ISSN 1828-5961

Sara Gonizzi Barsanti
Assistant Professor at the Department of Engineering, Università della Campania Luigi Vanvitelli. One doctorate in Civil Engineering and one in Mechanical Engineering. Research interests in photogrammetry, laser scanning, Reverse Engineering, FEA of Cultural Heritage, 3D reconstruction, HBIM and virtual reality technologies.

Juergen Frick
Head of staff position Research and Development, vice-head of departments "Building Preservation", and head of unit "Climate, Comfort, Pollution" at the Institute of Materials Testing at University of Stuttgart. Expert for non-destructive testing and monitoring in civil engineering. He is active in the Advanced Material and Nanotechnology Cluster for EeB projects. Member of the new founded WTA working group "Damage Monitoring".

FROM 3D REALITY-BASED MODELS TO VOLUMES FOR STRUCTURAL ANALYSIS: SOME CRITICAL ISSUES

Abstract
Structural health monitoring of Cultural Heritage (CH) is a key topic in research, as well as damage identification and failure assessment. Hence, it is mandatory to have a proper documentation as basis for further analysis.
3D models from photogrammetric and laser scanning surveys usually provide 3D point clouds that can be converted in meshes. These models can be used for different purposes, from documentation to visualization to structural analysis. The point clouds usually contain noise data due to different causes: non-cooperative material or surfaces, bad lighting, complex geometry, and low accuracy of the instruments utilized. Noise not only deforms the unstructured geometry of the point clouds, but also adds useless information and reduces the geometric accuracy of the mesh model obtained and, consequently, the results of any analysis performed on it. Point cloud denoising has become one of the hot topics of 3D geometric data processing, removing these noise data to recover the ground-truth point cloud, adding smoothing to the ideal surface. These cleaned point clouds can be converted in mesh with different algorithms, some automatically processed by photogrammetric software and then turned into volumes, suitable for different uses, mainly for structural analysis.
The paper wants to analyse the geometric accuracy of few automatic processes available into commercial and open-source software for the conversion of superficial 3D meshes into volumetric models that can be used for structural analyses through FEA process.

Keywords:
3D reality-based modelling; Geometrical analysis; Retopology; Voxel; NURBS.

DOI: https://doi.org/10.20365/disegnarecon.32.2024.15

1. INDTRODUCTION

The passage from an unorganized 3D point cloud to surface reconstruction (3D mesh) is a tough issue, especially for applications related to the digitization of architectural sites, virtual environments, reverse-engineering for the creation of CAD models and sensing and geospatial analysis. With the developments of instruments, mainly the scanner technology, it is possible to acquire dense 3D point clouds consisting of millions of points. The results obtained through the 3D survey are usually affected by different circumstances, such as non-cooperative material or surfaces, bad lighting, complex geometry, low accuracy of the instruments utilised that can bring to noise data.
The use of Finite Element Analysis for structural investigation has become a normal procedure. Initially developed for structural mechanics, was then applied to the solution of other kind of problems, such as dynamics, thermal, etc. When dealing with ancient structures, the best result from FEA is derived from analysis on 3D volumetric models. To avoid the potential propagation of error, a possibility is to directly model a volume from an unorganised 3D point cloud from a 3D survey. The main issue is the accuracy that must be as close as possible to the initial one. The methodology usually followed implies the use of Non-Uniform Rational B-splines (NURBS) surfaces, characterising the shape of the object to be simulated. Applying this process to 3D models of CH may introduce a high level of approximation leading to wrong simulation results.
In this paper it was decided to test some automatic tools for the transformation of 3D superficial meshes to volumes.

1.1 3D reality-based modelling and structural analysis

Reality-based models can be obtained from photogrammetry [1], laser scanning [2] or the integration of both [3]. The process is now well established, and it became easier thanks to the development of computer vision algorithms for photogrammetric procedures and relatively low-cost scanners. The best and most appropriate technique depends on the object to be surveyed or the area to be examined and the user experience, on the budget, on the time available and on the goals of the research. Photogrammetric surveys are typically cost-effective and time-efficient and provide, simultaneously, 3D geometry and texture, with accuracy values for each determined 3D point, although a known distance or some ground control points are necessary to derive metric 3D results. Active sensors, such as laser scanners, collect directly metric 3D point clouds that can afterwards be used to produce highly accurate and detailed 3D models. Both surveying techniques have their advantages and disadvantages [4]. An accurate 3D reality-based documentation is fundamental for the conservation of cultural heritage, being a prerequisite for the following data post processing for structural analysis. This process is important in contemporary times because of atmospheric agents, the growing of the cities and of the density of constructions, carelessness over the centuries, and the present political instability in certain areas. Hence, it is mandatory to find the best pipeline to obtain results as close as possible to reality. Finite element analysis (FEA) is a recognized technique used in engineering for various purposes starting from a CAD 3D model made by non-uniform rational B-spline (NURBS) surfaces. Preliminary experiments were carried out on real CH artefacts surveyed with active or passive methods [5] for simulating stress behaviour and predicting critical damages. The approaches used to generate the volumetric model from the acquired 3D point cloud are different: (a) using CAD software for the drawing of a new surface model following the superficial mesh originated by the acquired 3D cloud [6]; (b) using the triangular mesh generated by the 3D survey [7]; (c) generating a volumetric model from the 3D point cloud without preliminary surface meshing [8]; (d) using the 3D reality-based model as the basis for a BIM/HBIM for FEA [9 – 13]; (e) creating new tools [14].
Since the process to obtain a model for structural analysis implies a sort of approximation, that has to be summed to the approximation of the meshing process from a sparse 3D point cloud and the approximation of the simplification of the mesh to create a volume, the main issue is to start with the most truthful data possible, which can guarantee the geometrical accuracy and the less loss of details possible. The main problems while dealing with this process regard:

1. The way for obtaining a volume is not yet clearly defined and may greatly influence the result.
2. The balance between geometric resolution and confidence level of the simulated results is often not compliant with the shape of a volume originated by a 3D acquisition process.

Topology is referred to the study of geometrical properties and spatial relations between the polygons of a mesh, independently by continuous variation of shape and size of them. Any abrupt change in this relationship is considered a topological error, like for example the flip of the normal in two adjacent polygons.
The reconstruction of surfaces from oriented point cloud is rather difficult. The point sampling is often non-uniform and the positions and normal are generally noisy due to sampling inaccuracy and scan misregistration. Starting from these assumptions, the meshing part of the process supposes the topology fitting accurately the noisy data and filling holes reasonably. The reconstruction of meshes from 3D point cloud is usually made of triangles, which barycentre describes a linear surface representation.
Quad-based topology is used by most 3D artists and has a topology that is simple, offers edge flow easily adjustable, and the outcome can be easily subdivided. A model with triangle-based topology can product sharp angles that can affect the design of a mesh. With quads, it's easier to add or manipulate edge loops to obtain a smoother deformation. The quadrangulation method samples the original mesh at a spatial resolution lower than the original with a degree of accuracy higher than sampling the mesh with triangular elements, because it preserves the global geometry of the original mesh, re-defining from scratch its topological structure. It's called quadrangle mesh because is

DOI: https://doi.org/10.20365/disegnarecon.32.2024.15

mainly made by quads apart from some unavoidable triangular polygons.
The method based on a strong simplification of the mesh associated to a topological rearrangement of it using retopology aims at generating the most accurate 3D representation of a real artefact/ scenario from highly accurate 3D digital models derived from image- and range–based techniques, maintaining the accuracy of the high–resolution polygonal models. In addition, the process keeps into account the suitability of the simplified mesh to be converted in a set of NURBS surfaces through an automatic procedure.
There are different solutions to turn a 3D mesh into a volume suitable for FEA.

1. The creation of a new topology with retopology [4], without losing the initial accuracy of the models even when creating a NURBS.
2. Use voxels, 3D pixels, to model a 3D point cloud into a volume. In the process called voxelization, points in the point cloud that fall in certain voxels are maintained, while all others are either discarded or zeroed out to obtain a sculpted representation of the object.

The use of retopology implies different passages which led to possible inaccuracies and approximations. Of course, the level of approximation depends on how strong the interventions on the mesh were and on the complexity of the object analysed:

1. From point cloud to mesh
2. Post processing of the mesh (closing holes, check topology).
3. Retopology (smoothing)
4. Closing holes, check topology.
5. NURBS

Both processes allow to obtain volumes that can be imported into FEA software to provide structural analysis, and both present advantages and disadvantages as in Table 1:

ADVANTAGES RETOPOLOGY	DISADVANTAGES
Permits to create a new layer made of quad elements	Adds a smoothing to the mesh
Permits a strong simplification of the mesh	It needs a proper check on the parameters and type of element to better adjust to the surface and geometry
Is almost an automatic process	It causes lack of part especially on complex geometries and needs a huge manual effort

ADVANTAGES VOXEL	DISADVANTAGES
A more accurate 3D building block than any other modelling type, as they mimic particles	Without a very good 3D survey, it is much harder to build complex objects
Unlock new simulation techniques that would be impossible with other modelling methods	It lacks the mathematical precision of BRep modelling
Are the quickest way to model and visualize volumetric data	It requires a high-performance computer

Table 1. Pro and cons of retopology and voxelization of 3D point clouds.

1.2 Voxel and denoising

Voxelization is for sure faster than the process that leads to the creation of NURBS but the parameters have to be chosen wisely since a strong smoothing is often added to the model. This process seems, however, the most promising in terms of timesaving and accuracy since avoids all the problems related to the different steps needed when dealing with a 3D mesh and its transformation. No studies have by now compared volumetric models obtained with different techniques and procedure to identify the best in terms of precision and accuracy. Most of the related works apply voxelization to object detection [15-20] especially for autonomous driving or detection of elements for segmentation of 3D point clouds. A huge amount of application of voxel-based modelling is in the medical field [21-25]. There have been some tests on the use of voxels for FEA, for example for calculating ballistic impacts on ceramic-polymer composite panel [26] where voxel-based micro modelling allowed to build a parametrical model made of composite structure. Another study used voxel modelling of caves to predict roof collapses. Using this technique allowed to overcome difficulties in the reconstruction of the geometry of the caves and the limitation of FEM software [27]. Then, to improve accuracy of FEA, since using voxels reduces the time in mesh generation but on the other hand there is a lack of accuracy when dealing with curved surfaces, [28] presents a homogenization method for the voxel elements.
To improve the accuracy of the 3D point cloud, a denoising algorithm can be used. Point cloud denoising aims at removing undesirable noises from a specified noisy dense cloud. In the past years, diverse algorithms have been proposed for 3D point clouds cleaning to make them more geometrically close to real objects. Bilateral filtering [29] is a nonlinear technique to smooth an image. This concept has been extended for denoising point clouds [30]. This denoising methods applies the bilateral filter directly to point clouds based on point position, point normal, and point colour [31]. The guided filter [32] is an image filter that can play as an edge-preserving smoothing operator [33]. Recently, most filter-based algorithms employ the normal of the points as guidance signals. The points are then iteratively filtered and updated to match the estimated normal. There is then graph-based point cloud denoising methods that first interpret the input point cloud as a graph signal, and then perform denoising via chosen graph filters [34]. The patch-based graph builds the graph on surface patches of point clouds where each patch is defined as a node [35]. Optimization-based denoising methods look for a denoised point cloud

DOI: https://doi.org/10.20365/disegnarecon.32.2024.15

that can best fit the input point cloud [36]. Finally, deep learning algorithms have been applied to point cloud processing [37]. The denoising of point cloud starts from the noisy in-puts to learn a map to be superimposed of the ground-truth data in an offline stage. Deep learning-based methods can be categorized into two types: supervised denoising methods as PointNet-based [38] and unsupervised denoising methods [34]. The algorithm used in this paper is proposed in [39] and was analysed comparing the point clouds of different objects to underline its usefulness. It consists of a point cloud score-based denoiser in a three-dimensional space. The technique simulates an intelligent smoothing operation on potential surfaces based on a majority voting (or density/magnitude of points) approach.

2. Methodology

3D meshes of four different objects have been considered for this study:

- A portion of the wall of the Solimene factory in Vietri (Fig.1a).
- Several amphorae of the same wall (Fig.1c).
- The statue of Moses of the tomb of Julius II in Rome (Fig.1b).
- A suspension of a car, chosen for its simple geometry (Fig.1d).

The objects have been surveyed with photogrammetry, with an APS-C Canon 60D camera coupled with a 20mm lens. Parameters like ISO and f-stop have been set according to the environmental light and GSD. Agisoft Metashape was chosen for the creation of the 3D models, using high parameters for the alignment of the images and the creation of point clouds and different number of elements for each mesh, depending on the number of points in the dense cloud. These meshes have been then post-processed in different ways:

1. For retopology, Instant Meshes have been used, while, for the creation of NURBS, the automatic tool in Rhinoceros has been used.
2. 2For voxelization of meshes and point clouds, several automatic tools have been analysed and compared: the voxel process in Blender, 3DCoat voxelization process, Meshmixer volume creator and Slicer.
3. 3For denoising the point cloud, Score-based point cloud denoising algorithm has been used since it is one of the latest and more stable by now [39].

2.1 Retopology and NURBS

Figure 1. The four objects investigated: (a) the Solimene factory in Vietri; (b) the statue of Moses I Rome; (c) a portion of the façade of the Solimene factory; (d) the suspension of a car.

a b c d

DOI: https://doi.org/10.20365/disegnarecon.32.2024.15

For the creation of 3D simplified meshes through retopology, InstantMeshes opensource software have been used [40;41;42]. It automatically calculates the more suitable number of elements in the final, simplified model, starting from the number of elements in the high-resolution one. The operator can always change it approximately with a sliding tool, but the result is not always satisfactory: sometimes, holes and missing parts are largely visible (Fig.2a-d). The process was quite straightforward except for the portion of the Solimene's façade [43-44], which counted more than 5 million polygons. The simplified models had 530K polygons, still too many for the mesh to be converted to a volumetric model.
The retopologised models have then been transformed in NURBS to export a volumetric model. A mesh represents 3D surfaces with a series of discreet faces, more likely as pixel form an image. NURBS, on the contrary, are mathematical surfaces, able to represent complex shapes with no granularity as in the mesh. The conversion from a mesh to a NURBS in implemented in CAD software or similar (e.g., 3DMax, Blender, Rhinoceros, Maya, Grasshopper, etc.) and it transforms a mesh composed by polygons or faces to a faceted NURBS surface. In details, it creates one NURBS surface for each face of the mesh and then merge everything into a single polysurface.
Depending on the mesh, the conversion works in different ways:

- If the starting point is a triangular mesh, and while, by definition, triangles are plane, the conversion creates trimmed or untrimmed planar patches. The degree of the patches is 1x1 surface trimmed in the middle to form a triangle.
- If the starting point is a quadrangular mesh, the conversion creates a 4-sided untrimmed degree1 NURBS patches, meaning that the edges of the mesh are the same as the outer boundaries of the patches.

For a simple test regarding the better geometrical reproduction of the real object, the denoising algorithm was applied to the statue of the Moses, that presents a complex geometry and the most

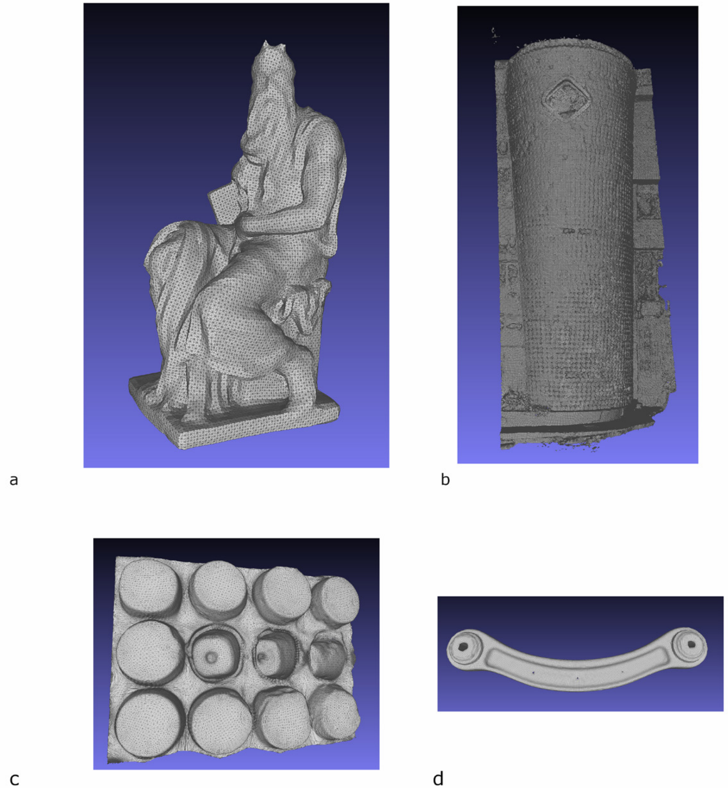


Figure 2. Retopologised models of: (a) Moses'statue; (b) Solimene factory; (c) portion of the wall of the Solimene factory; (d) suspension of car.

clean and accurate 3D point cloud. Then, the mesh from the initial point clouds and the denoised ones have been compared (Fig. 3). The purpose was to analyse how the geometric approximation in the meshing process can be influenced by the denoising algorithm, so if the geometrical accuracy of the point cloud can be an added value to the process. The first passage was to investigate the topological errors in the meshes: the one derived from the raw data showed many topological errors while the denoised one did not any (Fig3a, b), meaning that the algorithm helped in adjusting the geometrical accuracy of the data. After the meshing process, the models were then simplified using retopology. The meshes showed few topological errors, the denoised one less than the other (Fig.3c, d). As a plus, both retopologised meshes were then converted into NURBS to check the accuracy of the volumetric model and the one

DOI: https://doi.org/10.20365/disegnarecon.32.2024.15

obtained from the raw point cloud failed in the construction, meaning that the data were too noisy and too dense for the tool.

2.2 Voxels

The creation of the voxel models has been completed with the use of four software that automatically create a voxel model from the input mesh. It was decided to test these tools to understand how the automatic transposition works, without using python coding. The test was done on retopologised meshes because they are lighter than the high-resolution models and because the quad elements are more adaptable to geometry. The operator can decide the accuracy and the number of elements in Blender and Meshmixer, while Slicer and 3DCoat automatically apply the conversion. Slicer is a software used in the medical field. This software was the one that showed difficulties in applying the process to models derived from other devices. It was decided to test this software to analyse the results, since the medical field largely uses voxels for the 3D visualization of CT scan data and the results are accurate and reliable. It appeared that it is not suitable for other models that the ones resulting from medical imaging. In fact, the only model that it was possible to extract from the original mesh was the portion comprehending the vases of the Solimene factory. The result, unfortunately, was not satisfactory (Fig.4).
Blender showed the most straightforward process, the only parameter the operator can control is the number of the elements approximated, indicating the resolution or the amount of detail the remeshed mesh will have. The value is used to define the size, in object space, of the voxel. These voxels are assembled around the mesh and are used to determine the new geometry. For example, a value of 0.5m will create topological patches that are about 0.5m. Lower values preserve finer details but will result in a mesh with a much denser topology.
3Dcoat create voxels using all three axes of the object imported. However, sometimes when the object is imported, it can be experienced the creation of ugly triangular geometry because the voxel process is based on a uniform distribution of polygons. So, certain edges and curves do not translate well. This is why retopologised models work better for this process, since quadrangular elements are more suitable to be turned into voxel avoiding sharp edges.
Meshmixer, finally, creates a watertight solid from mesh surfaces by recomputing the object into a voxel representation. The process is easy, the only parameter the operator can change is the solid type, if fast or accurate, the solid accuracy with a sliding tool that gives a certain number and the mesh density. These number are not correlated to the final number of polygons of the volume.

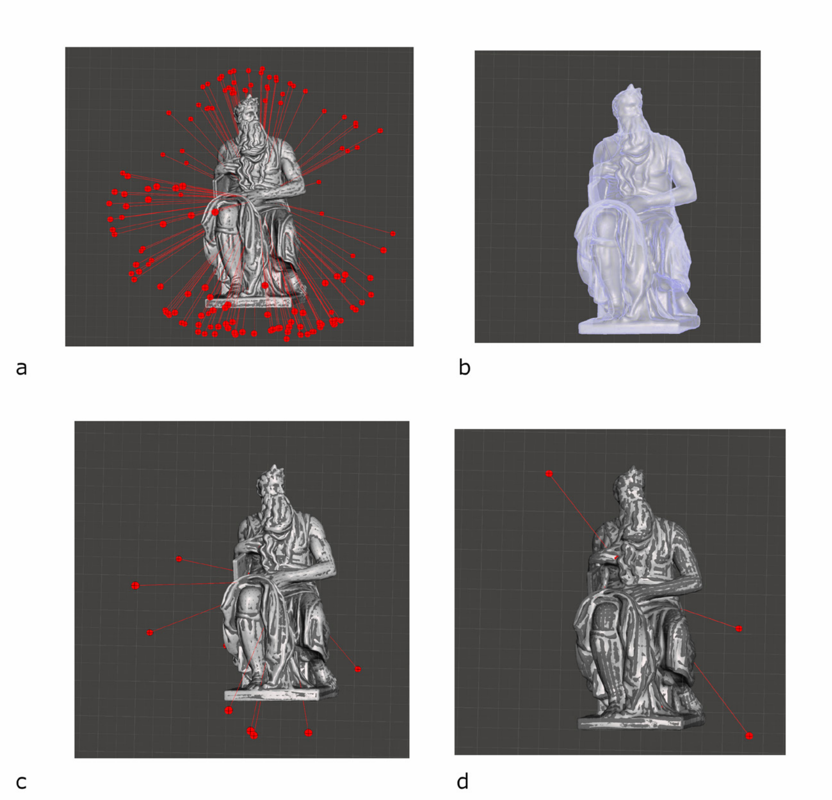


Figure 3. Topological analysis of the Moses' meshes: not denoised (a); denoised (b); retopologised not denoised (c); retopologised denoised (d).

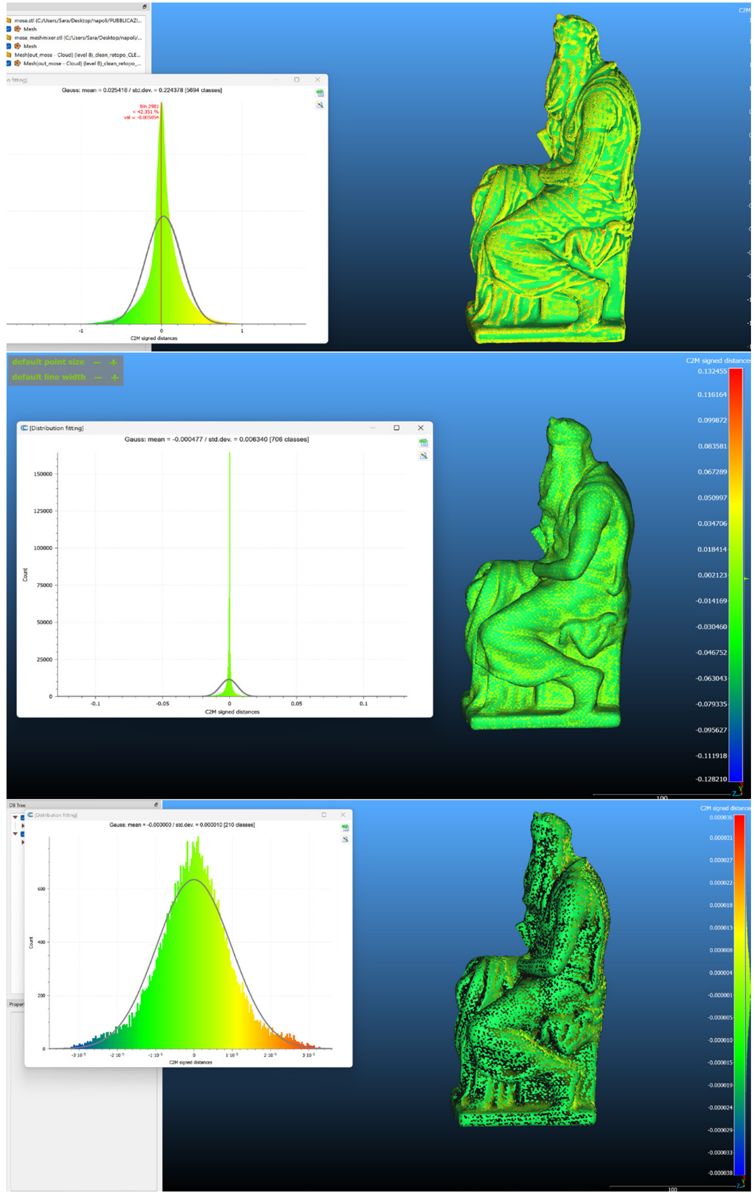
3. Results

The volumes obtained with the different software have been compared with the high-resolution models to analyse the mean gaussian deviation and the standard deviation. The mean distribution,

DOI: https://doi.org/10.20365/disegnarecon.32.2024.15

ISSN 1828-5961

expressly the normal or Gaussian distribution, is a sort of continuous probability distribution for a real-valued random variable. The mean of a distribution gives a general idea about the value around which the datapoints are centred. The standard deviation is a measure of the total of variant of a random variable expected about its mean. A low standard deviation signifies that the values veer to be close to the mean, while a high standard deviation indicates that the values are extended over a wider range. It tells how close the datapoints are to the mean of the distribution. If the standard deviation is small, it tells that most of the datapoints are close to the mean of the distribution.
The tool used was the cloud-to-mesh comparison in the open software CloudCompare, that searches for the nearest triangle in the reference mesh and only computes the distances from the vertices of the meshes. The first model analysed was the statue of the Moses (Fig. 4a-c).
The statue was a perfect test object given its geometrical complexity, a cooperative material. In this case, the creation of a closed volume was an easy task because the starting point was a 3D closed mesh. Nevertheless, the results gave an error of a centimetre, probably due to the smoothing added in the voxelization process.
The Solimene factory's mesh offered a different problematic (Fig.5a-c).
The geometry has a different level of complexity, due to the presence of the bottle's bases composing the façade and because the mesh is not closed, which brought the voxelization process to randomly compose the mesh to create the volumes. The results are then not satisfactory at all, giving the erroneous shape of the model in the back, with a maximum standard deviation of 49m.
The portion of the wall of the Solimene factory was the only model that the software Slicer was able to convert in voxels. The problem in the results for all the software tested was that the volume was randomly closed following the profile of the mesh, creating an abstract surface with no geometrical references with the reality. The errors are clearly visible in Fig.6a-d.



a

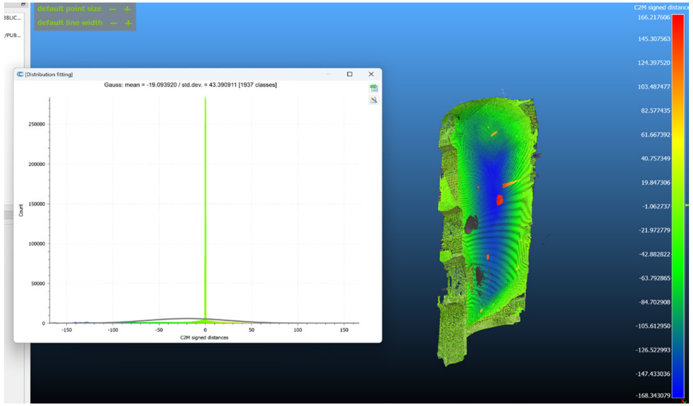
b

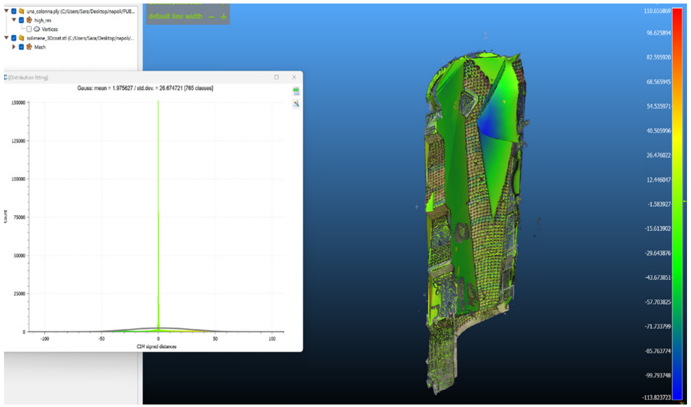
c

Figure 4. Comparison of the high-resolution models of the statue of Moses with (a) volume in blender; (b) volume in 3D coat; (c) volume in Meshmixer.

DOI: https://doi.org/10.20365/disegnarecon.32.2024.15

ISSN 1828-5961


a


b

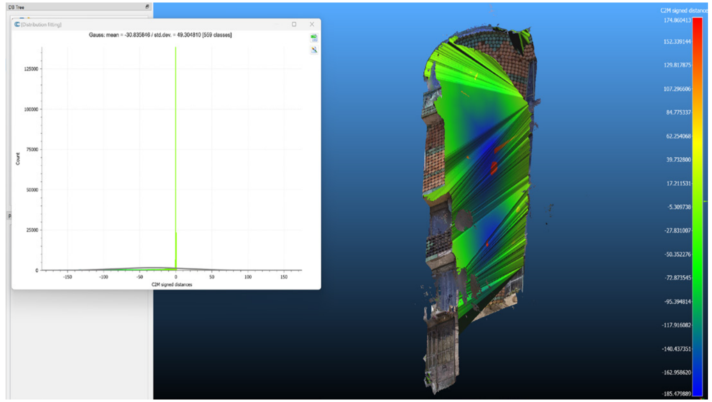

c

Figure 5. Comparison of the high-resolution models of the Solimene factory with (a) volume in blender; (b) volume in 3D coat; (c) volume in Meshmixer.

As in the façade of the Solimente Factory, the closing of the model does not follow the real geometry of the object surveyed.
The suspension, even though has a simple geometry, presented some problems in the distribution of the errors along the model. This can be explained because of the presence of holes and the roughness of the surface due to the non-cooperative material that caused reflections (Fig.7a-c).
The results, expressed in meters, are summarised in Table 2 for the standard deviation and in Table 3 for the normal distribution.
The graph of the Gaussian distribution depends on two factors, the mean and the standard deviation. The mean determines the location of the centre of the graph, the standard deviation determines its height and width. The height is determined by the scaling factor and the width by the factor in the power of the exponential. When the standard deviation is large, the curve is short and wide, when is small, the curve is tall and narrow. Analysing the data and the distribution of the gaussian curve, if the standard deviation is greater than the mean, a high variation between values is present, hence an abnormal distribution for data. If the curve is high and narrow, the bulk of the data is in an average area and the standard deviation is small (at most a vertical straight line of infinite height), otherwise it will be lower and wider and the standard deviation large (at most flat). The larger the standard deviation, the lower and flatter the curve, which is not a good thing.
This is highly visible for the volumes of the Moses by Blender, all the volumes for the Solimene factory, the models for the portion of the façade and the models of the suspension by Blender and 3DCoat. The meaning of this result can be analysed first considering the algorithm used in Blender for the creation of the volume: the specification of the dimension of the voxel can't be set autonomously but is channelled inside pre-sets. This means that the density of voxels is a lot lower than the density of element composing the meshes. This is why even a closed mesh as the one of the Moses presents a high standard deviation considering the comparison with the mean value.
For the other models, the main problem is the fact that the result of the photogrammetric process is not a closed model. To create a volume, the software has to close the model in a way or another, hence creating false surfaces and geometries that amplify the divergence between data.

4. Discussion

DOI: https://doi.org/10.20365/disegnarecon.32.2024.15

ISSN 1828-5961

The volumetric models useful for structural analysis software are the result of several subsequent passages, each one of which add a sort of approximation to the different results. From the unorganized point cloud to the mesh, the approximation derives from the 3D surface reconstruction. The simplification through retopology add a smoothing to the surface even if it has proved to maintain a high accuracy [41]. The creation of NURBS apply patches equal to the number of the superficial elements of the mesh and approximate the shape of the object. Considering all these passages, starting from a less accurate data (point cloud), brings to a less accurate result, and since the structural analysis through FEA add another approximation, summing all these passages, the results will be far from reality. The use of the denoising algorithm proved the usefulness in term of geometrical accuracy and geometrical reconstruction.
The better distribution of the points in the cloud showed that the mesh resulted in a geometry with less topological errors avoiding geometric inaccuracy with a high concentration of noisy points. This led to a less noised mesh, with no intersecting elements or spikes that modify the surface geometry of the model. This geometric alteration, if on a mesh to be used for visualization or virtual applications, does not substantially influence the results, in structural finite element analyses it can lead, at best, to a further approximation of the results if not even a failure in the process.
The present work aimed at analysing the factuality of using precompiled tools for the creation of volumes from 3D reality-based models of object of different shape, geometrical complexity, size, and material. The main problems are related firstly to the input data, that for these software needs to be a mesh and to the output of 3D survey: a 3D superficial mesh that gives as main information the surface of the object surveyed. If the object is a 3D closed shape, turning its mesh into volume does not add too many approximations, even with automatic tools. On the other hand, if the result is just a surface, the volume needs the thickness of the model to close it properly. This is not something available on custom software. It seemed, consid-

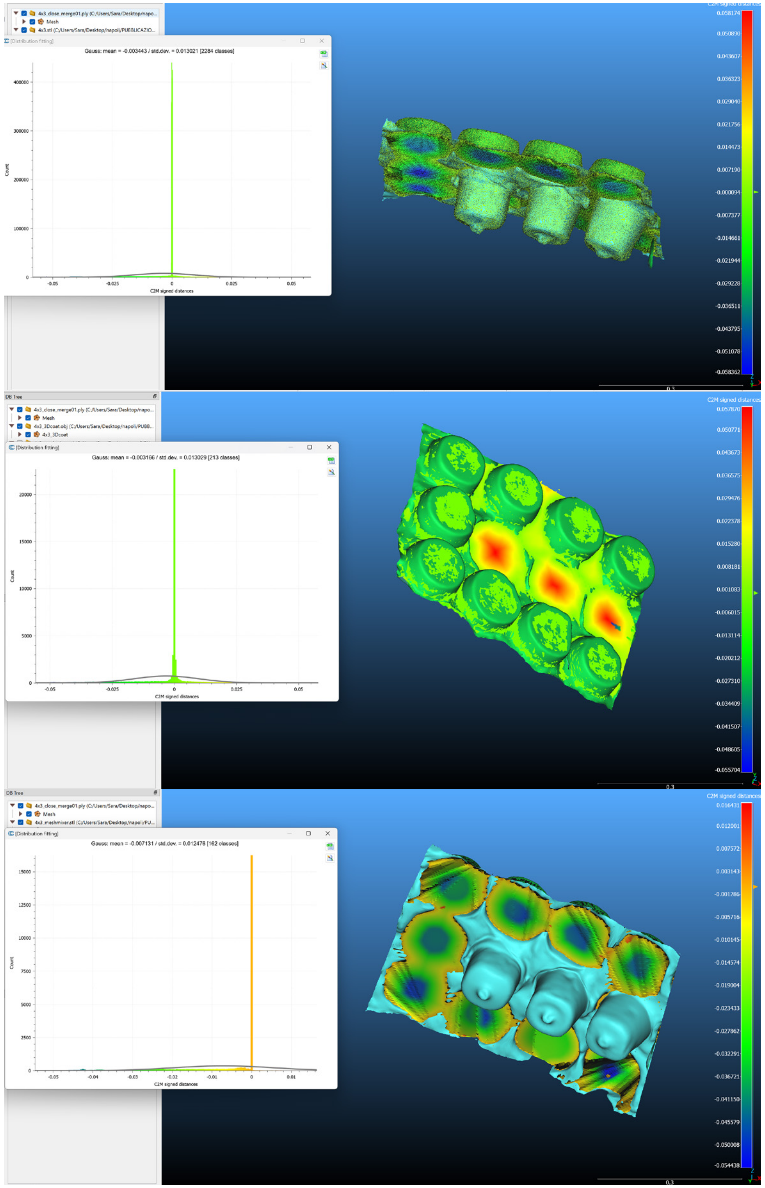
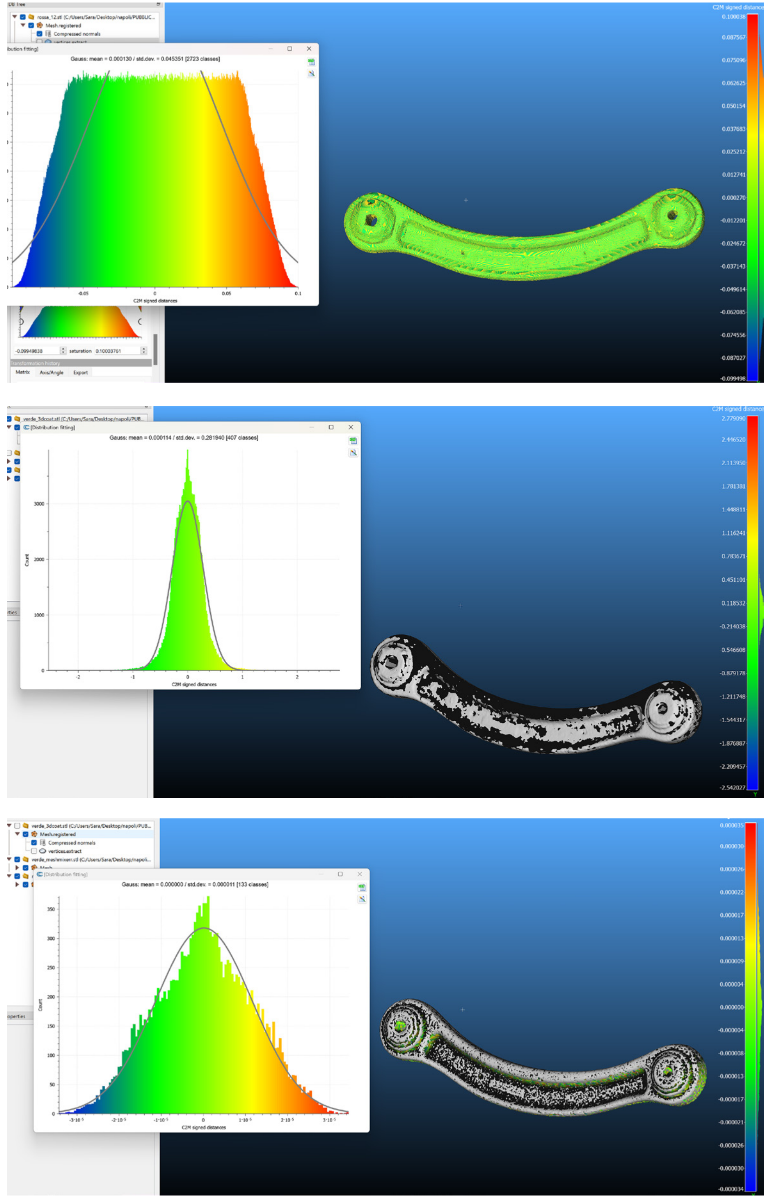

a
b
c

Figure 6. Comparison of the high-resolution models of the portion of the façade of the Solimene factory with (a) volume in blender; (b) volume in 3D coat; (c) volume in Meshmixer; (d) volume in Slicer.

DOI: https://doi.org/10.20365/disegnarecon.32.2024.15

ISSN 1828-5961

ering the results obtained, that the automatic tools are not useful for the creation of accurate volumes if the initial mesh is not a full 3D. One possibility is to test the VGStudio Max software that showed promising results on the portion of the wall of the Solimene factory (Fig.8), and compiled algorithms in Python to analyse if writing the script and operating on the parameters, it will be possible to overcome this problem, especially because the coding allow to start from 3D point clouds.


a

b

c

Figure 7. Comparison of the high-resolution model of the suspension with (a) volume in blender; (b) volume in 3D coat; (c) volume in Meshmixer.

Table 2. Results of standard deviation from the comparison of high-resolution meshes and volumes.

	BLENDER	3DCOAT	MESHMIXER	SLICER
Statue of Moses	0.224378	0.006340	0.000010	
Solimene factory	43.390911	26.674721	49.304810	
Portion of façade	0.013021	0.013029	0.012476	0.017368
Suspension	0.045351	0.281940	0.000011	

Table 3. Results of normal or Gaussian distribution from the comparison of high-resolution meshes and volumes.

	BLENDER	3DCOAT	MESHMIXER	SLICER
Statue of Moses	0.025416	-0.000477	-0.000000	
Solimene factory	-19.093920	1.975627	-30.835846	
Portion of façade	-0.003443	-0.003166	-0.007131	-0.005933
Suspension	0.000130	0.000144	0.000000	

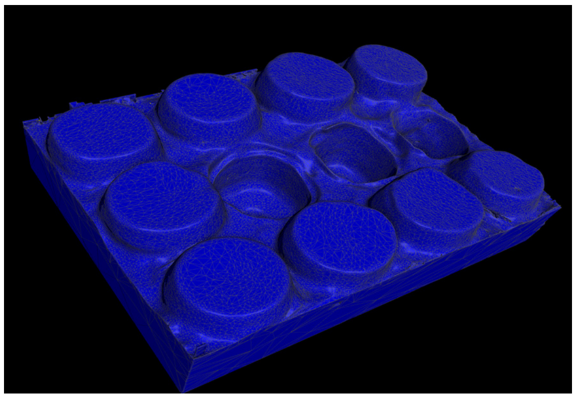


Figure 8. VGStudio Max's result: the software is able to close the models and provide its thickness.

DOI: https://doi.org/10.20365/disegnarecon.32.2024.15

ISSN 1828-5961

REFERENCES

1. Remondino, F., El-Hakim, S. (2006). Image-based 3D Modelling: a Review. Photogrammetric Record, Vol. 21(115), 269-291. Wiley-Blackwell Publishing Ltd, England.
2. Remondino, F. (2011). Heritage Recording and 3D Modelling with Photogrammetry and 3D Scanning. Remote Sens., Vol. 3, 1104-1138, MDPI, Basel, Switzerland
3. Fassi, F., Achille, C., Fregonese, L. (2011). Surveying and modelling the Main Spire of Milan Cathedral using multiple data sources. The Photogrammetric Record, Vol.26, 462–487 Wiley-Blackwell Publishing Ltd, England.
4. Gonizzi Barsanti, S., Remondino, F., Visintini, D. (2013). 3D Surveying and Modeling of Archaeological Sites – Some Critical Issues –, ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci., II-5/W1, 145–150, https://doi.org/10.5194/isprsannals-II-5-W1-145-2013.
5. Alfio, V.S., Costantino, D., Pepe, M. & Restuccia Garofalo, A. (2022). A Geomatics Approach in Scan to FEM Process Applied to Cultural Heritage Structure: The Case Study of the "Colossus of Barletta". Remote Sens. 14, 664
6. Brune, P. & Perucchio, R. (2012). Roman Concrete Vaulting in the Great Hall of Trajan's Markets: A Structural Evaluation. J. Archit. Eng. 18, 332–340.
7. Castellazzi, G., Altri, A.M.D., Bitelli, G., Selvaggi, I. & Lambertini, A. (2015). From Laser Scanning to Finite Element Analysis of Complex Buildings by Using a Semi-Automatic Procedure. Sensors 15, 18360–18380.
8. Shapiro, V., Tsukanov, I., Grishin, A. (2011). Geometric Issues in Computer Aided Design/Computer Aided Engineering Integration. J. Comput. Inf. Sci. Eng. 11, 21005.
9. Karanikoloudis, G., Lourenço, P.B., Alejo, L.E. & Mendes, N. (2021). Lessons from Structural Analysis of a Great Gothic Cathedral: Canterbury Cathedral as a Case Study. Int. J. Archit. Herit. 15, 1765–1794.
10. Erkal, A. & Ozhan, H.O. (2014). Value and vulnerability assessment of a historic tomb for conservation. Sci. World J. 357679.
11. Riveiro, B., Caamaño, J.C., Arias, P. & Sanz, E. (2011). Photogrammetric 3D modelling and mechanical analysis of masonry arches: An approach based on a discontinuous model of voussoirs. Autom. Constr. 20, 380–388.
12. Milani, G., Casolo, S., Naliato, A. & Tralli, A. (2012). Seismic assessment of a medieval masonry tower in northern Italy by limit, non-linear static and full dynamic analyses. Int. J. Archit. Herit. 6, 489–524.
13. Zvietcovich, F., Castaneda, B. & Perucchio, R. (2014). 3D solid model updating of complex ancient monumental structures based on local geometrical meshes. Digit. Appl. Archaeol. Cult. Herit. 2, 12–27.
14. Freytag, M., Shapiro, V., Tsukanov, I. (2011). Finite element analysis in situ, In Finite Elements in Analysis and Design, Volume 47, Issue 9, Pages 957-972, ISSN 0168-874X, https://doi.org/10.1016/j.finel.2011.03.001
15. Sun, J., Ji, Y.M., Wu, F., Zhang, C. & Sun, Y. (2022). Semantic-aware 3D-voxel CenterNet for point cloud object detection, Computers & Electrical Engineering, 98
16. He, C., Li, R., Li, S., & Zhang, L. (2022). Voxel set transformer: A set-to-set approach to 3d object detection from point clouds. In Proceedings of the IEEE/CVF conference on computer vision and pattern recognition, 8417-8427.
17. Mahmoud, A., Hu, J. S., & Waslander, S. L. (2023). Dense voxel fusion for 3D object detection. In Proceedings of the IEEE/CVF winter conference on applications of computer vision, 663-672.
18. Shrout, O., Ben-Shabat, Y., & Tal, A. (2023). GraVoS: Voxel Selection for 3D Point-Cloud Detection. In Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition, 21684-21693.
19. Deng, J., Shi, S., Li, P., Zhou, W., Zhang, Y., & Li, H. (2021, May). Voxel r-cnn: Towards high performance voxel-based 3d object detection. In Proceedings of the AAAI conference on artificial intelligence, 35, 2, 1201-1209.
20. He, C., Zeng, H., Huang, J., Hua X.S. & Zhang L. (2020). Structure Aware Single-Stage 3D Object Detection from Point Cloud, IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR), Seattle, WA, USA, 11870-11879
21. Lv, C., Lin, W. & Zhao, B. (2022). Voxel Structure-Based Mesh Reconstruction From a 3D Point Cloud in IEEE Transactions on Multimedia, 24, 1815-1829
22. Sas, A., Ohs, N., Tanck, E. & van Lenthe, G.H. (2020). Nonlinear voxel-based finite element model for strength assessment of healthy and metastatic proximal femurs, Bone Reports, 12, 100263
23. Lee, T.Y., Weng, T.L., Lin, C.H. & Sun, Y.N. (1999). Interactive voxel surface rendering in medical applications, Computerized Medical Imaging and Graphics, 23, 4, 193-200
24. Han, G., Li, J., Wang, S., Wang, L., Zhou, Y. & Liu, Y. (2021). A comparison of voxel- and surface-based cone-beam computed tomography mandibular superimposition in adult orthodontic patients. Journal of International Medical Research 49(1)
25. Goto, M., Abe, O., Hagiwara, A., Fujita, S., Kamagata, K., Hori, M., Aoki, S., Osada, T., Konishi, S., Masutani, Y., Sakamoto, H., Sakano, Y., Kyogoku, S. & Daida, H. (2022). Advantages of Using Both Voxel- and Surface-based Morphometry in Cortical Morphology Analysis: A Review of Various Applications, Magnetic Resonance in Medical Sciences, 21, 1, 41-57
26. Babich, M., & Kublanov, V. (2019). Voxel Based Finite Element Method Modelling Framework for Electrical Stimulation Applications Using Open-Source Software, Ural Symposium on Biomedical Engineering, Radioelectronics and Information Technology (USBEREIT), Yekaterinburg, Russia, 127-130
27. Sapozhnikov, S.B. & Shchurova, E.I. (2017). Voxel and Finite Element Analysis Models for Ballistic Impact on Ceramic-polymer Composite Panels, Procedia Engineering, 206, 182-187
28. Dogan, S. & Güllü, H. (2022). Multiple methods for voxel modeling and finite element analysis for man-made caves in soft rock of Gaziantep. Bull Eng Geol Environ 81, 23
29. Watanabe, K., Iijima, Y., Kawano K. & Igarashi, H. (2012). Voxel Based Finite Element Method Using Homogenization," in IEEE Transactions on Magnetics, 48, 2, 543-546,
30. 3Tomasi, C. & Manduchi, R. (1998). Bilateral filtering for gray and color images, in: IEEE Sixth International Conference on Computer Vision. 839–846
31. Chen, H. & Shen, J. (2018). Denoising of point cloud data for computer-aided design, engineering, and manufacturing, Engineering with Computers 34 523–541, Springer Nature, London, UK
32. Digne, J. & Franchis, C.D., (2017). The bilateral filter for point clouds, Image Processing online 7 278–287, Centre Borelli, ENS Paris-Saclay, France
33. He, K., Sun, J. & Tang, X. (2013). Guided image filtering, IEEE Transactions on Pattern Analysis and Machine Intelligence 35 (6) 1397–1409
34. Han, X., Jin, J.S., Wang, M. & Jiang, W. (2018). Guided 3D point cloud filtering, Multimedia tools and Applications 77 17397–17411, Springernature, London, UK
35. Irfan, M.A. & Magli, (2021). E. Exploiting color for graph-based 3d point cloud denoising, Journal of Visual Communication and Image Representation 75 103027, Elsevier, Amsterdam, The Netherlands
36. Dinesh, C., Cheung, G. & Baji´c, I.V. (2020). Point cloud denoising via feature graph Laplacian regularization, IEEE Transactions on Image Processing 29 4143–4158
37. 3Xu, Z., & Foi, A. (2021). Anisotropic denoising of 3D point clouds by aggregation of multiple surface-adaptive estimates, IEEE Transactions on Visualization and Computer Graphics 27 (6) 2851–286
38. Rakotosaona, M.J., La Barbera, V., Guerrero, P., Mitra, N.J. & Ovsjanikov, M. (2021). Pointcleannet: Learning to denoise and remove outliers from dense point clouds. In Computer graphics forum, 39, 1, 185-203, Wiley, New York, US (2021)
39. Shitong, L. & Hu, W. (2021). Score-based point cloud denoising Proceedings of the IEEE/CVF International Conference on Computer Vision, Montreal, QC, Canada, 4563-4572
40. Jakob, W., Tarini, M., Panozzo, D. & Sorkine-Hornung, O. (2015). Instant field-aligned meshes. ACM Trans. Graph. 34, 6, 189 15 pages.
41. Gonizzi Barsanti, S., Guagliano, M., Rossi, A. (2022). 3D Reality-Based Survey and Retopology for Structural Analysis of Cultural Heritage. Sensors; 22(24):9593, MDPI, Basel, Switzerland.
42. Gonizzi Barsanti, S., Guagliano, M., Rossi, A. (2022). 3D Reality-Based Survey and Retopology for Structural Analysis of Cultural Heritage. Sensors, 22, 9593. https://doi.org/10.3390/s22249593
43. Rossi, A., Palmero, L., Gonizzi Barsanti, S., Giner, S.L. (2024). Between Memory and Reason: The Brick Wall. TEMA, vol. Vol. 10 n. 1, p. 19-30, ISSN: 2421-4574, doi: 10.30682/tema100002
44. Rossi, A., Palmieri, U. (2020). Modelling Based on a Certified Level of Accuracy: The Case of the Solimene Façade. NEXUS NETWORK JOURNAL, vol. 22, p. 10-25, ISSN: 1590-5896, doi: 10.1007/s00004-019-00474-z

DOI: https://doi.org/10.20365/disegnarecon.32.2024.15