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ANALYSIS OF SCANNING AND 3D PRINTING ACCURACY OF AN ANCIENT ARCHAEOLOGICAL ARTIFACT: A CASE STUDY

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Abstract
The paper presents results on accuracy assessment of scanning procedure and of subsequent 3D printing of the object copies. The investigated object was an archeological artifact made out of burnt constructional clay, found at the archaeological site No. 6 in Gasawa, Poland, assigned to the end of 2nd or of 3rd century C.E. The analysis enabled to determine the taxonomic marking, the type and species of the tree used for the construction. The object was scanned with portable HandyScan3D device, and the repeatability of the single point identification assessed from 10 repetitions was %EV=19% for this application.

Keywords:
3D Printing, Scanning, Repeatability

1 INTRODUCTION

Rapid development of 3D scanning techniques allowed for their wide application in various scientific disciplines. Scanners of various types, accuracies and ranges can be used for analysis of large engineering constructions [Majchrowski 2015], paleontological objects [Garashchenko 2022], or even face shape patterns for anthropological research [Windhager 2019]. In archeology, application of photogrammetry and laser scanning was reported to be advantageous for documentation due to achievable precision and metric reliability of the combination of both techniques [Sánchez 2023]. There are reports both on large-scale archeological objects monitored with photogrammetric techniques [Ostrowski 2024] and on geometry and surface texture of small artifacts [Polo 2022], and even on macro-porosity of ancient objects [Miriello 2006].

There are numerous published reports related to the feasibility of 3D scanning methods applied to various objects in a wide range of fields of science. However, no standard criteria of feasibility determination for different applications can be formulated. Thus, the proper choice of a scanning method remains the individual task requiring purpose-oriented analysis, considering different properties of the scanned surface (e.g. roughness, reflectivity, texture) and their effect on the scanning process.

Repeatability is understood as “closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement” [JCGM 100:2008]. Repeatability study usually involves statistical calculations of data obtained from several repetitions of the measurement. This is applicable also to the scanning devices in relation to small objects [Jacobs 2023] and to examination of large objects with rough surfaces using 3D scanning techniques [Piekarczuk 2024].

In the present study, the feasibility analysis was performed for a portable scanner in relation to an archeological artifact made out of burnt constructional clay. The accuracy of reproduction was not limited to the scanner only, but also widened with 3D-printed copy of the object. Using the scanned digital model of the original artifact, a copy was made with additive technology. This copy was then scanned to assess the differences between the original artifact and its replication. Feasibility of the scanning device was assessed through the repeatability parameter *EV*, usually applied for the industrial measurement systems.

2 DESCRIPTION OF THE ANALYZED OBJECTS

The investigated scanned and 3D-printed objects were two archeological artifacts made out of burnt constructional clay, found at the archaeological site No. 6 in Gasawa (Znin district, Kuyavian–Pomeranian province, Poland), assigned to the end of 2nd or first half of 3rd century C.E. The location of the archeological site is shown in Fig. 1, and in detail in Fig. 2.

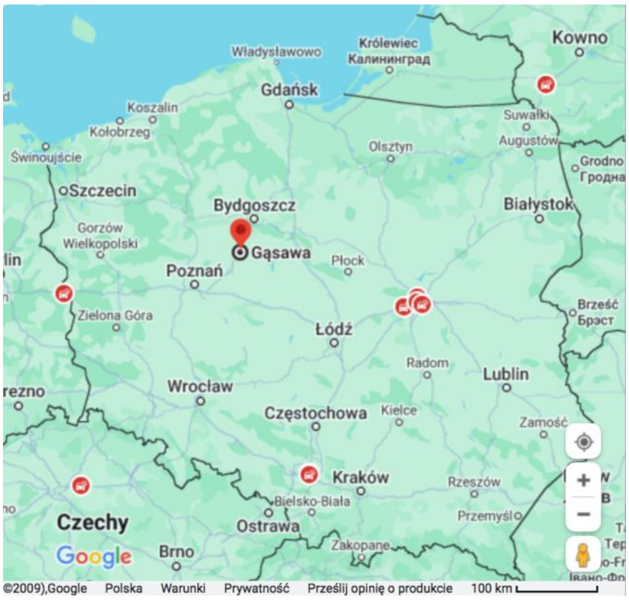

Fig. 1: Gasawa location in Poland.

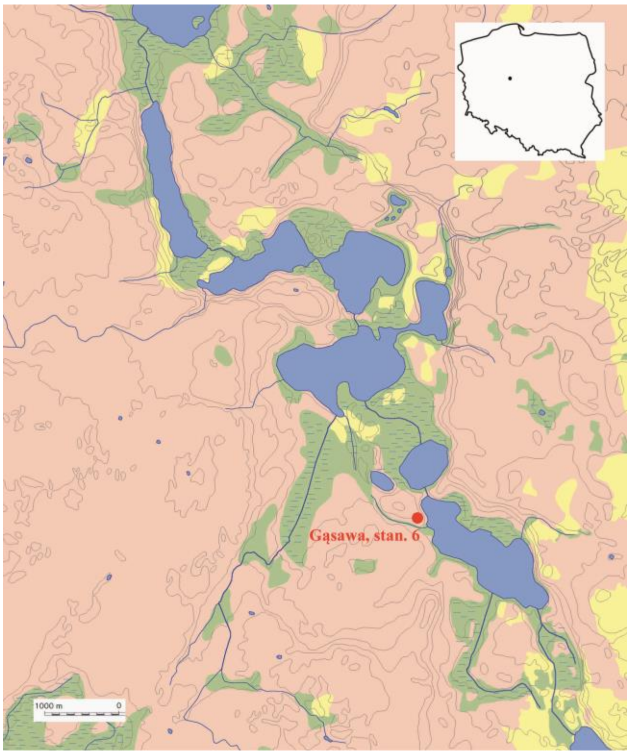

Fig. 2: The archeological site No. 6 at Gasawa.

The analyzed pieces of burnt clay belonged to object No. 242. These were the remains of the dugout building, which presumably used to serve as a weaving workshop [Grossman 2024]. The dugout construction was made out of the wooden pillars, and its walls were made of branches, covered with clay and painted with lime. The building has been destroyed by fire, which caused burnout of the clay used in the construction. Thus the hardened clay preserved all the imprints that are seen relatively well even today. Among the imprinted materials are branches, pieces of wood, or laths, some leafs can be found. The latter objects are of especial significance, since they are not often and they can precisely indicate the species of wood used for the construction. This information is very important for understanding the architecture and engineering of the ancient times.

The remains of the dugout building contained ca. one ton of the burned clay pieces. So far, archeological analysis of this finding focused on the analysis of imprints of wooden constructional elements, which has been divided to three groups. The first group consisted of the clay pieces with imprints of branches of diameter ca. 1-2 cm that used to form woven walls of the building. To the second group, the clay pieces with imprinted adjacent wall beams of ca. 20 cm diameters has been classified. And to the last group belonged flat pieces of burnt clay, about 2-3 cm thick, with clear imprints of leafs. The function of the last group is still uncertain. It is supposed to be fragments of the threshing floor or walls.

In the present analysis, two objects were considered, one representing the last group, seen in Fig. 3, left, and one from a mixed category, with imprinted branches and leafs, seen in Fig. 3, right. Other categories did not require accurate scanning due to the lack of small surface features worth detailed analysis.

Fig. 3: The objects with markers before scanning.

Significance of the digitization and further analysis was determined by the ability to collect precise data on the ancient architecture, accurate information on the construction of the building, choice of the constructional materials, and ornamentation applied in the architecture of ancient Polish lands. Especially important was identification of the plants used, quality and dimensions of the material, and ability to indicate the season.

In the present study, the objective was to assess feasibility of the available scanning and 3D printing methods to support the environmental archeology in taxonomical identification of the findings or quality of the constructional materials. Accurate reproduction of the objects using 3D printing technology was important also from the educational perspective as well as for reconstruction and visualization [Hageneuer 2020]. Surfaces of original ancient clay artifacts would quickly degrade when touched, while 3D-printed models could be reproduced in many copies.

In the present research, analyzed features were the shape of the leaf imprinted in clay, its veining, surface structure, and edge. The analysis enabled to determine the taxonomic marking, the type and even species of the tree used for the construction of the dugout building.

3 MATERIALS AND METHODS

3.1 Advanced scanner Keyence

The initial accurate analysis of the objects was performed using Keyence VR 5000 device with rotary table, available at Łukasiewicz Research Network – Institute for Sustainable Technologies in Radom (Poland). According to the specification, it allowed for vertical measurement with resolution of 0.1 µm, ensuring repeatability of 0.4 µm without stitching. The massive, stable table eliminated vibrations, and the computer was equipped with the dedicated software for analysis. Figure 4 presents the device during the scanning of the archaeological artifact.

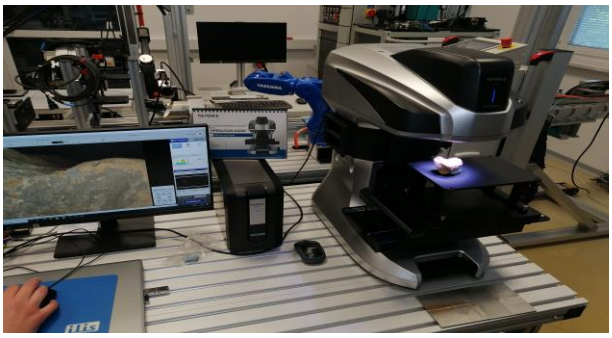

Fig. 4: The scanning process using Keyence VR 5000 device.

The results of the measurement could be exported in STL format as a 3D model, in PNG format as pictures or in form of ASC or SolidWorks datasets. This way the results could be further used for additional analysis or necessary modifications. Figures 5 and 6 show the optical image obtained from the scanner and the 3D image with height color map.

Fig. 5: The optical images obtained from Keyence VR 5000 device.

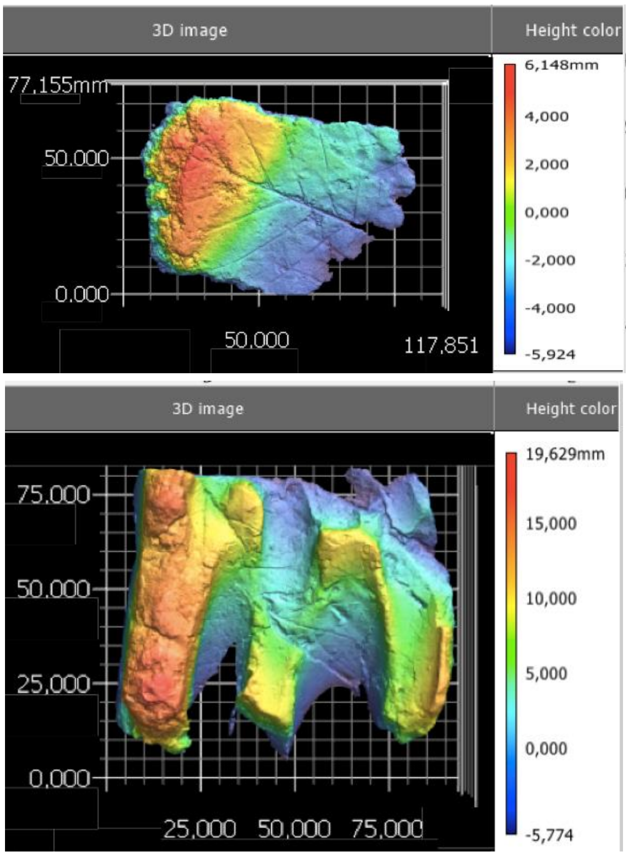

Fig. 6: The height color maps obtained from Keyence VR 5000 device.

In fact, analysis of the leaf imprint in the clay does not require accuracy of 0.4 µm. This level of reproduction of surface features can be useful for advanced technological surfaces, but for the assessment of an imprinted leaf details such a small irregularities became a noise. Moreover, the costs of the device and time consumed by the scanning process are unreasonably high for this application. However, from the metrological perspective it was important to collect the additional data for reference.

3.2 Portable HandyScan3D device

The experimental research consisted of scanning the object with portable HandyScan3D device (Creaform, Levis, Canada). The scanner was convenient for the field research since it was a lightweight device with a dynamic referencing self-positioning. Its accuracy declared by the manufacturer was 0.025 mm and measurement rate up to 1,800,000 measurements per second. Before being scanned, the object had to be marked with reference points, placed around according to the manufacturer's recommendations, as it is seen in Fig. 3 above. Figure 7 shows the measurement of the object with HandyScan3D.

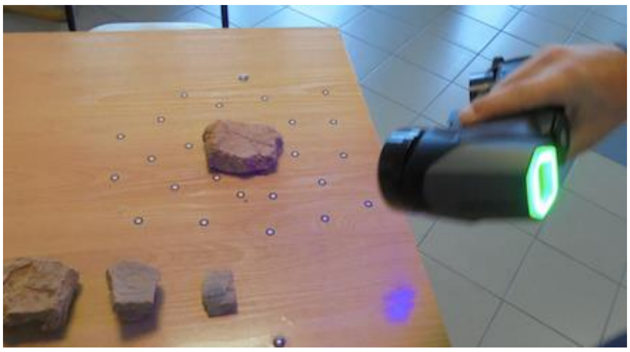

Fig. 7: The objects scanned with HandyScan3D.

The digitized scanned surface appeared to be useful for the analysis in terms of archeological sciences, plant taxonomy, etc. The peculiarities of the clay surface were smoothened emphasizing the proper features of the imprinted leaf. Figures 8 and 9 present the digital model obtained with HandyScan3D and exported to the STL format.

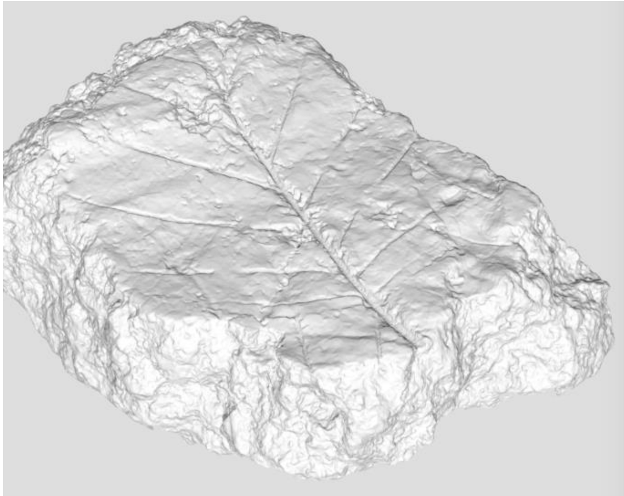

Fig. 8: The digital model obtained from HandyScan3D.

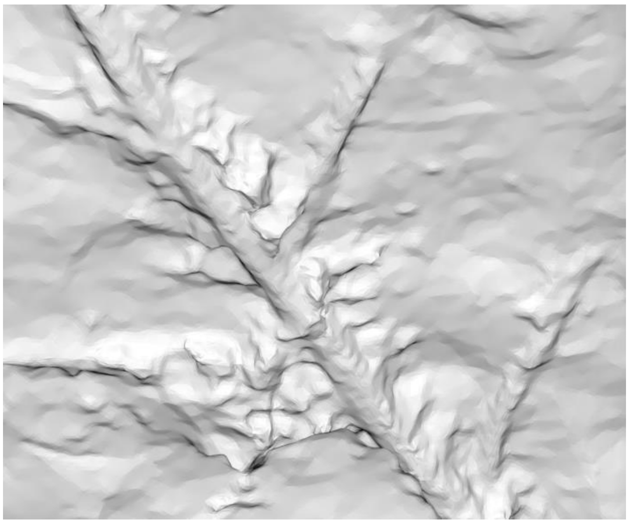

Fig. 9: The enlarged surface from the digital model.

3.3 3D printed copy

A 3D printer EOS P396 (Electro Optical Systems GmbH, Munich, Germany) with a laser of a maximum nominal power of 70 W was used for the production of the object's copy. The building volume of the printer was 340 × 340 × 620 mm^3 and the scanning speed reached up to 6 $m \cdot s^{-1}$. Commercial PA12 powder EOS PA2200 (EOS GmbH) was used. This material was chosen because it is very popular in selective laser sintering due to its excellent mechanical properties, easy processibility, reduced porosity, and high reusability potential [Yang 2023]. In the experiments, the new powder was mixed in a 50:50 ratio with the used powder of the same type. The recovery rate of new and used powder was recommended by the manufacturer and was extremely important for the sustainability and reduction of overall environmental impacts [Pusateri 2024]. This way the material choice is in line with industrial development trends oriented toward environmental protection [Mesjasz-Lech 2023]. The 3D printing parameters are listed in Table 1.

4 REPEATABILITY ASSESSMENT

In this work, the following observation was used as a basis for the assessment: "Areal topographic measurements typically consist of many measured heights (>10^5) and hence an equal number of comparisons. This is the most fundamental means of evaluating repeatability and reproducibility in topographic measurements, each individual height measurement at each location" [Peta 2024]. To use this observation for repeatability assessment in this particular application, the following procedure was performed.

First, the scanned surface of the original artifact obtained from HandyScan3D was treated as reference. Second, similar surface was obtained after scanning of the 3D-printed reproduction of the object. After superposition of these two surfaces, a color map of the distances Δx_i between their points was generated. The difference Δx_i had positive values when the point was above the reference surface, and negative one when it was below. Repeated scanning of the reproduction provided different results, presented in Tab. 2.

Next, for each repeated scanning of the same surface, a grid of points was identified, as it is shown in Fig. 10. Each point represents the value of difference Δx_i between the reference and repetition surface. When the scanning was repeated 10 times, the same points were supposed to have the same values, which in reality was not the case due to the equipment variation (*EV*). Based on the abovementioned assumption, individual measurement result at each location could be used for the repeatability evaluation.

Fig. 10: The scanned object with a grid of the tested points.

To perform the repeatability analysis, two points on the surface were chosen randomly, marked with red ovals in Fig. 10. They represented respective differences Δx_1 = 0.040 mm and Δx_2 = –0.035 mm for the first repetition. The values of Δx_i from 10 repetitions for the same points are collected in Tab. 3. The number of two points was sufficient to perform the procedure correctly, and the previous experience suggested that analysis of more points would not change significantly the resulting value of *EV*.

And finally, following the procedure described in detail in [Dietrich 2011], equipment variation *EV* was calculated considering the confidence level 99% from equations (1), (2) and (3).

$$EV = 5.15 s_E \tag{1}$$

$$s_E^2 = \frac{1}{n(k-1)} \sum E \tag{2}$$

$$\sum E = \sum_{i=1}^{n} \sum_{j=1}^{k} (X_{ij} - X_{i.})^2 \tag{3}$$

where:

$X_{i\bullet}$ - mean value for the given point in the grid,

i – number of points, from 1 to n; here n=2;

j – number of repetitions, from 1 to k; here k=10.

The obtained value EV = 0.229 mm characterized the repeatability of this sort of measurement with this equipment, and covered all possible deviations. It covers the variations of the single point identification on the surface of the imprint of a leaf in the ancient constructional clay when scanning with Handy Scan3D device. Since the repeatability was assessed using the distances Δx_i between the object's scanned surface and the scan of its 3D-printed copy, it reflects also the fidelity of the artifact's reproduction using 3D printer EOS P396 and PA12 powder in 50:50 recovery rate.

Since there was no technical requirement specified for the tolerance, it was reasonable to appoint the reference value from the experiment. It could be, e.g., the range between the maximal and minimal values obtained from the first repetition, specified in Tab. 2. Then, for the reference value RF = 1.193 mm, repeatability in percentage was calculated as $\%EV$ = 19%. In industrial applications, equipment variation below 20% is usually considered a good result [Dietrich 2011]. Evaluation of the reproducibility was found unnecessary due to the automated data collection and processing.

Thus, in similar conditions of archeological research, when the scanned object will be of similar kind, HandyScan3D device and 3D printer EOS P396 will ensure good digital model and material reproduction, feasible for further research, storage or educational purposes.

5 ARCHEOLOGICAL CONCLUSIONS

The results of scanning and 3D-printing accuracy analysis provided solid ground for object identification and archeological conclusions, as follows. One of the most important morphological features enabling the identification of leaves is the shape of their blade. Characteristics of its shape include, among others, the following features: the shape of the entire leaf, the shape of its edge, and the structure. Another important feature to be recognized is the specific network of leaf veins.

The leaf imprinted in clay found at object No. 242 at Gasawa, shown in Fig. 8, has been preserved only partially, which makes difficult its unequivocal identification. The surface of imprint is roughly 70 mm × 100 mm, as it is seen in Fig. 6. The clay block preserved its clear and convex veining, deeply imprinted on the underside, and small and poorly marked traces of the shoreline. Analysis of the scanned and enlarged details focused on the following features of the leaf: its type (a single leaf), estimated original size (probably about a dozen of cm), wide oval shape, and typical strong veining of the leaf blade. The features seemed to indicate that it is probably the imprint of a hazel leaf. It should be emphasized, however, that the lack of information on the entire shape and edges of the leaf left a gap posing limitations on the certainty of its taxonomic identification. It should be noted, however, that the probability of classification is significantly enhanced by the object's scanning and 3D imaging.

Common hazel (*Corylus avellana* L.) is a shrub classified to the birch family. It is a common plant in Poland, both in lowlands and mountainous locations up to an altitude of about 1,300 m above the sea level. It grows in deciduous, mixed forests or xerothermic thickets. It prefers sunny or semi-shaded places. In the classification of plant groups, the species are typical for Cl. Querco-Fagetea, Ass. Stellario-Carpinetum. Hazel grows in the form of a multi-stemmed shrub that can grow up to 5 m high. Its branches are raised high and form a spreading crown. The trunk has dark gray, smooth bark with visible horizontal cross-hatching on the surface. The leaves of this species are twisted, single, set on a short, glandular, hairy petiole. The leaf blade is broadly oval to round, up to 10 cm long, double serrated, pointed at the top, heart-shaped slightly at the base. Male flowers are collected in catkins, female flowers in buds. The fruit is a nut, which is light brown in color and almost oval in shape. Its common name is hazelnut. Ripens from September to October.

It may be assumed with high probability, that the availability of the common hazel in the region was the main factor for using it as a constructional material. Since it has relatively thin, strong and flexible branches, hazel found its application as reinforcement in the clay-matrix composite material for building construction. Scanning of all the leaf imprints found at the object will make possible statistical analysis and provide insight on the proportion of other species used for the construction.

6 SUMMARY

This paper presents the results of interdisciplinary study on the feasibility of portable 3D scanning method for the archeological research. In particular, its purpose-oriented repeatability was assessed in relation to the leaf imprints in clay. The study provided solid background for application of similar devices in analysis of similar objects. Having proven sufficient fidelity of 3D scanning and 3D printing, archeologists can make a huge database of the imprinted leafs for further analysis in cooperation with botanists and for numerous educational and scientific purposes.

7 ACKNOWLEDGMENTS

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Tab. 1: 3D printing parameters.

Layer Thickness	Process Chamber Temperature	Removal Chamber Temperature	Beam Offset	Material Dependent Scaling			
				X	Y	Z (0 mm)	Z (600mm)
[μm]	[°C]	[°C]	[mm]	[%]	[%]	[%]	[%]
120	171	130	0.33	3.15	3.23	1.4	2.55

Tab. 2: Differences between the repeatedly scanned surfaces of 3D copy and the original artifact [mm].

Repetition	1	2	3	4	5	6	7	8	9	10
Min	–0.692	–0.479	–0.408	–0.381	–0.400	–0.464	–0.373	–0.403	–0.387	–0.464
Max	0.501	0.335	0.359	0.347	0.440	0.400	0.636	0.469	0.514	0.511
Range (Max – Min)	1.193	0.814	0.767	0.728	0.840	0.864	1.009	0.872	0.901	0.975

Tab. 3: Repetition results used for EV calculations [mm].

Repetition	1	2	3	4	5	6	7	8	9	10
Point 1	0,040	–0.008	0.034	0.117	–0.018	0.123	–0.017	–0.039	0.058	0.036
Point 2	–0.035	0.000	0.037	0.028	0.043	–0.015	0.027	0.052	–0.020	0.003