Evaluation of records using terrestrial laser scanner in architectural heritage for information modeling in HBIM construction: The case study of the La Anunciación church (Seville)

Juan Moyano a,*, Ángel Justo-Estebananz b, Juan E. Nieto-Julián a, Alfonso Ojeda Barrera c, María Fernández-Alconchel a

a University of Seville, Department of Graphical Expression and Building Engineering, Ave.Reina Mercedes, 4A, 41012, Seville, Spain
b University of Seville, Director of the SGI Fototeca-Laboratorio de Arte, Spain
c University of Seville, Laboratory Technician Specialist of the SGI Fototeca-Laboratorio de Arte (CITIUS), Spain

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ABSTRACT

In recent years, significant progress has been made in the creation of equipment that captures the so-called personal spatial data records. The size and its price compared to other equipment, make it ideal for works related to historical-artistic heritage. In this research, a comparison is made between two scanners used in geodetic measurements for the purpose of Building Information Modeling (BIM) in historic buildings. A stationary BLK360 personal scanner has been chosen, which is considered to be a scanner that is easy to use and very operational in transport. Despite its precision, this equipment has been used in numerous Scan-to-BIM studies. To know the reliability conditions of the equipment, the Riegl VZ400i scanner, a state-of-the-art stationary scanner, is taken as a reference. The objective is to know the precision of both teams to develop planimetric surveys of a historic building in BIM. The methodology used is based on comparing both point clouds, knowing the density and organization and the attributes that can help as parameters in the BIM methodology. Also, and as an auxiliary base, two topographic equipment, a total station and a state-of-the-art laser measurer were used, and the precision of both was analyzed. The results show that the differences between the PLS and TLS are not excessively large, reaching differences of 10 mm in small lengths and 16 mm in longer lengths and, therefore, admissible for a Scan to BIM procedure.

1. Introduction

A large part of the official institutions and organizations that manage the Architectural Heritage echo the use of geomatic technologies in the drafting of projects. The final perspective is to obtain models with geometric precision that represent and the state of conservation of the cultural assets. The integration of sensors for 3D reconstruction and the visualization of scenes in the real world is an important issue for the applicability of museums, video games, and properly that which has to do with architectural and...
archaeological rehabilitation [1] and even in the world of civil engineering and construction. Taking into account that architecture, engineering, and archaeology are sciences that use spaces and 3D reconstruction in their usual context, the registration of spatial data components is taken as essential in investigations. In this context, the precision of the representation of complex spaces and objects is essential to obtain models of reality. With the arrival of new geomatics technology equipment such as the Personal Laser Scanning (PLS) mobile laser scanner, data capture in the measurements of architectural spaces is simplified. This technology is relatively new and has yet to be developed [2], the greatest advantages of these personal teams is the easy handling for being a small team and in the capture of data. On the other hand, the study of metrology as a science of exact dimensions highlights the importance of new technologies that are acquired in increasingly cheaper equipment. The price differential between scanners can mean up to 65% savings. Therefore, everything is at the level of the function of the needs of both the researcher and the academic or professional in the use of these instruments. Another interesting aspect is the Scan to BIM methodology, which makes it essential to use Light Detection and Ranging (LiDAR) techniques or Structure from Motion image acquisition techniques (photogrammetry or SfM) or new Structure from Motion/Multi-View-Stereo (SF/MVS) for modeling both objects and architectural spaces in a BIM environment. LiDAR technologies have become one of the key elements in BIM by capturing geometric representation in terms of point clouds [3]. The use of PLS improves the operability of data collection and its transfer to BIM. It would be a matter of dispensing with millimeter precision in favor of speed in processing and the economy of the equipment. An important part is that the transfer to BIM of large-scale historical monuments and archaeological sites makes the operation of the point cloud inoperable on the platform itself, which is why it is sometimes necessary to segment or decimate the global point cloud of the registry. We are facing a new situation that puts the point of view in the BIM workflow for existing buildings and buildings of historical character. BIM has its roots in computer-aided design research and was considered an intelligent architecture simulation of architecture [4]. The truth is that this methodology that uses 3D digital components allows planning, designing and managing architectural projects in all stages of the useful life process. The term BIM applied to architectural heritage is of recent creation and includes complementary fields such as the analysis of complex geometries [5]. The connectivity between LiDAR and BIM known as “Scan to BIM” makes it possible to replicate complex geometry in parametric objects, that is, from the point cloud to the 3D model. The response to a search for precision ranges in the different LiDAR equipment makes this work unprecedented and interesting for the research and professional community, responding to a knowledge gap that unites two disciplines: geomatics with intelligent 3D representation systems.

2. Related word

The technological development that LiDAR system technologies have acquired, such as SFM/MVS image capture, has the potential to be used at all levels in cultural heritage (HC). The use of terrestrial LiDAR scanners (light stop and range) scanners in architectural heritage works has been widely studied, for example, Moraza et al. [6]. He developed his work in the church of San Miguel in Vitoria-Gasteiz where resolution and reflectivity stand out as attributes provided by the point cloud acquired by this technology. Also noteworthy is the stone mapping work on the facade of the San Nicolas church in Pacinotto (Italy) developed by Lezerini et al. [7]. Mañana-Borrázás et al. [8] establish the evaluation of the use of the laser scanner at two levels; in a large frame and in engravings whose dimension occupies a small space within the vault. In relation to its use in large architectural spaces such as a cathedral, Landes et al. [9] work at the St. Lawrence Chapel of the Strasbourg’s Cathedral. If we focus on the “Scan to BIM” methodology or workflow, Quattrini et al. [10] worked on the development of a high-quality 3D model for information registration. The model achieves precision through the use of TLS. Santagati et al. worked on semantic units in the cathedral in Nicosia (Cyprus) using TLS for modeling in HBIM-in a first work [11] and later in a second publication [12]. Therefore, in the context of the registration of historical monuments, there is a large portfolio of studies that use TLS for 3D recording and reconstruction purposes using new BIM technologies. With the rise of the BIM application, reality capture in construction has become more important in the scientific community [13]. When introducing the terms of restriction in quality of time, cost and other parameters, the authors call the process (PAS Planning for Scanning the massive data acquisition technology). In terms of comparing the accuracy of the equipment that encompasses topographical techniques, there are few relevant works; therefore, MatousKová et al. [2] performed accuracy tests between BLK360 and ZEB-REVO scanners, tested in the basement of the Faculty of Civil Engineering in Prague, also using two other SFM techniques. From what is interesting about the work, it is extracted that the variations between both scanners can be around 2 cm. Very similar is the work of PavelKa et al. [14] who worked with the aforementioned researcher, this time as the first author, comparing the equipment between BLKgo, BLK360 and ZEB-REVO, without establishing optimal conclusions. Desk et al. [15] work with the same PLS and Simultaneous Location and Mapping technology (SLAM) equipment, comparing the BLK360 scanner with the BLK2GO, at measurement distances of 5 to 10 m, which are reduced units of measurement for spaces in architectural heritage. The study concludes that the difference in small measurements of approximately 10 m is found in 2 cm, in the same way they affirm that they present a great similarity. Therefore, in the scientific literature, despite joint work with TLS and PLS of the BLK360 laser scanner with the RIEGL-VZ-400, Tao et al. [16] to map tropical forest trees, Becker et al. [17] to bring BIM to an architectural space, BlasKow et al. [18] to evaluate the geodetic precision of the BLK360 for data collection and management, there are no works that are similar to this investigation. Therefore, this unpublished work represents a contribution to scientific knowledge on metrology in architectural heritage. In this sense and to know the different levels of precision that we can find between the PLS and TLS, a study of a medium-sized church, 32 m long, has been taken, evaluating the different parts at two levels. A first level on a reduced scale and great artistic value. We refer to the altarpiece of San Juan Bautista, designed by Juan Martínez Montañés, with reliefs by the author himself and paintings and polychromy by Juan de Uceda, made in 1610–1620. The object belongs to the area of movable property and has dimensions of 4.33 m wide by 8.57 m high. The next level has taken the longitudinal axis of the church. Therefore, the study scale is larger, comprising lengths of 46.69 m long by 24.11 m high. Next, a study is established on the levels of precision that can attend to historic buildings in BIM and from here, study the results
obtained from the two surveys. This approach will solve such important issues as the precision of the PLS equipment, compared to the TLS and its applicability in HBIM. Another of the great challenges currently exists is the generation of BIM from a precise survey that integrates complex geometric shapes [19] both of historical nature and for reuse of existing buildings [20]. Most of the studies focus on the feasibility and sustainability of the use of historical BIM for restoration activities [21]. This allows users to reuse the model as a project file where information is recorded in the life cycle of the process [22]. The properties that the BIM environment has mean that the reconstruction of digital 3D models has semantic elements in such a way that the parameterization of objects such as walls, arches or pillars and all the elements that make up a church can have associated physical-mechanical characteristics. Combining this quality of BIM platforms with the exhaustive representation of physical reality means that this environment has become the great commitment of the design and management sector of the Architecture, Engineering, and Construction (AEC) industries.

3. Level of Accuracy from point cloud to BIM and the case study

Terrestrial laser scanning technology allows the acquisition of three-dimensional data necessary to obtain complex geometries of cultural heritage. Its use ensures coverage of the surface of the object studied as long as the appropriate number of records are taken to obtain measurement data, capturing the coordinates of millions of points. Therefore, it is an ideal instrument for registers that can serve as auxiliary replicas and build in BIM the sites, spaces or objects of cultural heritage assets. One of the first studies to use the TLS combined with the total station for the creation of BIM models in existing buildings is found by Tarvo et al. [23], defining the essential details in the process of creating a BIM. The GSA BIM guide for 3D images [24] mentions tolerances for as-built deliverables, plans and point clouds. The COBIM guide suggests precision by BIM elements for existing buildings and referring to historical details with a precision of 5 mm, without establishing at what level of scale it is required. Bonduel et al. [25] set the guidelines for the Level of Accuracy (LOA) precision levels from level 10 to 50, taking into account the technical guidelines of each country. Tarvo et al. publishes the precision levels in BIM from USIBD [26] without re-echoing that Bonduel had already established them before publication. Maiella [27] publishes in a case study of a window from St. Basilio monastery in L’Aquila three levels of LOA; low, average, high plotted in three colors. Therefore, it must be taken into account that the specific LOA ranges for heritage buildings can be between 0 and 5 cm from a lower range to a higher range. Another question is the tolerance levels for a BIM modeling that can be found in Barbosa et al. [28] and in Historic England [29] or the reliability levels (LOR) Atteni [30] as an indicator of reliability, difference between the numerical and the parametric model. To establish the basis of the scientific contribution, a case study of the Church of the Annunciation, one of the most outstanding temples of the Renaissance in Seville (Spain), is carried out. The surveys were taken on different days adjusting to the schedule of mass and guided tours of tourists.

Built between 1565 and 1579 according to plans by Hernán Ruiz II, it was originally the temple of the Professed House of the Society of Jesus [31]. This construction is made of brick, although the stone is reserved for the portal of the feet and that of the Conception, dated 1568 and located in the transept, which connected the church with the cloister of the Professed House. The church, with a Latin cross floor plan, covers the nave with ribbed vaults separated by transverse arches (arches transverse to the axis of the main nave), with half-barrel vaults in the arms of the transept and in the main chapel, and a half-orange vault in the transept, all of them coffered. The better half and two arms of the transept now have emblematic decoration dating from the mid-eighteenth century [32]. The choir is located at the feet, high up. The tower, to the left of the presbytery, consists of a body of bells with semicircular openings, without finial [33]. The main altarpiece is the work of the Jesuit brother Alonso de Matías (1603–1606). But this case study has an added singularity that is found in the nave on the side of the epistle, a medium-sized altarpiece made by one of the great image makers of the sculptural art of the Spanish Golden Age [34]: the altarpiece of San Juan Bautista, which we have mentioned before.

4. Characteristics of the equipment

Currently, companies dedicated to supplying precision geodetic equipment have the mission of developing improvements in the resolution of terrestrial laser scanners and increasing the rate of measurement in distances and angles. Another objective is also to design more ergonomic and economical equipment, such as the BLK2GO, used in interior architecture [15] or on other occasions to detect movements of the earth in the presence of intense vegetation [35]. Among the PLS Personal Laser Scanners is the BLK360 weighing 1 kg, used as an evaluation comparison [36] in heritage for the maintenance of structures and ornamentation of historic buildings [37] in combination with photogrammetry [38]. Despite being a recently built scanner, it is frequently used in MDCSs records in the area of architectural heritage. The Leica BLK360 laser scanner uses Waveform Digitizing (WFD) technology, with a maximum scanning speed of 360,000 points/second. It has three HDR digital cameras with color sensor and fixed focal length (single image 2592 x 1944 pixels, 60° × 45° (vx hz), full-dome scanning of 30 images and automatic space rectification, 150 Mpx, 360° × 300°), as well as an infrared thermal camera (single image 160 x 120 pixels, 71° × 56° (vx hz), full-dome scan of 10 images, 360° × 70°), the four included in the kit. This instrument achieves a range precision according to the manufacturer of 4 mm at 10 m, and 7 mm at 20 m. In this case, this scanner can operate through Cyclone FIELD 360 software using a tablet for field work.

New generation equipment based on full-waveform LiDAR technology records the amount of laser energy returned to the sensor over the time of each emitted pulse [39]. The full waveforms LiDAR advantage aids in understanding and algorithm development in scenes. Among these teams, we have selected the RIEGL-VZ-400, used in many fields of knowledge, among which it is worth highlighting to develop deformation evaluation tasks in mining areas [40], in monitoring of hydraulic engineering structures [41]. The latest generation 3D laser scanner RIEGL VZ-400i has Internet connectivity with the latest LiDAR waveform processing technology. Real-time data flow is performed through two processing platforms: a dedicated processing system for the simultaneous acquisition of scan data and image data, waveform processing, and system operations, and a second processing platform, processing that allows automatic registration on board. Provides a built-in 3G/4G LTE modem, Wi-Fi, and Ethernet communications hardware. It has an
integrated orientation sensor (MEMS IMU, compass, and barometer), and has a pulse repetition frequency of up to 1200 kHz.

Its main features include a high laser pulse repetition frequency of up to 1.2 MHz; high-speed data acquisition of up to 500,000 measurements per second; eye-safe operation in laser class 1; wide field of view, 100° x 360°; range up to 800 m, accuracy 5 mm; high accuracy, high accuracy range based on echo digitizing, online waveform processing, and multiple response time processing; innovative processing architecture for simultaneous real-time data acquisition and georeferencing; automatic registration on board; simultaneous acquisition of image and scan data; user-developed applications via python software; and cloud connectivity via Wi-Fi and 3G/4G LTE. Attached to the system is a Nikon D810 camera (Format: FX; Image sensor: CMOS; Frame size: 35.9 mm x 24 mm; Total pixels 37.09 million) and an AF Nikkor Fisheye lens (14 mm f/2.8) (see Fig. 1).

5. Data acquisition processing

To obtain data processing once the records were made, several point cloud post-processing software was used. LEICA Cyclone REGISTER 360, Fig. 2, was used for the BLK360 scanner. It is a processing software with a cloud-to-cloud matching algorithm to register overlapping point clouds automatically. This recently created software is an intuitive tool for handling and generating reports from the different records, which ensures the quality of the data obtained. It also uses the Visual Inertial System (VIS) RTC360 to automatically place the data in coordinate values. All final log data are published to a Leica Geosystems Universal (LGS) project file for software compatibility. Table 1 shows the result of each exploration set, after post-processing with the link quality matrix. Confidence or strength level is greater than 70% between sets.

The SisCAN PRO software is in charge of organizing, saving, and treating all the data obtained by the RIEGL VZ400i scanner in a digitization session. Project oriented in such a way that the data acquired during the measurement campaign is organized and stored in a project structure. Among these data are the scanning surveys, captured details, photographs taken by the Nikon D810 camera, GNSS data, and the coordinates marked by the control points and refractors. The operation of the algorithm is based on transformation matrices to obtain multiple data from several scans in the same defined coordinate system. With all this, the system is capable of generating the 3D model, editing it, viewing it, and exporting it to various formats, for example: .las; .obj; .pts; .stl. Fig. 3 shows the processing result in the SisCAN PRO software.

6. Record checkpoints

To record the coordinates of the Ground Control Points (GCPs), two topographical instruments were used. Points of two categories have been taken, some physical points through circular targets and other recognizable geometric points. On the one hand, the Leica Flexline TS02 with precision (precision of 2 mm) in order to register the coordinates of the GCP of the area delimited in the study with a short strip (altarpiece) and the long strip area (length of the nave of the epistle). The structure of the points is represented in Fig. 4, where the section of the interior space of the church is shown, in a subset of horizontally segmented points and on it the distribution of points. Precision that Leica DISTO S910 could have as an auxiliary work team, the dispersion of the measurements in the axes (x,y,z) was evaluated. The precision according to the manufacturer is ±1.00 mm in 300 m. Equipment has been used in civil engineering works and in heritage. These laser measurement devices are relatively cheap, easy to transport, and are currently used in certain investigations so their evaluation could be a gap in knowledge in the field of geomatics.

As we can see, the distribution of points is done homogeneously and longitudinally through the central nave, with measurements on
Table 1
Result of the report with expression of the set error.

<table>
<thead>
<tr>
<th>TLS Placements</th>
<th>Level 1 instrument height</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number:</td>
<td>18 placements</td>
</tr>
<tr>
<td>Number of connections:</td>
<td>85</td>
</tr>
<tr>
<td>Strength:</td>
<td>70%</td>
</tr>
<tr>
<td>Overlapping:</td>
<td>60%</td>
</tr>
<tr>
<td>Set error:</td>
<td>0.007 m</td>
</tr>
<tr>
<td>Cloud to cloud error:</td>
<td>0.007 m</td>
</tr>
</tbody>
</table>

Fig. 2. Location image in Cyclone REGISTER 360 software.

Fig. 3. Interior scanning of the church by the RIEGL VZ400i scanner.
the epistle side and on the gospel side. The points in green are those distributed by the total station, and the points marked in red show the selection of the set of points registered by the laser measurer that saves them in a.dxf file. In addition to generating a photograph of the point with the telescopic sight for orientation purposes, this instrument can generate the 3D point coordinates in.xml format managed through direct software in connection with the computer.

The experiment for the evaluation of the two teams mentioned had a single registration process to obtain the sets of points throughout the church. The black line in Fig. 4 shows the plan length of the position taken by the equipment. The difference values are measured from the interior of the central nave of the church from 6 m to the value of 25 m. Once the two records were made, they were taken to CAD software to see the differences between the coordinate points in 3D. For the evaluation, the data shown in Fig. 5 are transferred and are obtained from the different measurements between points and their correlation with the distance of the equipment used.

Table 2 shows the different deviations between the points in their reference (x,y,z) representing the average distance and the standard deviation expressed in metric units.

7. Methodology. Equipment evaluation

7.1. Introduction

For the evaluation of the two scanners, the methodology has been structured in several parts of the analysis. On the one hand, the
point cloud-to-point cloud is analyzed using comparison algorithms. The global point cloud (TLS_i) reproduces representation records of the total geometry of the Church of the Annunciation. The insertion of the TLS_i BLK360 and TLS_i RIEGL VZ400i into the CloudCompare (C2C) v2.91 software for Microsoft Windows [52] makes the comparison work unfeasible, as the point cloud exceeds one million KBytes. The CloudCompare software is open source and has been used by many researches in evaluation studies, including Scan-to-BIM [22,25,53] or structural behavior analysis [37,54].

7.2. Comparison between points

According to Aryan et al. [13] the point cloud data quality criterion is that all scan targets are captured in the final point cloud. For operational reasons, it was decided to work at the two levels mentioned above, on a smaller scale, segmenting the altarpiece into a longitudinal section of the church nave. The segmentation work is carried out through a set of points that are representative of the sample. In the usual procedures, there is a first approximation of the sets of points manually for their alignment, and then the closest point algorithm is used, which recalculates the transformation parameters for the distance of the homologous points. Before starting the comparison, the outliers are filtered and then the roto-transformation between the subset of TLS_B points and the subset of TLS_B points. The result of the filtering is sometimes not as effective as shown if the subsets of points are filtered before the back-transformation. There are probably outliers that are not visible at first glance and that can affect the results. As an example, we can see in Table 3 the results of performing several cloud couplings in the different phases of experimentation. Until reaching the end

<table>
<thead>
<tr>
<th>Experimental Surveys</th>
<th>Standard deviation (σ) (m)</th>
<th>RMS (m)</th>
<th>Min. Distance (m)</th>
<th>Max. Distance (m)</th>
<th>Average distance (m)</th>
<th>Estimated standard error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Survey 1</td>
<td>0.1520</td>
<td>0.0336</td>
<td>0</td>
<td>3.2457</td>
<td>0.0910</td>
<td>0.0363</td>
</tr>
<tr>
<td>Survey 2</td>
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<td>0</td>
<td>1.4516</td>
<td>0.0564</td>
<td>0.0363</td>
</tr>
<tr>
<td>Survey 3</td>
<td>0.0327</td>
<td>0.0209</td>
<td>0</td>
<td>0.4226</td>
<td>0.0086</td>
<td>0.0362</td>
</tr>
<tr>
<td>Survey 4</td>
<td>0.0256</td>
<td>0.0452</td>
<td>0</td>
<td>0.3903</td>
<td>0.0061</td>
<td>0.0362</td>
</tr>
<tr>
<td>Survey 5</td>
<td>0.0199</td>
<td>0.0441</td>
<td>0</td>
<td>0.2214</td>
<td>0.0061</td>
<td>0.0350</td>
</tr>
</tbody>
</table>

Table 2 Deviation between the aligned Station Total with Leica_910 datasets in metres.

Table 3 Deviation between the point cloud of the BLK360 and RIEGL VZ400i equipment in the different phases of segmentation and elimination of outliers.
where it yields some results according to the figure Histogram and image of the comparison.

\( \text{TLS}_{\text{IR}} \) has a weight of 2,548.514 points compared to \( \text{TLS}_{\text{IR}} \), which has a weight of 893.022 points. In this process, it was detected that the BLK360 point cloud presents a greater number of atypical points, concentrated on the edges and limits of the sculptures and the gaps between the works of art and the niche that surrounds them.

Among the objectives of the research is to establish the difference that may exist in lengths greater than those analyzed in the altarpiece. For this case, the longitudinal section of the church is analyzed from a range of 5 to 45 m, representing the environment of the central nave on its epistle side. This comparison can determine the difference between the two instruments used: the BLK360 scanner and the Riegl VZ400i scanner. Once the two global point clouds have been obtained; \( \text{TLS}_{\text{IR}} \) through 18 scenes with a thickness of 209 million points and \( \text{TLS}_{\text{IR}} \) with two scenes with a thickness of 142 million points, the precision between the scanners is quantitatively compared. For the process to be operational, it was segmented by reducing the file to facilitate the operation of alignment between the point clouds. Six pairs of points (R0-A0, R1-A1, R2-A2, R3-A3, R4-A4, R5-A5 and R6-A6) distributed throughout the church were found. This comparison can determine the difference between the two instruments used: the BLK360 point cloud and \( \text{TLS}_{\text{IR}} \) a point from target point cloud. By using Nearest Neighbors search and euclidean distance calculation, the algorithm estimates the closest point between \( p_i \) and \( q_i \) as correspondence points. To calculate the rotation \( R \) and the translation \( t \) between the two indicated points according to Equation (1).

\[
E(R, t) = \min_{R, t} \sum_i \left\| p_i - (Rp_i + t) \right\| ^2
\]

The cloud-to-cloud comparison is then performed using the Iterative Closest Point (ICP) algorithm in CloudCompare, based on finding pairs of adjacent points in the two data sets, and then calculating the transformation parameters between the two subsets [56, 57]. Let us not forget that these comparison algorithms have been used especially to detect levels of changes in landslides that affect buildings [58], in inspection of bridge and tunnel structures [55], in historic buildings [37]. In geomorphic changes that affect sea cliffs [59], in flood risk management [60], in earthquake-induced landslides [61], that is, in aspects of significant changes that can be recorded through a cloud of points. In the processing of the point cloud set, it is common for noise and outliers to appear that can alter the final results. For this reason, several series of experiments were carried out, eliminating the atypical points, specifically at four evaluation levels, obtaining the data from the graph in Fig. 7, until reaching level four, where the results are obtained in Table 4 are obtained. As far as we know, this type of analysis has not been evaluated in any research.

7.3. Point cloud resolution

The density of points could determine the geometric quality of a 3D mesh when it is consistent and accurate with the geometry of complex objects in architecture [49]. From what we know to now, there are some works related to civil engineering, where Pirotti and Taroli [62] analyzed the suitability of the density of points for the curvature of the relief in the extraction of channels, or Gargoum and El-Basyounny [63] for the extraction of traffic signs: more generally, Zahra and Ayman [64] to analyze the physical surfaces of large-scale buildings. The works of Peña-Villasenín et al. [65] were intended to know the density of dots per square meter in photogrammetry experiments. Therefore, the density of points is an important parameter for knowing the surface area that has been recorded. To know the proximity of the points, the best way to verify the spatial resolution is to see the 3D Euclidean distance according to equation (2).

\[
d_{\text{Eu}}(P_1, P_2, P_3) = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}
\]
where $d_E$ is the Euclidean distance between points in space, and $x$, $y$ and $z$ are the Cartesian coordinates of those points.

The sample for submitting the essays was made in the strip of the altarpiece of the sculptor Martínez Montañés located in the nave of the epistle of the church. To see the behavior of the point density distribution, two surfaces have been compared. One sample is the curved surface of the cornice of the third body, and another has been taken from the flat surface of the frame of a painting on the left side of the altarpiece. The first set of points has a sample with an area of $5 \times 5 \text{ cm}^2$ according to Fig. 10.

For the segmentation of the subsample, CloudCompare software has been used from the alignment of the point sets of the BLK360 and RIEGL VZ400i. Two samples are obtained, one of them from the Riegl VZ400i scanner with 61 points, which is equivalent to 1 point for every 41 mm$^2$. In the case of the BLK360 scanner, 146 points have been obtained, which is equivalent to 1 point for every 17 mm$^2$.

![Fig. 8. Analysis of the difference between the point cloud between BLK360 and RIEGL VZ400i in evaluation 3. Result of applying the C2C algorithm. Color map of the distribution of distances. On the color scale, red represents the maximum distance expressed in meters. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)](image)

![Fig. 9. Histogram of Fig. 8. Histogram units: meters (X axis) and number of points (Y axis).](image)

**Table 4**

<table>
<thead>
<tr>
<th>Experimental Surveys</th>
<th>Standard deviation (σ) (m)</th>
<th>Min. Distance (m)</th>
<th>Max. Distance (m)</th>
<th>Average distance (m)</th>
<th>Estimated standard error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evaluation 4</td>
<td>0.0973</td>
<td>0</td>
<td>1.0988</td>
<td>0.0161</td>
<td>0.1831</td>
</tr>
</tbody>
</table>

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For the segmentation of the subsample, CloudCompare software has been used from the alignment of the point sets of the BLK360 and RIEGL VZ400i. Two samples are obtained, one of them from the Riegl VZ400i scanner with 61 points, which is equivalent to 1 point for every 41 mm$^2$. In the case of the BLK360 scanner, 146 points have been obtained, which is equivalent to 1 point for every 17 mm$^2$.
mm²: The distribution of the point distribution can be seen in Figs. 11 and 12 (see Fig. 13).

The second set of points has the purpose of choosing a flat element, in this case, the part of one of the paintings of the altarpiece. For this, the segmentation of the subsample has been carried out in the same way as the previous one, once the sets of points of the BLK360 and the RIEGL VZ400i have been aligned, two samples are obtained, one of them from the Riegl VZ400i scanner with 62 points, which is equivalent to 1 point for every 79 mm². In the case of the BLK360 scanner, 198 points have been obtained, which is equivalent to 1 point for every 24 mm²: The distribution of the point distribution can be seen in Figs. 14 and 15 (see Fig. 16).

7.4. Evaluation in geomatics applied to BIM

One of the new paradigms that BIM encompasses is the application of the methodology to historical buildings; therefore, one of the objectives of HBIM is to create a 3D model with rich semantic coverage [10] providing parametric objects in the representation in historical buildings. This collaborative BIM methodology can handle information obtained from precise records, and allows the direct import of point cloud data in interoperable formats [66]. have devoted special effort to modeling historic architecture from the records generated by LiDAR. This information serves as an auxiliary tool where you can compare the different forms between records used in any investigation. Most of the heritage scanning jobs are used for Scan-to-BIM, since the records represent a potential in quality and precision to lift modeling jobs in both new buildings and historic buildings. As BIM technology can insert point clouds and work with auxiliary reference elements in real time, in this research work, the two captures of both the Global TLSGiB point set and the Global TLSGiv point set are tested. Both sets are superimposed in the same coordinate system according to the references of the RIEGL VZ400i scanner that has a real-time georeferencing system. Being an interior enclosure, and with the objective that the scanner’s GGSS receiver geopositions the point cloud, the scanning process began outside, right at the front of the church, the scanning record ends at the same point of source. The Level of Accuracy (LOA) and its specifications are a reference standard that enables Architecture, Engineering,
Fig. 12. Mesh distribution of cornice segmentation. a) Points registered with the BLK360 scanner, b) Points registered with the RIEGL VZ400i scanner.

Fig. 13. Box plots of survey point density in cornice segmentation.

Fig. 14. Distribution of points of the segmentation in box. a) Points recorded with the BLK360, b) Points recorded with the Riegl VZ400i.
Construction and Ownership (AECO) professionals to clearly specify and articulate the accuracy and means by which to represent and document the existing conditions (USIBD). The LOA levels are an attempt to address the challenges associated with digitization and in another sense to reach deformation measurements of existing buildings [67]. But especially the guide demands a certain accuracy in the capture of data and in the representation. This precision can be evaluated through BIM digital platforms, in which the point cloud is inserted in a georeferenced way in Autodesk® Revit or Graphisoft ArchiCAD as an interoperability element in which the point cloud can be viewed in plan, elevation and section, as well as 3D visualization. ArchiCAD, for example, can make sections to trace the geometric profiles of existing objects and buildings. This analysis and identification of the point cloud supposes seeing in its dimension information about the characteristics of the point cloud, in relation to proportionality, distribution, homogeneity, and density of points. Different levels of precision are expressed in standard deviation parameters. The deviation of a point cloud-based BIM object.

7.5. Distance and orientation deviation

Although the analysis established at point 7 can be considered as a good way to check the variation of the geometries obtained by both teams, it would be interesting to advance the knowledge of both techniques by providing information on the distance and orientation deviation between TLS$_{A}$ and TLS$_{B}$. The evaluation of the quality of BIM models with the point cloud is becoming a common practice through analysis of patterns of geometric deviations [37,68]. In addition, the analysis of orientation deviation in camera settings for photogrammetry in interior spaces [69]. Except for studies like Crob’s that address a new “AlignNet-3D” algorithm to align point clouds, none go beyond comparison in point-cloud orientation deviation [70]. From open-source software such as CloudCompare, it becomes complex to perform an evaluation of the distance and orientation deviation between the two point clouds. Thus, it has been decided to take advantage of the domain characteristics of both symmetry and specific regularities of both sets of points and make a selection of points through segmentation of units of chosen points. An origin is taken through a natural point that

![Fig. 15. Mesh distribution of box segmentation. a) Points recorded with the BLK360, b) Points recorded with the Riegl VZ400i.](image)

![Fig. 16. Box plots of density of survey points in the segmentation box.](image)
corresponds to point n°3 found in Fig. 4. From here, the measurements of the georeferenced points in a local system are taken until the angle to the point is measured in two planes. point n°16 of the aforementioned figure. The angles of variation in the (x,y) plane is 0.0214° and in the (y,z) plane it is 0.0079°.

In order to continue evaluating the orientation deviation, the different deviations that appear between TLS$_{IB}$ and TLS$_{IR}$ have been analyzed, through average distances that appear when a segmentation is made by cutting areas of 4 mm thick. In the capture of points discontinuities can be observed, these measurements of average distances in a universal angle system yield a graph where the blue line represents the orientation deviations between TLS$_{xy}$ equipment in the (x,y) plane and TLS$_{yz}$ representing online red referring to the plane (y,z).

8. Discussion of results

Personal Laser Scanning (PLS) has been configured as a very promising solution for the use of Scan-to-BIM. It is very light equipment and easy to use. In addition, the incorporation of advanced software on a digital tablet or smartphone allows the vision and management of the scanning work in the field. Applications for mobile devices, such as Leica Cyclone FIELD 360, link 3D data acquisition directly in the field with laser scanner equipment - RTC360, BLK360-, reinforcing the effectiveness of 3D virtual reality capture. On the site, the user captures, records, and examines the scan and image data. This cycle ends with the review and precise coupling of data from the different registers using Leica Cyclone REGISTER 360 software. An essential feature is added, and it is its price content that makes it affordable for many professionals. In the work presented, the post-processing was done entirely in Cyclone Register 360 on a PC.

Also in a data collection process it is important to be able to record the coordinates of the Ground Control Points (GCPs) that are used to verify measurements and coordinates, especially for complementary techniques carried out with Structure from Motion/Multi-View-Stereo. In this sense, a comparison was made between the topographic equipment between a total station and a laser meter. The results, as can be seen in Fig. 5, vary between 0.0250 m and 0.1300 m, in a range between 6 and 25 m in length of the equipment. The difference between the x and z axes is less than with respect to the y axis, with the readings acting more similarly between the red and green lines than between the blue lines. It is conclusive that the greater the distance of the record from the set of points to the equipment, the greater the variation between records. This fact is especially due to the fact that the Leica DISTO S910, even though it has a reading sight, has fairly relative precision given the low zoom of the camera. The readings are always referred to their center of measurement and therefore the accuracy of the laser is up to the operator. In the total station, the eyepiece joins the optical centers of the objective, being more precise, and its zoom magnification in long range stations is extraordinary. Even so, and if we compare the results obtained in Table 2, the average distance between these two GCPs measurement equipment is 0.0234 m, that is, two with 34 cm of difference, being an acceptable value for complementary measurements to photogrammetry or work of Scan-to-BIM (see Fig. 17).

In relation to the main study of the difference between the TLSi BLK360 and TLSi RIEGL VZ400i scanners, a study on the deviations of the measurements made using the ICP comparison algorithm. For the analysis we saw in the previous sub-chapter that it is carried out in two phases. The part of the altarpiece the average distance is 0.0061 m. And according to the analysis of the histogram (Fig. 6b) we can determine that more than 240 thousand points are below centimeter units, which means that the precision is quite similar between the equipment for these measurement ranges, such as a church or a temple. The standard deviation decreased considerably when segmenting and eliminating the outliers of the survey, reaching survey 5 with 0.0199 m, as can be seen in Fig. 18.

3% of the total analyzed are residual values, and therefore 75% of the analyzed points are below 0.010 m, which can be taken as a good result for ranges between 5 and 9 m from the object to be scanned.

In relation to the experimentation carried out with the subset of points that analyzes the longitudinal section of the church taken for

![Fig. 17. Graph of distribution of distance and orientation deviation between both teams.](image-url)
a range of 5 to 45 m (represents the environment of the central nave on its epistle side), the dispersion values and that appear in the graph of Fig. 7 are very constant, due to the elimination of the residual points. Thus, the factor that changes is the maximum distance, which includes values from 35.67 m to 1.09 m as these outliers are eliminated. The main consideration is that the average of the distances obtained results in a difference between the instruments of 0.0161 m, which expresses that the precession (precision) of the BLK360 equipment and taking as reference the best quality of the RIEGL VZ400i despite having considered only two logs is 16 mm in lengths up to 50 m. In the ICP evaluation histogram, Fig. 9, it is shown that eighty three percent of the points are below 3 cm of difference. The dispersion of the maximum values is due to the fact that, as appears in Fig. 8 and because the records were taken in two different stages, there has been movement of candlesticks and stretchers of Holy Week steps that were placed in the transept of the church and this motivates dispersion of 2.26 m.

In general, the BLK360 behaves well in capturing records, for example, in Fig. 18 it shows a variability of 0.0320 m that may be due especially to the position and angle of the scanner records made, noting that the point cloud of the RIEGL VZ400i registers is missing to absorb the angles of sculptures and pilasters of altarpieces, reaching dimensions of 11 to 23 cm as represented in Fig. 19 in the red scale.

There are also dispersions in the glasses according to Fig. 20 where it is shown that the RIEGL VZ400i scanner does not generate readings in the windows. When scanning a glass surface, much of the light emitted by the laser passes through the glass, producing very little reflection. Dot scattering on glasses may be due to change in sunlight at the time of scanning. This figure shows the overlap between the two point clouds.

The accuracy of the research study is carried out in all case studies at the submillimeter level, that is, at units of 100 μm (μm). The precision (precision) of the equipment according to the manufacturers is around 4 mm at distances of 10 to 20 m, although a priori it may not make sense to reach that level of analysis, it is determined that it is necessary to consider 3D models that are of the same

Fig. 18. Results of the five consecutive evaluations of segmentation in the altarpiece.

Fig. 19. This image forces the color map range parameters for further comparison. Data from the comparison C2C absolute distance between point clouds. Unit: meters (X-asis). Visualization mode. Heat maps of distance distributions. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)
operator should deal with the point cloud that serves as an auxiliary element or as an essential parameter in a flow. Automatic Scan-to-
structure is found in an orthogonal network. Instead, the BLK360 scanner BIM workflow. The results indicate that the point structure of the RIEGL VZ400i scanner is more robust in the sense that a better
two case studies, taking as an example a complex shape of a cornice and another taking into account the flat shape, affects how the BIM
from the RIEGL VZ400i scanner with 61 points, which is equivalent to 1 point for every 41 mm², and in the case of the BLK360 scanner,
density with which the complex forms from architecture are carried out to model the building. The idea of experimentally analyzing
being relatively new and unpublished. Thus, the first approach that is exposed is to consider if there are a number of points of average
Visualization mode. Heat maps of distance distributions.

In the same field of study, the suitability of the density of points in the records analyzed for modeling in BIM is analyzed, this field
being relatively new and unpublished. Thus, the first approach that is exposed is to consider if there are a number of points of average
density with which the complex forms from architecture are carried out to model the building. The idea of experimentally analyzing
two case studies, taking as an example a complex shape of a cornice and another taking into account the flat shape, affects how the BIM
operator should deal with the point cloud that serves as an auxiliary element or as an essential parameter in a flow. Automatic Scan-to-
BIM workflow. The results indicate that the point structure of the RIEGL VZ400i scanner is more robust in the sense that a better
structure is found in an orthogonal network. Instead, the BLK360 scanner’s registry is scattered and messy. The results are obtained from the RIEGL VZ400i scanner with 61 points, which is equivalent to 1 point for every 41 mm², and in the case of the BLK360 scanner, 146 points have been obtained, which is equivalent to 1 point for every 17 mm². These results are different from those obtained by DlesK et al. [15], which mentions density levels for the BLK360 scanner of 1 point by 4 mm², which seems excessive to us (without taking into account the number of parking lots, since it does not mention it according to our experimentation. It is estimated that the density of points depends on the number of scans, in this experiment, two setups were carried out with the RIEGL VZ400i scanner and 18 setups with the BLK360 scanner with an overlap force of 70%. The RMS values for the complex surface survey determine lower distance values for the first, second, and third quartiles of their range distribution for the RIEGL VZ400i survey. On the other hand, in the flat surface survey, both scanners show similar results, except for some scattered value of the BLK360. This means that both scanners have characteristic similarities in analyzing flat shapes, but on the other hand, in curved or complex shapes, the RIEGL VZ400i scanner behaves more solidly. This fact is important to subsequently bring to BIM the complex and organic forms that appear in architecture. In the Evaluation section through applied geomatics. Researchers such as Rebolj et al. [73] have mentioned the quality of the point cloud at three levels; i) defining the quality parameters, ii) evaluating those parameters, and iii) defining a scanning plan to achieve better quality. In general, accuracy and point density are the two most important measures for assessing point cloud quality [24]. In our work, the density of points has to do with the number of scans, so these data are totally indicative of how to achieve reliable and operational sampling in BIM. Regarding the minimum requirements between the two devices, it must be said that the Leica BLK360 scanner has a different handling, since it does not have an integrated touch screen like the RIEGL VZ400i scanner. To configure the scanning program, it must be done from the Cyclone Field 360 application integrated in the tablet that accompanies the scanner. One of the requirements is the orientation of the tripod leg that must be locked in the same orientation of the different parkings. The data post-processing time is very similar between the two (150 min). Another advantage is the availability of thermal images, an option that can be selected to configure a panoramic thermal image of 70 V × 360 Hz. In addition to reinforcing and verifying the geometric variations obtained by both teams, the orientation deviation was addressed, verifying that, aligned to the point clouds, the results of records that are separated from a point of origin referenced their orientation angles in the plane (y, z) are lower than those of the (x, y) plane, verifying that the values are included in very small units. These results can give us important data to calculate the deviations of the point cloud with respect to the construction of BIM models. The benefit of knowing the deviations of the respective angles according to the graph at point 7.5 will determine which point cloud to choose in the construction details, such as cornices, impost, and other architectural elements, and how the model will vary depending on the data capture. and its angle of incidence.
With regard to obtaining an evaluation of the global deviation of the two sets of points TLSA and TLSB, the cloud-to-cloud comparison is made using the Iterative Closest Point (ICP) algorithm in CloudCompare, based on the search for pairs of adjacent points. On the two data sets and then compute the transformation parameters between the subsets. To proceed with this comparison and in the same CloudCompare software, both point clouds were decimated to fifty percent by random procedure, eliminating additional points that would otherwise slow down the software’s processing capabilities. Decimating the point cloud is an operational way of working, and it is used in other investigations and with other software, such as Cyclone [74] or CloudCompare [75]. Next, it proceeds in two steps. Firstly, residual point treatment is not performed, such as the removal of internal noise of objects that have been modified or passing people is not performed. The results of the global deviation of this first phase show an average deviation of 0.2701 m and a standard deviation of ±0.5058 m. Secondly, and once the possible maximum deviations have been detected (visible more perceptibly when both clouds are merged), the points that alter the results and that include nonsignificant points are eliminated. The results in this second phase provide a global deviation of 0.0266 m and a standard deviation of ±0.1253 m, obtaining results that are closer to the value obtained in the analysis of the central nave.

9. Conclusions

This research establishes the precision that easy-to-use and cheaper devices related to reverse engineering can acquire, such as PLS, compared to conventional stationary ones. These instruments help engineering and scanning works in architectural heritage, as they scramble the modeling of complex 3D geometry with great ease. The study is developed on two levels, selecting two spaces within the interior of the Church of the Annunciation in Seville.

A space between 5 and 9 m, determined by reduced dimensions such as an altarpiece and another, at a global level that includes the length of the church nave of 45 m. The results of the analysis of the latter show that the difference between the two scanners, the PLS and TLS, are not large, reaching differences of millimeters and, therefore, we understand that they are admissible for a Scan to BIM procedure. If the specific LOA levels of precision for heritage buildings can be between 0 and 5 cm from a lower range to a higher range, the fact that the difference between both instruments is 16 mm indicates that their use is perfectly admissible. The USIBD Leve lof Accuracy Specification Guide dictates the levels of precision and here the LOA20 defines it in a range between 0.0500 and 0.0015 m. In relation to the distribution of the point cloud according to the section of both point clouds, the one obtained by the RIEGL VZ400i scanner is more uniform and coplanar than that of the BLK360, this may also be due to the large number of parking lots that took place at the PLS. It is evident that there must always be quality variations in this sense between both devices precisely because of the recording procedures used, the quality of the processing software algorithm and the scope that are not evaluated in this work and could be investigated in future works.

In different situations, due to the complexity of the historical buildings environment, it is necessary to segment the point cloud into smaller portions where more conclusive data can be extracted, therefore, the density of points is not a determining factor when using it as an auxiliary element to lift in BIM. A homogeneous distribution of points is necessary for complex figures to be fully defined. For example, in the case study, cornices or bases that have specific characteristics and shapes.

On the other hand, the evaluation in the use of two point clouds processed in different software complicates its execution. Although we perform georeferencing through control points, in the chosen comparison software there are alignments that are difficult to establish, but the approach algorithms used allow us to improve this task in the research process. In the use of control points, there are also low-cost topographical instruments, and in this research work the use of a total station, the Leica Flexline TS02, has been compared with the Leica DISTO S910 as an auxiliary work team. The results and the analysis that have been obtained mean that the low-cost measurement instruments are used for short measurements in architectural heritage, although, as we have seen, there are uses for civil engineering. The differences of 2 cm of these devices compared to those of the most qualified devices can have limitations in the field of engineering. Essentially, the variations that we have detected in the use are due to the precision of the sight that the control points can vary.

Regarding the minimum requirements between the two teams. It should be said that the Leica equipment has a different handling since it does not have a touch screen for the configuration of the scanning program like the RIEGL VZ400i. This must be done from the Leica Cyclone Field 360 application that is incorporated into the Tablet. It only requires the condition of locked orientation in the different positions of the scanner, which is done through a marking on the tripod leg. The processing time is faster than the RIEGL VZ400i due to its agility. A great advantage is the availability of thermal images. In addition to the aforementioned limitations, it must be said that the subsets of points obtained from the different teams allow for the analysis of the data carried out. The results must be interpreted according to the number of parking lots, the quality of the equipment, and the environmental conditions at the time of each registration. Ground measuring equipment occupies an essential space to record accurate measurements. For this reason, the RIEGL VZ400i scanner can achieve long-length measurements, while the BLK360 scanner is more limited in this regard. In shorter spaces, both scanners have similar characteristics to analyze flat shapes, but, on the other hand, in curved or complex shapes, the RIEGL VZ400i scanner behaves more solidly.

Author statement

Juan José Moyano Campos: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Software, Supervision, Visualization, Writing - original draft, Writing - review and editing, Angel Justo Estebanaráz: Data curation, Resources, Visualization, Writing - original draft, Writing, Project administration, Juan Enrique Nieto Julián: Data curation, Software, Supervision, Validation, Alfonso Ojeda Barrera: Data curation, Software, Resources, María Fernández-Alconcél: Visualization, Writing - original draft, Writing.
Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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