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ORIGINAL ARTICLE

# Various scenarios of measurements using a smartphone with a LiDAR sensor in the context of integration with the TLS point cloud

Joanna Janicka [1*] and Wioleta Błaszczak-Bąk [1]

[1]Faculty of Geoengineering, University of Warmia and Mazury in Olsztyn, ul. Oczapowskiego 2, 10-719 Olsztyn, Poland

*joanna.janicka@uwm.edu.pl

## Abstract

Smartphones with Light Detection and Ranging (LiDAR) sensors are increasingly used for engineering measurements. Although the processing of the acquired point clouds seems similar to the processing of point clouds measured with, for example, a terrestrial laser scanner, processing data from a smartphone requires a special approach, first of all, when it comes to methods of obtaining and registering point clouds to obtain one complete metric point cloud. The research consisted of comparing various scenarios of measuring using a smartphone with a LiDAR sensor (a smartphone held in hand, a smartphone on a selfie stick, and a smartphone mounted on a gimbal), two acquisition strategies (one direction and zigzag) and two registration methods (point to point and cloud to cloud). The aim of the study was to find the best solution for registering the obtained point cloud with referenced terrestrial laser scanning (TLS) point cloud. It turns out that how we obtain field data using a smartphone with a LiDAR sensor is important and affects the accuracy of point cloud integration. The results showed that the use of additional devices such as a gimbal supports the data acquisition process and has an impact on the point cloud registration. In the analysed case, the RMSE registration error was the smallest and amounted to 0.012 m and 0.019 m, while the largest registration error was 0.060 m and 0.065 m, for object 1 and object 2, respectively. The result obtained using the proposed methodology can be considered satisfactory.

**Key words**: LiDAR, Smartphone, TLS, Integration, Registration

## 1 Introduction

The use of a smartphone with a Light Detection and Ranging (LiDAR) sensor to measure the fragments of building structures, especially those rich in carvings, wall decorations, and decorations, is becoming more and more popular (Labędź et al., 2022; Dörtbudak and Akça, 2024). Due to the fact that a smartphone is not a typical geodetic instrument, performing measurements with this device requires a special approach and caution when it comes to the accuracy and metric nature of the data. In general, the technology of terrestrial laser scanning of buildings is well-known and used. However, there are many situations where the use of a large scanner is not possible or additional measurements need to be made on small parts of the object, or a point cloud must be obtained at a low cost. Then the best solution is to use a smartphone with a LiDAR sensor (SwL).

In 2020, Apple launched its first smartphone equipped with a LiDAR sensor. Hence, LiDAR is becoming an increasingly accessible low-cost technology. The possibility of using a smartphone with a LiDAR sensor for various engineering applications has already been tested by scientists. For example, it has been employed in cultural heritage documentation (Teppati Losè et al., 2022), building renovation diagnostics (Mêda et al., 2023), inventories of building walls (Błaszczak-Bąk et al., 2023), research on the effect of different surface materials on the quality of three-dimensional (3D) point clouds Razali et al. (2022) and geological fieldwork (Tavani et al., 2022).


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In addition, scientists tested the possibility of using an iPhone or iPad with a LiDAR sensor for forest inventories (Mokroš et al., 2021; Gollob et al., 2021; Tatsumi et al., 2022). Moreover, Apple LiDAR devices are also cost-effective alternatives to established techniques in remote sensing with possible fields of application for a wide range of geoscientific areas (Luetzenburg et al., 2021, 2024).

Depending which platform originally generated the point cloud requiring registration, LiDAR point cloud registration can be divided into same-platform registration and registration between different platforms. There are several LiDAR systems: airborne laser scanning (ALS), mobile laser scanning (MLS) and terrestrial laser scanning (TLS). A Same-platform registration mainly includes multi-station TLS registration and ALS strip adjustment. For LiDAR registration between different platforms, research mainly focuses on ALS-MLS, TLS-MLS, and ALS-TLS registration. One of the MLS techniques is measurement with a smartphone with a LiDAR sensor. The approach to registering point clouds from a smartphone with LiDAR requires special attention due to: the movement of the smartphone (change of position every second of measurement), distance from the object, high dependence on the structure of the object (flat or complex).

For measurements made with a TLS, there are many methods for registering point clouds and the integration of multi-platform, multiangle, and multitemporal LiDAR data has become important for geospatial data applications. Many registration methods can be found in the literature on the subject, for example:

- coarse registration methods, e.g., point-based method (Weinmann et al., 2016) or line-based methods (Al-Durgham and Habib, 2014),
- fine registration methods, e.g., iterative approximation methods (Faugeras and Hebert, 1986), random sample consensus methods (Fischler and Bolles, 1981).

Typically, scans are aligned using one of the two methods: cloud-to-cloud (C2C) registration or point-to-point (P2P) registration (Cheng et al., 2018). Georeferencing, in contrast, involves assigning the point cloud to a known coordinate system. The choice between C2C and P2P registration depends on the nature of your LiDAR data, the level of detail you require, and the computational resources available. Additionally, there are software libraries and tools, such as the Point Cloud Library (PCL) and commercial software packages that provide implementations of these registration methods to simplify the process.

The algorithms of these methods are often built into specialized software dedicated to point clouds. For example, Cyclone and Cloud Compare are popular software packages for LiDAR point cloud processing and registration.

C2C registration, also known as global registration, aims to align entire point clouds with respect to each other. It typically involves finding the optimal rigid transformation (translation and rotation) that minimizes the differences between two or more entire point clouds. P2P registration is very often called local registration and focuses on aligning individual points between two point clouds. This method is often used when cloud-to-cloud registration alone is not sufficient for accurate alignment, especially in cases where there are significant differences between the scans.

C2C techniques include:

i. ICP (Iterative Closest Point), which is one of the most commonly used methods within cloud-to-cloud registration (Li et al., 2020).

ii. Feature-based methods, which use distinct features (e.g., edges, corners, or other geometric primitives) identified in the point clouds to establish correspondences and compute the transformation (Hu et al., 2022).

iii. Global registration methods, which use global descriptors to align point clouds in cases where initial positions are highly misaligned (Wang et al., 2023).

**Table 1.** Abbreviations

| | |
|---|---|
| LiDAR | Light Detection and Ranging |
| TLS | Terrestrial Lase Scanning |
| SwL | Smartphone with LiDAR sensor |
| ALS | Airborne Laser Scanning |
| UAV | Unmanned Aerial Vehicle |
| MLS | Mobile Laser Scanning |
| C2C | cloud-to-cloud |
| P2P | point-to-point |
| PCL | Point Cloud Library |
| VCSEL | Vertical Cavity Surface Emitting Laser |
| sh | smartphone in hand |
| ss | smartphone on the selfie stick |
| sg | smartphone on a gimbal |
| ICP | Iterative Closest Points |
| RMSE | Root Mean Square Error |

Obtained TLS point clouds may require integration with versatile smartphone LiDAR acquisitions. The above-mentioned registration methods can also be used to integrate point clouds taken from SwL. However, this task becomes complicated due to the fact that smartphone measurements are usually supplementary measurements and there are quite large errors at the edges of the scan, which may cause problems with fitting. Another difficulty is the fact that the smartphone is constantly in motion at a short distance (up to 5 m according to iPhone LiDAR specification) and the scans must have time to connect during the measurement. Thus, scanning tips included in the instructions for the scanning application recommend slow and steady motion.

Applications that are used in smartphones with LiDAR to obtain point clouds are based on various measurement methods, including SLAM (Simultaneous Localization and Mapping). SLAM is a technique used to create a map of an environment while simultaneously determining the position of the sensor within that environment. When applied to smartphones with LiDAR sensors, SLAM significantly enhances the accuracy and functionality of measurements and mapping. Enhanced localization with SLAM helps to track the position of the smartphone as it moves through an environment. By combining data from the LiDAR sensor with other sensors (such as the accelerometer, gyroscope, and camera), SLAM can estimate the device's location and orientation with high precision, enabling more reliable measurements and navigation (Tamimi and Toth, 2024).

The use of appropriate measurement methods may not be sufficient to obtain point clouds of appropriate quality, so that they can constitute point clouds complementing previously performed measurements. Therefore, this study proposes the use of additional devices supporting SwL measurement and carrying out measurements in various post-measure scenarios.

The aim of the study was to compare various scenarios of measuring with a smartphone with a LiDAR sensor and to find the best solution for registering the obtained point cloud with the referenced TLS point cloud. Since the point cloud registration methods are known in the literature (Weinmann et al., 2016), the primary goal of the research was to check whether the method of acquiring point clouds using a smartphone with LiDAR (which is not a typical geodetic instrument) affects the merging of point clouds. For readability, the acronyms used in the article are listed in Table 1.

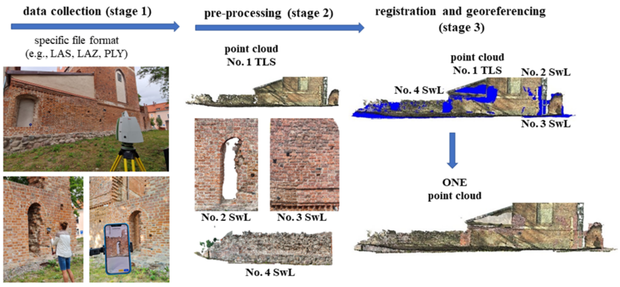



**Figure 1.** The steps of processing point cloud obtained with SwL

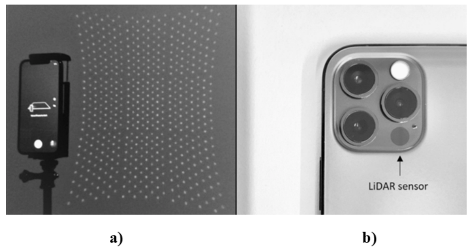



**Figure 2.** (a) Infrared dot projections for the LiDAR module; (b) LiDAR sensor (Luetzenburg et al., 2021)

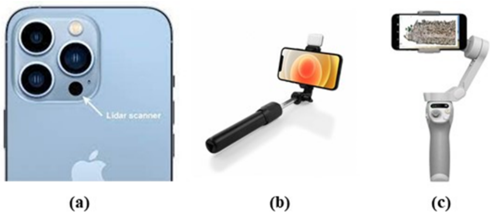



**Figure 3.** Equipment used during the measurements: (a) smartphone, (b) smartphone with selfie stick, (c) smartphone with gimbal

## 2 Materials and Methods

### 2.1 Smartphone with LiDAR data processing

Processing point clouds from measurements taken with a smartphone equipped with a LiDAR sensor involves several steps to prepare full 3D data set. The first step (step 1) is data acquisition. This process generates a point cloud, which consists of individual 3D points (XYZ coordinates) with additional attributes, such as intensity and color information. The LiDAR data captured by the smartphone are typically stored in a specific file format (e.g., LAS, LAZ, PLY) or as raw point cloud data. The format may vary depending on the smartphone and the app used for data acquisition. The second step (step 2) is pre-processing, which is essential to clean and refine the raw LiDAR data. A common pre-processing step covers first of all removing outliers and noise points to improve data quality: downsampling (Suchocki and Błaszczak-Bąk, 2019; Błaszczak-Bąk et al., 2020), optimization (Błaszczak-Bąk et al., 2018), cutting. Next, the fundamental stage in LiDAR data processing is registration and georeferencing (step 3). The processing steps are presented in Figure 1.

Measurements are typically carried out over multiple epochs (spanning several years at specific time intervals) and within individual sessions (involving multiple scans conducted on the same day). This process often results in various LiDAR scan variants that need to be aligned and integrated. As a result one usually gets several sets (point clouds) from different epochs. In Figure 1, these clouds are marked No. 1, No. 2, No. 3 and No. 4. It is extremely important to correctly combine point clouds into one in stage 3 of the presented methodology. Two scenarios can be identified: a combination of different point clouds depicting different parts of the same object, or a combination of point clouds from different epochs measuring the same area/object.

### 2.2 Equipment

An iPhone 12 Pro with iOS 17.6.1 was used for the 3D documentation of the various measurement scenarios. This iPhone is equipped with a 12 MP camera system that contains three different cameras (1x telephoto, 1x wide, and 1x ultrawide camera), a flashlight and a LiDAR sensor on the backside of the phone (Figure 2b).

The LiDAR is composed of two modules, with its lens mounted overlapping one another, consisting of a transmitter, the VCSEL (Vertical Cavity Surface Emitting Laser) and a receiver sensor. The first emits a series of points in the infrared which are detected by the sensor. The LiDAR sensor emits a pulsed infrared pattern that appears to be made up of a $8\times8$ dot matrix that is diffracted into $3\times3$ grids, making a total of 576 points (Figure 2a). The maximum range is up to 5 m.

Scanning using an iPhone with a LiDAR sensor is carried out using applications available in the AppStore. The choice is quite wide, there are paid and free applications; the most popular include: 3D Scanner App, Polycam, SiteScape, LiDAR Scanner 3D, Scany Pro (Vacca, 2023). Of the applications mentioned, this publication used the 3D Scanner App (https://3dscannerapp.com/, accessed: August 15, 2023). It is a free product that allows you to process photos and videos in real time to create high-resolution 3D models and high-quality textures. Data export formats supported in the application are XYZ color, PLY, PTS, LAS, LAS Geo-Referenced, E57, or PCD. When scanning using the mentioned application, you should move along the measured object and move the device slowly to collect data in the form of a point cloud. The collected measurement data can then be exported in several ways, using: AirDrop, e-mail, WhatsApp, and other applications.

Measurements using an iPhone 12 Pro with LiDAR sensor were carried out using additional equipment dedicated to smartphones: selfie stick and gimbal. Equipment used during measurements is presented in Figure 3.

A gimbal is a device designed to stabilize the movement of a camera or other equipment. It achieves stabilization through a system of pivots and counterweights in traditional mechanical models, or through motorized axes and sensors in modern electronic gimbals. It allows for smooth and steady shots, even in situations with smartphone movement. Gimbals are primarily used to eliminate vibrations, shakes, and jerky movements when capturing photos or videos. The main purpose of a gimbal is to provide stabilization. It keeps the camera level and steady regardless of the operator's movements, ensuring smoother and more professional-looking shots. Gimbals typically operate on three axes: pan (horizontal rotation), tilt (vertical rotation), and roll (side-to-side rotation). This allows for fluid movement in all directions. The use of a gimbal to stabilize a smartphone during LiDAR acquisition was tested in comparison with digital photogrammetry reconstructions, whereas in this study, it is tested against a TLS acquisition (Corradetti et al., 2022).

A selfie stick is primarily used only for extending the reach of a smartphone or camera when taking selfies or group photos. It allows the user to capture a wider perspective. Selfie sticks do not provide any mechanical stabilization for a smartphone.

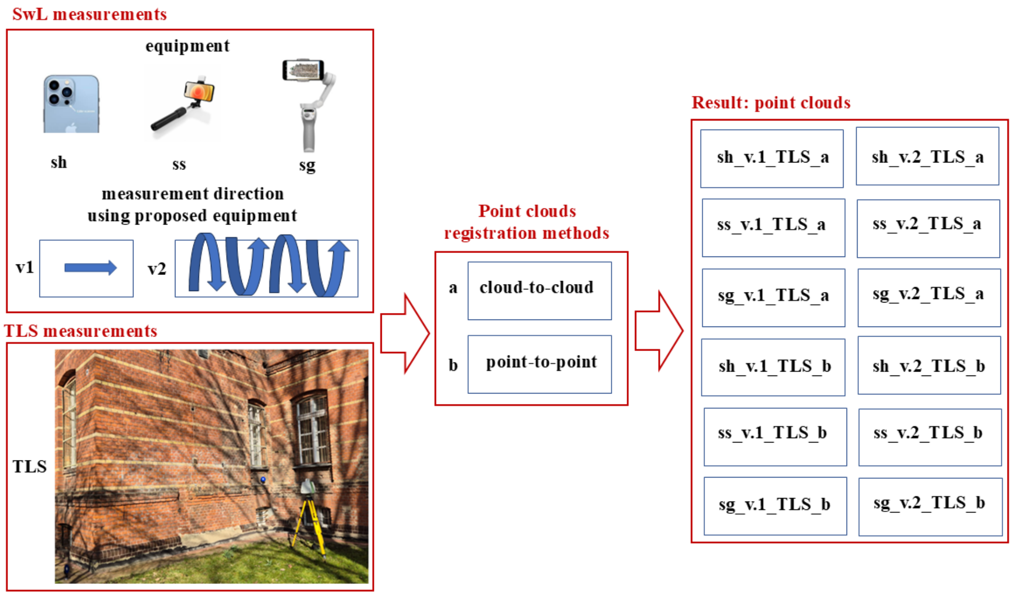



**Figure 4.** Measurement scenarios

They rely on the user's ability to hold the stick steady, which can result in less stable measurement, especially in dynamic situations.

## 2.3 Proposed methodology and measurement scenarios

The proposed methodology involves taking measurements using a terrestrial laser scanner (Leica ScanStation C10) and an iPhone 12 Pro with a LiDAR sensor. TLS measurements were performed from one position located opposite the tested wall fragment. Therefore, two TLS measurements were taken separately for each of the selected objects (building wall fragments).

The iPhone research was carried out taking into account various measurement scenarios: smartphone in hand (sh), smartphone on a selfie stick (ss), smartphone on a gimbal (sg), taking into account the way the smartphone moves: (a) in one direction, (b) zigzag. Figure 4 presents the measurement scenarios.

Such a designed measurement scenario makes it possible to check all possible variants taking into account the equipment used, the proposed trajectories, and the point cloud registration method.

## 2.4 Research objects

The objects of the research are two fragments of the wall of a building located at the campus of the University of Warmia and Mazury in Olsztyn, built of red brick with decorative elements made of yellow brick. Object 1 is the area of the brick wall with a length of about 6 m and a height of 2 m. Object 2 is a corner of the wall with dimensions of about 1.5×2 m. The research objects are presented in Figure 5.

Although smartphone data acquisition is usually treated as supplementary measurements, in subsequent time intervals, in this study the smartphone point clouds were not taken as multitemporal scans. The research was conducted in one epoch and aimed only at investigating the best smartphone measurement scenario to obtain optimal registration.

TLS Measurement was made using a Leica ScanStation C10 laser scanner and three targets with tripods from two stations.

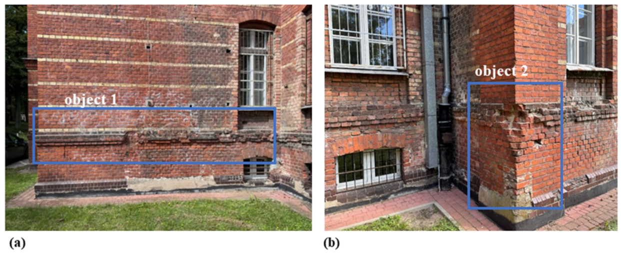



**Figure 5.** Reasearch objects: (a) object 1, (b) object 2

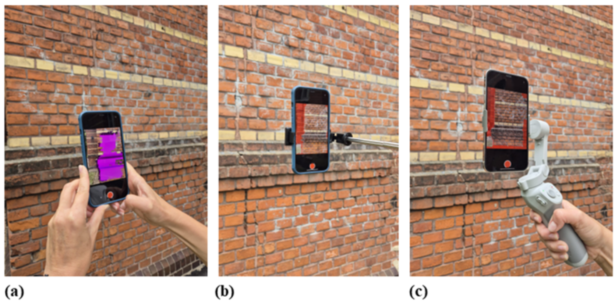
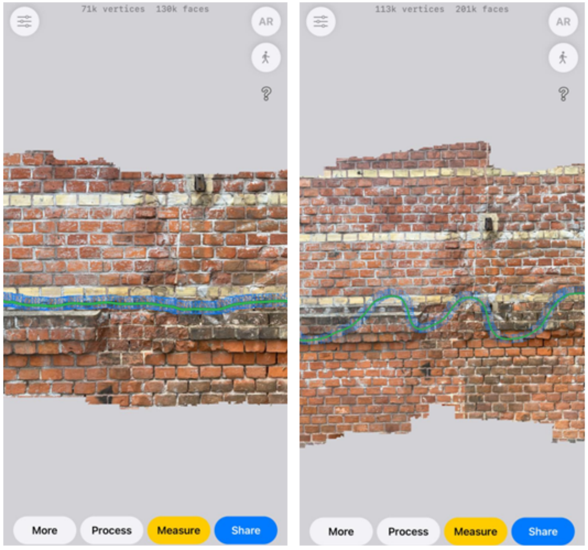



**Figure 6.** Measurement with SwL: (a) smartphone in hand, (b) smartphone on a selfie stick, (c) smartphone on a gimbal

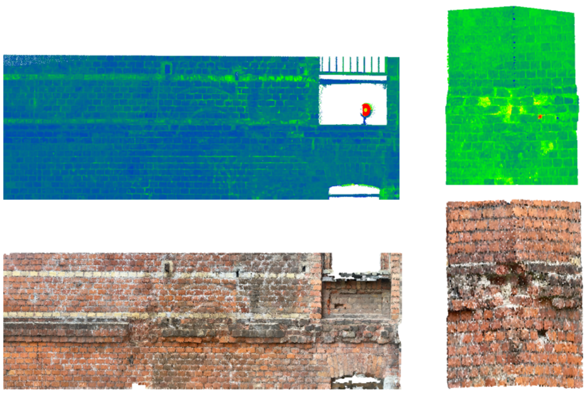
At each TLS position, the measurement was performed twice, in sample resolution (2 cm) of the entire scene and ultra-high resolution (1 mm) only for selected objects. In the next stage of measurements, an iPhone with a LiDAR sensor was used. For this stage of measurement, photographic documentation was made, which is presented in Figure 6.

During the SwL measurement, planned trajectories were used, which in turn is presented in Figure 7.




(a) (b)

**Figure 7.** The trajectory for object 1: (a) in one direction, (b) zigzag



a) b)

**Figure 8.** TLS (in intensity colors) and SwL (RGB colors) point clouds respectively: (a) object 1, (b) object 2

# 3 Results and analysis

## 3.1 Registration results

TLS point clouds were first pre-processed in the dedicated Cyclone software. The point clouds were cleaned from noise and cut to the selected area. As a result, two point clouds as two .pts files were prepared for the two research objects, respectively. SwL point clouds were exported from the device also in the same file format. SwL point clouds were acquired using the 3d Scanner App application. When measuring object 1 (Figure 8a), the application took an average of 60 to 70 scenes, registering them into one cloud. The entire point cloud is about 200 000 points, and the TLS point cloud for the same area is about 4 500 000 points. For object 2 (Figure 8b), 25–35 scenes were recorded, finally registered into one point cloud containing about 40 000 points. Respectively, the TLS point cloud contains 420 000 points. Figure 8 presents the obtained point clouds.

The obtained point clouds from TLS and SwL measurements were processed in the CloudCompare software. The point clouds registration stage as well as one resulting point cloud for each scenario for object 1 are presented in the following Figures 9–12. To explain the symbols used in the Figures, for the C2C method the aligned point cloud is marked in red, while the reference point cloud is marked in yellow (Figure 9 and Figure 11). In each registration, the SwL point cloud was assumed as the aligned point cloud, and the TLS point cloud was assumed as the reference point cloud.

**Table 2.** Calculated RMSE for each SwL and TLS point clouds registration scenario

| Scenario | RMSE [m] | | | |
|---|---|---|---|---|
| | Object 1 | | Object 2 | |
| | cloud-to-cloud (a) | point-to-point (b) | cloud-to-cloud (a) | point-to-point (b) |
| sh_v1_TLS | 0.032 | 0.027 | 0.031 | 0.065 |
| ss_v1_TLS | 0.037 | 0.060 | 0.035 | 0.023 |
| sg_v1_TLS | 0.024 | 0.023 | 0.019 | 0.028 |
| sh_v2_TLS | 0.025 | 0.039 | 0.027 | 0.029 |
| ss_v2_TLS | 0.020 | 0.040 | 0.024 | 0.026 |
| sg_v2_TLS | 0.012 | 0.042 | 0.021 | 0.023 |

where: blue color – the best solution, red color – the worst solution.

Figure 9 shows the result of registering the SwL point cloud with the reference TLS point cloud obtained using the C2C method. It shows the result of registering clouds measured according to the assumptions shown in Figure 4, i.e., the same object was measured by holding the smartphone directly in the hand, using a selfie stick and using a gimbal in the measurement v1 variant.

The second point cloud registration method was P2P. SwL point cloud is presented using RGB colors and the TLS point cloud using intensity values. Figure 10 and Figure 12 present the selection of reference points for the P2P registration. Six identical reference points were selected on the recorded TLS and SwL point clouds in places where their correct identification was possible. Four corners of the recess in the measured wall and two points on the left side at the end of the wall at the junction of the yellow and red bricks were selected.

The next step in the study was the registration of point clouds using scenario v2 with C2C method. Figure 11 shows the registration effect while maintaining three measurement methods sh, ss and sg measurement and zigzag direction.

Figure 12 presents the result using scenario v2 with P2P method.

The same scenarios were tested on object 2 with a different geometry with respect to the first object. The point clouds registration stage as well as one resulting point cloud for each scenario for object 2 are presented in the following Figures 13–16. Scenario v1 with C2C is shown in Figure 13.

P2P was performed by indicating 7 or 8 reference points on both bricks. Indicating the points on the presented object was extremely difficult due to the uniform color of the bricks and numerous defects in their structure. Scenario v1 with P2P is shown in Figure 14.

The next step for object 2 in the study was the registration of point clouds using scenario v2 with C2C (Figure 15) and P2P (Figure 16) method.

In the P2P method, 7–8 corresponding points were also identified in two point clouds. The visualization in Figure 16 shows that the registration effect varies depending on the equipment used and the movement of the smartphone.

The obtained RMSE values for each SwL point cloud registration scenario with TLS point cloud are presented in Table 2.

The best results for object 1 were obtained for the sg_v2_TLS with C2C algorithm scenario, for which RMSE is 0.012 m. For object 2, the best was the sg_v1_TLS with C2C algorithm scenario with RMSE of 0.019 m. In both considered

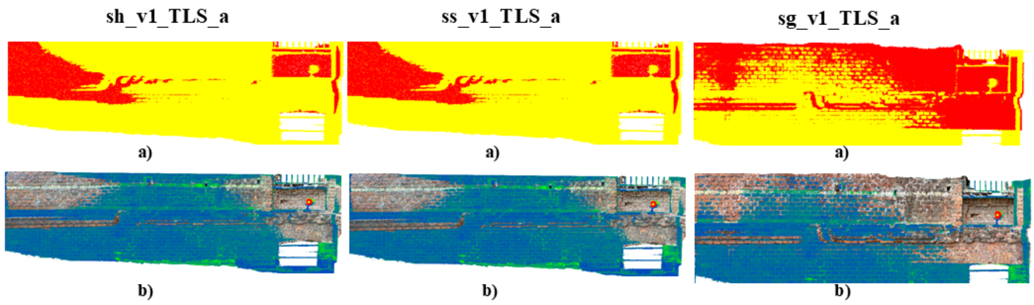



**Figure 9.** Scenario v1with C2C registration for object 1: (a) registration stage, (b) point cloud after registration

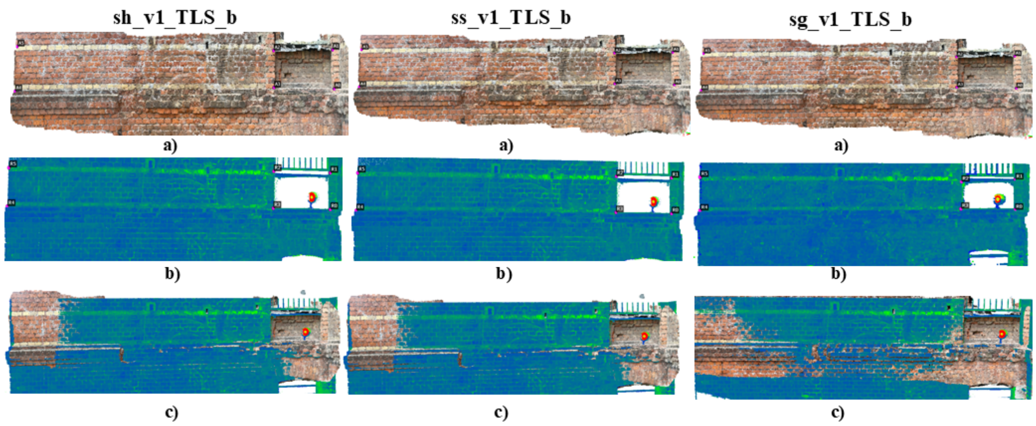



**Figure 10.** Scenario v1 with P2P registration for object 1: (a) registration stage SwL point cloud, (b) registration stage TLS (reference) point cloud, (c) point cloud after registration

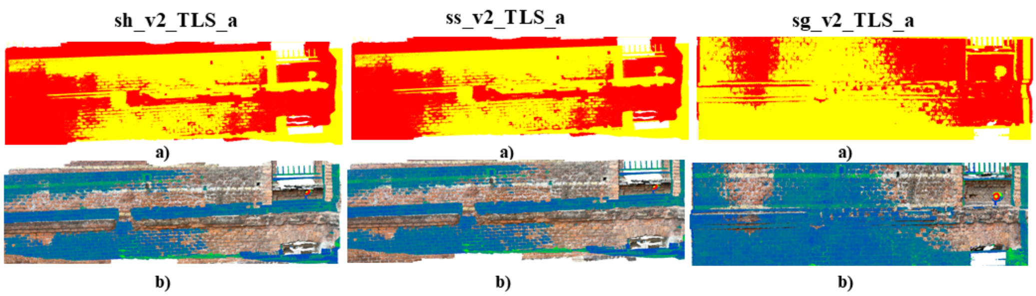



**Figure 11.** Scenario v2 with C2C registration for object 1: (a) registration stage, (b) point cloud after registration

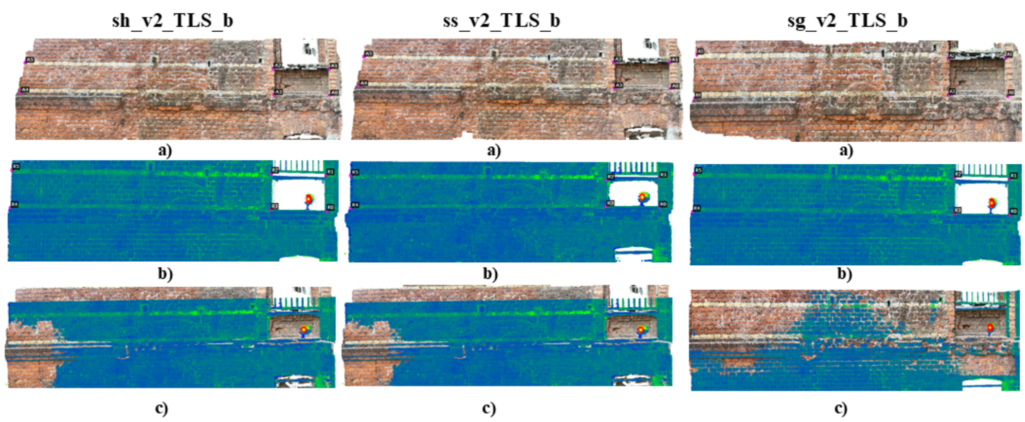



**Figure 12.** Scenario v2 with P2P registration for object 1: (a) registration stage SwL point cloud, (b) registration stage TLS (reference) point cloud, (c) point cloud after registration

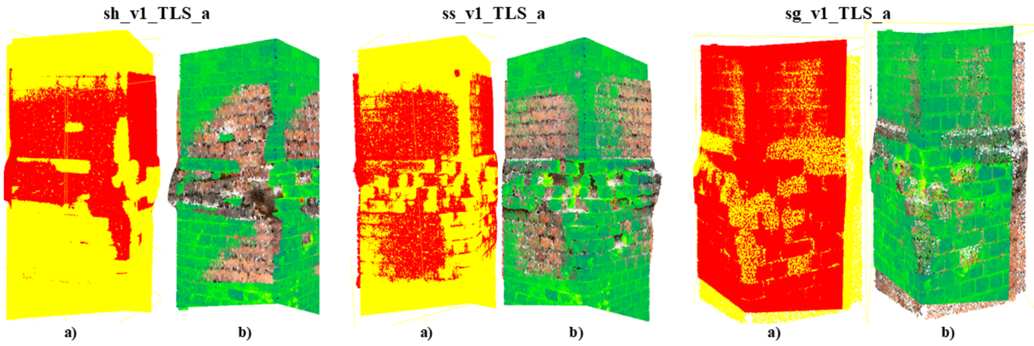



**Figure 13.** Scenario v1 with C2C registration for object 2: (a) registration stage, (b) point cloud after registration

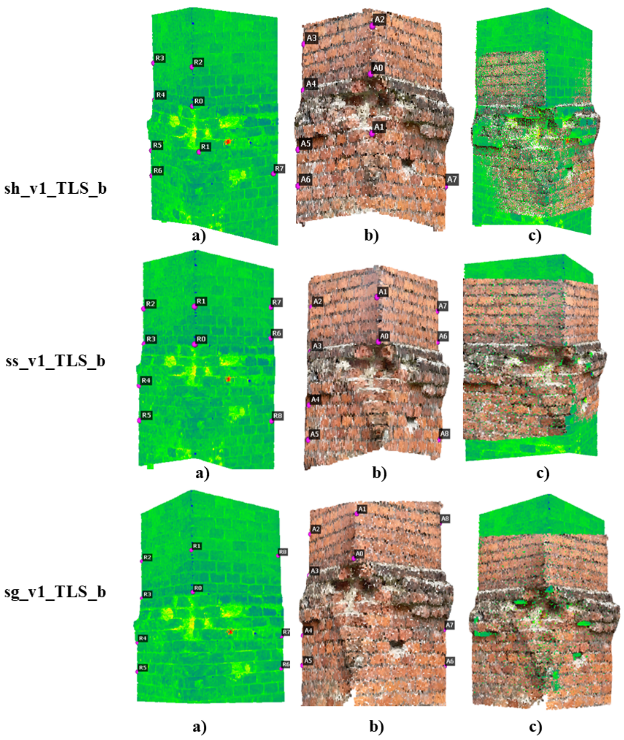



**Figure 14.** Scenario v1 with P2P registration for object 2: (a) registration stage TLS point cloud, (b) registration stage SwL point cloud, (c) point cloud after registration

scenarios, the use of gimbal and the point cloud registration method were significant. The way the smartphone moved had no impact on the final result.

Unsatisfactory results were obtained for measurements taken using a selfie stick (object 1) and while holding the smartphone in the hand (object 2). In both of these cases, the P2P method was used, and the RMSE registration errors were 0.060 m and 0.065 m for object 1 and object 2, respectively.

## 4 Discussion

The calculated RMSE dictated the plan for further analyses and only those datasets for which RMSE was the worst or the best were analyzed. Characteristic fragments were cut out from the study objects and presented in Figure 17.

In order to check the correctness of registration of the obtained point clouds, differential models were generated. A 3D model was generated for the TLS dataset, and then 3D models for datasets representing the selected scenario. The next step was to subtract these models from each other. This way, difference models were created which show how the models differ from each other.

Figure 18 presents the generated difference models.

The greatest differences are observed in places where there were large gaps in the structure of the brick wall. In addition, the structure of the brick wall made it difficult to indicate corresponding points on two clouds during P2P registration. The discussed aspects had an impact on the generated 3D model and the interpolation of points in the nephralgic areas.

## 5 Conclusions

The research presented in the paper used measurements taken with a smartphone with a LiDAR sensor and a point cloud obtained with TLS. The aim of the research was to register point clouds using different measurement variants. The tests analyzed different measurement scenarios in order to check how to perform measurements with a smartphone and what is important during processing point clouds obtained with this low-cost measuring device.

Based on the research conducted, it can be concluded that the way of obtain point cloud using a smartphone with a LiDAR sensor is important and affects the accuracy of point cloud integration. The following conclusions can be formulated:

i. It is recommended to use an additional tool such as a gimbal.
ii. It is also recommended to perform C2C registration.
iii. In our opinion, this is due to the fact that indicating the same points during P2P registration is not easy.
iv. It does not matter whether we measure in one direction

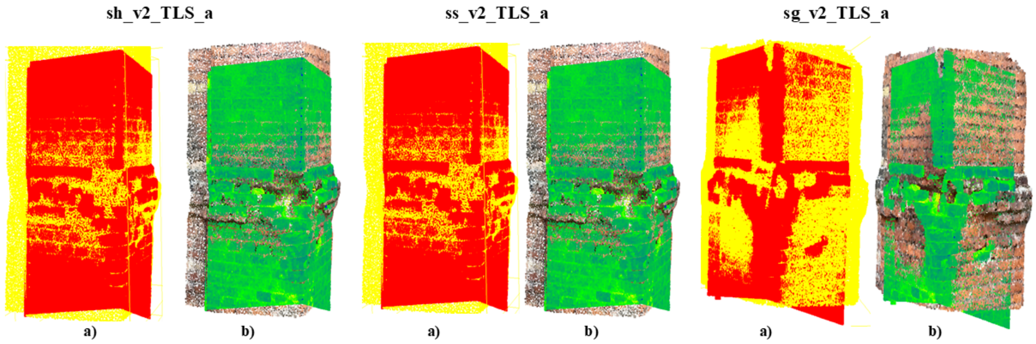


**Figure 15.** Scenario v2 with C2C registration for object 2: (a) registration stage, (b) point cloud after registration

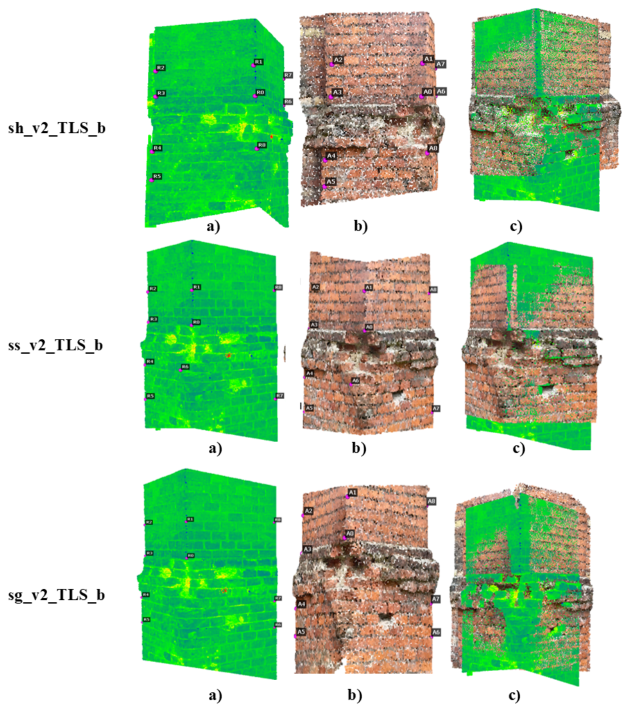


**Figure 16.** Scenario v2 with P2P registration for object 2: (a) registration stage TLS point cloud, (b) registration stage SwL point cloud, (c) point cloud after registration

or zigzag, it depends on the research object.

Among the presented main conclusions resulting from the research, the most important seems to be the first conclusion regarding the use of gimbal as a tool supporting smartphone measurement. It results from it that the use of gimbal significantly increases the accuracy of iPhone LiDAR acquisition by reducing sudden movements, which are particularly harmful in the context of mobile laser scanning technology. The presented results emphasize the role of gimbal in stabilizing data collection, which may be crucial for improving the quality of data in mobile LiDAR applications. This relationship is also confirmed by the 3D model of the object fragment (Figure 18), on which one can observe small differences between the reference model and the one generated on the basis of the point cloud obtained in scenario sg_v1_TLS_a for object 1 and sg_v2_TLS_a for object 2.

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**Figure 17.** Fragments selected for analysis: (a) fragment 1_object 1, (b) fragment 2_object 2

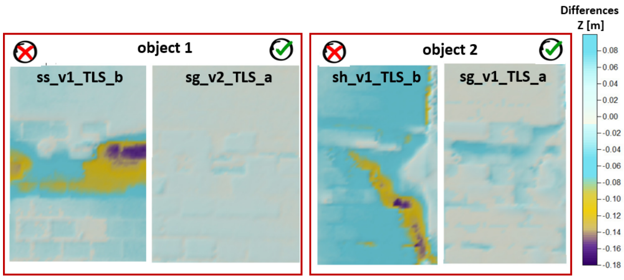


**Figure 18.** Differential models for selected fragments

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