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Extraction of a floor plan from a points cloud: some metrological considerations

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ABSTRACT
The design of evacuation plans for safety purposes is based on the graphical synthesis and visualization of data derived from high-performance measurement systems. The data post-processing requires some suitable procedures including many steps, to obtain the information needed. These are related to the global use of the measurement system, to the real measurement operating conditions, to the complexity of the building, to the simplifying hypotheses, to the data management. As a preliminary step, this work outlines a procedure for extracting a floor plan from a points cloud acquired by means of a laser scanner. The test case is a baroque cathedral, being a large structure and presenting some elements of irregular geometry. Some critical passages have been examined, presenting similar widths but different characteristics i.e., flat and regular geometries of the elements on the walls, in some cases, statues, columns and adornments, in some others. The data management plays a key-role in the correct interpretation of the outcomes, having a great impact on the results reliability. The obtained estimated variability of the passage width is in the order of few tenth centimeters. This is strictly related to the specific operating procedure. How this affects simulation software for route optimization of emergency paths will be the object of further investigations.

Section: RESEARCH PAPER

Keywords: complex buildings; evacuation plan; laser scanner; data synthesis; causes of variability; measurement uncertainty

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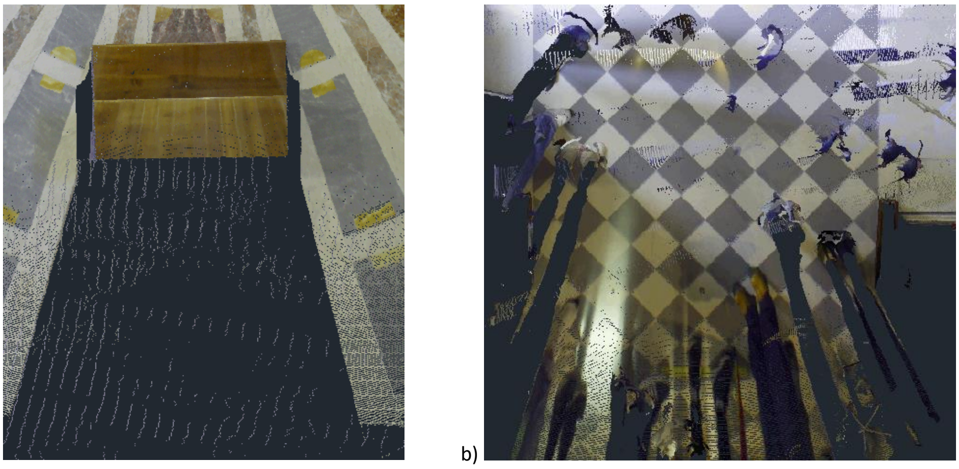
1. INTRODUCTION

Many fields of application require and benefit from approaches able to combine the information coming from several data sources, of both theoretical and experimental nature (i.e., deriving from analytical/design models and from measurement systems, respectively). In this context, data fusion and data validation techniques represent a core activity in the wider field of big data management, dealing with a large variety of data types. Graphical synthesis and visualization represent interesting areas of investigation, mainly due to the remarkable size of the acquired and stored data, and the need of adequate procedure for the correct interpretation of the outcomes, to support and exploit data reliability, mostly when they are used as an input for possible next steps of data processing.

At least 4 macro-areas of interest can be envisaged, to potentially benefit of enhanced techniques for assuring measurements accuracy:

- Air/water/up to space navigation systems, in the aeronautical/ aerospace sector [1],
- Military systems [2], [3],
- Industrial cyber-physical systems and sustainable mobility solutions [4]
- Cultural heritage and safety systems for civil infrastructures and buildings

To the best of the authors' knowledge, limitations regarding the accuracy of the existing solutions remain, thus the evaluation of the effects induced by both procedural and data processing aspects appear helpful in overcoming the related issues. In this



a) b)

Figure 1. Obstacles during the acquisition phase: a) shadowing effects due to a church bench; b) presence of people during the acquisition.

work, attention is paid to an application referred to safety operations, to support rescue procedures based on the use of 3D models of buildings and civil infrastructures.

Keeping into account only the last two fields, in the last years, 3D models of cities (or parts of city, or even of single buildings) have become valuable for several purposes beyond visualization, and are used in many domains, as [5]-[11]: estimation of the propagation of noise in an urban environment, urban planning, facility management, estimating solar irradiation, evaluating seismic damage, planning emergency response. A typical 3D model can be derived from various acquisition techniques, as, for instance, photogrammetry and laser scanning [12], [13], Unmanned Aerial Vehicle (UAV) tilt photography [14]-[16], Synthetic Aperture Radar (SAR) techniques [17]. Compared to other systems, the laser scanner technique appears to be a suitable measurement system when the reconstruction requires extreme detail and the acquisition conditions are critical, such as in emergency situations. These reflections are due to laser scanner characteristics of resolution, accuracy, ease of use, relative low cost, low acquisition and processing time, possibility to measure at safe distance [18].

The internal/external mapping of building, based on points cloud is a very diffused and studied application, for many purposes (rapid automatic drawing of building mapping for construction, restoring, maintenance purposes, safety requirements, support to rescue in emergency condition) and very recent studies could be found. Different instruments have been used, as, LIDAR laser scanning or time of flight terrestrial laser scanner. Manual processing of the points cloud is often used to process data, but some problems arise, especially for buildings of large dimensions as in the case-of historical building, like big churches, amphitheaters, and large monuments:

- Remarkable errors due to human effect in tracing the profiles and the connection lines in the maps,
- Huge number of measuring points, with the need of setting procedures for big data analysis
- Lack of reproducibility of results.

To prevent the above problems, the recent works typically present procedures for automatic drawing and mapping. Many solutions have been proposed for automatic drawing, based on point fitting, outlier removing and tracing of the wall, also including the use of artificial intelligence, (e.g., convolutional neural networks, used to both recognize perimetral elements like walls and individuate specific elements like windows and/or doors). Also, accuracy of results is discussed with reference to different parameters (IoT, the door of windows number, the area ratio with respect to the manual experimental data); even though modern buildings are studied, some difficulties are highlighted when the geometry of the area is not so regular, presenting niches, sharp variations of direction or of the angle between the walls.

The evaluation of the effects induced by both procedural and data processing aspects appear helpful in overcoming the related issues when safety of people is a key requirement.

Among all the applications, the procedures for supporting rescue in emergency conditions play a relevant role. These aim at tracing the escaping tracks and maps and/or checking the available areas for safe evacuation of people. In a previous application [19] the authors faced the above problem with reference to the definition of an evacuation plan of a baroque cathedral located in Italy, which is characterized by having a complex structure and where hundreds of people could be present at the same time. To this purpose, a preliminary mapping of the monument has been carried out by using a terrestrial laser scanning to obtain the cloud points.

All the objects between the ground and 2 meters of height should be included in the floor plan, to consider possible obstacles to the evacuation, e.g., tall people, or rescue objects. According to this criterion, reducing the available surface for escaping is important especially in historical buildings, like churches, where there are numerous architectural elements on the walls or on the pillars. In fact, these are generally not contained in floor plans. However, since the floor plan has been drawn using acquisition of real objects, some geometrical inconsistencies are presents:

- The walls are not always straight, so some lines in the floor plan are inclined in the range of a few degrees
- Curved or rounded elements like columns, corners or spiral staircases are not perfect. It is difficult to represent these parts in the floor plan according to their actual shape.

With reference to the final accuracy of data, some procedural aspects, which make the resulting floor plan strongly depending on the quality of the acquired points cloud, are equally important. Acta

The factors that influence the most the generated points cloud are:

- Presence of obstacles for the laser beam. This results in a loss of information and the created cloud has voids and holes.

- Since the church considered as test case is open to the public, the presence of people in the acquisition is inevitable. They create the same shadowing effects to the laser beam as the obstacles.
- Effect of the positioning of the laser scanner with respect to the target point, especially when the angle positioning is not favorable
- Presence of reflective objects like windows or glass doors because this kind of surfaces distort the reflected laser beam.

Figure 1 reports some errors during the acquisition phase like a church bench on the left or people on the right.

Based on these considerations, assessing the uncertainty of the data provided for the applications the points cloud are used is very difficult and the examples given in literature where the reference geometry is different from each other do not allow to define a standardized procedure, which could be very useful to realize reliable and trustworthy procedures.

A standard procedure, encompassing a whole uncertainty evaluation is a long-term goal. Nevertheless, a step-by-step approach could be useful to analyze the main components of the uncertainty budget, where a higher attention should be put to better describe the real situation. In this work, with reference to a previously obtained map of a church located in Italy, two situations are studied, being similar with respect to a general evaluation, (i.e., showing same minimum width of the passage and characteristics of the surrounding areas), but different with respect to the characteristics of the passage: flat walls and regular geometries of the elements in the former case; statues, altars and/or high/bas reliefs in the latter case. Having an idea of the variability of results at different heights of the same section, is expected to help to complete the information about the eventual dangerousness of the passage itself.

With reference to the main sources of uncertainty that can be recognized in the selected test-case, the entity of the induced effects of these causes of variability on the parameters used to extract a floor plant from a points cloud is quantitively evaluated making use of the canonical techniques for measurement uncertainty evaluation. The emerging metrological considerations referred to the extraction of a floor plant from a graphical information provided by the advanced measurement systems are expected to be easily transferred also to other similar applications.

In section 2 with reference to the selected test case (2.1), the methodology followed to evaluate quantitatively the effects of the variability in the determination of the needed quantity will be explained (2.2); it is worth noting that the definition of the parameter of interest is not a trivial task. In section 3, the outcomes will be analyzed and discussed. Conclusions and future works end the paper

2. MATERIALS AND METHODS

2.1. Test case peculiarities

The analysis of the most influencing uncertainty causes is referred to a complex structure where thousands of people have access daily, and hundreds could be present at the same time. The building is a baroque cathedral located in Italy. One of the direct implications of the metrological characterization of the method is the enhancement of algorithms devoted to indoor localization and positioning for emergency situations based on context-aware software requiring, among other, a detailed knowledge of buildings floor plans [20]-[23].

In this work, a Leica RTC360 3D Laser Scanner, and the related Leica software suite for the points cloud analysis, were used. The laser scanner technique has some strength points when used for the design of an evacuation plan or for safety purpose: (1) it allows an acquisition of the real dimensions of a building; (2) all the objects between the ground floor and an arbitrary height could be included in the floor plan. This is very important especially in historic buildings like churches where there are numerous architectural elements on the walls or on the pillars. These are generally not contained in floor plans, with a high level of detail.

The cathedral has a floor area of more than 15000 m^2 with the central aisle longer than 186 m. For these reasons, acquisitions in different positions are required to scan completely the internal area. In this case, the laser scanner has been in different position according to the complexity of the surroundings. The distance between different acquisition setups ranges from 10 m to 36 m. The distances have been chosen according to the complexity of the surrounding areas. Smaller values have been used when there are more architectural elements to have a better reconstruction. Greater distances between acquisitions setups have been used in areas with simpler shape to reduce the amount of data. When possible, the instrument has been placed halfway between two facing walls. For all the acquisition, the laser scanner has been placed on a tripod with a height of 1.6 m. Each acquisition has been joined with the subsequent using the Leica software Register360 Field. To have a better alignment of different acquisitions, the instrument has a visual inertial system (VIS) that tracks the movement of the unit relative to the previous scan position. Since the site has not been closed to the public during the acquisition campaign, the function "Double Scan" of the laser scanner has been used for each setup. This allows to eliminate all the objects and visitors that have moved between one scan and the other.

The points cloud of the whole building analyzed in this work is generated using 318 acquisitions setups and the resulting cloud is composed of 10414.4 million (10414448131) of points. A spherical photo is also acquired for each setup, and it could be useful for a visual inspection to better interpret the points cloud and extract the floor plans. In fact, especially in complex structures, it could happen that the laser beam could not reach some zones. To avoid this problem, the setups' locations must be carefully planned to scan all the zones. It must be pointed out that procedural and interpretative aspects, connected to synthesis and to the post-processing of the obtained data, have a great impact on the reliability of the results. The simplification of the procedures is needed as more as the buildings have a remarkable extension and complex shapes. To ensure the reliability of the measurement data, the calibration of the measurement systems is a necessary preliminary step [24]-[27].

The Leica RTC360 is a high-speed and high-accuracy 3D laser scanner, which was tested in a previous work of the authors under field conditions [28]. The measurement precision under repeatability conditions which has been estimated, and which is in line with what is declared by the manufacturer, is of the order of 1 mm. The resolution is of 3 mm at 10 m distance.

Therefore, such laser scanner performances appear adequate for the use of the instrument in the described application of interest, that is the design of an evacuation plan from a complex structure [29]. In addition, the good practices have been correctly carried out, according to the field procedures for testing geodetic and surveying instruments. It is worth noting the simplified test procedure provided in [30] makes joint use of two measurement

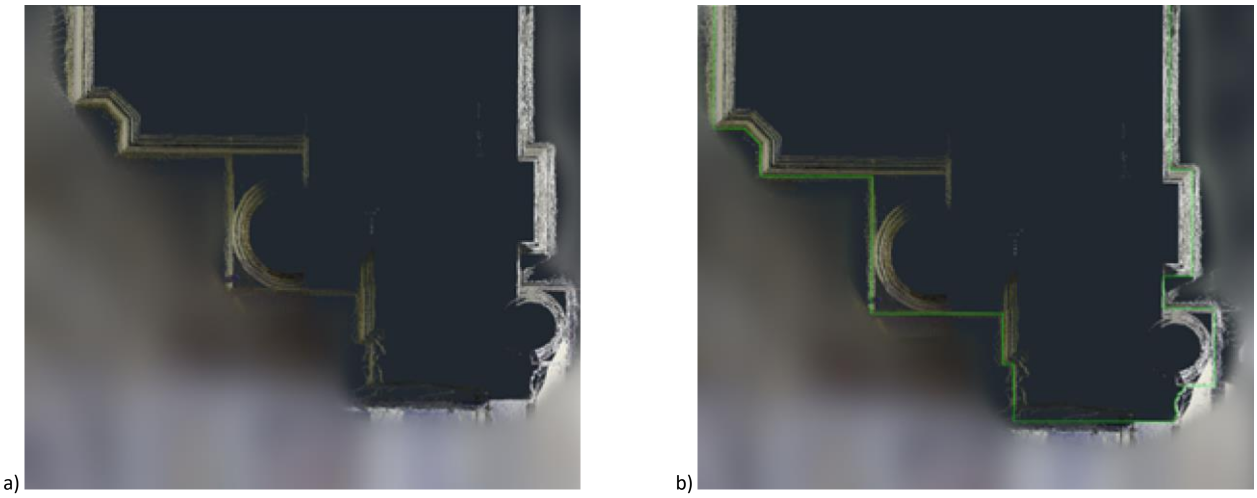


Figure 2. Top view of the sliced points cloud. a) Detail of a 2-meter-high section of the points cloud. b) Floor plan (in green) drawn considering the maximum dimensions on the floor.

stations, besides considering other main specific contribution to the standard deviation, which is not always feasible. Moreover, the operators could perform the set-up of the instrumentation as end-users and with no particular attention to the aspects of metrological interest.

Regarding the usage of a terrestrial laser scanner to design an evacuation plan, the results will describe the main problems concerning the extraction of a floor plan from a points cloud.

The different acquisitions have been joined and cleaned using Leica Cyclone Register 360 [31]. The points cloud has been processed using AutoCAD 2023 and the plugin Leica Cloudworx for AutoCAD; this has been used to extract from the points cloud a series of layers at different heights, parallel to the floor of the building, up to two meters. In facts, in safety applications, all the obstacles between the floor and two meters of height must be considered. Switching to the top view of the cloud, the points on this plane has been used for drawing the floor plan. Figure 2 shows an example of the process from the points cloud to the floor plan Figure 2. The comparison aims at highlighting the peculiar shape of the scanned profiles, that could mislead the interpretation of the extracted floor plan itself, given on the one hand, the top view of the sliced points cloud considering a 2-meter-high layer (Figure 2a), and manually interpolating the profile of the scanned objects, considering the maximum extension on the floor level, on the other hand (Figure 2b).

2.2. Methodology for quantitative evaluation

To provide quantitative evidence of the minimum area available for designing evacuation plans, the effects of the following main aspects were considered:

2.2.1. Number of critical regions on the horizontal plane (on x-y plane)

Seven passages are considered critical (on an arbitrary basis) for escape purposes. This criterion will require further analyses, using an iterative approach with the goal of covering the entire building.

2.2.2. Number of layers on vertical axis (z-axis)

On a height of 2.00 m, a total of 8 horizontal layers are analyzed at 0.25 m each from the next one. This choice is expected to be sensitive to shady areas that could not be captured by the system.

2.2.3. Definition of the parameter of interest

For each layer, two quantities have been identified:

- Distance, d_{ij}, between the walls of the aisles suitable for escape, evaluated on each critical region, i. The variability is evaluated considering 10 up to 15 widths, along the direction of the passage, j. In some cases, corresponding to 0.30 m to 0.50 m of passage depth. The standard deviation of a normal distribution is used to estimate the related variability.
- Variation of the construction points positions of the pillar perimeter, Δk, as the height increases, evaluated considering the difference between the layer that envelops the maximum perimeter minus the minimum one, with respect to a reference layer along the z-axis. The standard deviation of the differences assuming a uniform probability distribution is used to estimate the related variability.

2.2.4. Identification of the reference for the parameter evaluation

The parameters defined in 2.2.3 both require the choice of a reference for their estimation. Therefore, it is essential identifying the horizontal and vertical references, as it follows:

- Reference for the z-axis direction: the variability can be studied using a different reference plane, for the identification of the ground floor, which determines the slicing layers. This also affects Δk, which can refer to one of the available layers, e.g., middle layer (1 m).
- Reference for the x-y plane: the choice is driven by the processing opportunity offered by the software to operate manually to the selection of the quantity of interest. Some options could be the reference system of the CAD software, the median lines of aisles / naves of the church or a basic geometrical shape enveloping the architectonical element analyzed (e.g., a simple rectangle representing a pillar).

2.2.5. Effect of the irregularities of the contours

For each layer, the profiles of the scanned objects are based on the manual interpolation of the available points clouds, traced with closed broken lines. This is a task that can be automated with different techniques and by means of different software [32]-[34]; nevertheless, this aspect is a matter of investigation for metrological characterization purposes.

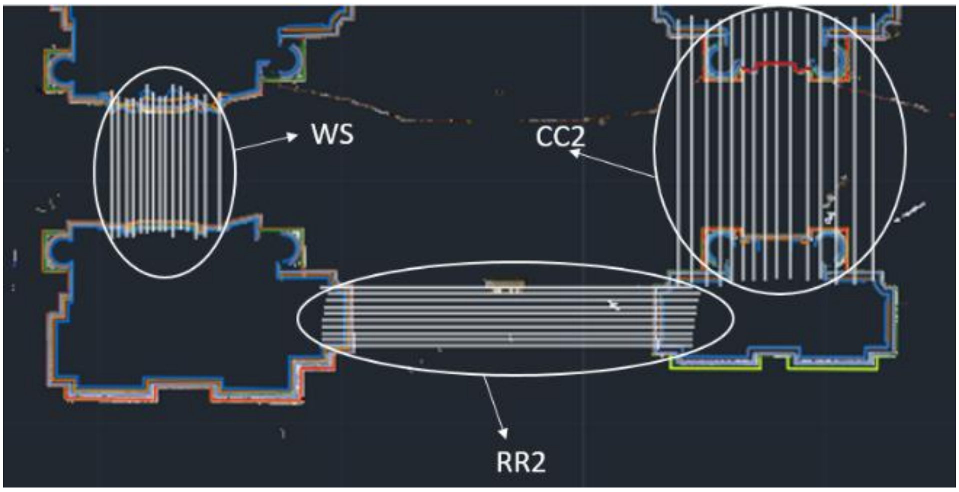


Figure 3. Example of three passages analysed: white 15 straight lines represent the direction for d_{ij} evaluation. The coloured contours are referred to the floor plans extracted at different layers.

2.2.6. Number of points cloud

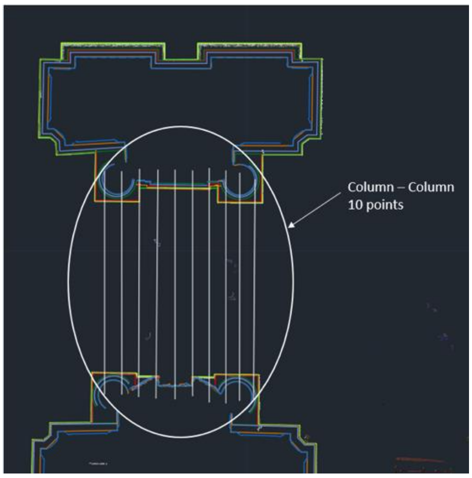
Reduced configurations to study accessibility can also determine further variability to the final measurements, from the point of view of the number of points considered in the calculations, compared to the reference configuration, which includes all the monitoring points [35].

3. RESULTS

For the evaluation of the width of the aisle (d_{ij}), seven different passages have been considered; for each passage, 10 up to 15 widths have been manually recorded, for each of the 8 layers. The passages have been selected as for the characteristics highlighted in the following bullet list; an example of the examined situations is depicted in Figure 3.

- The regularity of the opposite walls, meaning that no substantial anomaly is present, in terms of permanent obstacles, like columns, sculptures nor adornments, which may obstruct the passage itself; namely these are indicated as RR1 and RR2. “R” stands for “reference”: as a matter of fact, the expected variability within the layer and as the layer changes, is at its lowest here, and for this reason this can be thought as a reference width between the two walls. RR1 and RR2 can be assumed having similar absolute values, being in the same area.
- The presence of some irregularities at only one of the walls, with reference to the distance, d_{ij}, is evaluated. These are recalled as CC1 and CC2, where the letter “C” stands for “columns”. Again, in this case the expected absolute values for CC1 and CC2 are of the same magnitude, being the walls close to each other, and the columns of very similar shapes. The variability within the layer is evaluated considering 15 widths, as depicted in Figure 2. The passage indicated as CC10 should be considered as a sub-class of possible passages where both opposite walls show the presence of columns; the distance, d_{ij}, in this case is evaluated just on the minimum space available, considering only 10 widths per passage.
- The presence of some irregularities on both opposite walls, with reference to the width, d_{ij}. Namely, WS and SS refer to the cases Wall-Statue and Statue-Statue, respectively.

Figure 4a) shows an example of the sliced area, in the x-y plane, where 10 distances have been acquired (CC10). Looking at the obtained distances (Figure 4b), it can be easily recognized

a) 

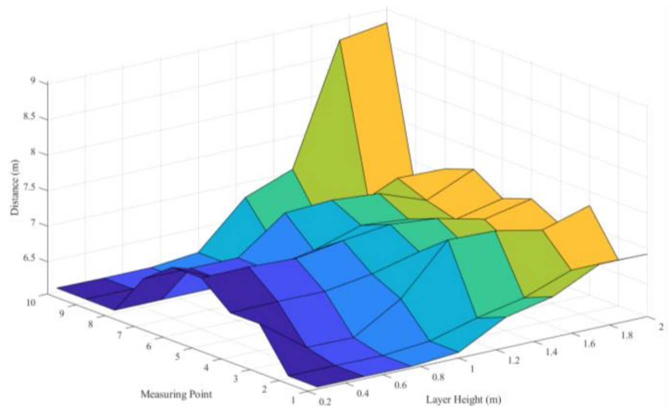
b) 

Figure 4. Analysis of the passage defined by two opposite columns, evaluated using 10 distances (Column-Column 10 points, CC10): a) sketch of the drawing; b) 3-dimensional representation of the obtained widths, at each layer height, at each measuring point.

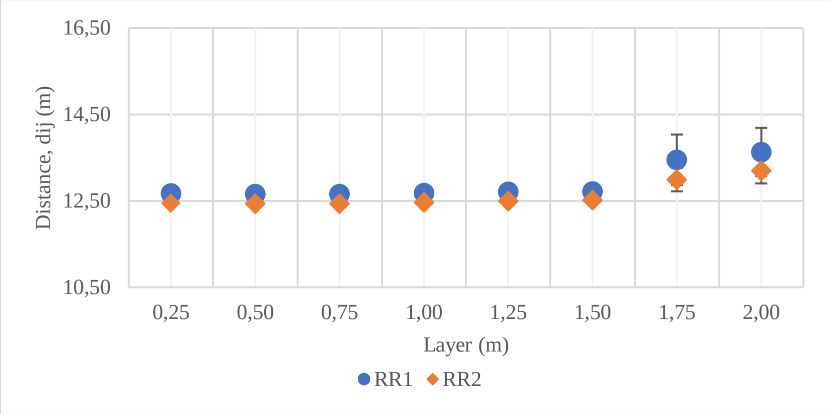


Figure 5. Width of the passages RR1 and RR2 i.e., regular opposite walls. The error bars consider the standard deviation of 10 widths.

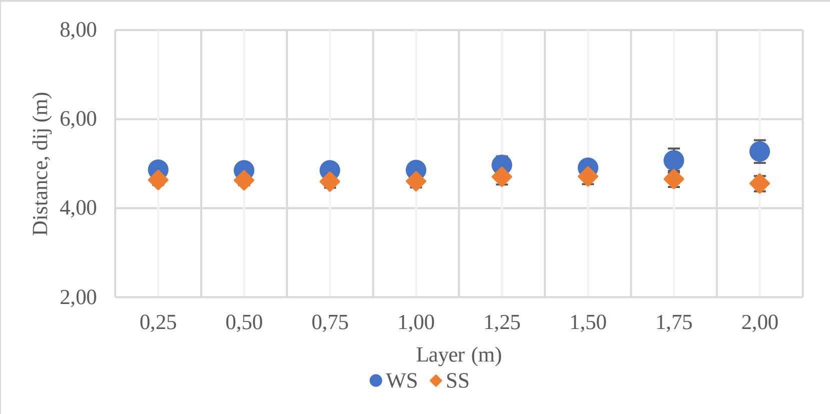


Figure 6. Width of the passages WS, i.e., regular wall, opposite to a statue, and SS, i.e. when both sides of the passage present a statue. The error bars consider the standard deviation of 15 widths.

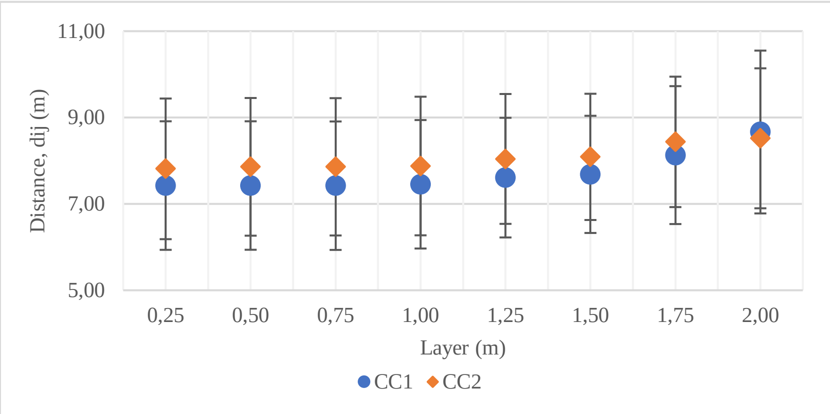


Figure 7. Width of the passages CC1 and CC2 i.e., both offering a passage delimited by columns, on both sides. error bars consider the standard deviation of 15 widths.

an increasing value of d_{ij}, due the peculiar shape of the columns. The uncertainty on the definition of the quantity to be measured can lead to the presence of some outliers, especially on the external edges (e.g., measuring point 10). The same effects can be noticed, looking at the graphs from Figure 5 to Figure 7, summarizing the results obtained in the three areas examined. The variability within the layer is indicated through error bars in the graphs, considering the standard deviation of 15 widths.

Looking at Figure 5, it can be noted a very low variability of the regular passage, up to 1.50 m. This confirms that this passage could be taken as a reference, at least in a part. The minimum variability of the method is in the order of 0.10 %. At the highest layers, however, it does not exceed 4.5 %. On the other hand, it is very difficult to find very regular walls up to 2 m of height in the cathedral.

Figure 6 refers to a more complex situation that is, when some disturbing elements can be found on the passage. The maximum variability occurs with reference to the 1.75 m section, being nearly 5 %. The variability among the layers is higher than RR1and RR2, being in the order of 2-3 %. It must be pointed out that the focus of the analysis, in this region, has been referred to the portion of the passage, affected by statues, without considering other types of irregularities.

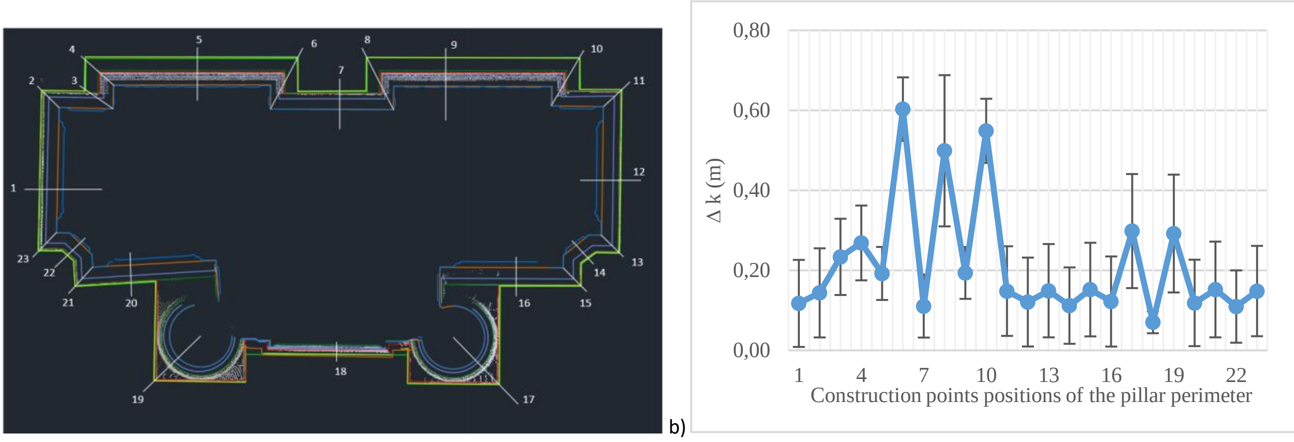


Figure 8. Analysis of a pillar perimeter evaluated using 23 construction points positions; a) scheme accentuating the irregular profile of the pillar; b) behaviour of the mean values of the construction point positions Δk, along the pillar perimeter; the error bars represent the variability of Δk evaluated on the seven layers.

In fact, looking at graph of Figure 7, here in the two regions a negligible difference is confirmed between the average values obtained for the distances, while the variability within the layers increases significantly (in the order of 20 %). The variability among the layers is in the order of 6 %. This is mainly due to the uncertainty of the measurand, which cannot disregard the edge effects linked to variations in the plan section of the identified architectural elements.

These effects are highlighted in Figure 8.

In Figure 8 the results obtained with reference to Δk are reported. Figure 8 shows the points considered and reports the obtained behavior of the absolute variation of the construction points positions of the pillar perimeter, Δk, averaged on the 7 available layers. Δk reaches values up to 60 cm. It is worth noting that changing the height of the layer and the type of the architectural elements crossed, the reconstruction perimeter changes layer by layer, as well. The error bars represent the standard deviation of the differences assuming a uniform probability distribution. This choice guarantees a conservative evaluation of the associated variability, which resulted in the order of 20 cm.

The values of Δk and its variability suggest a careful choice of the layer to be considered for the extraction of the floor plan.

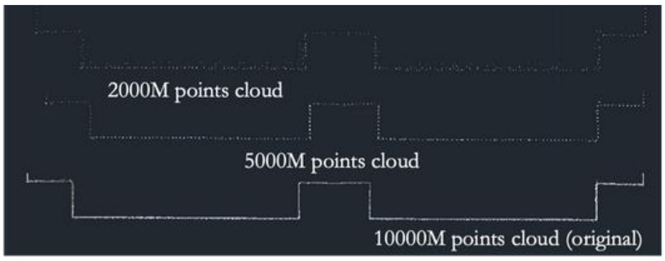


Figure 9. Example of the same profile (portion), obtained by subsampling at 50 % (5000 million points) and 20 % (2000 million points) of the original (10000 million points).

Table 1. Summary of the passage widths for each case considered. Values are reported in meters.

	R1	R2	WS	SS	CC 1	CC 2	CC_{10}
Mean value	12.68	12.47	4.95	4.63	7.73	8.06	6.69
Standard Deviation	0.002	0.01	0.15	0.06	0.45	0.28	0.31

Table 1 summarizes the mean of the widths and the standard deviation among layers, for each case considered (values in meters).

Concerning the number of the points cloud, this work laid the groundwork for further analyses linked to the effects of having available a smaller size of the stored data. The original points cloud has been created using more than 10000 million points. The cloud has been subsampled at 5000 million points (50 % of the original) and then in 2000 million points (20 % of the original).

Figure 9 illustrates an example of the same section of a pillar in the different points clouds. In the bottom there is the original point, moving to the top section there is the subsampled cloud in 2000 million points. It can be noted the number of points decreases so the borders of the element under analysis becomes less distinguishable but still visible. Using the manual floor plan extraction procedure explained in Section 2, the subsampling of the points cloud should not introduce further variability. This result is true especially in the change of direction for elements having a right-angle shape. In case of an automatic floor plan extraction algorithm the number of points should be taken into consideration for the variability of the result. This will be the object of further analyses, in future work.

3.1. Discussion

The obtained results show that the extraction of a floor plan from a points cloud requires careful examination of the causes of variability of the experimental data.

The variability is not attributable to the measurement system, and it is mainly due to:

- the adopted procedure for the floor plan mapping, due to procedural and interpretative aspects with a great impact on the reliability of the results (e.g., the cloud does not fully cover the whole areas due to obstacles, the selection of the slicing plane, …).
- the simplifying assumptions that could be made, especially for buildings with complex shape or great extension (reducing the number of measuring points, subsampling of the point cloud, …).
- Local peculiarities of the structure (approximations of architectural elements, irregularities in both the floor and walls, …).

In synthesis, the results highlight the following main aspects:

- The width of the passage both depends on the height at which the floor plan is extracted, and the shape of the specific elements, which are present in the passage itself.
- The variability both among layers and within layers are correlated with each other.
- Using a single value for the width of the passage, the relative variability reaches 20 %, since different heights and depths are considered.
- In case of very regular geometry of the walls of the passage, very precise measurements could be made, with an accuracy in the order of a few centimeters.

4. CONCLUSIONS

In the first step of the work, the metrological characteristics of using a laser scanner have been evaluated, as a preliminary study for the development of simplified procedures for the design of an evacuation plan for complex and large structures.

The whole measurement procedure was considered, starting from an infield calibration procedure. Previous results show that the laser scanner is suitable for the application of interest, if the accuracy in determining the single monitoring points is considered. However, the synthesis and data post-processing require that a procedure including many further steps is defined, to obtain information suitable to design an evacuation plan, which are related to the global use of the laser scanner, to the real operating conditions of measurement, to the complexity of the building, to the simplifying hypotheses, to the data management.

As a preliminary step, to investigate some of these aspects, a procedure for drawing a floor plan from a points cloud has been outlined and applied to a real case, being a cathedral.

Some critical regions of the church have been examined, which are similar with respect to a general evaluation, having the same minimum width of the passage and characteristics of the surrounding areas. These are different with respect to the characteristics of the passage, flat walls, and regular geometries of the elements in the former case, statues, altars and/or high/bas reliefs in the latter. The encountered problems during the application of the procedure mainly refer to the following aspects: the integration of data processing software, big data management, complexity of the structure, quality of the acquired points clouds. Variability of the estimated width of the passage in the order of a few tenths of centimeters could be estimated when different operating procedures are assumed. According to this preliminary result, for the design of an evacuation plan from a complex structure, the procedural and interpretative aspects have a much greater impact on the reliability of the results than the position measurement of single monitoring points.

In the next steps of the work, the extracted floor plan of the building will be used in evacuation simulation software for various analysis and further problems connected to the specific application analyzed will be studied, with reference to the identification of simplification strategies and their validation.

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