OPTIMAL MODELLING OF BUILDINGS THROUGH SIMULTANEOUS AUTOMATIC SIMPLIFICATIONS OF POINT CLOUDS OBTAINED WITH A LASER SCANNER

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Abstract

In recent years, the laser scanner has become the most used tool for modelling buildings in pure documentation and structural studies. Laser scanning provides large numbers of points in a minimum amount of time with great precision. The point clouds generated and the subsequent mosaics (data fusion of different clouds) contain millions of points with a heterogeneous density that define the 3D geometry of the buildings. Often, the number of points results in excessive information without offering a better definition. As a result, it is necessary to analyse which points can be eliminated and which ones cannot, based on precision criteria, to obtain a precise geometry with the smallest possible number of points for each part of the building. The algorithm developed in this work reduces the point clouds (in mosaics made up of clouds with over 10 million points) with precision criteria by as much as 99% while still accurately resolving the geometry of the object. The developed process is automatic such that different models with different resolutions can be obtained simultaneously. As a result, we obtain single clouds with homogenous distributions and densities throughout the model of the building (based on multiple overlapping clouds), with a computational cost of only a few seconds per cloud. The final result is a complete model of the entire building with the optimal resolution for each element of the structure.

Keywords: 3D model, measurement, simplification, laser scanner

1. Introduction

The evolution of laser scanners has made it possible to obtain point clouds with a spherical distribution of the entire measurement environment in under 2 minutes, achieving point clouds with over 10,000,000 points. The density of the points obtained is excellent, with densities exceeding 1 point/cm2. Although the recording time is sometimes high (recording a complex object requires multiple scans from different positions), it is preferable to conduct as dense a measurement as possible and then reduce it, if necessary.

The scope of application of laser scanning extends across in a variety of fields of engineering and architecture [5-9]. The suitability of laser scanners for the purposes of precise measurement has been studied in depth [1-4]. For example, one study focused on the of structural deformity measurements using this equipment [10-13]. The complementary use of photogrammetric techniques [14, 15] is also useful in many situations.

There are a number of recording procedures, depending on the type of object, which can be achieved in a single scan or in multiple scans. The latter case is more frequently used in order to avoid leaving hidden zones. This procedure generates different separate point clouds that overlap to generate a complete model; however, duplicate recordings for many zones of the object are formed. Regardless of the number of scans, the degree of accuracy necessary to obtain the subsequent sections is determinant, so the density of the data is a critical factor [16].

The recommended mesh size for measurements of this type is 0.5-2 cm. The continuing advancement of laser scanners makes it possible to record this density of points without any problem. However, for modelling, triangulation and texture generation, the number of points affects the number of triangles that will be generated, so while the scanner is capable of resolving very small features, the resultant mesh is often too fine for use in processing, e.g., building modelling. If the cloud has areas with densities greater than 1 point/cm2, it will need to be simplified.

This need for simplifying the scanned mesh is one of the largest challenges in the overall process of scanning, processing and modelling. There are interesting cloud simplification methods that require an initial triangulation of the clouds, thus eliminating points located in the flat zones of the triangles [17], analysing the curvature of the environment at those points [18], studying the effect of eliminating a point in the overall mesh through the distance between the point eliminated and the resulting mesh [19] or conducting a resampling of the surface based on the distance to the nearest points [20]. There are also frequent studies that divide the cloud into clusters [21, 22], analysing the distance between the points as a density classification [23] or adding edge detection constraints [24]. Although most of the published works follow these approaches, there are alternatives based on studying the normal in each point to analyse its importance and determine its elimination [25] or studies based on quadratic matrices with analysis of auto-values and auto-vectors [26]. However, they are not valid when the dimensions of the cloud result in immense volumes (3D clouds made up of millions of points and several gigabytes of information) or when there are several clouds simultaneously. Along this line, there are procedures that make it possible to process the information derived from the clouds but do not allow either the analysis or reduction of the clouds or subsequent modelling (except in cases in which the geometries are defined by known geometries, such as spheres, cylinders, etc.) [27,28].

In our work, we do not begin with an initial surface or with single clouds made up of manageable quantities of points. Additionally, it is not generally possible to record a building in a single scan, so the need for different scans will cause some zones to overlap, which, aside from an excess of points in the overlap zone, also necessitates identifying which overlapping scan provided higher quality feature resolution. Our work distinguishes the point density and evaluates the precision of the points eliminated, which will be determined based on the distance from the scanner and on the inclination of the surface with respect to the scanner—the greater the inclination or distance is, the lower the precision that is obtained. Thus, in the zone in which different scans overlap, it is necessary to eliminate certain points based on these precision factors.

This work shows a procedure that makes it possible to process and simplify millions of points in a matter of seconds. First, the point clouds from the different stations are simplified, generating new homogenous clouds, and then the data fusion of these clouds is created, taking into consideration the precision of the points in the overlapping zones. The final result is a simplified cloud of points that are homogenous in density and distribution, which define the geometry of the building.

2. Point cloud simplification algorithm

The laser scanner provides enormous quantities of points based on a uniform measurement strategy that, by contrast, provides clouds with an irregular density and distribution. The measurement strategy of these instruments responds to a spherical methodology based on constant increases of horizontal and vertical angles. While the increases are constant, it is not implied that the distribution of the points and their density are constant, as that depends on the position of the instrument with respect to the object (Fig. 1).

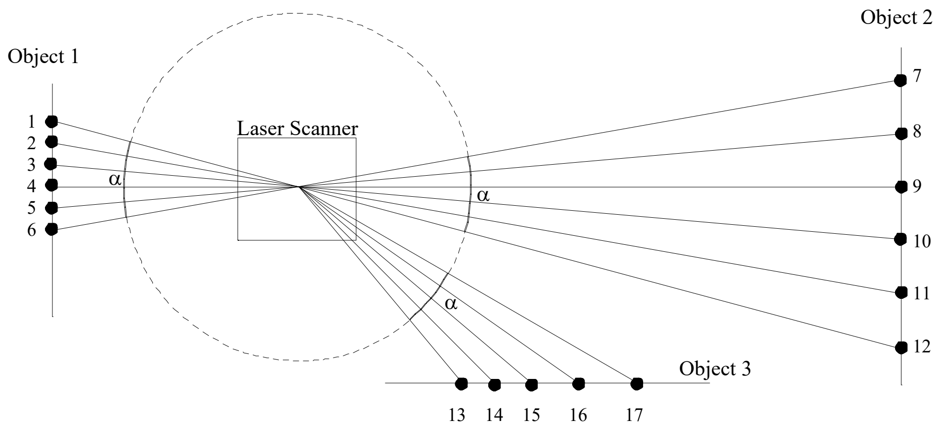


Figure 1: Scanning three objects at different distances/inclinations from the common laser scanner station.

The density obtained is influenced by the distance and the inclination of the surface with respect to the measurement direction. As shown in Figure 1, a constant increase in angle α provides a greater density of points in the areas nearest the instrument ("object 1" will be defined by a quantity of points much greater than "object 2"), as well as in the direction closest to normal to the object ("object 3" shows an increase between points due to inclination). The position in which there is a greater density of points is always in the direction of the rotation axis of the laser scanner with a null vertical angle (which is not the rotation axis of the mirror), which is where all of the scan profiles converge. In addition, due to the spherical measurement distribution, the zenith direction creates groups of all of the profiles made, which results in an unnecessarily high density.

Given that a measurement job is normally made up of multiple stations, the point density will be much greater in the zones in which the different scans overlap. In addition to affecting the point density in different zones of the object, different scanning positions impact the quality of the points measured, as the points belonging to two different scans will have different degrees of precision. This means that the final point cloud used to obtain the 3D model of the object is generated with data of varying precision that stem from both within the scan of a single zone and the combination of data from scans of different zones.

Following a measurement job, we obtain an enormous number of points with distribution, density and precision that are not uniform. Accordingly, it becomes necessary to design a procedure that makes it possible to obtain uniform point clouds, i.e., they must be simplified. To do so, the best option would be to leave the points based on a matrix distribution with a separation as similar as possible between them (uniform density) and with the maximum precision possible (choosing the points that have been measured with the greatest precision within overlapping zones).

The procedure is carried out in three stages: sorting the point cloud, simplifying the cloud and creating a mosaic of different clouds (with simplification in the overlaps).

2.1. Sorting the point cloud

Each point cloud is located within a rectangular prism whose maximum and minimum coordinates correspond to real extreme coordinate points in the cloud generated by the scan. This prism is divided into cubic cells with a side length of d defining a 3D matrix whose indexes are (1)

$$N_X = \frac{X_{\max} - X_{\min}}{d} \qquad N_Y = \frac{Y_{\max} - Y_{\min}}{d} \qquad N_Z = \frac{Z_{\max} - Z_{\min}}{d} \tag{1}$$

where,

$N_X * N_Y * N_Z$ is the total number of cubes in the three directions of space

$(X_{\max}, Y_{\max}, Z_{\max})$: maximum coordinates of the prism that contains the point cloud

$(X_{\min}, Y_{\min}, Z_{\min})$: minimum coordinates of the prism that contains the point cloud

Once the matrix is defined, it is necessary to eliminate the empty cubes first. The structure generated is on the order of 15000 GB, considering that 15 bytes are sufficient to store a cube, with a density of 1 point/cm2 at a distance of between 100-1000 m (a quantity that cannot currently be directed in memory). The position of the centre of any cube (Fig. 2) in the matrix (X_C, Y_C, Z_C) will be directed by whole values (i, j, k) within the matrix according to (2):

$$\begin{aligned} X_C &= X_{\min} + [(i - 0,5) * d] \\ Y_C &= Y_{\min} + [(j - 0,5) * d] \\ Z_C &= Z_{\min} + [(k - 0,5) * d] \end{aligned} \tag{2}$$

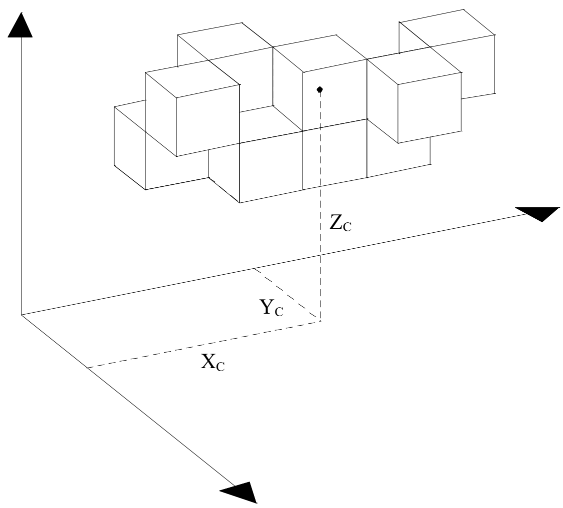


Figure 2: Coordinates of the centre of a cube in the matrix (with the prism simplified only with the cubes that are not empty)

The eight corners of the cube are located at a distance $\pm d/2$ from the centre of the cube (3):

$$X_{Esq} = X_C \pm \frac{d}{2} \qquad Y_{Esq} = Y_C \pm \frac{d}{2} \qquad Z_{Esq} = Z_C \pm \frac{d}{2} \tag{3}$$

The indexes (i, j, k) of a cube where any point is located at $P(X_P, Y_P, Z_P)$ will be given by the whole values resulting from (4):

$$i = \frac{X_P - X_{\min}}{d} + 1 \qquad j = \frac{Y_P - Y_{\min}}{d} + 1 \qquad k = \frac{Z_P - Z_{\min}}{d} + 1 \tag{4}$$

If we want to provide a single coordinate for each cube in the space (defined by three coordinates), we must establish a new coordinate system, which will be called the linear coordinate system (5):

$$Cl_P = \left[(k-1) * N_X * N_Y\right] + \left[(j-1) * N_X\right] + i \tag{5}$$

where

Cl_P : linear coordinate of the cube, which contains point P

i , j , k : Coordinates of the cube that contains point P

The application between the three-dimensional space defined by the spatial position of the cube and its linear coordinate will be bijective: having chosen a position for a cube in the space, it can have just one linear coordinate (5); having chosen a linear coordinate for a cube, it can have just one position in space, which is determined by the whole values resulting from (6).

$$\begin{aligned} i &= Cl - \left[(k-1) * N_X * N_Y\right] - \left[(j-1) * N_X\right] \\ j &= \frac{Cl - \left[(k-1) * N_X * N_Y\right]}{N_X} \\ k &= \frac{Cl}{N_X * N_Y} \end{aligned} \tag{6}$$

Having calculated the linear coordinate of each point, we obtain the number of points in each cube, identify each point and sort them by their linear coordinate. To do so, the Bubblesort algorithm was used, as it is a stable sorting algorithm and is simple and easy to program.

2.2. Simplifying the point cloud

The simplification objective is established based on a minimum distance between points $\sqrt[3]{d}$. After sorting the points by their linear coordinate, it is necessary to store the non-empty cubes and the index of the points that are in the cube. After sorting the points in a particular cube, they are consecutively ordered by the following criteria.

- The position of the non-empty cubes

- How many points are in each non-empty cube
- Which points are in each non-empty cube
- The distance from each point to the centre of the cube in which it is located

To do so, three matrices are generated:

- Matrix [L]: Linear coordinate of the non-empty cubes sorted by their linear coordinate (v)
- Matrix [I]: First point in the cube with linear coordinate (v)
- Matrix [U]: Last point in the cube with linear coordinate (v)

The flowchart for the algorithm for assigning sorted points in the matrices is shown in Fig. 3, where v is a non-empty cube and s is a point in the cloud.

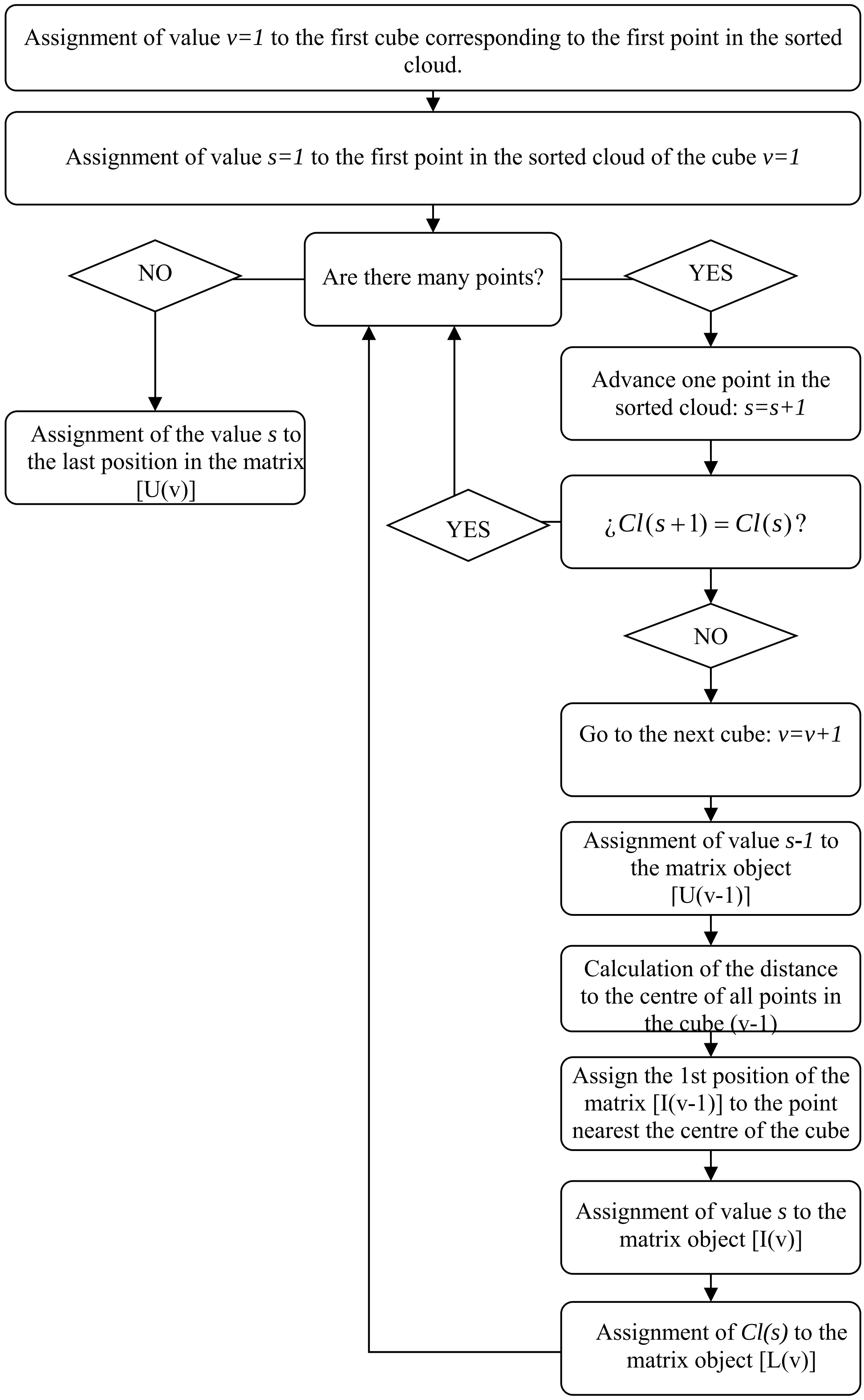


Figure 3: Flowchart for the simplification of a point cloud

Based on the procedure used, the point simplification will be carried out in two phases:

- Phase one: reduction of the cloud to the point nearest the centre of each cube. This phase yields the greatest simplification, as it reduces the point cloud to the number of non-empty cubes in the matrix. This also provides a very uniform distribution of points in the cloud.
- Phase two: the only remaining point in each cube may be very close to one or more adjacent cubes (it may be near the edge). In this situation, you must establish a tolerance below which only one of the points is left.

2.3. Creating a complete simplified mosaic

Once all of the point clouds belonging to different scans have been simplified, the overlaps between them must be simplified to create a uniform mosaic (with the same density and distribution of points in all of the zones).

To do so, the overlapped points of the greatest quality must be selected. As shown in Figure 1, a cube with many points comes from a close measurement and/or with a good reflection angle, and the precision of the points will be optimal. To make the necessary simplification, each cloud is compared with all of the others (there are many cases in which the overlap of some zones of an object does not occur between two clouds; however, there are many cases, commonly occurring in closed spaces, where the scans overlap nearly all of the rooms, as full rotation measurements are taken from several stations). To do so, cloud 1 and cloud 2 will be evaluated, and then the preceding result is evaluated against cloud 3; once again, the preceding result is evaluated against cloud 4, and so on until all of the clouds have been evaluated. If an overlap exists between two clouds, the cloud with fewer points, and thus lower precision, is eliminated from the cube prior to further evaluation against other clouds (Fig. 4).

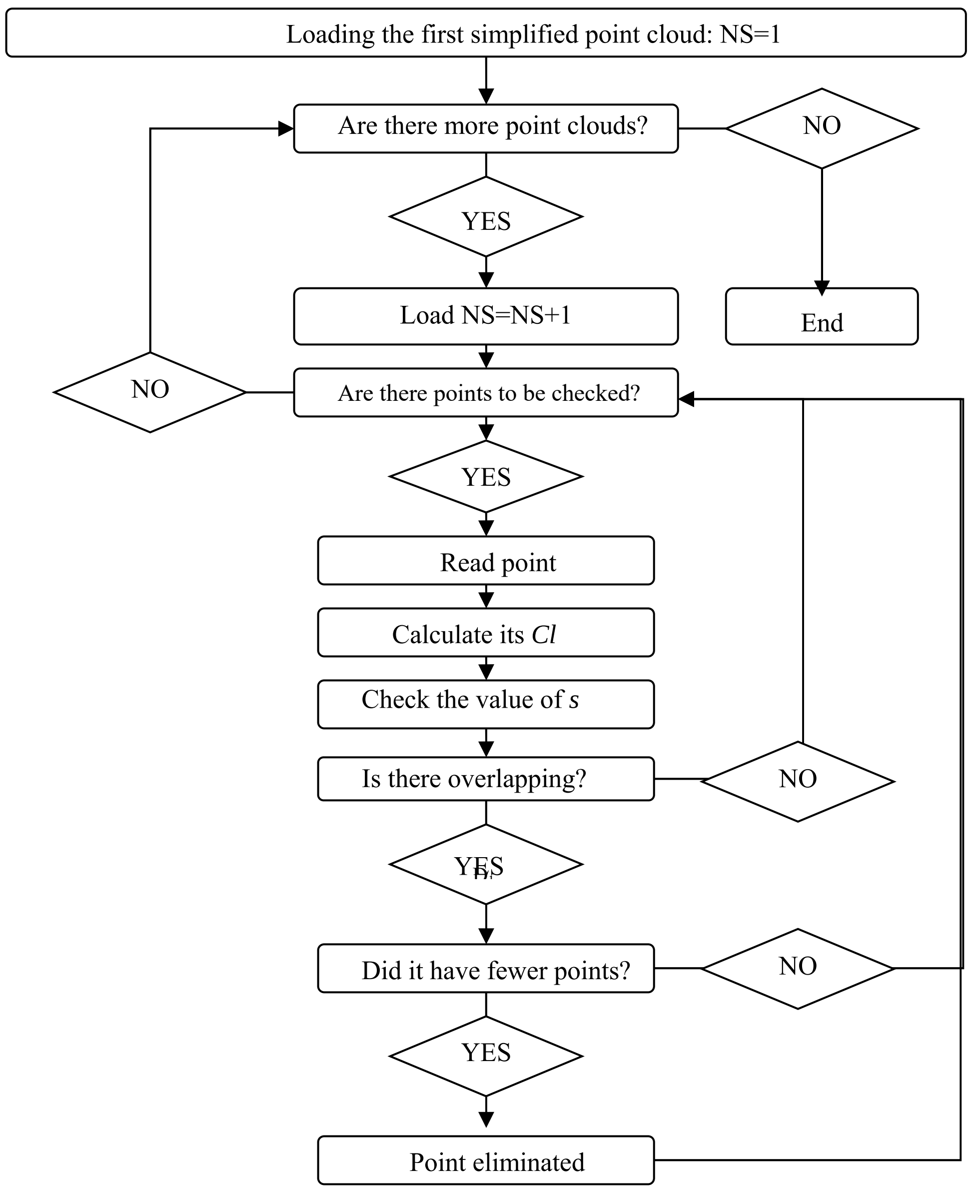


Figure 4: Flowchart of the simplification in the generation of the mosaic

3. Results Obtained

There are two different processes about the optimization of point clouds. The first one consists on obtaining the complete model with the highest resolution (the original one) through the decimation of the complete point cloud, after all the clouds have been merged. This stage supposes that the model has the same number of points per area (the resulting model will be optimal for pure documentation purposes). After that, different resolution models can be obtained through appropriate simplifications depending on the application fields where models will be used.

While in structural studies the accuracy of the model depends on multiple criteria (this means that high simplifications can be applied with optimal results in different parts of the building), in pure documentation the accuracy of generated models must be better to 5 mm. In this case, only point clouds with a higher number of points per cm2 should to be simplified (this situation often occurs in overlapping zones and around the rotation axis of the scanner laser, where measured points become higher).

To ensure that the applied procedure and algorithms work correctly in both cases, simplification of different objects for structural studies and pure documentation will be shown.

3.1. Structural studies

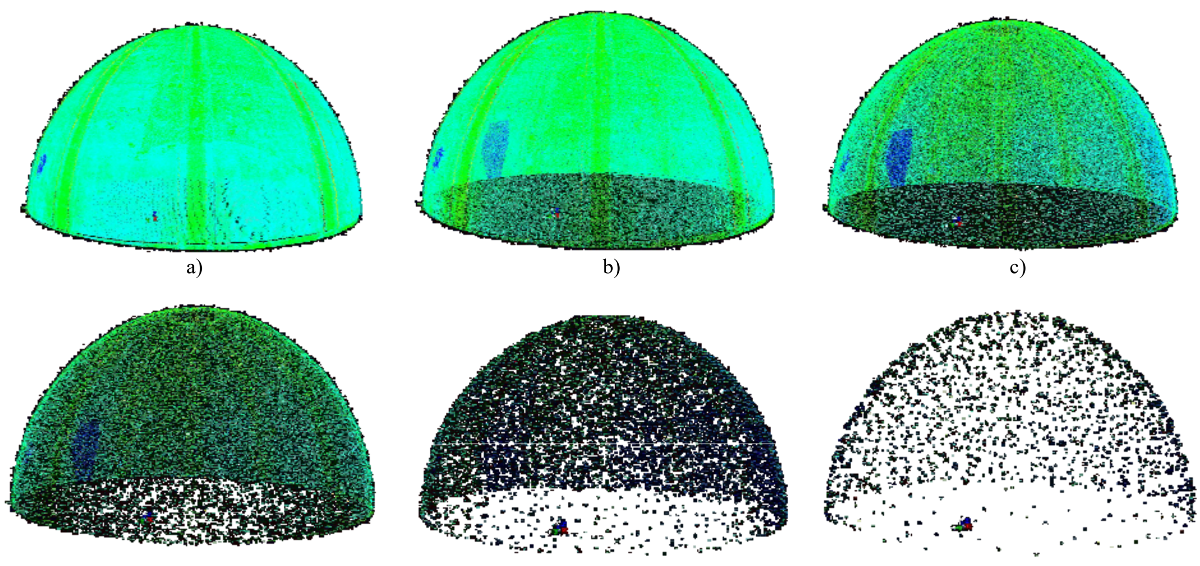
The following shows the simplification of an object with semi-spherical geometry that was captured with a single cloud (optimal for simplification with no overlapping) as well as a large object made up of 11 scans (a church). In both cases, simplifications show how we can obtain different resolution models from a structural point of view. This is, we will show different resolution possibilities that should be used in structural studies depending on the degree of accuracy needed.

3.1.1. Semi-spherical dome (isolated object with regular geometry)

A semi-spherical dome was measured with a Cyrax 2500 laser, which provided a cloud with 3638784 points in a single scan. Based on that, the following simplified clouds were generated (Table 1):

Mesh	Simplification	Eliminated	% Simplification	Time (sec)
5 cm	555891	3082893	84.72%	85
10 cm	150491	3488293	95.86%	76
20 cm	38671	3600113	98.94%	72
50 cm	6210	3632574	99.83%	68
100 cm	1553	3637231	99.96%	67

Table 1: Simplified point clouds of the semi-spherical dome (times recorded with a 1 GHz processor)



a) b) c)

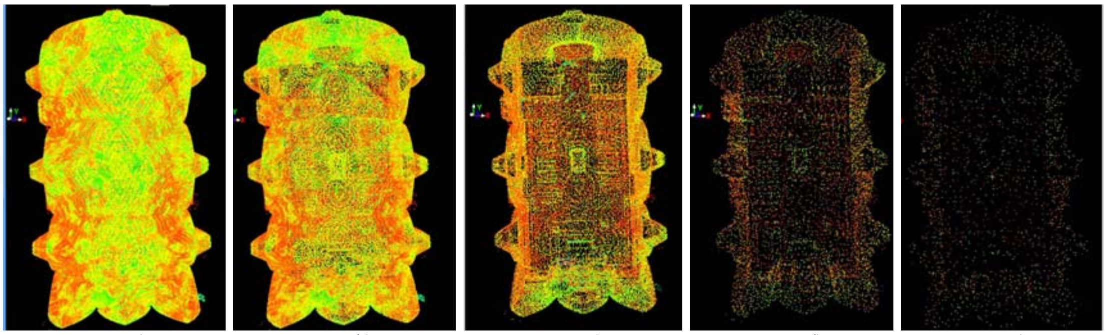
d) e) f)

Figure 5: Semi-spherical dome. a) Original cloud with 3638784 points. b) 5 cm simplified cloud (555891 points). c) 10 cm simplified cloud (150491 points). d) 20 cm simplified cloud (38671 points). e) 50 cm simplified cloud (6210 points). f) 100 cm simplified cloud (1553 points).

According to Table 1, we can observe that the reduction of points in the most precise case (5-cm cube) is 84.72%. As the resolution decreases, the reduction of points increases significantly. When decreasing from 5 cm to 10 cm, the reduction increases by 11%, with a simplification percentage of 95.86%. From there, the reduction to 20 cm increases to 98.94%, the reduction to 50 cm increases to 99.83% and the reduction to 100 cm increases to 99.96% (Fig. 5). The computation time for the case of the greatest simplification was 67 sec for the fastest case (the use of multiple processors with higher speeds would reduce computation time significantly).

3.1.2. Entire building

An entire church was scanned with an HDS 6500 laser using 11 scans and starting with a total of 78200800 points. The simplification process was carried out with 5-cm, 10-cm, 20-cm, 50-cm and 100-cm meshes; the results are shown in Figure 6.



a) b) c) d) e)

Figure 6: Church (conical perspective). Original cloud with 78200800 points. a) 5 cm simplified cloud (930169 points). b) 10 cm simplified cloud (352969 points). c) 20 cm simplified cloud (96937 points). d) 50 cm simplified cloud (10326 points). e) 100 cm simplified cloud (2242 points).

		Times with a 1-GHz processor (sec)				
Scan	No. of Points	5-cm mesh	10-cm mesh	20-cm mesh	50-cm mesh	100-cm mesh
1	225695	3.85	3.57	3.46	2.87	2.85
2	150883	2.55	2.52	2.40	2.38	2.35
3	3835289	72.73	70.14	66.93	64.96	63.29
4	8919506	191.31	181.74	174.08	158.38	156.05
5	9268584	202.46	196.55	189.26	178.31	168.80
6	9524396	206.51	199.51	190.76	182.47	168.67
7	9010513	195.74	192.62	182.59	172.63	161.89
8	9472251	206.77	197.31	192.70	179.39	171.48
9	9247630	196.60	189.73	187.86	172.94	165.20
10	8990051	191.81	183.03	180.28	168.80	160.87
11	9556002	218.25	210.72	218.64	188.09	172.98
Total	78200800	1688.58	1629.24	1589.96	1470.22	1396.57

Table 2: Cloud sorting process (5-cm, 10-cm, 20-cm, 50-cm and 100-cm meshes)

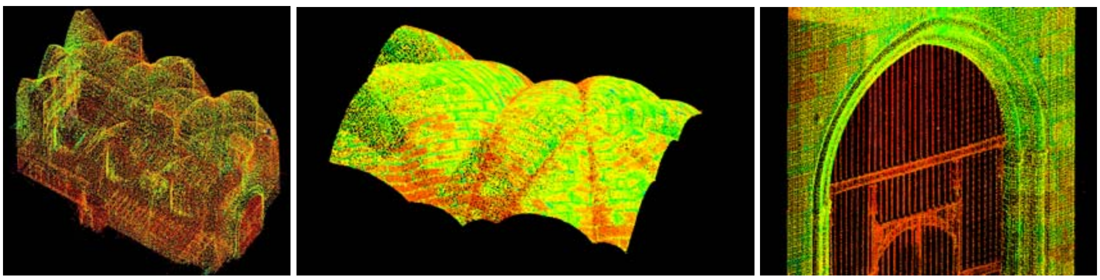
	Simplification				
Scan	5-cm mesh	10-cm mesh	20-cm mesh	50-cm mesh	100-cm mesh
1	13223	3987	1241	274	91
2	5209	1497	427	115	34
3	57409	15680	4356	847	250
4	269043	72290	19423	3422	911
5	524602	143634	36742	6888	1792
6	520123	141264	37894	6736	1763
7	499046	134522	36282	6517	1685
8	493729	133271	35826	6434	1676
9	473274	129325	35462	6454	1739
10	399097	106717	28641	5060	1331
11	533516	143946	38782	6798	1762
Total	3788271	1026133	245222	49545	13034

Table 3: Cloud simplification process (5-cm, 10-cm, 20-cm, 50-cm and 100-cm meshes)

	Mosaic				
Scan	5-cm mesh	10-cm mesh	20-cm mesh	50-cm mesh	100-cm mesh
1 vs 2	13223	3897	1241	274	91
1-2 vs 3	15880	4590	1433	317	96
1-3 vs 4	59717	16132	4530	878	254
1-4 vs 5	282530	73700	20058	4300	926
1-5 vs 6	564183	147236	40832	7969	1841
1-6 vs 7	704420	165183	78726	8782	1993
1-7 vs 8	728146	175693	84946	9161	2064
1-8 vs 9	739426	183222	87825	9434	2098
1-9 vs 10	761389	200142	93256	9936	2177
1-10 vs 11	772730	209023	95836	10204	2230
1-11 vs 12	930169	352969	96937	10326	2242
Time (sec)	161.78	45.53	14.63	1.98	0.47

Table 4: Cloud mosaic process (5-cm, 10-cm, 20-cm, 50-cm and 100-cm meshes)

As shown in Tables 2, 3 and 4, the final result is a cloud made up of 930169 points (5-cm mesh), 352969 points (10-cm mesh), 96937 points (20-cm mesh), 10326 points (50-cm mesh) and 2242 points (100-cm mesh). These results represent a degree of simplification of 98.81%, 99.55%, 99.88%, 99.98% and 99.99%, respectively. In the case of greatest resolution, we obtained a reduction of 77270631 points in less than 31 minutes.



a) b) c)

Figure 7: a) Entire building simplified to 20 cm resolution. b) Vaults simplified to 10 cm resolution. c) Front door simplified to 5 cm resolution.

Automatic simplification with different resolutions allows us to use different degrees of accuracy in different parts of the building using the most appropriate or convenient in each case (Fig. 7)

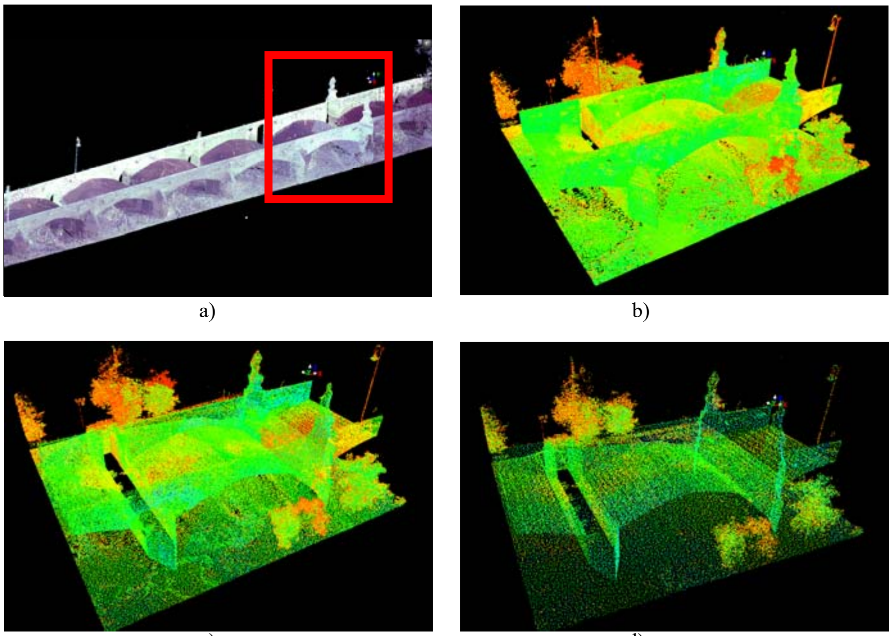


Figure 8: a) Entire model of a bridge. b) Span simplified to 5 cm resolution. c) Span simplified to 10 cm resolution. d) Span simplified to 20 cm resolution.

In the same way, it is possible to determine the optimal resolution for the study of a specific structure. As an example, the span of a bridge with different resolutions for analysing the performance of its structure is shown in Fig. 8.

3.2. Pure documentation

Cases of pure documentation usually use the original point clouds, so that required accuracy must be better to 5mm. However, advances in developing of new scanner lasers provide the possibility to get models with more than one point per cm2. In these cases the simplification of point clouds result necessary too, especially in overlapping zones. Besides, the number of points measured around the rotation axis of the scanner laser, results higher. Figure 9 shows the density of points per cm3 measured by the scanner laser in a 10000000 cloud (distribution and density are not uniform).

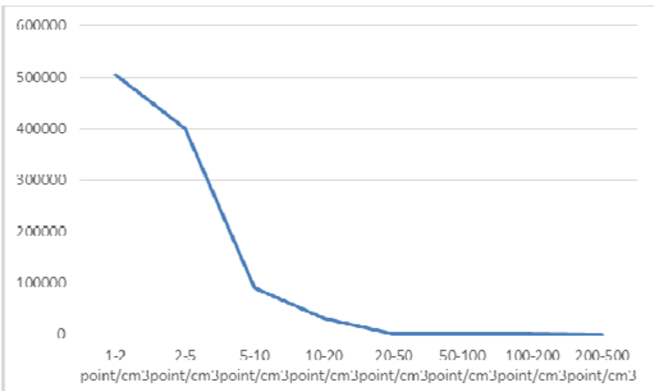
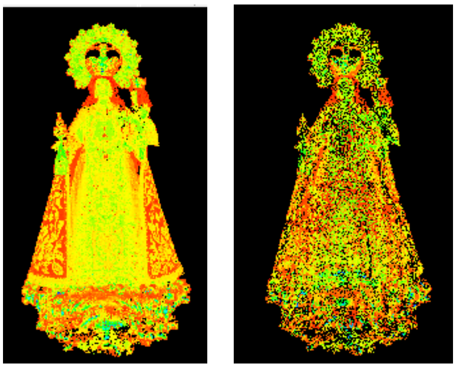


Figure 9: Density of points per cm3 in a 10000000 cloud (Y axis shows the number of cubes, X axis shows the number of points per cube).

In the following example for cultural heritage restoration, a statue measuring 160 cm high and 250 cm around was scanned with a Cyrax 2500 laser, using 6 scans, starting with a total of 490049 points (Figure 9).



a) b)

Figure 10: Statue. a) Original cloud with 490049 points. b) 5mm simplified cloud (61352 points)

Scan	No. of points (original clouds)	Cloud sorting process Time with a 1 Ghz processor (sec)	Cloud simplification process (5mm)
1	318542	7.26	41776
2	52934	1.10	28545
3	6899	0.18	6874
4	34283	0.67	24530
5	70480	1.58	26291
6	6931	0.13	6905
Total	490049	10.92	134921

Table 5: 5mm simplification process

	Mosaic
Scan	5mm mesh
1 vs 2	40102
1-2 vs 3	44213
1-3 vs 4	55375
1-4 vs 5	60756
1-5 vs 6	61352
Time (sec)	5.8

Table 6: Cloud mosaic process

As shown in the tables 5 and 6, the final result is a cloud made up of 61352 points that represents a simplification of 87.5% (we obtain a reduction of 428697 points in a few seconds).

4. Conclusions

The method presented in this paper allows one to simultaneously obtain automatic simplifications with variable resolution from laser scanned data of an object. This makes it possible to study each part of an object with the optimal accuracy needed for that particular region. This range in permitted accuracy is critical in structural studies considering that in a building, there are many different elements: First, simple surfaces that can be resolved accurately with a very low density of points. Second, complex features that require a high density of points can also be accommodated without imposing the high density of points across the entire object. The accuracy of each simplification is optimal because it is performed on the original point cloud for all cases.

The linear coordinate algorithm we have implemented makes it possible to process millions of points both quickly and easily. The results are inherently optimal, as the process generates a single point cloud (based on several overlapping clouds) with homogenous point density and distribution that selects each point to be the one best defining the geometry of the object.

The times obtained in the simplifications were a few seconds per cloud with a total time of 30 minutes in the case of the complete church (the original cloud was made up of 78 million points from 11 different scans). However, these times could be greatly reduced by parallel processing.

The developed procedure distinguishes the point density by area and evaluates the precision of the points eliminated based on the distance from the scanner and on the inclination of the surface with respect to the scanner. Thus, in the zones in which different scans overlap, certain points are eliminated based on these precision factors.

The results show simplification values of 85% in the case of the least reduction with a resolution of 5 cm (the case of a single scan in the semi-spherical dome), and it is clearly shown that in the 10 cm, 20 cm and 50 cm simplifications, the point cloud can be reduced by as much as 99.8%.

In the case of a large object, such as an entire church, the simplification reached 98.8%, even for the most precise case of 5 cm, and reached 99.9% in the case of 100 cm. For these cases in which a large 3D model is required, it is possible to guarantee exact geometric replication of the object (5 cm in a building can be considered an exact degree of detail for structural studies) with just 1% of the original points.

Finally, simplification model in pure documentation reaches a great simplification in a few seconds, even when a high resolution better than 5 mm is required (87.5%).

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Table captions

Table 1: Simplified point clouds of the semi-spherical dome (times recorded with a 1 GHz processor)

Table 2: Cloud sorting process (5-cm, 10-cm, 20-cm, 50-cm and 100-cm meshes)

Table 3: Cloud simplification process (5-cm, 10-cm, 20-cm, 50-cm and 100-cm meshes)

Table 4: Cloud mosaic process (5-cm, 10-cm, 20-cm, 50-cm and 100-cm meshes)Table 5: 5mm simplification process

Table 6: Cloud mosaic process

Figure captions

Figure 1: Scanning three objects at different distances/inclinations from the common laser scanner station.

Figure 2: Coordinates of the centre of a cube in the matrix (with the prism simplified only with the cubes that are not empty)

Figure 3: Flowchart for the simplification of a point cloud

Figure 4: Flowchart of the simplification in the generation of the mosaic

Figure 5: Semi-spherical dome. a) Original cloud with 3638784 points. b) 5-cm simplified cloud (555891 points). c) 10-cm simplified cloud (150491 points). d) 20-cm simplified cloud (38671 points). e) 50-cm simplified cloud (6210 points). f) 100-cm simplified cloud (1553 points).

Figure 6: Church (conical perspective). Original cloud with 78200800 points. a) 5-cm simplified cloud (930169 points). b) 10-cm simplified cloud (352969 points). c) 20-cm simplified cloud (96937 points). d) 50-cm simplified cloud (10326 points). e) 100-cm simplified cloud (2242 points).

Figure 7: a) Entire building simplified to 20 cm resolution. b) Vaults simplified to 10 cm resolution. c) Front door simplified to 5 cm resolution.

Figure 8: a) Entire model of a bridge. b) Span simplified to 5 cm resolution. c) Span simplified to 10 cm resolution. d) Span simplified to 20 cm accuracy.

Figure 9: Distribution and density of points per cm3 in a 10000000 cloud (Y axis shows the number of cubes, X axis shows the number of points per cube)

Figure 10: Statue. a) Original cloud with 490049 points. b) 5mm simplified cloud (61352 points)