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Combining the Technology of Long-Range Laser 3D Scanners and Structured Light Handheld 3D Scanners to Digitize Large-Sized Objects

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ABSTRACT

This paper presents a new method of merging the results obtained with long-range laser 3D scanners and structured light handheld 3D scanners to digitalize large-sized objects. An overview of the solutions in which these types of scanners are used was conducted and combined with the analysis of the studies related to the measurement accuracy they offer. The focus was on the problems that may arise during the digitization of detailed large-sized objects. A reference test object was then selected, which not only included the fine details that needed to be represented but also met the size criterion. The object was scanned by two 3D scanners and the data was then compared in various aspects, such as resolution, accuracy, and the measurement procedure. Significant discrepancies in the results were identified. They related to the resolution and quality of results as well as accuracy, reaching more than 20 mm. Therefore, a method of combining the results was developed to collate the advantages of both devices and eliminate their disadvantages. In the end, the analysis of obtained results was repeated and the results were presented.

Keywords: optical measurement, long-range laser 3D scanners, structured light handheld 3D scanners, Time-of-flight

INTRODUCTION

Digitization of objects with the help of 3D scanners has been gaining popularity and is increasingly applied in many fields of science and technology. Structured light scanners, both handheld, and stationary, are used when it is necessary to ensure a detailed mapping of an object whose shape is complex, whereas, the size is usually less than two meters.

Among others, they are applied by reverse engineering [1]. We have been also noticing some attempts to use them in the precise positioning of complex-shaped objects in the working space of a machine tool or welding machine to improve or automate the process [2, 3, 4]. 3D scanners may also be used to measure people, for instance for medical purposes [5, 6]. The list of the potential applications of 3D structured light scanners could be continued. All the examples mentioned here confirm that these devices are used whenever high resolution of a measurement and the capacity to map complex surfaces relatively easily and quickly are required.

However, it is necessary to be aware that these devices are subject to measurement errors, which has been repeatedly studied and verified. Analyses have been conducted to compare 3D scanners to CMMs, as well as to CT-obtained results [7, 8, 9, 10].

The accuracy of 3D scanners is most often tested on small objects. The technical specifications of structured light handheld scanners provide information about the accuracy that decreases when the size of the object increases, which is the consequence of the accumulated matching error of individual measurements [11]. Moreover, by analyzing the fact that individual measurements are linked based on geometrical features and features connected with the scanned objects' texture, we may assume that in certain cases, this error will become bigger than the specification one. It may be the result of a small number of the aforementioned features that enable accurate matching of the measurements. It may cause problems when digitizing large-scale objects.

To scan very large objects such as buildings or even building complexes, long-range ground-based laser scanners are used. These scanners are also often described as time-of-flight terrestrial scanners. They offer relatively high accuracies over long distances. Depending on the device used, the claimed accuracy of 3D point mapping can be as high as 0.7 mm at 15 m. Their specifics make them ideal for the fast scanning of vast areas with little detail.

A question may arise, how to approach the digitizing of a large-scale object, when its size is several meters if both high mapping accuracy and high detail reproduction are required. To improve the resolution and quality of results, a combination of laser scanners and photogrammetry is often applied [12, 13, 14]. This method is particularly useful when digitizing buildings decorated with bas-reliefs.

The purpose of this study is to investigate the possibility of combining the results obtained with a long-range laser scanner and a structured light handheld scanner to generate a detailed triangular mesh and at the same time ensure high accuracy for a large-scale object. Not much is said about combining the results offered by different types of 3D scanners, and this method has great potential, especially when detailed large-sized objects are involved.

MATERIALS AND METHODS

In order to conduct the analysis, we decided to scan a representative object using two instruments. A long-range Artec Ray laser scanner (Fig. 1) as well as the Artec Leo structured light handheld scanner were chosen. The highlights of the technical specifications of both scanners have been shown in Tables 1 and 2. As the measurement object, we decided to choose a historic staircase consisting of 8 flights of twelve steps each, a section of which can be seen in Figure 2.

In the past, other authors made attempts to use 3D scanners to map the flight of stairs [15, 16]. Nevertheless, the geometry of the staircase we selected is definitely more complicated. The dimension of a single measured flight falls within a rectangle of 1.9×3.3 m as shown in Figure 3.

It is worth noting the fact that each step has a rather complicated pattern when the underside of the step is considered (Figure 4). Despite the similar pattern, each step is unique and differs from the other ones.

This is an important piece of information because the task involved making the skirting for this staircase. Usually, an aesthetically satisfactory effect is achieved by undercutting the step and installing the skirting that is hidden in the undercut. In this case, because it is a historic building, interference with the original steps was ruled out, so it was necessary to replicate as closely as possible the shape of the staircase flight right by the wall.

The size of the staircase could theoretically qualify it for a long-range laser scanner digitization. The detailed pattern and hard-to-reach surfaces would suggest the use of a structured light handheld scanner, but on the other hand,

Table 1. The essential parameters of the applied long-range scanner

Distance measurement method	Phase shift
Laser class: (IEC EN60825-1:2007)	Class 1
Work range	1-110 m
Ranging error	0.7 mm @ 15 m
Angular accuracy	25 arcsecs
Speed of scanning	208,000 points/s
Laser wavelength	1550 nm
Laser type	Continuous wave
Weight with battery (only scanner, without a tripod)	5.74 kg

Table 2. The essential parameters of the used structured light handheld scanner

3D point accuracy	up to 0.1 mm
3D resolution	up to 0.2 mm
3D accuracy over distance	up to 0.1 mm + 0.3 mm/m
Tracking algorithm	Hybrid geometry and texture tracking
Working distance	0.35 – 1.2 m
Volume capture zone	160,000 cm³
3D reconstruction rate for real-time fusion	up to 22 fps
3D light source	VCSEL
Weight	2.6 kg

Fig. 1. Artec Ray scanner measuring the staircase

Fig. 2. Fragment of the scanned staircase

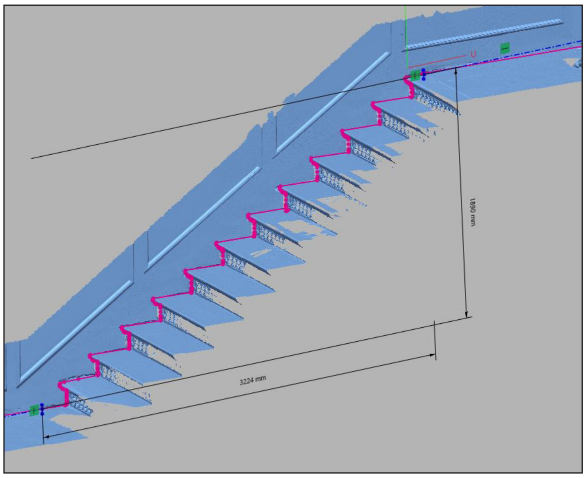

Fig. 3. One flight of staircase presented with dimensions

Fig. 4. The bottom section of the step

the small geometrical and textural variation of the object, as well as the repetitive geometry and the size of the object, implied the possibility of low scanning accuracy.

Measurement procedure

First, measurements were taken with a long-range laser scanner. To minimize the time necessary to complete the measurements, and at the same time ensure enough data to correctly align the point clouds, it was decided to perform two measurement positions on each of the landings excluding the first and last landing, as in their case, one position was performed on each of them. The first five measurement positions have been schematically shown in the scan (Figure 5).

It was not possible to repeat the measurements, so it was decided to connect the scanner to a computer and control the process from a laptop. This approach is unusual when working with this type of 3D scanner, but it makes it possible to accurately and continuously verify the results during the scanning. Due to the short distances between the scanner and the scanned surfaces, a scanning resolution of 25×25 was set, which means that on both the horizontal and vertical directions, 25 measurements were taken for each degree of rotation. Increasing the resolution in this case would not increase the resulting resolution of the resulting scan (It would not increase the level of detail), but would only increase the number of points on a single scan. Mapping the entire staircase with the Artec Ray scanner required 16 individual measurements and took about 90 minutes, which included repositioning as well.

Next, it was possible to move on to measurements performed with the structured light handheld scanner. In this case, the measurements can be compared to recording a video with a smartphone, except that it is necessary to watch the proper distance of the device from the scanned object and pay attention to the correct scanning technique. To obtain valuable data, it was necessary to make sure that during the measurements the scanner's detectors accurately recorded the bottom area of the steps, since the geometry there is the most complicated. Because of the short distance separating the steps, this procedure required a lot of focus and precision. It is worth noting that the quality of the results obtained with handheld 3D scanners can very much rely on the operator's skill and proficiency. In this case, in order to minimize the error associated with the size of the object, each flight of stairs was completed as a separate project. In the case of the handheld scanner, the entire staircase was not scanned, only the flights of stairs themselves at a range of about 50 cm from the wall. It took about 40 minutes to scan all the flights of stairs with the scanner.

Once the measurements were taken, all the data was imported into the Artes Studio 15 software, where point clouds from the long-range scanner were aligned to recreate a scan of the entire stairwell. Next, each of the scans from the handheld scanner was processed separately using a global registration algorithm, which minimizes the error between the individual frames in the scan based on the geometric and textural features contained in the scan. In the next step, the appropriate scans of the stairs obtained with the handheld scanner were superimposed on the point cloud obtained with the long-range scanner.

The flights were extracted from the point clouds and used as a basis for generating triangle mesh (Figure 6). The triangle meshes were generated separately based on scans from the long-range scanner and the handheld scanner.

Thereafter, we moved on to the analyses, during which three criteria were selected according to which the quality of the results and the feasibility of individual devices in this type of application were evaluated.

Resolution of the results and the amount of data captured

Figures 7 and 8 show the results of scanning the first flight of stairs and close-ups of the pattern details on the same step. The target object that was scanned was a section of the staircase, about 0.2 m wide as measured from the wall, and only this section should be considered when evaluating the results. At first glance, it can be seen that the data obtained with the long-range scanner is incomplete. On many of the steps, the top or bottom part of the step is invisible, which is not the case with the handheld scanner. Moreover, one can also see a significant difference in the mapping of details in the presented close-up. The data obtained with the handheld scanner generated a triangle grid with a resolution of 1 mm, while with the data from the long-range scanner, the best grid quality was captured with a resolution of 3 mm.

Accuracy

Because of the high measurement accuracy in large objects, the results obtained with the long-range laser scanner became a reference for the analysis. After superimposing the data, we can clearly see a proportional increase in the discrepancy between the results as the scanned object size increases. Figure 9 shows the list of measured discrepancies between the results at a given location. A color-coded deviation map visually depicts the distribution of discrepancies across the object. Figure 10 shows the data obtained from both scanners overlaid on top of

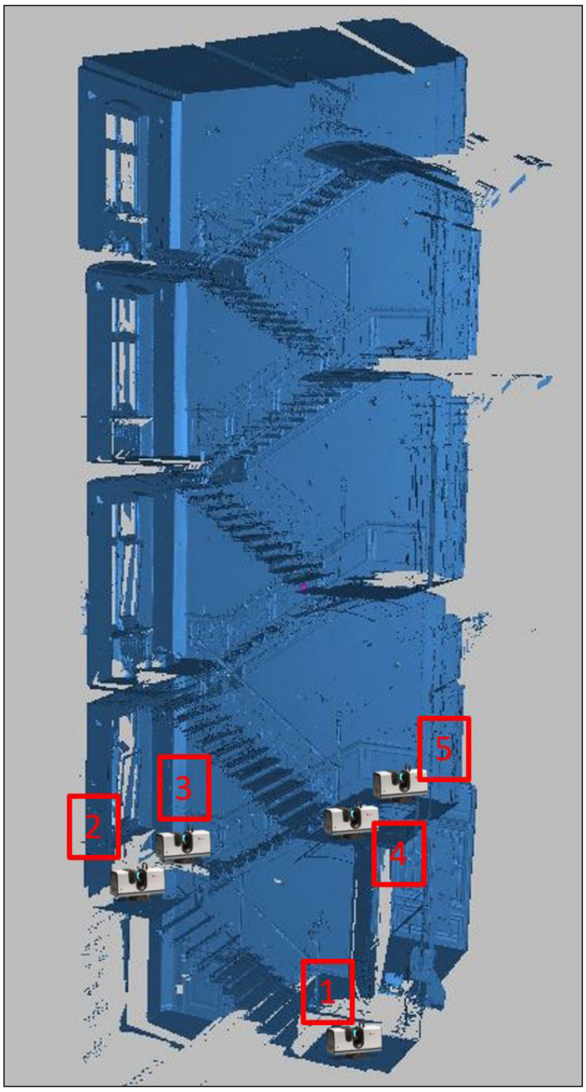

Fig 5. A diagram presenting the first five measurement positions on the resulting point cloud

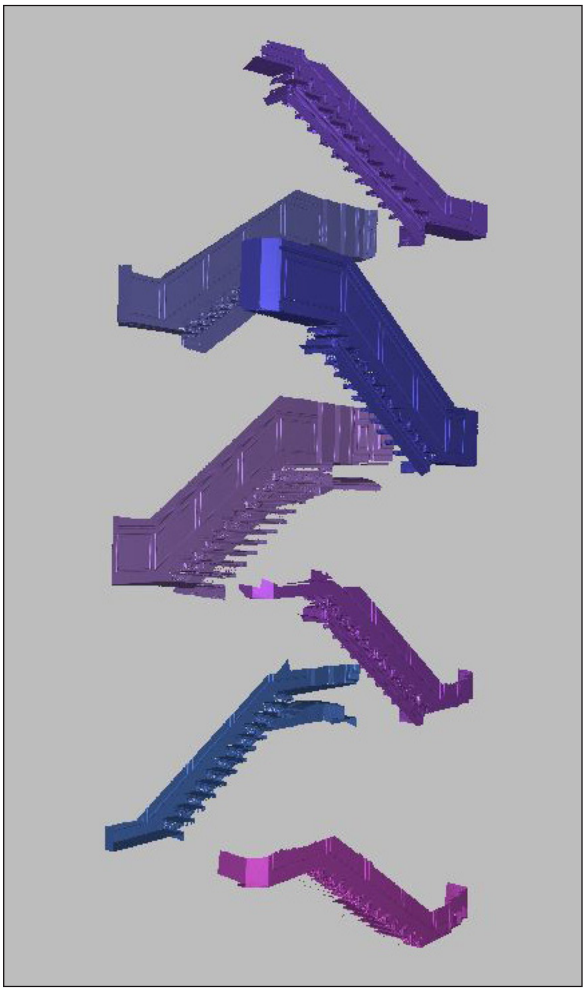

Fig 6. Individual stair flights in the preserved coordinate system of the entire staircase

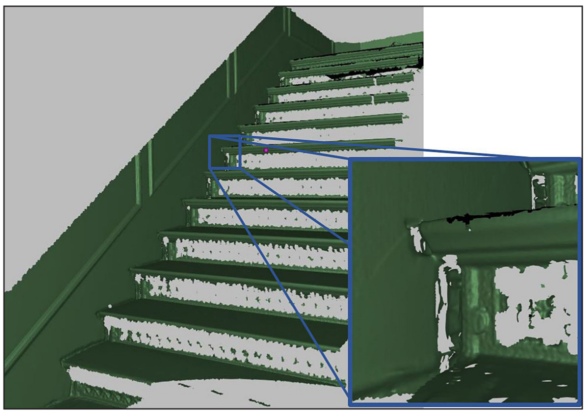

Fig 7. Data obtained with the long-range laser scanner

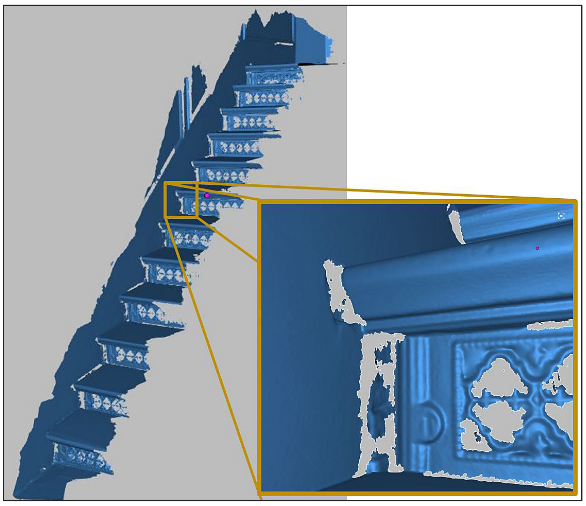

Fig 8. Data obtained with a structured light handheld scanner

each other, along with a linear measurement of the discrepancies at the last steps, which amounts to over 22 mm. At first glance, we can see that the data fails to match. Considering that the long-range laser scanner is treated as a reference, it can be inferred that the results from the

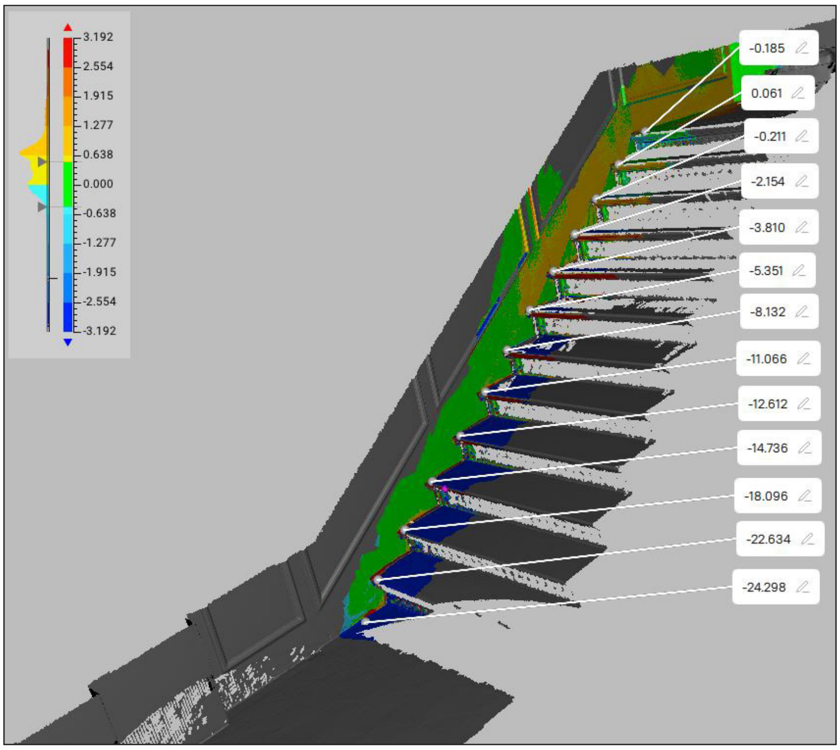

Fig 9. Comparison of the results obtained with the two 3D scanners

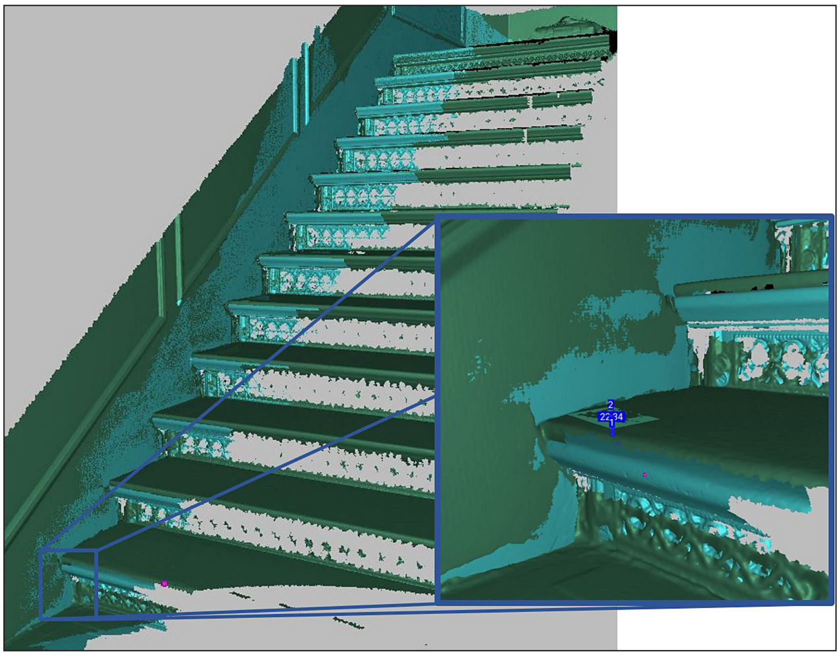

Fig 10. Superimposed results obtained with both 3D scanners

handheld scanner were "swollen". This is due to the size of the scanned object, which affects the accumulation of errors related to frame matching at a distance. This confirms the fact that discrepancies between the results increase with the size of the object, which can be observed in Figure 9, where the alignment error at the first step is small, at the level of 0.2 mm, then increases at each step, and at the last step it reaches 22 mm. This effect is reinforced by the fact that the scanned object has a small number of geometric and textural features that can be used for frame matching, which affects incorrect matching of individual frames during measurement.

Easy to use and scanning time

It takes 55% less time to complete measurements with the handheld scanner. A handheld scanner is also definitely simpler to use in this type of environment. Certainly, the scanning process with the help of a long-range scanner does not require operator intervention, but moving around a staircase with a heavier scanner equipped with a tripod is more complicated. It is also necessary to make a reference to the previous point relating to the quality of the obtained results. In order to pursue a better mapping of the steps' shape with a long-range scanner, it would be necessary to repeatedly increase the number of measurement positions, so that the laser beam can reach hard-to-reach surfaces.

Summary of the analysis

As expected, the long-range laser scanner maintained high measurement accuracy and allowed quick mapping of the entire staircase. However, the results are much less detailed and many sections failed to be scanned. This is caused by the operating characteristics of the device. To complete the non-scanned areas for a reference object, many more measurements would have to be taken. The data obtained with the handheld scanner maps the details much better, but because of the small number of features to be tracked with the help of the 3D scanner, and because of the dimensions of the reference object and the accumulation of errors associated with matching individual measurements, the data is subject to a greater error.

Method of combining scans

Because of the need to combine the advantages of both devices while eliminating their disadvantages, attempts were made to combine the results from both 3D scanners. The procedure in the method we developed has been presented in Figure 11.

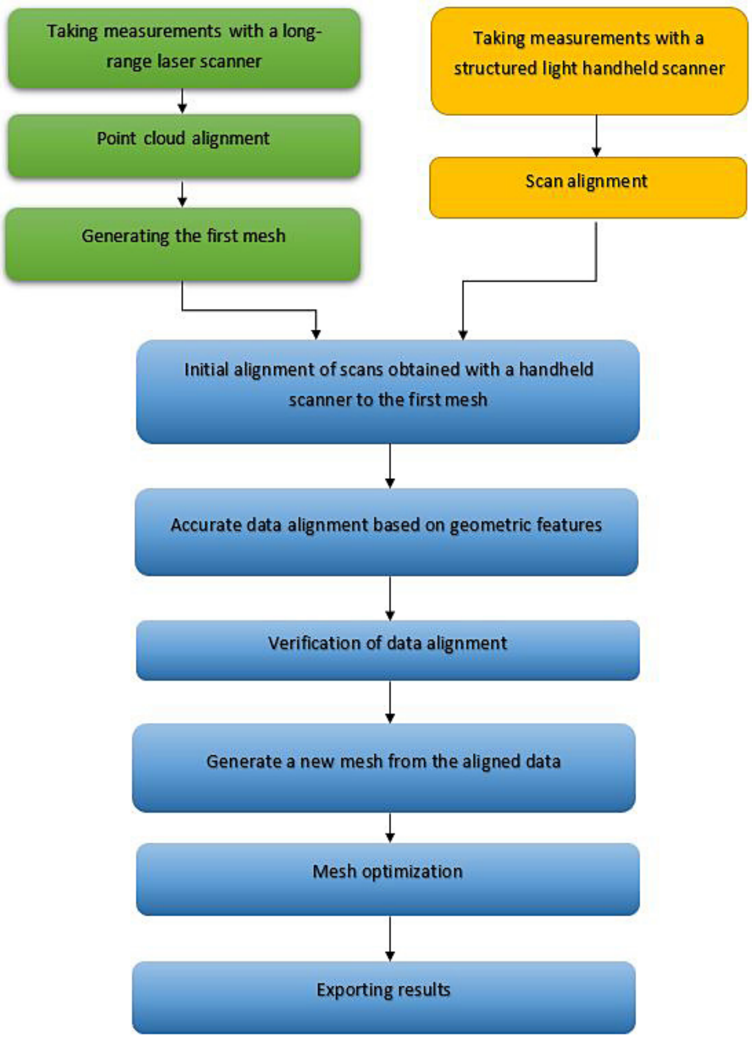

Fig. 11. Method scheme

It was a benefit that the data collected by the handheld scanner is collected in the form of frames, i.e. individual fragments. They are matched to each other in real time, and thus a complete image of the scanned object is created. Then, using appropriate algorithms, the geometry of the individual frames is recalculated to improve data matching. We decided to use the data obtained with the long-range scanner in this process as well. In the first step, a triangle mesh was prepared based on the data obtained with the long-range laser scanner.

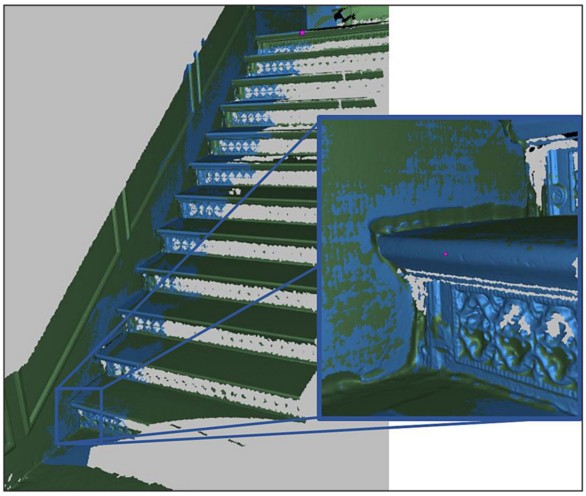

Fig. 12. Comparison of the results obtained with the two 3D scanners after alignment using our method

Then the raw data obtained with the handheld scanner in the form of frames were aligned together with the obtained triangle grid. Next, we applied the algorithm responsible for aligning the data simultaneously with the data obtained with the handheld scanner and the triangle grid generated from the long-range scanner data. As a result, the individual frames obtained with the handheld scanner have been aligned not only with each other, but also with the triangle grid generated on the basis of the data provided by the long-range scanner. Subsequently, the error associated with matching individual measurements is eliminated, as individual frames are aligned with characteristic points derived from the triangle grid prepared earlier. In Figure 12 you can see the aligned data after our method was applied.

Having reanalyzed the accuracy, we can see that the data obtained with the handheld scanner no longer deviates significantly from the triangle grid prepared on the basis of the data provided by the long-range scanner. Discrepancies between the results on the last step decreased from 24 mm to less than 1 mm. The discrepancies are now much more balanced at all steps. A visual comparison of data has been presented in Figure 13. Finally, a triangle mesh was generated based on the converted data provided by the handheld scanner and the previously prepared mesh, which is shown in Figure 14.

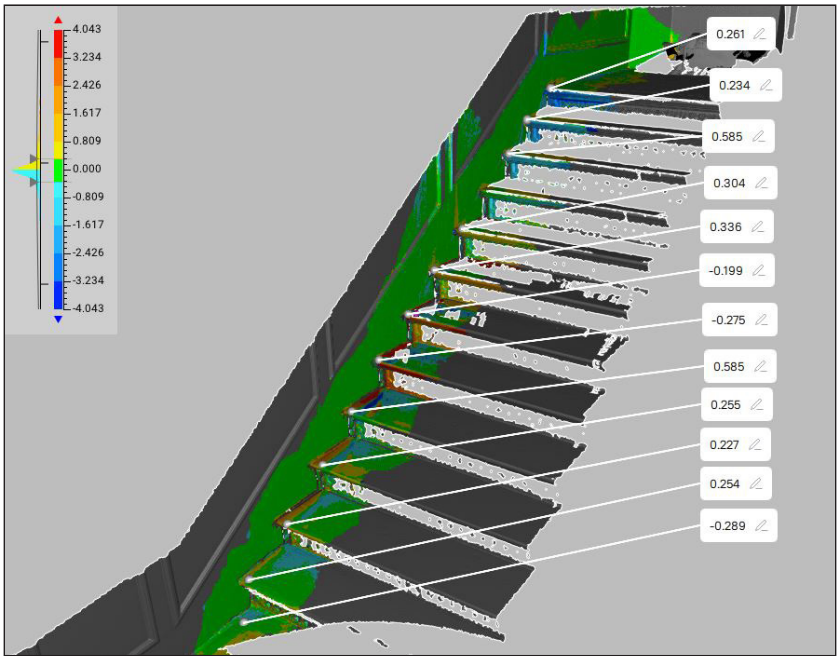

Fig. 13. Comparison of the results obtained with the two 3D scanners after alignment achieved by using our method

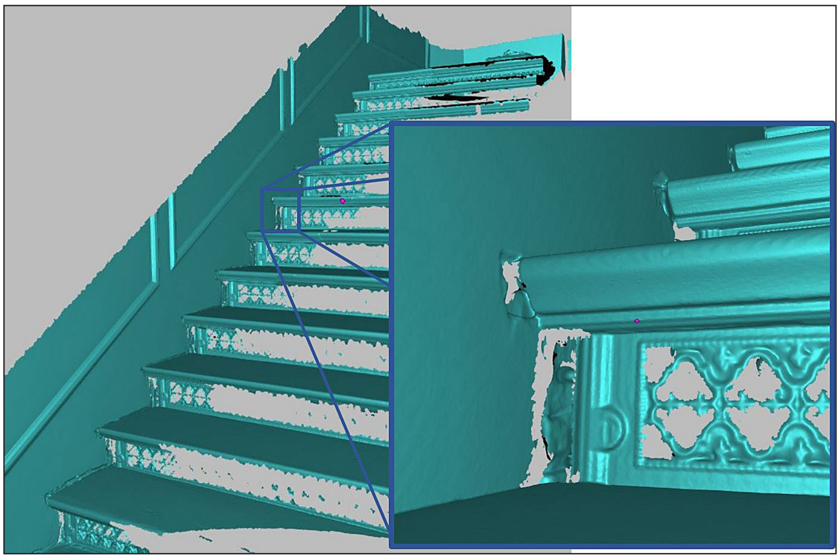

Fig. 14. Final triangle mesh generated

CONCLUSIONS

Our approach helped to eliminate errors connected with the size of the scanned object, thus, increasing significantly the accuracy of the results. At the same time, the resolution of the resulting data, and thus the level of detail mapping, increased by 200% as compared to the data obtained with a long-range scanner. These results were achieved while keeping the method simple and the time required for measurements relatively short. However, the method requires geometric features to match the measurements. If they fail to be present in sufficient quantity, it may be necessary to vary the geometry of the object through appropriate markers, or in extreme cases, its application may not be possible. Nonetheless, this method is intended for digitizing detailed objects, so this problem should not often occur.

The second disadvantage of this method is that it requires the use of two pieces of equipment, which involves transporting a lot of expensive equipment to the scanning site, but at the same time, it can be considered an advantage that the equipment is completely mobile and does not require complicated procedures once it is set up at the target site.

A possible direction for further development seems to be the design of appropriate markers that would allow for complete automation of this process and perhaps minimize the error associated with a limited number of features for tracking in the case of a handheld scanner.

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