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COMPARISON OF SURVEYING TECHNIQUES FOR THE BUILT ENVIRONMENT: A LITERATURE REVIEW AND PRACTICAL EVALUATION

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SUMMARY*: The rehabilitation of buildings and old structures is becoming more frequent in developed countries, but information about them is often limited. The basic necessary information consists of the geometry of the elements, to which other attributes such as the state of conservation can be added. This paper evaluates geometric survey techniques in which non-invasive methods are used to collect detailed data on buildings, structures, and their surroundings. These techniques enable the generation of 3D digital models from point clouds representing surfaces, and may include properties such as colours and textures. In this research, survey techniques and their associated equipment are first identified. They are then grouped and compared, in order to summarise their benefits and limitations. Following this, a practical evaluation based on four small-scale case studies comprising several tests was conducted in indoor and outdoor environments. The experiments were intentionally limited in scope and equipment availability and were designed to provide comparative evidence under real-world conditions rather than a comprehensive validation of all surveying scenarios. The qualitative and quantitative results were analysed and compared with findings reported in the literature. The findings indicate that when choosing the most suitable technique for obtaining an accurate and high-quality model, it is necessary to consider the characteristics of the construction and the requirements of the survey to be carried out. Laser scanning gave results with better accuracy and consistency; in contrast, photogrammetric surveying was found to be highly dependent on the on-site conditions, with a non-negligible variation in accuracy, although photogrammetry may offer a favourable cost-benefit ratio under suitable acquisition conditions.*

KEYWORDS*: surveying, photogrammetry, laser scanning, built environment, digitisation.*

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1. INTRODUCTION

The architecture, engineering, construction, operations and maintenance (AECOM) sector is currently undergoing a significant transformation in terms of the materials, technologies, practices, and techniques applied as part of its daily activities (Li et al., 2025; Tan et al., 2022; Biswas et al., 2024).

Rehabilitation, which involves the reuse of existing infrastructure and resources (Thibodeau et al., 2019), has become one of the most important aspects of the AECOM industries, due to the large number of existing buildings. This trend has led to a significant increase in the number of rehabilitation projects, making it necessary to implement new technologies that facilitate more efficient and faster interventions (Riveiro and Lindenbergh, 2019; Casapulla et al., 2025; Kallas and Napolitano, 2023; Cheng et al., 2019; Werbrouck et al., 2020). However, a lack of detailed information about the current conditions of the buildings and spaces to be rehabilitated has increased the need to collect greater amounts of data (Penjor et al., 2024). This issue arises due to inadequate information collection during the construction phase and a lack of updated data regarding the state of these buildings. To address this problem, techniques have been developed that enable the detailed collection of geometric data on the buildings and environments under consideration (Albeaino et al., 2019). There are various non-invasive methodologies, techniques, and tools, including both manual and digital, for performing geometric surveys of buildings without compromising them, which generate a point cloud representing the surface of the surveyed element (Fu et al., 2021; Drobnyi et al., 2023). A point cloud is a set of three-dimensional data that represents the surface of an object; each point has a set of coordinates, which may be either global or local, and the data may also include properties such as colours (ACCA, 2023; Groetelaars, 2016). The density of a point cloud enables the creation of not only simple representations but also highly detailed models (Al-Bayari and Shatnawi, 2022; Nadolinets et al., 2017).

Previous studies generally indicate that terrestrial laser scanning provides greater geometric accuracy and consistency than photogrammetry and handheld laser scanning, although these advantages are associated with higher equipment costs and more structured acquisition procedures (Peña-Villasenín et al., 2019; Mulè et al., 2022). Handheld laser scanning offers greater portability and operational flexibility, but its accuracy may be affected by movement, physical obstacles, and the characteristics of the surveyed environment (Fawzy, 2019; Mulè et al., 2022).

Photogrammetry is generally more accessible, versatile, and cost-effective, and can produce photorealistic models (Fassi et al., 2013; Talha et al., 2019; Masiero et al., 2018). However, its performance is strongly influenced by lighting conditions, camera quality, the number and overlap of images, acquisition geometry, and accessibility (Fawzy et al., 2019; Ismail, 2022; Cunha et al., 2022). Although several studies report greater accuracy for laser scanning, other investigations indicate that terrestrial or aerial photogrammetry can achieve competitive results under favourable acquisition conditions (Eker, 2023; Cunha et al., 2022). Photogrammetry may consequently be used either as a complementary method or as the principal surveying technique, depending on the project requirements (Guarnieri, 2004; Cunha et al., 2022).

Hybrid approaches combining laser scanning and photogrammetry can improve model completeness and accuracy by integrating the geometric consistency of laser scanning with the visual information provided by photogrammetry (Alshawabkeh et al., 2020). Overall, the literature identifies consistent trade-offs between accuracy, cost, portability, acquisition constraints, and model quality, rather than a surveying technique that is universally superior.

Although photogrammetry and laser scanning have been extensively investigated, previous findings are often specific to particular technologies, equipment configurations, acquisition conditions, or application contexts. Limited attention has been given to integrating the classification of surveying techniques, the comparison of currently available equipment, and their practical evaluation using common assessment criteria. To address this gap, this paper combines a structured comparison of geometric surveying techniques and equipment with a practical evaluation of selected technologies under different acquisition conditions.

The contribution of the study therefore lies not in proposing a new surveying technology or methodology, but in providing an integrated and application-oriented synthesis that connects equipment characteristics, literature-based assessment criteria, and practical observations obtained under different real-world acquisition conditions.

Accordingly, the following research question was defined: How do the performance trends reported in the literature for photogrammetry and laser scanning translate into practical trade-offs in terms of accuracy, acquisition effort, cost, portability, environmental sensitivity, and model quality under different real-world acquisition conditions?

The scope of this study is limited to the comparison of data acquisition technologies and the geometric quality of the resulting models. Although these models may subsequently support building inspection, condition assessment, or defect mapping, the automatic or manual identification and classification of building defects is not evaluated in this work.

Section 2 describes the methodology used for the study. In Section 3, existing geometric survey techniques are classified, the advantages and disadvantages of each are discussed, and the latest equipment available on the market is summarised and compared. Section 4 introduces the various case studies, along with the techniques and equipment used. In Section 5, the qualitative and quantitative results are analysed and discussed. Finally, Section 6 presents the conclusions of the work carried out here.

2. METHODOLOGY

In order to meet the objectives of this study, a methodology was implemented (Figure 1) that consisted of three phases: (i) research, classification, and comparison of the respective techniques and the equipment available on the market; (ii) execution of a practical case study in which some of these techniques were applied to real cases; and (iii) analysis of the qualitative and quantitative results, including identification of the advantages and disadvantages of each technique and an evaluation of their accuracy.

In Phase 1, a survey of currently existing surveying techniques was carried out, which involved first identifying and classifying the techniques, and then subdividing them by the type of application. Next, for each technique, research was conducted on the main equipment available, and the most up-to-date equipment on the market was sought from among the leading brands dedicated to the development of these technologies.

In Phase 2, several case studies were conducted, each with specific objectives and study variables (exterior and interior spaces, techniques, equipment, and other variables from surveys). Geometric surveys were then carried out, which culminated in the processing of the digital information to create 3D models.

In Phase 3, the results obtained from each test of the case studies were analysed through both qualitative and quantitative analysis, in order to determine which parameters influenced the measurements most strongly, and to calculate the accuracy of each technique.

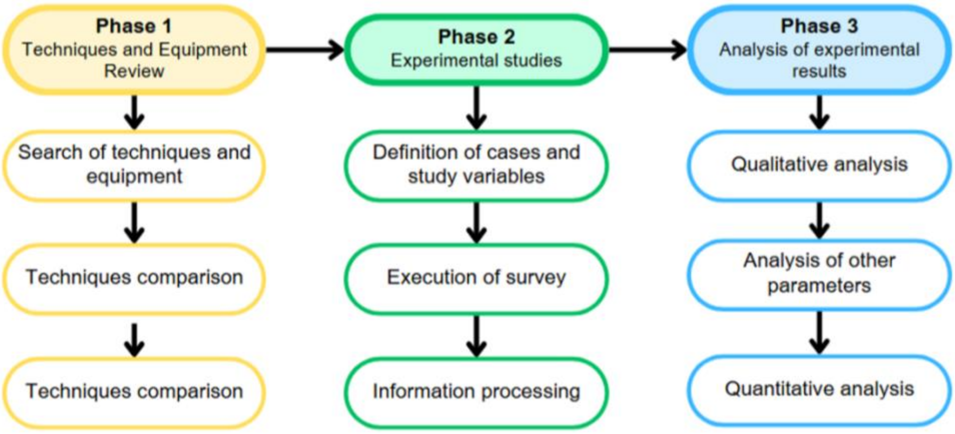

Figure 1: Methodology.

3. REVIEW OF SURVEYING TECHNIQUES AND EQUIPMENT

3.1 Surveying techniques

A search for scientific publications in ScienceDirect was conducted using the following Boolean operators: ("existing heritage" OR "heritage buildings" OR "historic buildings") AND ("surveying techniques" OR "survey methods") AND ("photogrammetry" OR "laser scanning" OR "laser scanner"). Only publications from the last 10 years were considered, and a total of 98 results related to geometric surveying techniques were obtained. After analysing the titles and abstracts of the papers, the most relevant ones were selected, resulting in 35 papers. An additional 35 papers from other searches conducted by the authors were considered, giving a total of 70 papers that were considered at this stage. Based on these publications, the geometric surveying techniques were classified, grouped based on the technology used to carry out the surveys, and then subdivided according to the mode of operation and functioning of the equipment. Table 1 shows the classification for each of the geometric surveying techniques considered here.

Table 1: Classification of geometric surveying techniques.

Techniques	Type	References
Traditional Surveying	Manual Measurement	(Al-Bayari and Shatnawi, 2022; Nadolinets et al., 2017; Dimitriou and Kontovourkis, 2024; Cavalagli et al., 2020); Biagini et al., 2016; Jeong et al., 2020; Shanoer and Abed, 2018; Avram et al., 2016)
	Optical Measurement	
Photogrammetric Surveying	Terrestrial Photogrammetry	(Dimitriou and Kontovourkis, 2024; Cavalagli et al., 2020; Biagini et al., 2016; Jeong et al., 2020; Shanoer and Abed, 2018; Solla et al., 2024; Giuffrida et al., 2022; Yan and Wang, 2025; Al shawabkeh and Arar, 2024; Gomes and Tomé, 2023; Pérez-Martínez et al., 2024; Lagüela et al., 2024; Lukito, 2025; Fiorillo et al., 2023; Pirchio et al., 2021; Trizio et al., 2024; Maltezos and Ioannidis, 2018; Radanovic et al., 2020; Shariq and Hughes, 2020; Paal et al., 2020; Baik, 2017; Ferri et al., 2019; Cabaleiro et al., 2015; Fryskowska and Stachelek, 2018; Collier, 2020; Wolf et al., 2014; Shen et al., 2023)
	Close-Range Photogrammetry	
	Aerial Photogrammetry	
	Spatial Photogrammetry	
	Underwater Photogrammetry	
Satellite Surveying	Absolute Positioning	(Maltezos and Ioannidis, 2018; Jerez and Marra Alves, 2022; Leica Geosystems, 2023, Galhardo, 2018; Guandalini, 2012)
	Relative Positioning	
Laser Scanning	Terrestrial Laser Scanning	(Solla et al., 2024; Giuffrida et al., 2022; Yan and Wang, 2025; Ursini et al., 2022; Pham et al., 2024; Gomes and Tomé, 2023; Pérez-Martínez et al., 2024; Lagüela et al., 2024; Lukito, 2025; Dimitriou and Kontovourkis, 2024; Trizio et al., 2024; Cavalagli et al., 2020; Wilson et al., 2018; Biagini et al., 2016; Radanovic et al., 2020; Valero et al., 2018; Korumaz et al., 2017; Buill et al., 2015; Shariq and Hughes, 2020; Paal et al., 2020; Baik, 2017; Ferri et al., 2019; Jeong et al., 2020; Cabaleiro et al., 2015; Fryskowska and Stachelek, 2018; Shanoer and Abed, 2018; Sanhudo et al., 2018; Keitaanniemi et al., 2021; Bornaz and Rinaudo, 2004)
	Aerial Laser Scanning	
	Mobile Laser Scanning	
	Handheld Laser Scanning	

From an analysis of the selected publications, the various advantages and disadvantages of each of the geometric surveying techniques were identified, to enable a determination of which approach is best suited to the needs of the work to be carried out. The following subsections present an analysis of each technique.

3.1.1 Traditional survey

A wide variety of measurement equipment is available for use in surveys, which is referred to in this paper as traditional techniques. This equipment is used in various fields to give reference measurements or as a practical and quick way to obtain point measurements (Nadolinets et al., 2017; Avram et al., 2016).

The most important aspects when choosing equipment for a particular piece of work are its versatility in terms of use and transport, cost-benefit ratio, and ease of use. Table 2 shows the main advantages and disadvantages of this technique, based on the information in the selected papers, websites, and specialised books. This type of survey can only be used as a support and reference tool; as a standalone approach, it cannot give a complete survey of elements in great detail, but due to its versatility, it continues to be commonly used.

3.1.2 Photogrammetric surveying

Over time, and following technological developments, there have been significant improvements in the quality of images captured with photographic devices. This technology is now within the reach of most people, as it is integrated into the cameras of the mobile devices that are used daily, as well as into other equipment such as drones, aquatic and submersible vehicles, which can be adapted to the purposes for which they are used (Collier, 2020; Wolf et al., 2014; Shen et al., 2023). Some of the most important aspects when choosing the equipment that is best suited to the objectives of a survey are its versatility, the cost-benefit ratio, the quality of the images obtained, and the battery life. Table 3 summarises the main advantages and disadvantages of photogrammetric surveying. Although photogrammetry surveys can be both complete and accurate, and may include colour and texture data on the elements, the quality of these surveys is strongly conditioned by the conditions of the space, such as accessibility and lighting, as well as the resolution of the equipment (Peña-Villasenín et al., 2019; Cunha et al., 2022).

Table 2: Advantages and disadvantages of traditional surveying techniques.

Technique		**Type**	**Advantages**	**Disadvantages**
Traditional Survey	Manual Measurement	General	• Practical and versatile; • Does not require advanced technical knowledge.	• Subject to human error.
		Measuring Tape	• No need for specialised equipment.	• Low precision; • Time-consuming for complex surveys; • Only suitable for linear measurements; • Limited to the physical length of the tape; • May require assistance from 2 or more users.
		Odometer	• No need for specialised equipment; • Can be operated by a single user; • Allows continuous measurement of long distances.	• Low precision; • Only suitable for linear measurements with minor deviations; • Not suitable for irregular terrain.
		Laser Distance Meter	• Faster and more accurate measurements; • Can be operated by a single user; • Can measure long distances.	• Only suitable for linear measurements; • Requires a clear and defined line of sight; • Most expensive among manual measuring tools.
	Optical Measurement	General	• Higher precision compared to manual measurements; • Allows distance measurement; • Good accuracy.	• Visibility issues with target points; • Requires more than one user; • Expensive equipment; • Time-consuming setup and data collection; • Requires specialised equipment; • Bulky equipment; • Requires frequent calibration; • Uncertainty in relocating the equipment.
		Theodolite	• Lower cost compared to a Total Station.	• Requires knowledge of trigonometry; • Manual recording of surveyed points.
		Total Station	• Digital data recording; • Surveying using local coordinate systems; • Integrated laser distance measurement.	• Time-consuming for surveys involving a large number of points.

3.1.3 Satellite surveying

Global Navigation Satellite System (GNSS) receiver antennas are used for georeferencing in surveys carried out in the field. There is a wide variety of antennas available on the market, which can be used for geometric surveying on their own or coupled with other surveying equipment (Jerez and Marra Alves, 2022).

Table 3: Advantages and disadvantages of photogrammetric surveying techniques.

Technique	Type	Advantages	Disadvantages
Photogrammetric Surveying	General	• Easy and rapid deployment; • Use of common photographic equipment; • Capable of creating photorealistic models; • Non-invasive technique; • Easy to transport; • Can be operated by a single user; • Lower cost compared to Laser Scanning	• Sensitive to poor lighting conditions; • It is necessary to have software capable of processing all the details and the large amount of data.
	Terrestrial	• Can be used in the monitoring of spaces to study their evolution over time;	• Problems with limited access to certain areas; • Has reduced accuracy when compared to other techniques.
	Close Range	• Greater precision in the details of the elements; • When small elements are studied, they are easy to handle and control in terms of light exposure; • Used in various fields such as archaeology and medicine.	• Used only in the survey of small elements where greater precision is required.
	Aerial	• Capable of obtaining information from elements that are not reachable from the ground; • Can capture larger areas from the air; • Equipment for individual use in the field and even remote-operated.	• Problems controlling UAS in windy weather; • Depending on the distance to the objects, it may have trouble capturing small details; • Its use is not recommended in areas with many obstacles, cities, or zones with dense vegetation; • Depending on the UAS, it is necessary to request the respective licenses; • Risk of losing the equipment.
	Spatial	• Accessible to anyone; • Provides an overview of any element, without the need to mobilize equipment or personnel; • Used for monitoring in areas such as communication routes, agriculture, forestry studies, urban planning, etc.; • Approximate models of the terrain are obtained.	• Low precision in the details; • The 3D models need to be complemented with more information from other techniques.
	Underwater	• Capable of collecting data from submerged elements; • Can be used in the monitoring of underwater ecosystems to study their evolution over time.	• Requires specialised equipment and qualified personnel; • Low accuracy due to distortion caused by water; • At greater depths, problems occur due to low lighting; • Operational problems due to pressure when submerged; • Risk of losing equipment.

A very important factor to consider when selecting a receiver is its accuracy in surveying georeferenced coordinates, which can vary depending on the method by which the coordinate information is transmitted between the base station and the antennas (Guandalini, 2012). Other aspects to consider when choosing a GNSS receiver are its battery life, cost-benefit ratio, ease of transport, and the possibility of integration with other geometric surveying equipment. Table 4 shows the main advantages and disadvantages of satellite surveying, drawn from the selected literature. This technique serves as a support tool for the orientation and correction of the collected data, and cannot be used on its own to carry out a complete geometric survey of a space.

3.1.4 Laser scanning

Laser scanning is one of the most accurate techniques, and leads to the creation of very precise and complete models. It requires more complex equipment than the other approaches, thereby allowing for a better survey of the elements of interest (Sanhudo et al., 2018; Keitaanniemi et al., 2021; Bornaz and Rinaudo, 2004). The main aspects to consider when choosing the most suitable equipment for carrying out work are its versatility of use and transport, cost-benefit ratio, measurement accuracy, scanning speed, battery life, and in some cases, maximum range. Table 5 summarises the main advantages and disadvantages of laser scanning.

This surveying technique can be considered the most complete and accurate method for obtaining complete geometric surveys of various spaces and elements, but the high cost of acquiring the equipment imposes a major limitation on the execution of this technique (Peña-Villasenín et al., 2019; Masiero et al., 2018).

Table 4: Advantages and disadvantages of satellite surveying techniques.

Technique	Type		Advantages	Disadvantages
Satellite Surveying	General		• Easy and rapid deployment.	• Requires specialised equipment.
	Absolute		• Real-time data acquisition; • Mainly used for navigation systems.	• Low accuracy; • Data is not processed; • Time-consuming to obtain more precise data.
	Relative	RTK/UHF	• Good performance in rural areas with limited network; • Fast data acquisition.	• Poor performance in areas with many buildings; • Lengthy installation process; • Use of two receivers in the field is necessary; • Accuracy problems in rainy weather; • The base station and the receiver should have a maximum separation of 5 to 10 km; • More equipment is needed in the field; • They can be targets for theft.
		RTK/GSM	• Good performance in urban areas with more developed telecommunications networks; • Only one receiver is needed in the field; • Can be operated by a single user.	• Poor performance in rural areas or with limited network.
		Network RTK	• Good performance in urban areas with more developed telephone networks; • Greater accuracy in the data obtained; • More practical and simple; • Use of only one receiver in the field; • Can be operated by a single user.	• Poor performance in rural areas or with limited network; • It is necessary to hire an NTRIP service, making it more costly.

3.2 Equipment

For each type of equipment available for each of the geometric surveying techniques, a search was conducted using the Google search engine to identify existing equipment from the brands mentioned in the bibliographic research papers, as these included some of the main brands to have developed this type of technology. Technical information for each piece of equipment was obtained directly from the websites and technical sheets for each brand, based on a selection of the most current equipment. The most important characteristics of each type of equipment were identified and compared to enable the most comprehensive study possible.

For each surveying technique, the most suitable equipment varies according to aspects such as the site conditions, accuracy of the final model, survey and processing times, and the costs associated with the equipment. The following tables describe the most relevant equipment currently on the market for the execution of each of these geometric surveying techniques, as well as their most relevant characteristics.

3.2.1 Traditional survey

Due to the large diversity of equipment currently available for manual measurements, Table 6 presents only optical measurement equipment. To evaluate factors such as versatility, practicality, autonomy, data quality, and cost-benefit ratio, it was necessary to analyse various technical characteristics.

3.2.2 Photogrammetric surveying

There is a large range of photographic equipment available, any of which can be used for this type of surveying; however, there are also more specialised forms of equipment for photogrammetric surveying, and Table 7 describes only this type. To evaluate factors such as versatility, practicality, autonomy, data quality, and cost-benefit ratio, it was necessary to analyse various technical characteristics.

Table 5: Advantages and disadvantages of laser scanning techniques.

Technique	Type	Advantages	Disadvantages
Laser Scanning	General	• High accuracy; • Can be operated by a single user; • Easy and rapid deployment;	• Requires knowledge of data-processing software and equipment; • It is not possible by itself to create photorealistic models with real textures; • Problems in reading the laser beam and controlling UAS in adverse weather conditions;
	Terrestrial	• High accuracy.	• Requires specialised equipment and software; • Time-consuming to install the equipment and carry out the survey; • Bulky equipment;
	Aerial	• Capable of obtaining information from elements not reachable from the ground; • Can capture larger areas from the air.	• Depending on the distances to objects, it may have trouble capturing small details; • Its use is not recommended in areas with many obstacles, cities, or zones with dense vegetation; • Depending on the UAS, it is necessary to request the respective licenses;
	Mobile	• Use of various vehicles to collect data; • Practical to use in areas with heavy traffic.	• Lower accuracy may result from data acquisition while the scanner is in motion.
	Handheld	• Equipment easier to transport and handle.	• Lower accuracy may result from data acquisition while the scanner is in motion.

3.2.3 Satellite surveying

Satellite surveying can be considered a complementary method to obtain complete surveys, since it cannot give enough information to create detailed and complete digital models when used alone. The most important factor to consider when choosing this type of equipment is the accuracy of the different positions of the surveyed points. To evaluate factors such as versatility, practicality, autonomy, data quality, and cost-benefit ratio, it was necessary to analyse several different technical characteristics, as shown in Table 8.

3.2.4 Laser scanning

Table 9 summarises the main equipment used for laser scanning. There is a wide variety of equipment that is capable of performing this type of survey, which allows for the creation of complete models from point clouds obtained by a laser that is capable of detecting various surfaces with great precision. To evaluate factors such as versatility, autonomy, data quality, and cost-benefit ratio, it was necessary to analyse the technical factors shown in Table 9.

3.3 Assessment criteria

To establish a consistent basis for linking the literature review with the practical evaluation, the main criteria influencing the selection and performance of surveying techniques were identified and synthesised, as presented in Table 10. Based on the literature review, seven major criteria were identified for comparing surveying technologies: accuracy, acquisition time, processing time, equipment cost, portability, sensitivity to environmental conditions, and detail. These criteria were subsequently used to interpret and discuss the results obtained in the practical evaluation.

4. PRACTICAL EVALUATION

4.1 Procedure

To achieve the objectives of this study, a practical evaluation of selected techniques and equipment identified in Section 3 was conducted. This evaluation consisted of a series of case studies with the aim of comparing various surveying equipment and techniques, with a primary focus on the field of civil engineering. To obtain the greatest amount of information possible with the available resources, the case studies were conducted with some variations in the survey conditions, such as changes to the equipment, techniques, and physical aspects of the spaces.

A total of four case studies were performed, each of which was divided into several tests that varied in terms of the techniques implemented and the way in which the necessary information was obtained to generate the final 3D models. From these models, information and measurements were extracted and compared with reference measurements, to enable an evaluation of the effectiveness and accuracy of the models in terms of digitising the various spaces and elements involved. In each case study, 18 reference measurements were defined, with six in each direction (X, Y, and Z). The calculated errors represent discrepancies relative to the adopted reference measurements and should not be interpreted as absolute instrument accuracy.

The procedure used for the practical evaluation consisted of the following steps:

1. Definition of the case studies, in both exterior and interior environments.
2. Definition of techniques, based on the equipment available for each case study.
3. Definition of the tests to be conducted for each case and the variables to consider.
4. Definition of the reference dimensions.
5. Identification of the reference dimensions using manual techniques on site.
6. Execution of the digital survey.
7. Data processing and creation of the point clouds.
8. Qualitative analysis of each point cloud.
9. Measurement of the reference dimensions for the point clouds.
10. Comparison of dimensions and calculation of the mean absolute errors.

4.2 Case studies

The case studies were selected to evaluate the quality and accuracy of the generated 3D models under different acquisition conditions and to explore the practical limitations of the surveyed techniques when applied to existing buildings. The investigated cases comprised non-heritage elements and environments and were selected primarily according to their suitability for comparing the available surveying techniques under different acquisition conditions. The case studies were not designed as identical experimental setups, but as complementary evaluations developed at different stages and locations. Cases 1 and 2 focused primarily on terrestrial photogrammetry, allowing the influence of variables such as lighting, image quantity, camera characteristics, accessibility, and acquisition geometry to be investigated. Cases 3 and 4 enabled a broader comparison between photogrammetry, terrestrial laser scanning, and handheld laser scanning in indoor and outdoor environments. Figure 2 illustrates the spaces considered: Cases 1 and 3 concern indoor environments, while Cases 2 and 4 concern outdoor environments.

Table 6: Equipment data for traditional surveying techniques.

Hardware	Type	Last Update	Dimensions (mm)	Reference Prices (€)	Battery Life (hr)	Accuracy (mm)	Maximum Range (m)	Photorealism	Automatic Prism Targeting	Prism Lock	Compatible with Remote Controllers	Compatible with GNSS Receivers
New MS60 MultiStation* Leica Geosystems	MultiStation: Terrestrial Laser + Automatic Total Station + Satellite + Photorealism	2020	7,7kg	47 K	9	1,0 [a] 2,0 [b]	10000 [a] 2000 [b]	✓	✓	✓	✓	✓
New TS60 Total Station Leica Geosystems	Automatic Total Station	2020	7,30kg		9	0,6 [a] 2,0 [b]	10000 [a] 1000 [b]	✗	✓	✓	✓	✓
New TM60 Total Station Leica Geosystems	Automatic Total Station	2020	7,20kg		9	0,6 [a] 2,0 [b]	10000 [a] 1000 [b]	✗	✗	✓	✓	✓
FlexLine TS10 Leica Geosystems	Manual Total Station	2022	4,40kg		26	1,0 - 5,0 [a] 2,0 - 4,0 [b]	10000 [a] 1000 [b]	✗	✗	✗	✓	✗
FlexLine TS07 Leica Geosystems	Manual Total Station	2022	4,30kg		32	1,0 - 5,0 [a] 2,0 - 4,0 [b]	10000 [a] 1000 [b]	✗	✗	✗	✓	✗
SX12* Trimble Geospatia	MultiStation: Terrestrial Laser + Automatic Total Station + Photorealism	2022	150x328x258 7,50kg		7	Laser: 2,5mm Optical: 1,0 [a] 2,0 [b]	5500 [a] 800 [b]	✓	✗	✗	✓	✗
S9 HP Trimble Geospatial	Automatic Total Station	2021	5,50kg		6,5	0,8 [a] 3,0 [b]	7000	✓	✓	✓	✓	✗
S7 Trimble Geospatial	Automatic Total Station	2021	5,50kg	23 K	6,5	1,0 [a] 2,0 [b]	5500	✓	✓	✓	✓	✗
C5 HP Trimble Geospatial	Manual Total Station	2022	4,40kg		18	1,0 [a] 2,0 [b]	3000 [a] 500 [b]	✗	✗	✗	✓	✗
POS 18 HILTI	Manual Total Station	2014	149x145x306 4,00kg	14 K	16	3,0	340	✗	✗	✗	✗	✗

[a] With Prism, [b] Without Prism

Table 7: Equipment data for photogrammetric surveying techniques.

Hardware	Technique	Last Update	Dimensions (mm)	Reference Prices (€)	Battery Life	Image Resolution
DMC-4 Leica Geosystems	Aerial Photogrammetry + Satellite	2024	435x560 37,10kg	-	-	40MP
ContentMapper Leica Geosystems	Aerial Photogrammetry + Satellite	2022	435x560 37,10kg	-	-	40MP
MX7 Trimble Geospatial	Terrestrial Photogrammetry + Satellite	2019	11,30kg	95 K	-	30MP
Camera 3D Pro2 Matterport	Terrestrial Photogrammetry + Satellite	-	230x260x110 3,40kg	3 K	4,5 h	134,2MP
Ricoh ThetaX Matterport	Terrestrial Photogrammetry + Satellite	-	51,7x136,2x29 0,17kg	800	3,0 h	61MP
Insta360 X3 Matterport	Terrestrial Photogrammetry	-	46x14x33,1 0,18kg	450	1,5 h	72MP
DJI Mini 4 Pro DJI	Aerial Photogrammetry	2023	148x94x64 0,25kg	809	34 min	48MP
DJI Mavic 3 Pro DJI	Aerial Photogrammetry	2023	231x98x95 0,96kg	2 K	43 min	20MP
DJI Air 3 DJI	Aerial Photogrammetry	2023	207x100x91 0,72kg	1 K	46 min	48MP
DJI Mini 3 DJI	Aerial Photogrammetry	2022	148x90x62 0,25kg	379	38 min	12MP
DJI Mavic 3 Classic DJI	Aerial Photogrammetry	2022	221x96x90 0,90kg	1 K	46 min	20MP

4.2.1 Equipment and Software

The surveys were carried out using the equipment listed in Table 11. The selection of the equipment used in each case study was determined by the specific objectives of the respective tests and by the equipment available during each data acquisition campaign. As the case studies were conducted at different times and locations, the same range of equipment could not be used in all surveys. Professional DSLR cameras were not available during the acquisition campaigns and could therefore not be included as an additional benchmark for terrestrial photogrammetry. Consequently, the terrestrial photogrammetric tests primarily focused on evaluating readily available mobile devices under different acquisition and environmental conditions.

For the terrestrial photogrammetric surveying, images were acquired manually using the mobile devices listed in Table 11, without the use of a tripod. The operators moved around the surveyed spaces and objects while attempting to maintain adequate image overlap and coverage. This handheld acquisition approach reflects the practical and low-cost nature of the evaluated workflow, although it may have introduced additional variations in camera position and orientation.

Table 8: Equipment data for satellite surveying techniques.

Hardware	Last Update	Dimensions (mm)	Reference Prices (€)	Battery Life	Absolute Positioning Accuracy	Static Relative Positioning Accuracy	Rapid Static Relative Positioning Accuracy	Relative Positioning Accuracy with Radio	Relative Positioning Accuracy with Mobile
GS18 I Leica Geosystems	2021	173x173x109 1,25kg	23 K	7 h	Hz: 25,0mm V: 50,0mm	Hz: 3,0mm + 0,1ppm V: 3,5mm + 0,4ppm	Hz: 3,0mm + 0,5ppm V: 5,0mm + 0,5ppm	Hz: 8,0mm + 1,0ppm V: 15,0mm + 1,0ppm	Hz: 8,0mm + 0,5ppm V: 15,0mm + 0,5ppm
GS18 T Leica Geosystems	2017	173x173x109 1,23kg	-	7 h	Hz: 25,0mm V: 50,0mm	Hz: 3,0mm + 0,1ppm V: 3,5mm + 0,4ppm	Hz: 3,0mm + 0,5ppm V: 5,0mm + 0,5ppm	Hz: 8,0mm + 1,0ppm V: 15,0mm + 1,0ppm	Hz: 8,0mm + 0,5ppm V: 15,0mm + 0,5ppm
Viva GS16 Leica Geosystems	2021	190x90 0,93kg	-	7 h	Hz: 25,0mm V: 50,0mm	Hz: 3,0mm + 0,1ppm V: 3,5mm + 0,4ppm	Hz: 3,0mm + 0,5ppm V: 5,0mm + 0,5ppm	Hz: 8,0mm + 1,0ppm V: 15,0mm + 1,0ppm	Hz: 8,0mm + 0,5ppm V: 15,0mm + 0,5ppm
GS07 Leica Geosystems	2021	186x71 0,70kg	-	7 h	Hz: 25,0mm V: 50,0mm	Hz: 3,0mm + 0,5ppm V: 6,0mm + 0,5ppm	Hz: 5,0mm + 0,5ppm V: 10,0mm + 0,5ppm	Hz: 10,0mm + 1,0ppm V: 20,0mm + 1,0ppm	Hz: 10,0mm + 0,5ppm V: 20,0mm + 0,5ppm
R12i Trimble Geospatial	2020	119x136 1,12kg	20 K	6,5 h	-	Hz: 3,0mm + 0,5ppm V: 5,0mm + 0,5ppm	Hz: 3,0mm + 0,5ppm V: 5,0mm + 0,5ppm	Hz: 8,0mm + 1,0ppm V: 15,0mm + 1,0ppm	Hz: 8,0mm + 0,5ppm V: 15,0mm + 0,5ppm
R780 Trimble Geospatial	2022	139x130 1,55kg	20 K	5,5 h	-	Hz: 3,0mm + 0,5ppm V: 5,0mm + 0,5ppm	Hz: 3,0mm + 0,5ppm V: 5,0mm + 0,5ppm	Hz: 8,0mm + 1,0ppm V: 15,0mm + 1,0ppm	Hz: 8,0mm + 0,5ppm V: 15,0mm + 0,5ppm
R580 Trimble Geospatial	2023	140x114 1,08kg	9 K	5 h	-	Hz: 3,0mm + 0,5ppm V: 5,0mm + 0,5ppm	Hz: 3,0mm + 0,5ppm V: 5,0mm + 0,5ppm	Hz: 10,0mm + 1,0ppm V: 20,0mm + 1,0ppm	Hz: 10,0mm + 0,5ppm V: 20,0mm + 0,5ppm
SP60 TerraGes	2015	210x210x70 0,93kg	-	10 h	Hz: 500,0mm V: 850,0mm	Hz: 3,0mm + 0,5ppm V: 5,0mm + 0,5ppm	Hz: 3,0mm + 0,5ppm V: 5,0mm + 0,5ppm	Hz: 8,0mm + 1,0ppm V: 15,0mm + 1,0ppm	Hz: 8,0mm + 1,0ppm V: 15,0mm + 1,0ppm
SP85 TerraGes	2021	222x194x75 1,17kg	-	10 h	Hz: 500,0mm V: 850,0mm	Hz: 3,0mm + 0,5ppm V: 5,0mm + 0,5ppm	Hz: 3,0mm + 0,5ppm V: 5,0mm + 0,5ppm	Hz: 8,0mm + 1,0ppm V: 15,0mm + 1,0ppm	Hz: 8,0mm + 1,0ppm V: 15,0mm + 1,0ppm

Hz: Horizontal, V: Vertical

Table 9: Equipment data for laser scanning techniques.

Hardware	Technique	Last Update	Dimensions (mm)	Reference Prices (€)	Battery Life	Maximum Accuracy (mm)	Maximum Range (m)	Scanning Speed (pts/s)
Scan Station P50 Leica Geosystems	Terrestrial Laser Scanning	2017	238x358x395 12,65kg	65 K	5,5 h (2 Internal batteries)	1,2 (to 120-270m) 3,0 (to 570-1 000m)	1 000	1 M
RTC360 Leica Geosystems	Terrestrial Laser Scanning + Photorealism	2018	120x240x230 6,03kg	52 K	4 h (2 Internal batteries)	1,9/2,9/5,3 (to 10/20/40m)	130	2 M
BLK360 Leica Geosystems	Terrestrial Laser Scanning + Photorealism + Thermography	2022	155x80 0,85kg	24 K	Up to 70 minutes of operation per battery.	4,0 (to 10m)	45	680 K
BLK2GO Leica Geosystems	Handheld Laser Scanning + Photorealism	2019	279x80 0,78kg	42 K	45-50 min	15,0-20,0	25	420 K
BLK2FLY Leica Geosystems	Aerial Laser Scanning	2021	530x600x190 2,60kg	40 K	13 min (Hot-swappable battery)	20,0	-	420 K
Pegasus TRK700 Evo Leica Geosystems	Mobile Laser Scanning + Satellite + Photorealism	2022	720x460x560 29,00kg	800 K	2,5 h	1,0	182	1 M
CountryMapper Leica Geosystems	Aerial Laser Scanning + Photorealism + Satellite	2024	435x770 55,00kg	1 500 K	8 h	V:50,0 H:130,0	6 000	8 pts/m2
X12 Trimble Geospatial	Terrestrial Laser Scanning + Photorealism	2022	150x328x258 7,70kg	100 K	5 h	0,6 (to 10m) 2,2 (to 35m) 3,1 (to 50m)	250	2 M
3D Pro3 Camera Matterport	Terrestrial Laser Scanning + Photorealism		181x76x161,4 2,20kg	5 K	3,5 h	20 (to 10m)	100	100 K
Focus Premium 350 FARO	Terrestrial Laser Scanning + Satellite	-	230x103x183 4,40kg	-	4 h	0,1 (to 10m) 0,2 (to 25m)	350	2 M
Orbis FARO	Handheld Laser Scanning	-	500x250x625 3,60kg	-	3 h	5,0 (in motion) 2,0mm (stationary)	120	640 K
S1 PRO TerraGes	Handheld Laser Scanning	-	-	-	4 h	0,8	120	640 K
VLX 3 NavVis	Handheld Laser Scanning + Photorealism	2023	570x330x1110 8,50kg	-	1,5 h	5,0 (on 500^2)	300	2.5 M
Ray II Artec 3D	Terrestrial Laser Scanning + Photorealism	2023	120x240x230 6,03kg	52 K	4 h (2 Internal batteries)	1,9 (to 10m) 2,9 (to 20m) 5,3 (to 40m)	130	2 M
ZEB Horizon GeoSLAM	Handheld Laser Scanning	-	1,40kg	-	-	10,0-30,0	100	300 K

H: Horizontal, V: Vertical

For each case study, various support software programs were used to obtain the final digital models. These software programs were used for different functions, such as modelling from photogrammetry, visualisation and measurement of models, storage of point clouds, support for monitoring surveys in the field, and post-processing of the point clouds in the office, among others. The software applications used in the study are listed in Table 12.

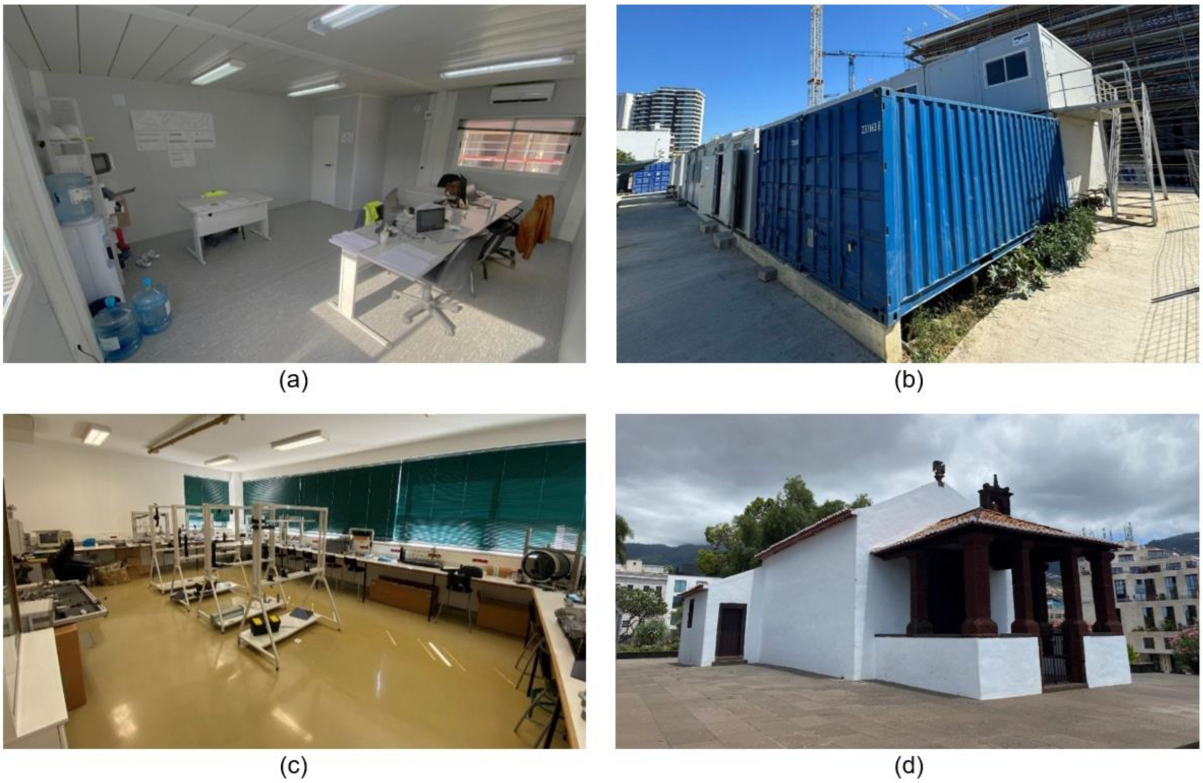

Figure 2: Case study spaces: (a) Case 1; (b) Case 2; (c) Case 3; (d) Case 4.

Table 10: Assessment criteria identified from the literature.

Criterion	Photogrammetry	Laser Scanning	References
Accuracy	Medium to High	High	Peña-Villasenín et al. (2019), Fawzy (2019)
Acquisition Time	Low	Medium	Fassi et al. (2013)
Processing Time	High	Low to Medium	Masiero et al. (2018)
Equipment Cost	Low	High	Mulè et al. (2022)
Portability	High	Medium	Cunha et al. (2022)
Lighting Dependency	High	Low	Fawzy et al. (2019)
Level of Detail	Medium to High	High	Various authors

Table 11: Equipment used in the practical evaluation.

Brand	Model	Technique	Tests
KIPRIM	Laser measurer LD50E	Manual Measurement	All
DEXTER	Measuring tape 8m x 25mm	Manual Measurement	All
Apple	iPhone 11	Terrestrial Photogrammetry	1.1, 1.2, 1.3, 1.4, 2.1, 3.2, 4.1
Xiaomi	Redmi 12C	Terrestrial Photogrammetry	1.5, 2.2, 3.3, 4.2
DJI	Airborne Mavic 3 Classic	Aerial Photogrammetry	4.3
Leica Geosystems	BLK360	Terrestrial Laser Scanning	3.4, 4.4
Leica Geosystems	BLK2GO	Handheld Laser Scanning	3.5, 4.5

All photogrammetric datasets were processed in Agisoft Metashape using the standard software workflow, without customised procedures. Image alignment and point-cloud generation were performed using the "High" accuracy and quality settings for all tests. The resulting point clouds were subsequently used for the qualitative analysis and extraction of the reference measurements.

Table 12: Software used.

Software	Brand	Technique	Function	Tests
Metashape	Agisoft	Photogrammetric Surveying	Modelling and Measurement	1.1, 1.2, 1.3, 1.4, 1.5, 2.1, 2.2, 3.2, 3.3, 4.1, 4.2, 4.3
Cyclone FIELD 360	Leica Geosystems	Laser Scanning	Field Management	3.4, 4.4
BLK 2 GO Live	Leica Geosystems	Laser Scanning	Field Management	3.5, 4.5
Cyclone REGISTER 360 PLUS	Leica Geosystems	Laser Scanning	Storage and modelling of point clouds	3.4, 3.5, 4.4, 4.5
ReCap	Autodesk	Laser Scanning	Visualisation and measurement of point clouds	3.4, 3.5, 4.4, 4.5

4.2.2 Case 1

The interior space of a container at a construction site was used for Case Study 1, and terrestrial photogrammetry was applied as the surveying technique. The purpose of this case study was to determine the influence of certain variations in the physical conditions of the space (the use of Post-it Notes as reference points and changes in lighting conditions) and the equipment used for the survey and for acquisition of the geometric model. To evaluate this influence, the measurements obtained from each of the tests were compared, which allowed for determination of the factors that can improve the results of the models obtained by photogrammetric surveying.

This case study was subdivided into five tests, with some parameters and conditions being altered for each survey, with the aim of understanding the influence of these changes on the accuracy of the final model.

4.2.3 Case 2

In Case Study 2, a photographic survey was conducted of the exterior of some containers at a construction site, with the objective of determining the quality of the model generated using the terrestrial photogrammetry technique in an outdoor environment. For this survey, the two available mobile devices were used together to capture the same number of photographs with similar orientations and positions.

4.2.4 Case 3

In Case Study 3, the aim was to obtain models based on data collected using three techniques: terrestrial photogrammetry, terrestrial laser scanning, and handheld laser scanning. In addition to the models obtained from the study site, measurements were taken from a previously existing model created with Matterport software. These models were then compared with manually obtained measurements, which were considered as reference values. Thus, the case study was composed of five tests, each conducted using different surveying techniques and equipment.

In this case study, the laser scanning technique was used, with the goal of comparing its efficiency with that of photogrammetric surveying when applied to an interior space with a large number of elements, which resulted in a much more complex model than in the previous case studies. Similarly to the previous cases, the terrestrial photogrammetry technique was applied to the space and its elements using the two mobile devices used earlier. Following this, terrestrial laser scanning was conducted from five different positions within the space, and finally, the five point clouds were aligned with each other to give a complete point cloud.

4.2.5 Case 4

Case Study 4 involved an exterior survey of a chapel, and the objective was to quantify the accuracy and quality of the final model by comparing the techniques of terrestrial photogrammetry, aerial photogrammetry, terrestrial laser scanning, and handheld laser scanning. In this case, all four techniques were applied, using the relevant equipment for each. Terrestrial photogrammetric surveys were carried out using the same mobile devices as in the previous cases, and laser surveys were then performed using the available equipment for that purpose.

In the terrestrial laser scanning test, 10 locations were defined at which the equipment was positioned to perform the respective scans. Following this, the point clouds were aligned to create a complete model of the entire chapel envelope. For the handheld laser scanning test, the scan was conducted continuously along the entire chapel. Finally, an aerial photographic survey was performed with the help of a drone, giving a complete survey of both the perimeter and the roof of the chapel.

Table 13: Summary of the case studies and experimental tests.

Cases	Tests	Type of space	Surveying technique	Equipment	Initial conditions	Survey duration (min)	Point Cloud (pts)	File size (MB)
Case 1	1.1	Indoor	Terrestrial Photogrammetry	iPhone 11	• Good lighting	2	5.2 M	118
	1.2		Terrestrial Photogrammetry	iPhone 11	• More photos • Good lighting	8	10.7 M	238
	1.3		Terrestrial Photogrammetry	iPhone 11	• More photos • Post-it notes as control points • Low lighting	12	5.6 M	132
	1.4		Terrestrial Photogrammetry	iPhone 11	• More photos • Post-it notes as control points • Good lighting	10	9. 5 M	213
	1.5		Terrestrial Photogrammetry	Xiaomi Redmi 12C	• Photos similar to those from Test 1.4 • Post-it notes as control points • Good lighting • Use of different equipment	10	26.6 M	620
Case 2	2.1	Outdoor	Terrestrial Photogrammetry	iPhone 11	• Good lighting • Low people flow	5	11.2 M	257
	2.2		Terrestrial Photogrammetry	Xiaomi Redmi 12C	• Good lighting • Low people flow • Use of other equipment	7	9.6 M	230
Case 3	3.1	Indoor	Terrestrial Photogrammetry	RICOH THETA Z1	• Existing model	-	-	-
	3.2		Terrestrial Photogrammetry	iPhone 11	• Medium lighting conditions	5	2.5 M	57
	3.3		Terrestrial Photogrammetry	Xiaomi Redmi 12C	• Medium lighting conditions	5	7.1 M	163
	3.4		Terrestrial Laser Scanning	BLK360	• Medium lighting conditions	16	101.4 M	4 217
	3.5		Handheld Laser Scanning	BLK2GO	• Medium lighting conditions	7	31.8 M	686
Case 4	4.1	Outdoor	Terrestrial Photogrammetry	iPhone 11	• Good lighting • Accessibility of the chapel perimeter	5	3.9 M	89
	4.2		Terrestrial Photogrammetry	Xiaomi Redmi 12C	• Good lighting • Accessibility of the chapel perimeter	5	18. 1 M	408
	4.3		Aerial Photogrammetry	DJI Mavic 3 Classic	• Good lighting • Accessibility of the perimeter and roof of the chapel	60	12.3 M	279
	4.4		Terrestrial Laser Scanning	BLK360	• Good lighting • Accessibility of the chapel perimeter	32	66.7 M	1 333
	4.5		Handheld Laser Scanning	BLK2GO	• Good lighting • Accessibility of the chapel perimeter	14	19.2 M	373

Following the individual description of the case studies, Table 13 provides a consolidated summary of the surveying conditions, techniques, equipment, acquisition times, and resulting point-cloud characteristics for all tests.

5. EXPERIMENTAL RESULTS AND DISCUSSION

The practical evaluation of the case studies described in Section 4 was conducted according to the main criteria identified in the literature review, namely accuracy, acquisition time, processing requirements, equipment cost, portability, sensitivity to environmental conditions, and quality of the resulting models. The objective was not only to compare the techniques and equipment used under different surveying conditions, but also to assess whether the trends reported in the literature were confirmed by the practical results. Accordingly, the accuracy of the results was considered together with the execution times, expected economic feasibility, and quality of the final models.

5.1 Qualitative analysis

The point clouds obtained from each of the tests (Figures 3 to 6) were evaluated qualitatively. This analysis included aspects such as the presence of voids in the point clouds, the correct representation of the elements in the space, visual realism, and the orientations and locations of the surfaces that composed them.

5.1.1 Case 1

In Case Study 1 (Figure 3), each of the tests gave a poor representation, without a correct depiction of the surfaces of the elements and a large number of voids in various areas. A better reading of the surfaces was possible in areas where there was a higher density of elements, as these served as control points that enable a better alignment of the obtained points.

This case study was conducted using only mobile device cameras, which do not have good resolution compared to professional photographic equipment. Better results were obtained in tests 1.3 and 1.5, suggesting that the combined effects of image quantity, reference points, lighting conditions, and camera characteristics influenced the quality of the reconstructed models. Other factors such as the number of photographs and proper lighting of the space were important in obtaining a higher-quality model, as these helped to reduce the voids in the point clouds and improved the reading of the surfaces of the elements.

5.1.2 Case 2

The models obtained in both tests (Figure 4) failed to yield good results, with a significant lack of information, incomplete elements, and incorrect orientation of the points in space. Even with good lighting conditions and a large number of photographs of the area, it was not possible to obtain well-defined and properly oriented models. This may have been caused by the orientation at which the photographs were taken; due to the very limited space available around the construction site, it was not possible to take photographs perpendicular to the surfaces of the containers, and the photos had an approximate inclination of 30º relative to the surfaces of the containers.

5.1.3 Case 3

The models obtained in Case Study 3 (Figure 5) gave good results, especially in the tests where laser scanning techniques were used, and particularly in the terrestrial laser scanning test. Due to the density of the elements within the space, the models contained some voids that may not have existed in less overloaded spaces.

It should be noted that in test 3.1 (Figure 5a), the result presented here is a surface model rather than a point cloud. The model is well defined and without voids, which indicates that there was a more complete redefinition of the surfaces.

5.1.4 Case 4

In this case study, one can observe (Figure 6) a significant improvement in the models obtained, with a good representation of the surfaces and the elements that make up the space. The surveys were executed under excellent conditions (good natural lighting and enough space to manoeuvre around the church), which allowed for higher-quality readings.

The model obtained with the aerial photogrammetric surveying (Figure 6c) had the best quality, a finding that is justified by the high quality of the camera and the versatility of the drone; this allows for a correct reading from any angle, as long as the site allows it, in addition to an excellent representation of colours and textures, which cannot be obtained in the models created using laser scanning.

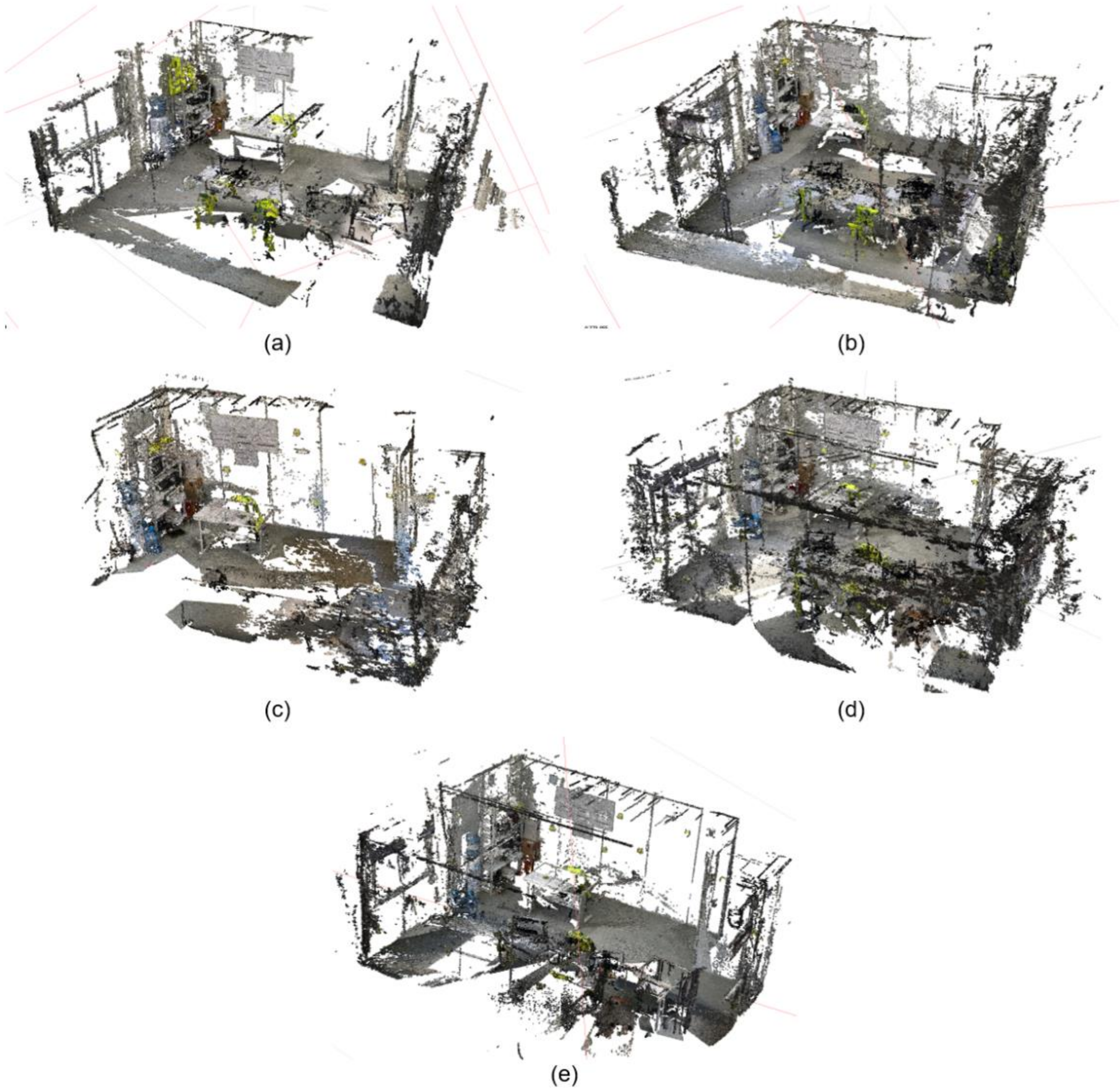

Figure 3: Point clouds from Case Study 1: (a) test 1.1; (b) test 1.2; (c) test 1.3; (d) test 1.4; (e) test 1.5.

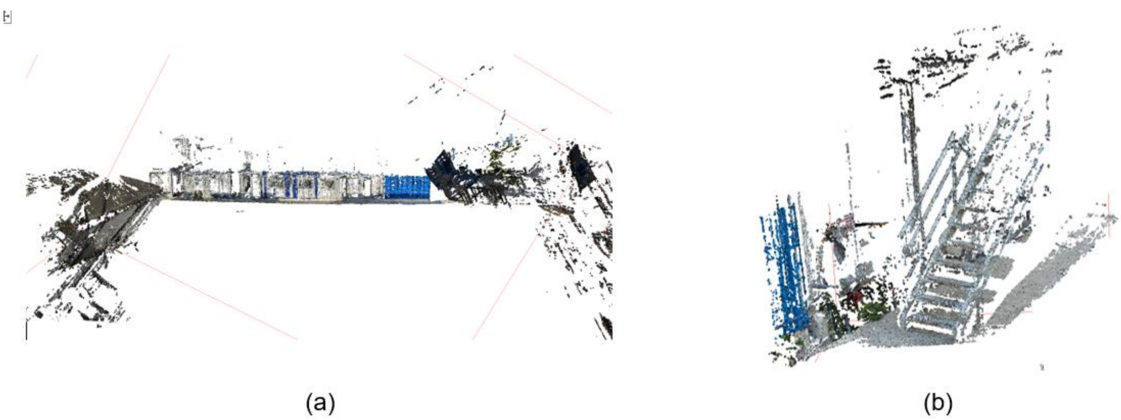

Figure 4: Point clouds from Case Study 2: (a) test 2.1; (b) test 2.2.

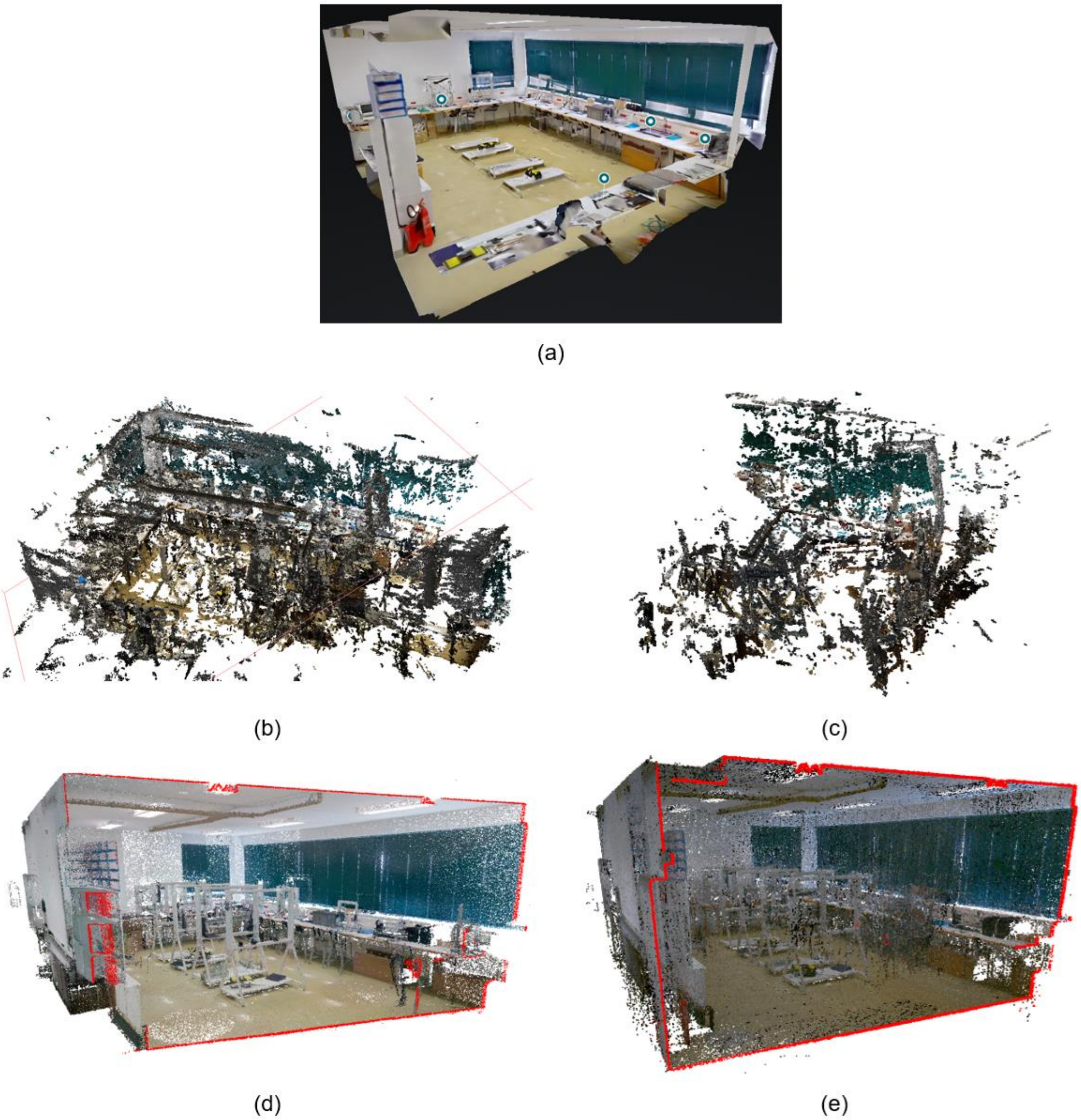

Figure 5: Point clouds from Case Study 3: (a) test 3.1; (b) test 3.2; (c) test 3.3; (d) test 3.4; (e) test 3.5.

5.2 Quantitative analysis

As described in Section 4.1, the accuracy of the 3D models was evaluated by comparing some distances from the 3D models with reference measurements obtained using manual techniques. The deviations were then calculated by determining the absolute (minimum, average, and maximum) errors (Figure 7).

In Case Study 1, the average errors ranged between 4 and 9 cm, values that are fairly similar; however, the maximum errors were between 15 and 45 cm, representing a significant difference. Test 1.3 had the lowest accuracy in this case study.

For both tests in Case Study 2, there were large numbers of voids and problems with the orientations and locations of points, making it impossible to obtain the measurements necessary to calculate the final model errors; hence, this case study was not considered.

Figure 6: Point clouds from Case Study 4: (a) test 4.1; (b) test 4.2; (c) test 4.3; (d) test 4.4; (e) test 4.5.

In Case Study 3, the lowest average absolute error was found for test 3.4, which was carried out using the terrestrial laser scanning technique, with an average absolute error of 4.3 cm, although test 3.5 gave a very similar value (5.0 cm).

In Case Study 4, the lowest average absolute error was observed for test 4.3, which was carried out with aerial photogrammetry; the error value was only 4.0 cm, and this result surpassed those of the tests conducted with laser scanning.

Overall, the average error obtained from the set of tests (excluding the inconclusive ones) was 6.3 cm. When the techniques are considered individually, we see that the photogrammetry surveys had an average error of 7.3 cm, while the laser scanning surveys had an average error of 4.4 cm. This represents a difference of 2.9 cm between the two techniques, with laser scanning achieving the best accuracy in this overall comparison of results.

For the maximum errors, we note that for the photogrammetric surveying, the errors were smaller when the lighting of the space and the elements was optimal. The minimum errors were all very close to zero, reflecting the high precision of the 3D digital models produced by the various techniques.

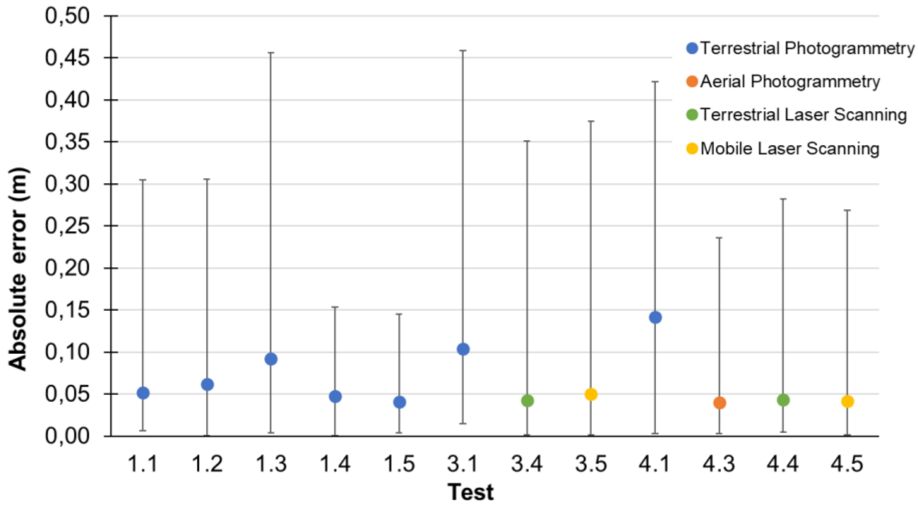

Figure 7: Absolute errors for the case studies.

The accuracy of the model is of great importance for the correct representation of elements when using a digital model. The choice of geometric survey technique will depend on the needs of the work to be carried out, although cost should also be considered as a determining factor. Photogrammetric surveying has lower costs but a lower accuracy (7.3 cm), while laser scanning has higher costs but better accuracy (4.4 cm).

Table 14 compares the results obtained in this paper with those obtained by other researchers from the application of various geometric survey techniques in different types of spaces. The average difference between the accuracy obtained by other authors and the accuracy obtained in this study was 0.9 cm.

The comparison presented in Table 14 shows that the trends observed in the practical evaluation are generally consistent with the findings reported in the literature. Laser scanning technologies consistently provided the highest geometric accuracy, while photogrammetric approaches offered lower acquisition costs and greater operational flexibility. These findings confirm that the choice of surveying technology should not be based solely on accuracy, but rather on a balance between cost, required level of detail, acquisition constraints, and intended application.

Consistent with the literature, photogrammetric performance was strongly influenced by lighting conditions, image quality, acquisition geometry, and accessibility, whereas laser scanning provided more consistent geometric results under the investigated conditions. On the other hand, photogrammetry can provide a more favourable cost-benefit ratio in situations where centimetric accuracy is sufficient and photorealistic representation is important.

Table 14: Comparison of accuracy between our results and those of other researchers.

Surveying Techniques	**Type of space**	**Average error (m)**			
		Own	**Other authors**		**Difference**
Aerial Photogrammetry	Exterior	0,040	0,018	(Cunha et al., 2022)(Gonizzi Barsanti et al., 2012)	+ 0,022
Terrestrial Photogrammetry	Exterior	0,142	0,131	(El-Din Fawzy, 2019)(Kadobayashi et al., 2004)(Gonizzi Barsanti et al., 2012)	+ 0,011
	Interior	0,066	0,021	(Masiero et al., 2018)(Guarnieri et al., 2004)	+ 0,045
Terrestrial Laser Scanning	Exterior	0,043	0,012	(El-Din Fawzy, 2019)(Mulè et al., 2022)(Cunha et al., 2022)(Gonizzi Barsanti et al., 2012)	+ 0,031
	Interior	0,043	0,054	(Guarnieri et al., 2004)	- 0,011
Handheld Laser Scanning	Exterior	0,042	0,090	(Mulè et al., 2022)	- 0,048
	Interior	0,050	0,161	(Masiero et al., 2018)	- 0,111

In the investigated cases, laser scanning generally provided better accuracy than photogrammetry. However, in Case Study 4, aerial photogrammetry achieved the lowest average error among the evaluated techniques. Although the differences are small, handheld laser scanning has better accuracy for outdoor spaces than indoor ones; similarly, terrestrial laser scanning also has better accuracy in outdoor spaces. These results illustrate the potential of these techniques to provide geometric and visual information under the investigated surveying conditions. Although the resulting models may support subsequent inspection and condition-assessment activities, defect detection and building diagnostics were not evaluated in the present study.

5.3 Practical trade-offs and applicability

The selection of a surveying technique should not be based exclusively on geometric accuracy. The practical results indicate a trade-off between accuracy, equipment cost, field acquisition time, processing requirements, portability, and the intended use of the resulting model. Terrestrial laser scanning generally provided the most consistent geometric results, but it required specialised and comparatively expensive equipment, as well as multiple stationary scans and subsequent point-cloud registration. Handheld laser scanning reduced field acquisition time and simplified movement through the surveyed space, although this advantage was accompanied by a moderate reduction in accuracy and model quality.

The errors obtained with handheld laser scanning may nevertheless be sufficient for applications that do not require millimetric accuracy, such as preliminary surveys, general spatial documentation, asset inventories, feasibility studies, and the creation of approximate existing-condition models. Conversely, applications involving detailed deformation assessment, dimensional control, structural analysis, or the documentation of small geometric features may require the greater accuracy and consistency provided by terrestrial laser scanning.

Photogrammetry offered the lowest entry cost and the greatest equipment accessibility, particularly when mobile devices were used. It also provided more realistic colour and texture information. However, its performance was more sensitive to lighting, accessibility, image quality, camera position, and image overlap. Consequently, the apparent economic advantage of photogrammetry may be reduced when incomplete or incorrectly aligned models require additional image acquisition or extensive processing and correction. Aerial photogrammetry was particularly useful for capturing roofs and other areas that were difficult to access from ground level, although its application depends on suitable operating conditions and site accessibility.

In the investigated cases, lower equipment cost and shorter field acquisition time did not necessarily imply a lower overall workflow effort. Incomplete models, voids, or alignment problems, such as those observed in Cases 1 and 2, may require repeated acquisition or additional corrective processing. Conversely, terrestrial laser scanning involved higher equipment costs and a more structured field procedure, but generally produced more complete and consistent datasets. Nevertheless, since processing times and corrective effort were not systematically recorded, these observations should be interpreted qualitatively rather than as a quantitative comparison of the complete workflows.

Field acquisition time and post-processing effort must therefore be considered jointly. A technique that is faster in the field may require greater processing or corrective work, while a longer and more structured acquisition may produce a more complete dataset and reduce subsequent intervention. The most appropriate solution consequently depends on the required accuracy and level of detail, the characteristics of the surveyed environment, available equipment and expertise, project budget, and intended use of the resulting model.

5.4 Limitations

The practical evaluation has several limitations that should be considered when interpreting the results. The number of case studies and the range of equipment available were limited, and the acquisition conditions were not identical across all tests. Furthermore, the investigated cases comprised non-heritage elements and environments; consequently, the transferability of the experimental findings to heritage buildings should be considered with caution.

Professional DSLR cameras and tripods were not available during the terrestrial photogrammetric surveys, preventing a direct comparison between mobile-device and professional-camera photogrammetry. In addition, not all surveying technologies were applied in every case study.

Although field acquisition times were recorded, post-processing times were not systematically compared. Processing duration depends strongly on the computational resources used, software configuration, processing parameters, and user experience. A direct comparison could therefore be misleading unless identical hardware, software settings, and processing procedures were used. The reported results should consequently be interpreted as practical comparative evidence under the investigated conditions rather than as universally applicable performance values. Future studies should address these limitations through controlled comparisons involving a larger number of environments, surveying systems, and acquisition procedures.

6. CONCLUSION

Due to the need to preserve and rehabilitate existing structural and architectural elements, it is becoming essential to obtain updated and precise information about built environment. The aim of this paper was to define and categorise the most up-to-date methods for geometric surveying through scientific research, by reviewing each technique and the respective equipment available on the market, and by highlighting their advantages and disadvantages, to facilitate the choice of the best solution for conducting a given survey. Furthermore, we evaluated the accuracy and practical performance of selected techniques through their application to several case studies conducted under specific acquisition conditions.

Based on the synthesis of the reviewed literature and the practical observations obtained under the investigated conditions, the following conclusions can be drawn:

- The diversity of techniques, equipment, and software available for geometric surveys of built environment was verified both theoretically and practically.
- Each technique has specific characteristics, and particular advantages and disadvantages in terms of its application, which must be known in order to select the most appropriate approach in each case.
- Adequate site conditions are required, including favourable weather, good accessibility, and minimal disturbance from pedestrians or other obstacles.
- When used alone, traditional surveying and satellite surveying techniques cannot give a complete and accurate survey of the elements, and satellite surveying is used only as a complementary method for the georeferencing of point clouds created by other techniques.
- Photogrammetric surveying is generally the most versatile technique, due to the variety of widely available equipment that can be used. However, good lighting conditions are required on site, since overexposure or a lack of light leads to problems in the correct orientation and reading of the elements in photographs used for creating 3D models. An adequate number of photographs and sufficient overlap between photographs are important factors in obtaining a complete model. The high density of elements in the space can cause problems with the correct orientation of points in the models. This technique gives the most photorealistic models, and can simulate colours and textures that are very close to reality. The quality and resolution of the photographic equipment is a determining factor in preventing voids and problems with model creation.
- In most cases, terrestrial laser scanning produced the most accurate and consistent models, including under inadequate lighting conditions. However, it involves higher equipment and software costs and requires a more structured field workflow. Handheld laser scanning reduces acquisition time and improves portability, although its geometric accuracy and model quality may be lower. It may therefore provide a suitable compromise for preliminary surveys, spatial documentation, and other applications where centimetric accuracy is sufficient.
- Photogrammetric surveying can offer a favourable cost-benefit ratio due to the accessibility, portability, and comparatively low cost of the required equipment. However, this advantage depends strongly on suitable lighting, accessibility, image quality, acquisition geometry, and image overlap, and may be reduced when incomplete models require repeated acquisition or additional corrective processing.
- The use of remotely controlled equipment makes it possible to obtain information from elements located in areas inaccessible to people, although appropriate conditions for drone accessibility must be ensured.

- The selection of the most appropriate surveying technology should consider the complete workflow, including accuracy and level-of-detail requirements, equipment cost, field acquisition effort, processing requirements, environmental constraints, available resources, and the intended use of the resulting model.

The following quantitative findings refer exclusively to the investigated case studies and should not be interpreted as statistically generalisable performance benchmarks:

- In the case studies performed here, the average error for photogrammetry was 7.3 cm, while for laser scanning it was 4.4 cm, the latter technique providing the highest accuracy.
- Terrestrial laser scanning achieved better accuracy than handheld laser scanning, with average errors of 4.3 cm and 4.6 cm, respectively.
- Aerial photogrammetry yielded better accuracy than terrestrial photogrammetry, with average errors of 4.0 cm and 7.7 cm, respectively.

The combination of the literature review and practical evaluation demonstrated that no surveying technique is universally superior. Instead, each technique presents specific advantages and limitations, and its suitability depends on the characteristics and requirements of each application.

Future studies should extend this evaluation to a larger number of indoor and outdoor environments and include controlled comparisons involving mobile devices, DSLR cameras, tripods, and different laser scanning systems. This would enable a more systematic assessment of the influence of acquisition equipment and procedures on model quality and geometric accuracy.

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