
4. Adjust the cube to the extension of the object.



5. Build dense cloud

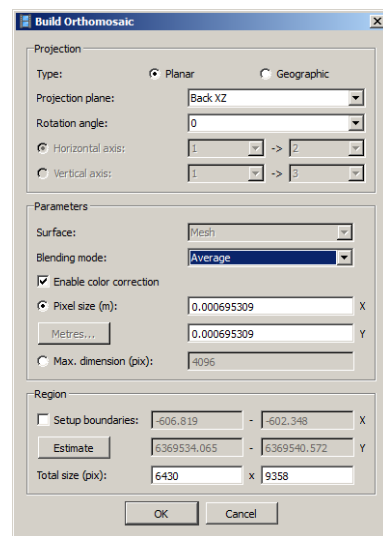


6. Build the mesh, in this case it was necessary to use the surface type as “Arbitrary”, because it was not a DEM (Digital elevation model)

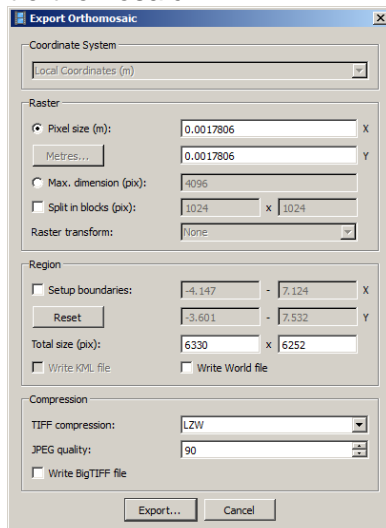


7. Build orthomosaic, the projection plane to be exported were:

- Top XY
- Front XZ
- Back XZ
- Right YZ
- Left YZ
- Bottom XY



8. Export orthomosaic



As soon as some orthomosaics had some wrong parts, some pictures were turned off and then recreated (Figure 7.61)



Figure 7.61. Dazzled image (left) and corrected image (right) (Photoshop)

This exported orthomosaic was used in 3DReshaper to import this texture to the mesh. This data was used in the section “7.5.8.2. Texturing the mesh”.

7.6.3. Applied the thermal images to the 3D model

These thermal images were not modified with Photoshop to remove the targets and the electrical installation. In this case, the thermal texture was applied to the mesh in PhotoScan. This process is described below for each silo.

7.6.3.1. Thermal texture of Silo 01 and Silo03

Since these images did not have a good resolution and quality, also they were taken half-silo and then the other half-silo in “Silo_01”. The software didn’t recognize well the correspondence between images, because the photographs were not taken in continuous circles. It only recognized similarities between some images, this can be seen in Figure 7.62.

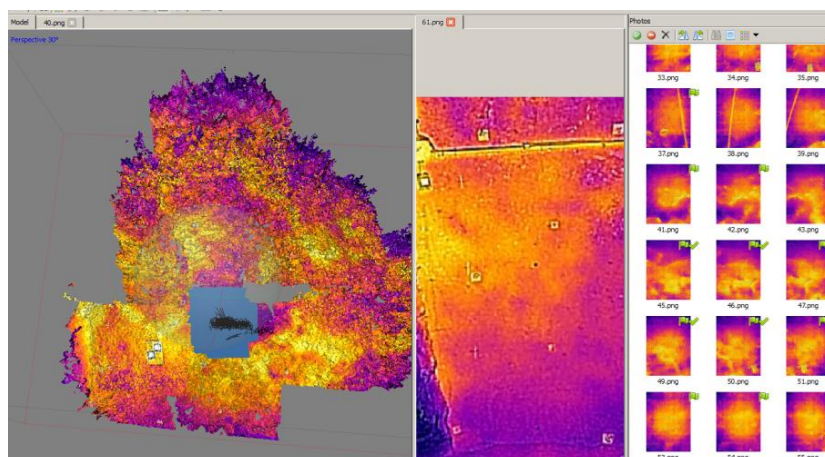


Figure 7.62. Aligned photos of the thermal images of “Silo_01” (Agisoft PhotoScan)

Then, the model obtained from 3DReshaper (Tools > Import > Import Mesh) was imported, once it was loaded, afterwards the texture was created to see which images were not appearing in the texture. In order to complete the model, new marks were assigned and only these photos were realigned. Finally, the thermal texture of the model from 3DReshaper was created and can be seen in Figure 7.63.

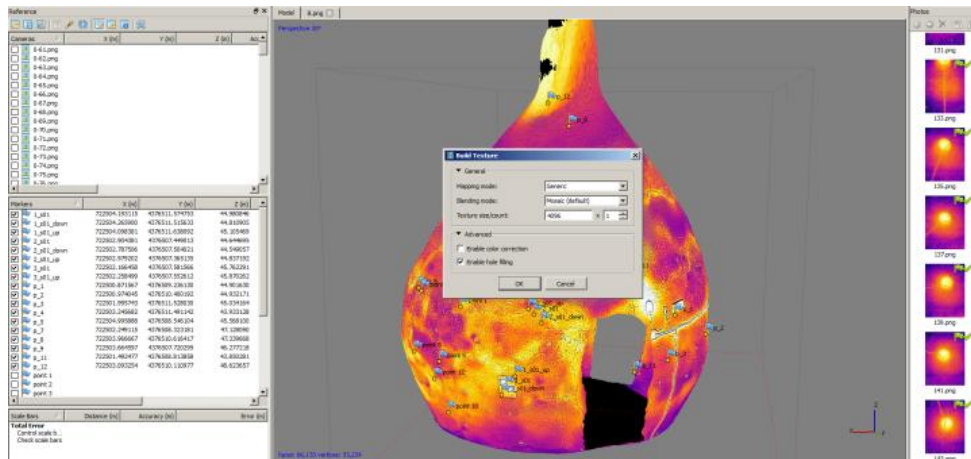


Figure 7.63. Creating the final thermal texture of the 3DReshaper model (Agisoft PhotoScan)

In the last step, the model was exported with the texture in OBJ format (File > Export model). Then, the model was compared in 3DReshaper with the original mesh to see that its geometry was not modified, see Figure 7.64.

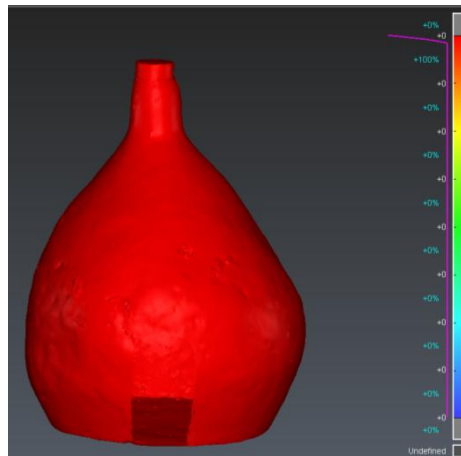


Figure 7.64. Comparison of the original mesh with the PhotoScan texture mesh (3DReshaper)

7.6.3.2. Thermal texture of Silo 02

There was no access to the images of “Silo 02” to do the same process of that in the previous section. Nevertheless, we had access to the final data of last year, using the last year’s thermal model created by Carbonell obtained from the model used in Unity software by Hadabay.

Then this model of the silo was imported into 3DReshaper to create the orthomosaic of the same views that was obtained in PhotoScan. Finally, these images were applied as in the section “7.5.8.2. Texturing the mesh”.

7.7. Processing with Blender to create the virtual reality

This section presents the processing in Blender software. The most important task was to compact the images used by a 3D model in an image and create the virtual reality.

7.7.1. Description of the Blender software

Blender is free and open source software, as a community-driven project under the GNU General Public License (GPL). It is a cross-platform and runs equally well on Linux, Windows, and Macintosh computers.

Blender supports the entirety of the 3D pipeline—modeling, rigging, animation, simulation, rendering, compositing and motion tracking, even video editing and game creation. This software also has Blender's API for scripting to customize the application and write the specialized tools.

The following is a more detailed explanation of the modules that can be used in Blender if there is sufficient time in this work.

Camera and Object tracking

With this module the aim is to create an animation to show the 3D modeling of the Valencian Silo-Yard resulting from the 3DReshaper software.

This module includes auto and manual tracking of the camera and object, a powerful camera reconstruction and a real-time preview of the tracked footage and 3D scene.

Game Creation

This module is included in Blender, it is a complete game engine, it allows to create a fully featured 3D game right inside Blender.

This module includes for example, the ability to port the models to any third-party game engine. It is possible to create or code with own game logic, also Python scripting API for advanced control and AI. It is supported for all OpenGL™ dynamic lighting, toon shading, animated materials as well as Normal and Parallax Mapping. It is allowed to playback games inside Blender without compiling or preprocessing 3D spatial audio using OpenAL.

7.7.2. Compacting the images of a 3D model

The 3D models exported from 3DReshaper of the first three silos with RGB texture, exported their six images with every model, so when trying to import this data into the virtual reality these images of the meshes were very big.

The solution to this problem was to process this data with Blender and unify all the images to one image per model. The tool that was used was "Object UV Editing", this tool allowed integrating all the images in one image. Firstly, the mesh was imported in OBJ format, when all sub-meshes were selected. Then click "MultiObject UV Editing" (Tool > MultiObject UV Editing), to edit the UV (these are the coordinates that assign to each vertex of the model, the value of the texture) of the sub-meshes at the same time. Secondly, a new UVMap was created and the

“Smart UV Project” (Mesh > Unwrap > Smart UV Project) was executed, which can be seen in Figure 7.65.

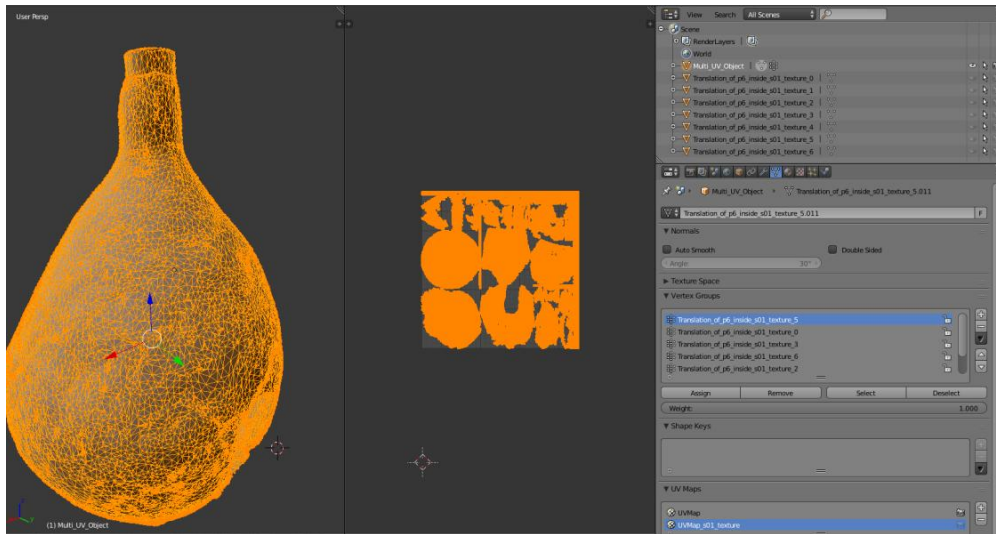


Figure 7.65. “Smart UV project” executed (Blender 2.78)

Thirdly, at the time of assigning the texture to the mesh, a new image with the resolution was created (Figure 7.66, left) to generate the texture there. In the case of the silos 4096 x 4096 pixels were used, see Figure 7.66. Then, the “Bake” button was clicked to bake the image with the texture of the selected objects. The result can be seen in Figure 7.67.

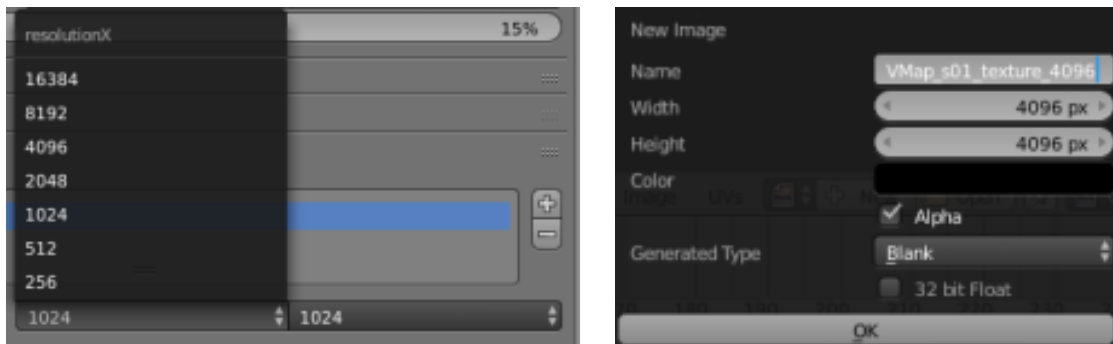


Figure 7.66. Recommended resolution values (left) and creation of the new image (right) (Blender)

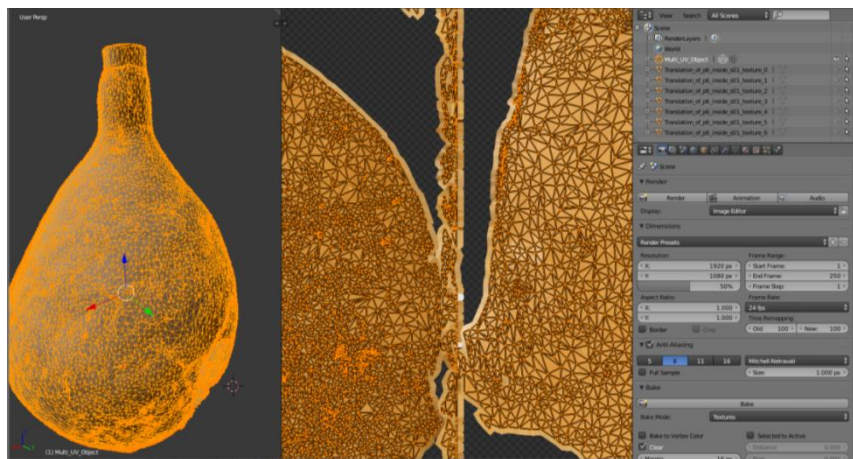


Figure 7.67. Baked texture of the “Silo_01” (Blender)

Fourthly, when the texture was created, all sub-meshes were joined (Ctrl + j), the old UVMap and the old textures were deleted. Subsequently, the new image was loaded and assigned the new UVMap, see Figure 7.68.

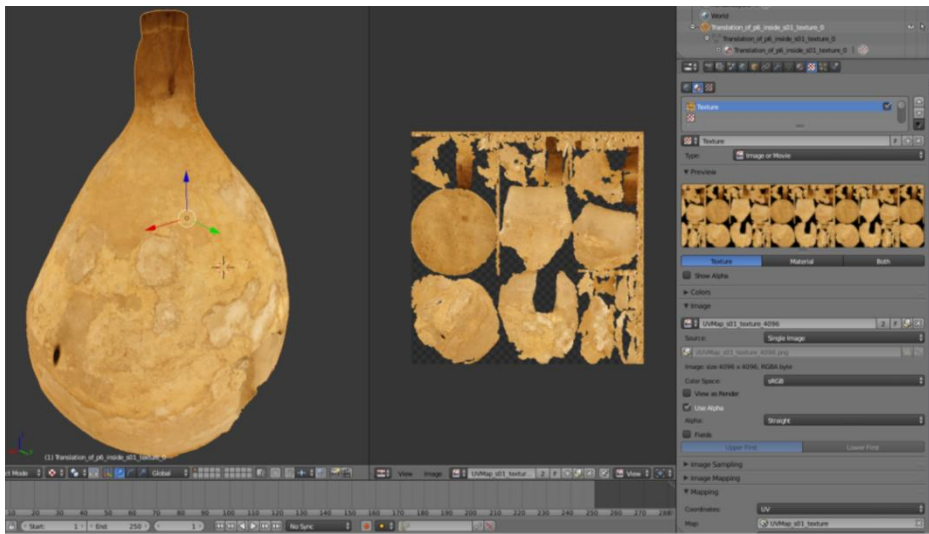


Figure 7.68. Assigning the new texture of an image (Blender)

This process was performed with all meshes that were included in the virtual reality (inside the silos and also outside the silos with the results of Yepes (2017) where more than one image was used in the texturing process. Sometimes, it was necessary to apply a rotation of -90° in x with the OBJ format for the correct visualization in Blender.

7.7.3. Create virtual reality

The most important thing was the object that travels on the 3D model. The camera (1,5 meters from the floor) and the light was associated with the cube, the objects were selected and clicked on "Object > Parent > Object > Set Parent to Object". It is not able to cross the walls (Physics type > Dynamic), the parameters can be seen in Figure 7.69. With this process the children of the cube are the camera and the light, in other words, when the cube moves the children also move.

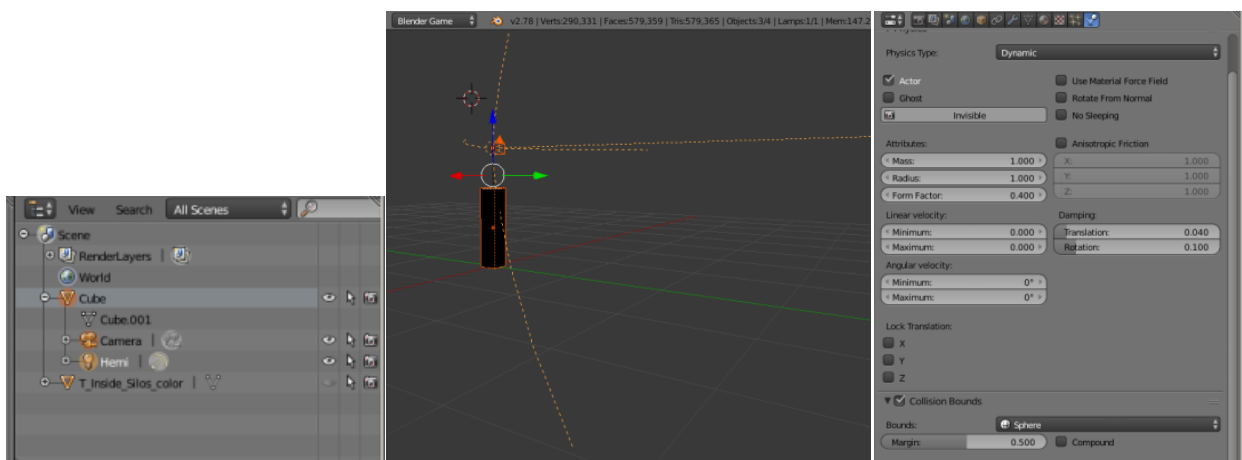


Figure 7.69. Cube parent with the camera and the light as children (Blender)

This object can be moved with the mouse and the arrows, the game logic of the cube can be seen in Figure 7.70. The movements were:

- Move proceed: up arrow
- Move back: down arrow
- Turn left: left arrow or move mouse
- Turn right: right arrow or move mouse
- Movement of the view: move mouse
- Jump: right-click mouse

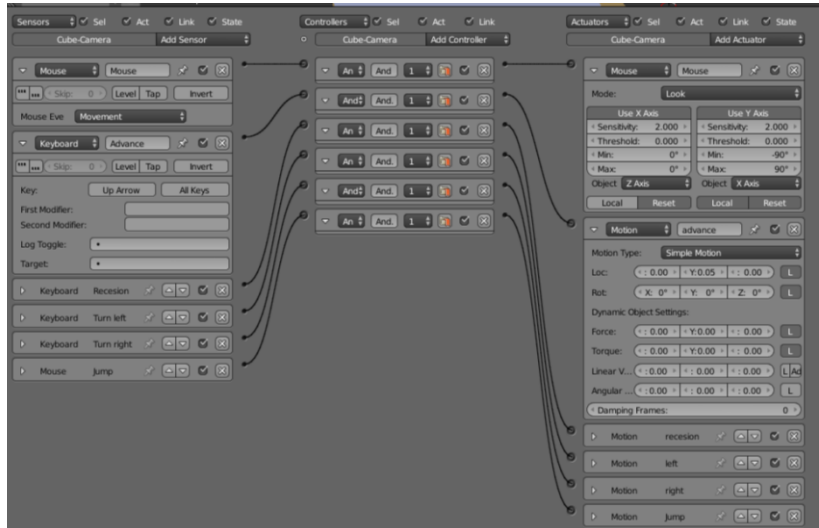


Figure 7.70. Game logic of the cube (camera) (Blender)

The texture in the first three silos (“Silo_01”, “Silo_02”, “Silo_03”) can be chosen pressing some keys: (the logic game can be seen in Figure 7.71)

- If you **press** the number “1” key on the keyboard: The color to visualize is the color mesh (the color of the laser scanner colors the mesh)
- If you **press** the number “2” key on the keyboard: The texture to visualize is the real texture – realistic color (normal camera color)
- If you **press** the number “3” key on the keyboard: The texture to visualize is the thermal texture (color of thermal pictures with thermal camera)

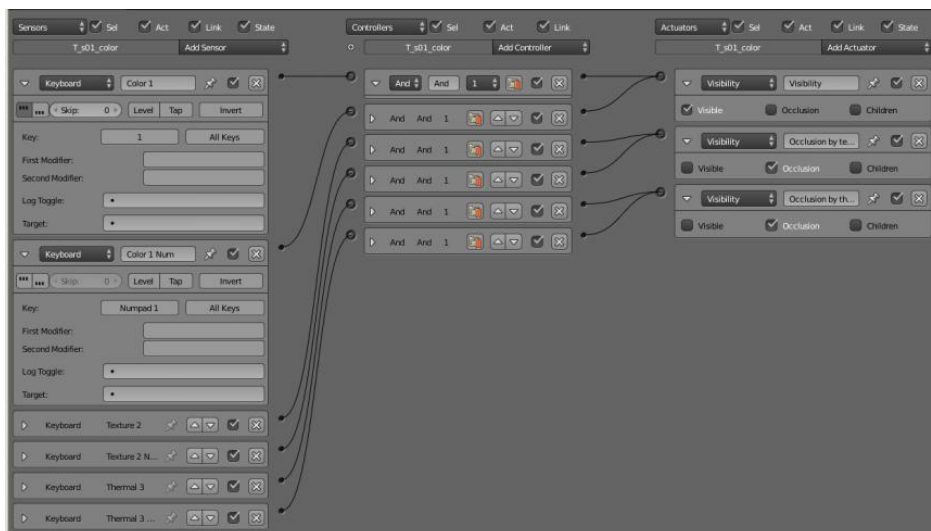


Figure 7.71. Silos color game logic by pressing the number “1” (Blender)

The efficiency of the virtual reality with the silos was very good, the frame-time was around 16.7 ms can be seen in Figure 7.72.

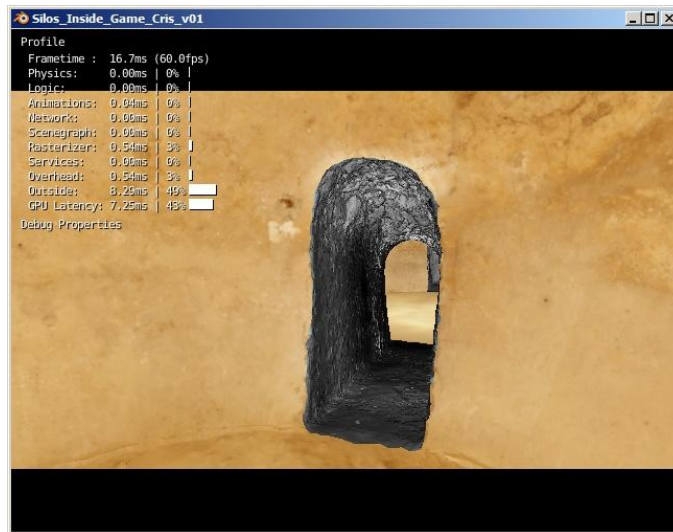


Figure 7.72. Efficiency of the virtual reality of the silos (Blender)

7.7.4. Export final data

In order to export the final virtual reality of the Valencian Silo-Yard with the model inside and outside of the silos. It was necessary to activate the Add-ons “Save As Game Engine Runtime”. Then, it was clicked File > Export > Game Engine Runtime. This tool generated all the files necessary to open the virtual reality on any computer. It depends on the characteristics of the computer if the game may take a little longer to start the virtual reality. The final result integrated in the virtual reality of Blender can be understood in Figure 7.73.

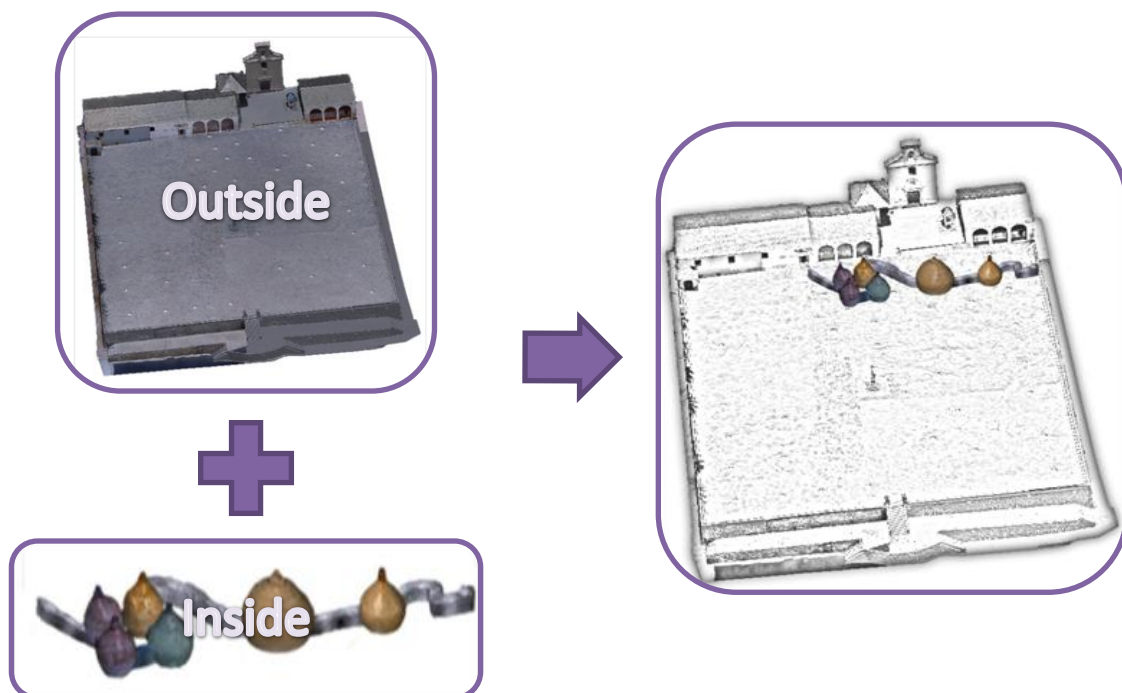


Figure 7.73. Explicative diagram of the emplacement of the silos in the Valencian Silo-Yard

7.7.5. The game's instructions

In order to visualize the virtual reality was clicked on the file "Final_Silos_Burjassot_AYepes_MCGomez.blend.exe". The movements in the virtual reality, when it was loaded (the image of the Silos appears):

- Press any key to start
- Move proceed: up arrow
- Move back: down arrow
- Turn left: left arrow or move mouse
- Turn right: right arrow or move mouse
- Movement of the view: move mouse
- Jump: right-click mouse
- Change the texture of the first three silos:
 - If you **press** the number "1" key on the keyboard: The color to visualize is the color mesh (the color of the laser scanner colors the mesh)
 - If you **press** the number "2" key on the keyboard: The texture to visualize is the real texture – realistic color (normal camera color)
 - If you **press** the number "3" key on the keyboard: The texture to visualize is the thermal texture (color of thermal pictures with thermal camera)
- Press "ESC" on the keyboard to exit

Conclusion

8. Conclusion

With the completion of the project, all objectives have been completed and the knowledge about the operation of specialized programs such as SCENE, CloudCompare, 3DReshaper, Agisoft PhotoScan and Photoshop has been increased, among others.

The realization of this work has been very interesting and rewarding, due to that the Valencian Silo-Yard had been never visited, the results of the project are faithful to the reality of 2016. This is true, because some people that participated in the field work in Burjassot checked the results of the 3D model obtained. With the help of virtual reality, the importance and the appearance of this heritage area of the Middle age can be imagined.

In conclusion, with this project, the information measured in the 2016 campaign in Burjassot can be merged, and will be of easy interaction for the people. These types of projects are crucial because they preserve the history and the culture. Thanks to the heritage recording, the knowledge about this place will be possible after the fall of the historic monument. Consequently, studies like this can promote and increase the tourism in these areas and approach difficult places like caves.

Some reflections on this topic of projects was that in this kind of projects normally there isn't any mentioning of how the final model in the documentation can be obtained, due to this, this thesis was done like a tutorial of a possibility about the work done in the Valencian Silo-Yard. In that way when someone needs to do the same, he just has to follow the steps, but it is possible that in other work the same steps can be use but in another sequence. For that, it was very important to do testing of the results of every process, this was the only way to fulfill the correct 3D model and patience with the software.

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Appendix I: Silo Volume in Plan View

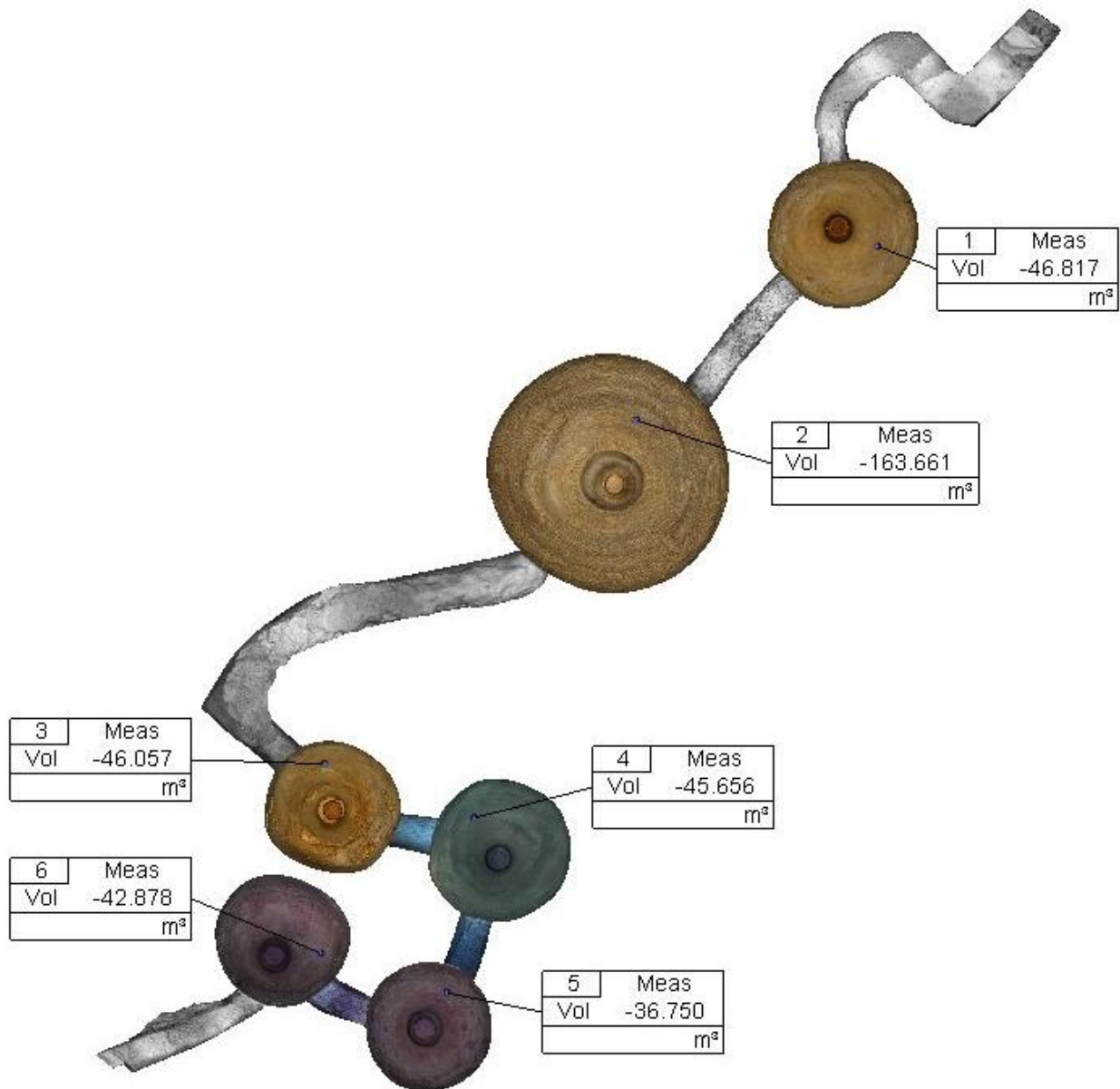


Figure Appendix I. Silo Volume in Plan View (3DReshaper)