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Analysis of the Dimensional Accuracy of Point Clouds Created by Photographic Scanning

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ABSTRACT

The article concerns the analysis of the dimensional accuracy of point clouds reproducing spatial object made by photographic scanning in the Agisoft Metashape program. Due to the lack of available scientific literature describing the results of research on the accuracy of this type of objects created in the Metashape program, analyses were carried out to determine it. In order to demonstrate the possibilities of wide application of point clouds also in opinion-making practice, three examples of objects with dimensions typical for the area of road accident research were described: a tread trace, a car and a fragment of a road. The obtained point clouds were compared with real objects in terms of dimensional accuracy. It was found that the method is able to provide very good accuracy, with a margin that meets the requirements of typical accident analysis.

Keywords: photo scanning, short range photogrammetry, point cloud, dimensional accuracy, Agisoft Metashape.

INTRODUCTION

This work deals with a complex research topic. Reconstruction of road accidents itself, from a technical perspective, is strictly based on mechanical engineering issues, while from a forensic perspective, it also takes into account key aspects of forensics and legal sciences. Focusing on technical aspects, the proposed method, despite its original use in other fields of science (e.g. geodesy), is increasingly often used in accident reconstruction. The importance of the topics discussed, resulting from reconstructions in road accident lawsuits, clearly justifies the need to use various methods to achieve the greatest possible accuracy. Due to the evidential nature of the reconstruction, the use of the described method and other available methods must be preceded by analysis and accuracy validation. Taking into account the strictly technical nature of the reconstructions prepared, it is justified to consider this work in the field of mechanical engineering.

An integral part of road accident reconstruction is the need to efficiently solve various problems. One of them is recording the accident place (road with markings and traces) and vehicle damage. It sometimes happens that an expert appointed to a case in the next instance, a long time after the accident, relies solely on the collected photographic documentation and reports on the inspection of the accident place and vehicles. Often, photographic documentation contains only a few illustrative photos, which does not facilitate reliable reconstruction of vehicle damage, whereas deformation is a key element enabling the estimation of strain energy.

The first cases of documenting vehicle deformations after collisions using photogrammetry were described in [1], but currently the most desirable solution would be to document accident scenes and vehicles using spatial digital models, preferably using a laser scanner or a structured light scanner [2–6]. However, due to the significant cost of management, these methods are not used very often.

Nevertheless, obtaining spatial models of objects in the form of point clouds is possible at a much lower cost, and is possible owing to photographic scanning, also known as Closed Range Photogrammetry [7–9]. This method involves the geometric transformation of a series of photos of an object or area taken from different angles into its spatial model represented by a point cloud. These processes are now automated due to the availability of commercial or free software. Metashape program from Agisoft was used in this research.

Although the general principles of operation of this type of programs are known, from the point of view of the user (and even more so the participants in the legal proceedings), dimensional accuracy of the recreated object is primarily interesting. It should be noted that in order to recreate objects of significantly different sizes, it is necessary to use different object scales and the resulting photography techniques [10–13].

The article analyzed three examples, selecting objects with dimensions typical of the road accident investigation area:

- micro scale – a small object important due to the details of its shape, e.g. an imprinted wheel trace,
- intermediate scale – a whole single object, e.g. a car,
- macro scale – topographic object, e.g. a road section.

Photographic scanning was performed on the objects. On the basis of the obtained photos, a digital spatial object in the form of a point cloud was created using Metashape software [14–16]. In order to analyze the accuracy of reproduction and proportions, several measurements were made on the real one. One of the dimensions was used to scale the point cloud, and the remaining dimensions were used as references to check the representation of shape and proportions.

The determination of dimensional accuracy was carried out quantitatively by determining the differences between the obtained point clouds of given objects and the measured corresponding dimensions of real objects.

The use of methods based on short-range photogrammetry requires taking a series of photos of the object that is to be imaged in the form of a point cloud. Important aspects are the quality, number and technique of taking photos [17].

When considering the quality of photos, one should pay attention to the photographic equipment. They can be performed using smartphones, digital and analog cameras, sports cameras (e.g. GoPro). Additionally, cameras can be hand-held, mounted on a high tripod or suspended from a drone (so-called UAV – unmanned aerial vehicle).

Cameras vary in terms of the quality of the photos obtained, possible settings, dimensions and weight. Equipment suitable for shooting at a micro or intermediate scale may be inconvenient at a macro scale (e.g. a stretch of road) and vice versa. A perfect example is a digital camera, which allows quickly and conveniently taking photos of a car tire tread, but will be very inconvenient for documenting a stretch of road several hundred meters long (it will require taking several hundred photos with a camera or smartphone held in raised hands). On the other hand, photographic documentation of a long section of road using a drone will be quick and convenient for the operator and will ensure good quality reconstruction of the topography of the area, but photos taken from too high a height may have too low a resolution to depict details on a micro scale (e.g. a trace of imprinted tread tires).

METHODS

The spatial models in the form of point clouds presented in the article were generated on the basis of photos taken with various devices. A tire tread trace (micro-scale object) was photographed with an Oppo Reno 7 5G smartphone, a passenger car (intermediate scale) with a GoPro Hero 11 camera, and a road section (macro scale) with a camera integrated with a DJI Phantom 4 Pro drone [13]. The basic parameters of these photos are presented in Table 1.

The creators of the Metashape program recommend using the RAW format first (the so-called digital negative, i.e. original data from the photosensitive matrix, unprocessed or compressed) [7, 18], because it allows the identification of the largest number of common points in the photos. Not every camera has this option (e.g. smartphone cameras), and the Metashape program may not support some varieties of the RAW format (e.g. from a GoPro camera). The most popular JPG format is inherently flawed because it uses a lossy JPEG compression algorithm [18]. In the examples presented, the use of the RAW format was

Table 1. Basic parameters of photos taken with a GoPro camera, smartphone and drone camera

Parameter	GoPro Hero 11	OPPO Reno 7 5G	DJI Phantom 4 PRO
Resolution	5568 × 4872 27 Mpx	9248 × 6936 64 Mpx	5472 × 3648 px 20 Mpx
File format	JPG	JPG	DNG

only possible for photos from a drone. The use of the remaining photos in the JPG format resulted from hardware limitations, because in the case of the GoPro camera, the RAW format it generated was not supported by the Metashape program, and in the case of the Oppo Reno, the only available photo format was the JPG format. Determining the best format for other devices requires checking the possibility of obtaining specific file formats individually for specific devices [19].

An extremely important element of preparing photographic material is not only the use of appropriate technical equipment, but also the appropriate technique and methodology of taking photos. It should be noted that it may vary depending on the scale of the object that we want to digitally reproduce.

The objects on micro and intermediate scale were photographed in accordance with the methodology given in [20], objects on a micro and intermediate scale were photographed by circling the object and taking a series of subsequent photos so that they partially overlapped with each other or by taking photos linearly while maintaining their partial overlap. When taking photographs of the wheel imprint on a micro scale, additional shots were taken from a low perspective at various angles relative to the longitudinal axis of the photographed trace, which allowed for obtaining a good representation of the tire tread pattern (Figure 1). Low perspective should be understood as taking photos from a low (up to 15 cm) height in relation to the photographed surface, because such a perspective allows mapping not only the general topography of the trail, but also its depth.

The body of the passenger car (intermediate scale) was photographed at various angles around the vehicle and at several different heights (Figure 2).

As far as macro scale is concerned, in the case of road photos, a GoPro camera mounted on a boom (approx. 4–5 m above the road) directed towards the road at an angle of approx. 40–50° or a SLR camera with a 10 mm lens mounted on a high tripod works well (approx. 5–7 m above the road) and also inclined to the road [21], or preferably a drone that gives greater freedom in choosing the height [22].

In the described work, a drone was used to take photos of the road. The photos were taken along the road, concentrating their number in the area of the most important fragments. To capture objects such as signs and trees, photos were taken obliquely from above from a height of about a dozen or so meters. The point cloud with camera positions is shown in Figure 3.

It should be noted that it is important to maintain the appropriate technique of performing photographic scanning depending on the camera. The accuracy of the point cloud also

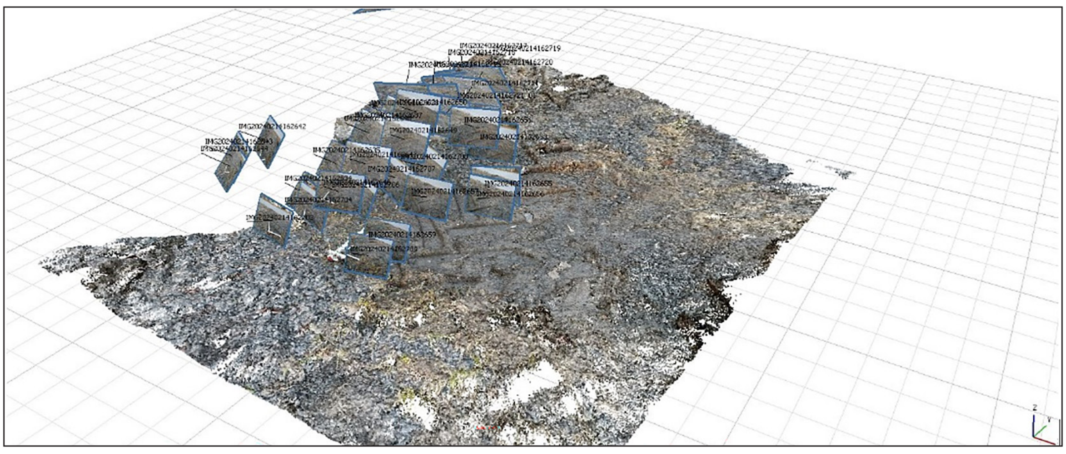

Figure 1. Example of taking photos of a tire tread impressed on the ground using a smartphone

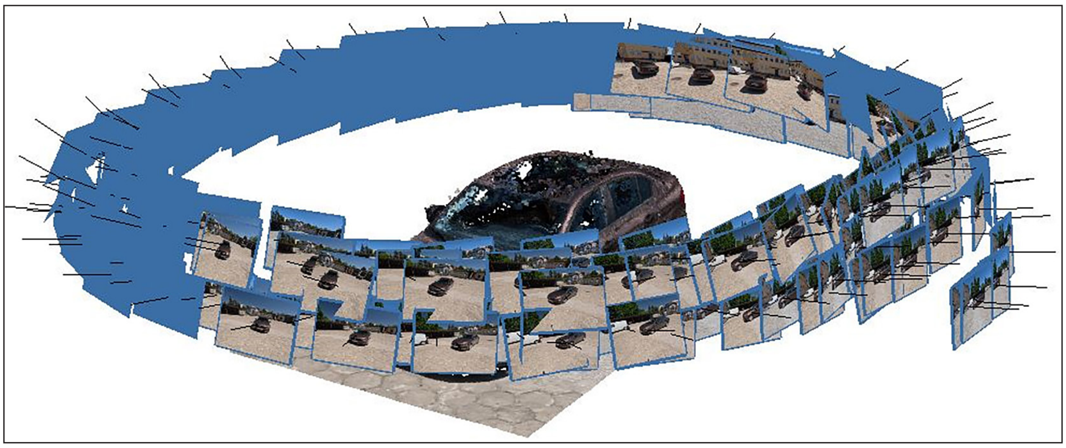

Figure 2. Example of taking photos of a car using a GoPro camera

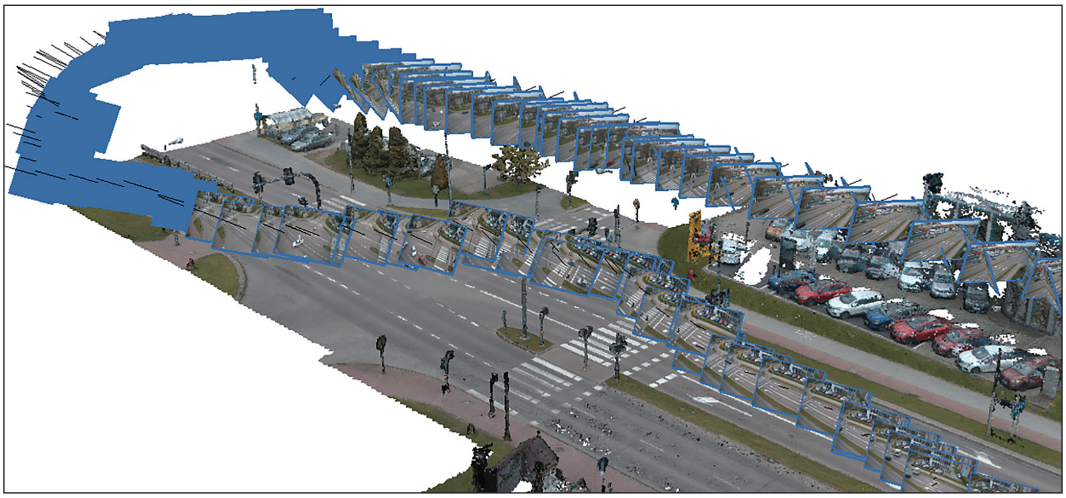

Figure 3. Example of taking photos of a road using a drone

depends on the scale (macro, intermediate, micro). When a detail is to be accurately reproduced on a macro object, one should create two point clouds. The first on the macro scale and the second on the micro scale of the scanned detail. Once scaled, both clouds can be combined in Cloud Compare or PC-Crash.

To analyze the accuracy of reproducing an object in the form of a point cloud, 1 object was selected for each of the defined scales. The quality and accuracy of their reproduction resulted from the number of photos on the basis of which the point cloud was created. A three-dimensional object on a micro scale reflecting the imprinted wheel track was created on the basis of 36 photos, and an object on an intermediate scale reflecting a car was created on the basis of 200 photos. It should be noted that only 282 photos were used to create a macro-scale object depicting an extensive fragment of the intersection with complex detail. Determining the number of photos required to recreate an object depends on the scale of the object and the photographic technique.

For the micro-scale object, photos were taken from two heights above the surface of the trace, i.e. from approx. 5 cm and approx. 15 cm, taking into account for each height the photos were taken at distances not exceeding 10 cm in relation to the length and width of the trace. Higher image density leads to longer point cloud preparation time without a noticeable increase in its density. When taking photos, efforts were made to keep the angle of the lens in relation to the photographed object as constant as possible.

For the intermediate scale, the photos were taken from a distance enabling the entire object to be photographed, with subsequent photos offset from each other by no more than 30–35° relative to the vertical axis of the car. The density of subsequent photos resulting from a shift of no more than 30° resulted in an increase in the number of photos and did not show a noticeable improvement in the accuracy of the obtained spatial object.

For the macro scale, subsequent photos were taken with a shift of no more than 1/3 of the area captured in the previous photo (covering no less than 2/3 of the photographed area). This coverage allowed the road to be reconstructed continuously, without any noticeable areas not filled with points, which were noticeable even when subsequent photos were shifted by more than approximately 40%. However, it should be noted that for this scale, determining the required number of photos is closely related to the number of characteristic elements present on the photographed object. For a large number of them, the point cloud can be recreated even with a shift slightly exceeding 40%, and for a small number of characteristic points, it may be necessary to cover the photographed area by up to 90%. It is obvious that the number of necessary photos for the macro scale results indirectly from the described parameters, and directly from the size of the area to be reproduced and the height of photography.

RESULTS AND DISCUSSION

The three series of photos described allowed for the creation of point clouds representing the three photographed objects. Since the standard version of Metashape does not use geolocation, they must be scaled in another program, such as PC-Crash or CloudCompare. The first of them was used in the work, based on known reference lengths: in the first case a scale, in the second case the wheelbase of the car, and in the third case the measured road section.

In each case, elements with variable positions could appear on the photographed objects, such as leaves moved by gusts of wind for the micro scale, people or other moving objects, e.g. vehicles for the intermediate scale, and vehicles, other road users or other moving objects with significant sizes for the macro scale. These elements, due to their movement in relation to the photographed objects, could have a negative impact on the accuracy of the obtained spatial objects and had to be filtered. This process was carried out manually by masking unwanted objects on the captured photos. Masking consisted of outlining areas of the photo with a tool that excluded the outlined areas from matching other photos when creating a point cloud. It should be noted that the photography methodology used allowed for masking the possible unwanted objects without losing the mapped areas, because they were visible each time in no less than 2 photos with coverage guaranteeing the continuity of the obtained point clouds.

For a micro-scale object model, it is important to capture spatial details. In a point cloud created by Metashape, each point is assigned a color, and their collection creates the illusion of a textured surface. A multicolored point cloud can appear to be an accurate model of an object (Figure 4), even though it does not reproduce shape details. It is easy to check this by setting the single-color mode, as in Figure 5, where the shading proves that the tread print has been reproduced correctly.

In Figure 6, on the left, the letters KRA are visible on the license plate, but the cloud observed in single-color mode on the right does not reproduce their spatial shape. To register it, it was necessary to take a separate series of

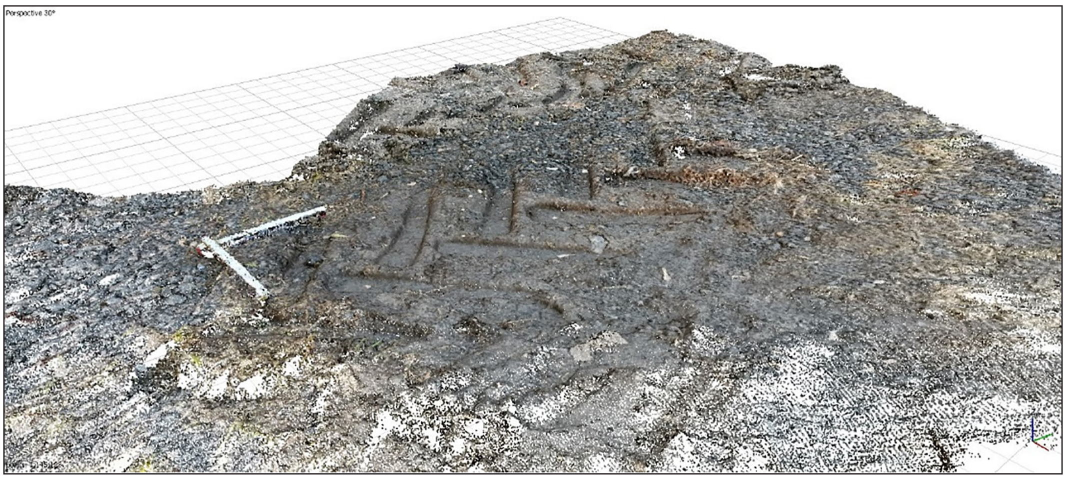

Figure 4. Multicolored point cloud of a micro-scale object, photos taken with a mobile phone camera

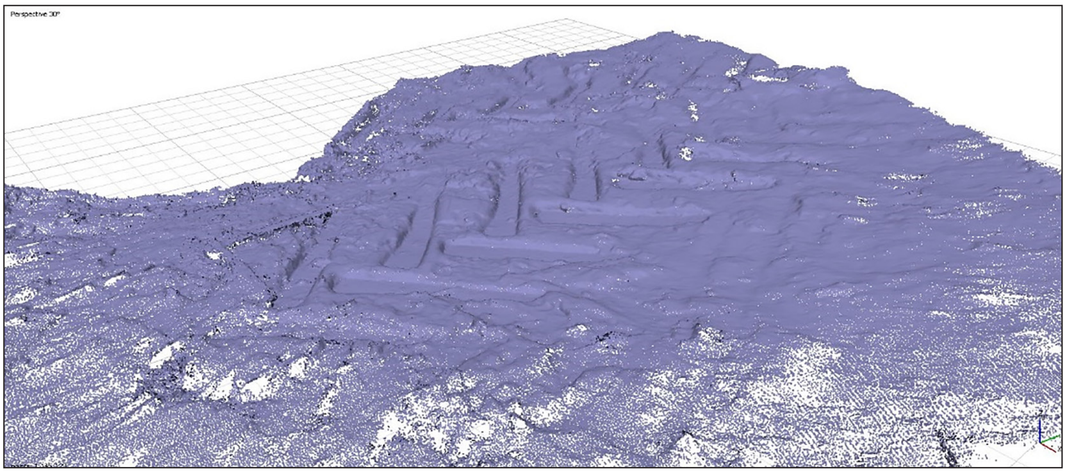

Figure 5. Single-color point cloud of a micro-scale object

photos from a close distance, as in the case of the micro scale - the effect is shown in Figure 7. In Figure 6 (bottom right), one can see that the created car model may have gaps on large shiny surfaces because the program cannot fill them due to light reflections. In such a case, in order to fill the resulting discontinuities in the spatial object, it is recommended to supplement the surface with characteristic elements, e.g. a forensic scale, or to matt the photographed area, e.g. by placing a drop of water on it (spraying water). An example of filling discontinuities in the point cloud by using forensic scales is shown in the large part of Figure 6.

An example on a macro scale is the photographically scanned fragment of the road shown in Figure 8. This cloud was scaled based on the actual measured distance between pedestrian crossings.

Figure 6. Filling point cloud discontinuities by using forensic scales (top) and fragment of the object's point clou on an intermediate scale – multi-colored (left) and single-colored (right); photos were taken with a GoPro camera

Figure 7. A fragment of a single-color cloud of license plate points with a visible, spatially mapped distinguishing feature of the KRA voivodeship (the model was generated from photos taken with a smartphone)

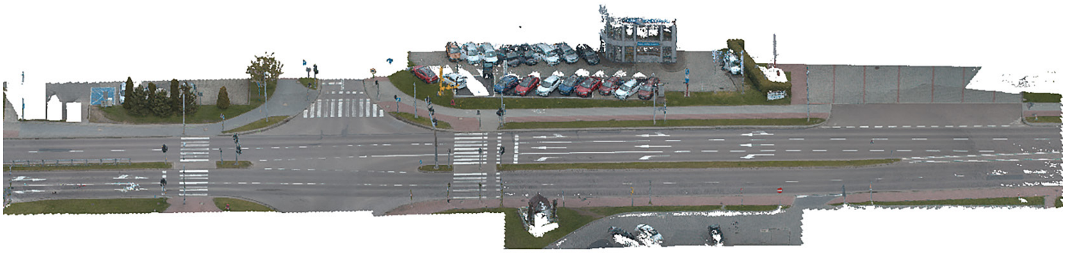

Figure 8. Point cloud of an object on a macro scale

The accuracy of reproducing scaled objects was tested by comparing various distances characterizing the shape details measured on point clouds with the corresponding real distances.

In the case of a micro-scale object, the best verification dimension would be the depth of the tire track, but this was very difficult due to the instability of the print in unpaved ground. The place marked in Figure 9 was used for verification. The measurement was performed three times at a short distance from each other to avoid increasing the depth of the trace due to the point pressure of the measuring device. The actual measured trace depths were in the range of 15–18 mm, and the average value was approximately 16 mm. The measurement accuracy of objects on this scale depends on the system capabilities of the programs used in the analyses performed. In this case, the smallest point size that can be used in the PC-Crash 14.0 program is 1 mm. The position of each point, taking into account the mentioned system limitation, may differ from the actual one by no more than 1 mm. Due to the unevenness of the measured surfaces, the measurement accuracy was assumed to be 1 mm.

In the PC-Crash 14.0 program, the point cloud was scaled based on the measure next to the trace, which is visible in Figure 9. The scaling uncertainty at a length of 200 mm was approximately 2 mm (division of the measuring tape every 1 mm) and resulted from the scaling technique in the PC-Crash program, which involved marking the length on the mapped measuring tape or a forensic scale and specifying the actual length. Then, a cross-section of a fragment of the trace was extracted on the cloud at the point where its actual depth was measured and the depth mapped on the point cloud was measured (Figure 10).

The comparison shows differences of 1 to 2 mm from the measured actual depth of 15–18 mm. The measurement error is not due to the inaccuracy of the cloud scaling, because the

Figure 9. Trace in the sand, the red arrows indicate the places where the depth of the trace was measured

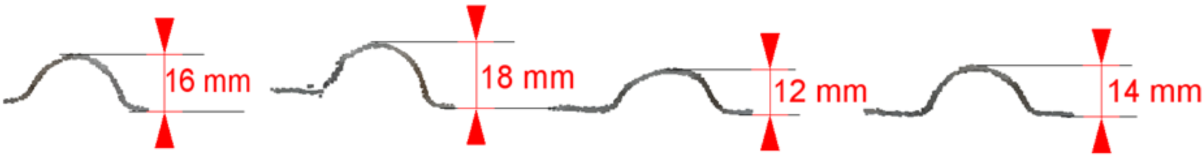

Figure 10. Measuring the depth of a trace on a point cloud

uncertainty of the cloud scaling is ± 1 mm over a reference length of 200 mm. It results from the impossibility of using a point smaller than 1 mm, and therefore from the limitations of the resolution system. Therefore, when making measurements on a point cloud on such a small scale, it should be noted that it may be subject to significant error. However, it should be mentioned that in the practice of road accident reconstruction, it is more important to recreate the shape of the tread pattern, rather than its depth. The accuracy of the trace reconstruction obtained allows it to be identified and matched to a specific tire with the accuracy resulting from the scaling accuracy.

The object on an intermediate scale was a Fiat Tipo passenger car. The object was scaled based on the wheelbase of the car, which is 2.638 m in the catalog, and the accuracy of scaling depends on the accuracy of marking the center of the axle taken as the center of the wheel with the mouse. The uncertainty for this scaling is approximately ± 0.05 m.

The width of a single-row license plate with a frame (0.525 m) and the diameter of the wheel cover (0.418 m) were used as verification dimensions. The mentioned dimensions were measured with a measuring tape with a 0.001 m division. After scaling the point cloud representing the car, the width of the license plate and the diameter of the cover measured on the cloud and on the real object are consistent with each other (Figure 11). The measurement uncertainty on the cloud results from the assumed size of the cloud point and for this example is ± 0.01 m.

On macro scale, verification of a point cloud of a large area of land is a geodetic problem. This study focused on verifying a fragment of the road, paying attention to the accuracy of reproducing details such as horizontal signs on the road surface.

The point cloud (macro scale) was scaled based on the measured length between the inner edges of the pedestrian crossings of 35.7 m (Figure 12). The measurement was made using an odometer with an accuracy of 0.1 m. Due to the measurement uncertainty of the device amounting to 0.05 m per 100 m and the error of the measurement itself, an uncertainty of ± 0.2 m was assumed.

Accuracy was verified for the road point cloud by comparing the width of the pedestrian crossing lines. On site, the actual width of the road between the sidewalk and the island was measured to be 9.2 m. This dimension on the point cloud was 9.213 m. It should be noted that the measurement performed on the cloud depends on the location and color of the point, as illustrated in Figure

Figure 11. Verification dimensions for an intermediate scale object

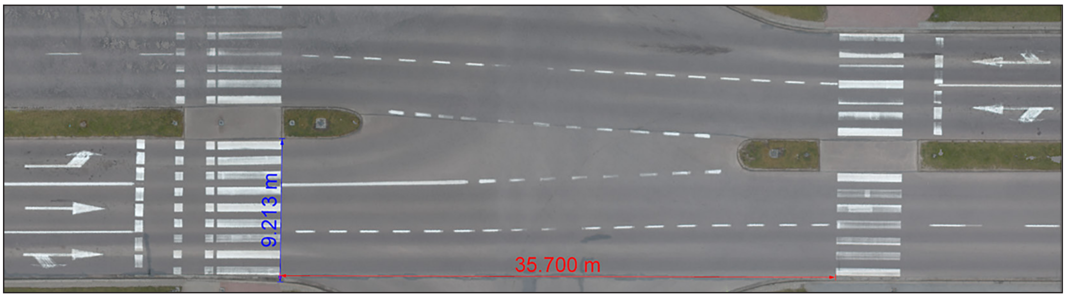

Figure 12. A point cloud representing a road; the red section is the reference dimension used for scaling, the blue section is the verification distance measured on the point cloud

13: two measurements were carried out, depending on the color of the point suggesting the edge of the belt (values a and b in Figure 13), and the third dimension corresponds to the typical width of the belt (value c in Figure 13). To achieve better results, a point cloud with a locally higher density should be created. It should be mentioned that a larger point size defined in the PC-Crash program (e.g. 0.0025 m) causes a visual filling of the space between the points due to their partial overlap. The uncertainty of measurement on a cloud is lower than the uncertainty of measurement with an odometer. The measurement results converge within the limits of measurement uncertainty.

In Figure 14, the scaled cloud of road points was compared with the orthophotomap from the geodetic portal (mapy.geoportal.gov.pl). Visible differences between the horizontal markings result from the photos taken on different days. The proportions of the point cloud and orthophoto are similar.

On the basis of the comparisons and measurements shown above, it can be concluded that the point cloud made in Metashape based on drone photos reproduces the proportions and spatial layout of the road with an accuracy that far exceeds the typical requirements in the reconstruction of road accidents.

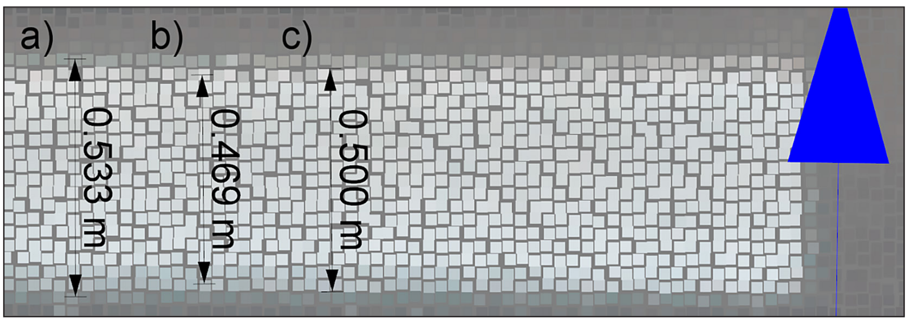

Figure 13. Fragment of the cloud from Figure 12, the gray squares are points with a given size of 0.025 m

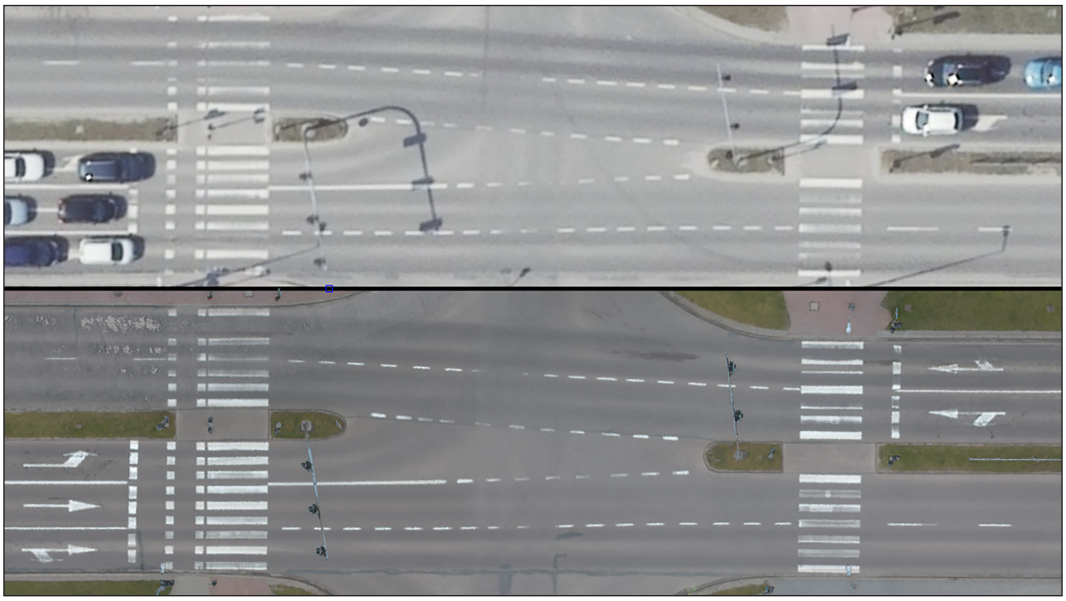

Figure 14. Comparison of the orthophotomap from mapa.geoportal.gov.pl (top) and the obtained point cloud (bottom)

Due to the large scale of the object, the point cloud has a lower resolution, which may affect the results of measurements made on it and cause a small difference from the actual measurement, reaching at most a few centimeters. This accuracy, in the absence of traces allowing precise reconstruction of the event parameters, is estimated at no more than ± 10% of the values obtained as a result of the analyses performed and results from the overlapping uncertainties arising at each stage of the calculations. The use of the described methods reduces the uncertainty resulting from the inaccuracy at the stage of measuring the depth of deformation from an accuracy of 0.1 m to its determination with an accuracy of not less than 1 cm (0.01 m), thus even narrowing it by a factor of ten, depending, of course, on the scale of the analyzed object.

In order to present the results in quantitative terms, the obtained measurement uncertainties were related to the actual dimensions characterizing each object. In this case, for the macro scale and the tire print, it was found that the measurement uncertainty did not exceed 7% (1 mm compared to the smallest measured actual dimension of 15 mm), but it should be noted that its relatively high value resulted not so much from the inaccuracy of reproducing the real object by the point cloud, and from system limitations in the form of point size in the software used for analysis. It is fully justified to conclude that if it were possible to use smaller points on a three-dimensional object, the measurement uncertainty could be significantly reduced to the values achieved for objects at other scales.

For an object on an intermediate scale, the diameter of the wheel cover measured on the point cloud was 0.424 m, while its actual diameter was 0.418 m. In this case, the difference between the values of 6 mm related to the actual dimensions allowed the calculation of measurement uncertainty, which did not exceed 1.5%. It is worth noting that for elements larger than the shield, the measurement uncertainty was much smaller, so for an intermediate-scale object it is also reasonable to assume that the specific uncertainty is related to the system limitations of the software used.

For the macro-scale object, the width of the pedestrian crossing measured on the three-dimensional object was 9.213 m, and its actual measured width was 9.2 m. The difference of 0.013 m related to the actual width of the crossing allowed for the determination of a measurement inaccuracy of approximately 0.15%. In the presented case, the obtained dimensional accuracy significantly exceeds the requirements accepted in the practice of judicial review of road accidents.

It should be noted that there is a clearly noticeable increase in the dimensional accuracy of point clouds obtained by photographic scanning as the scale of the object increases, and it should be emphasized that for larger-scale objects it is possible to locally use a smaller scale for important elements of the object in order to locally increase the accuracy of mapping real objects. On the basis of the obtained results, it should be clearly stated that the use of appropriate photo-taking techniques combined with a possible local increase in accuracy resulting from the use of photographic scanning for a smaller-scale object meets the expectations regarding the accuracy of three-dimensional objects in judicial opinions.

CONCLUSIONS

The Metashape program allows for the reliable reconstruction of spatial objects at each of the defined scales (micro, intermediate and macro) and the use of the resulting point clouds in the reconstruction of road accidents. The problem of reproducing the shape of a small detail can be solved by treating it as a micro-scale object and taking a series of additional photos.

Reconstructing the road based on photos taken from a drone allows obtaining a road model with horizontal signs with high accuracy, even higher than that obtained on orthophotomaps available on the Internet (geoportal.gov.pl). In the light of the analyses performed, the following conclusions were formulated:

1. Point clouds representing spatial objects, made using photographic scanning, maintain the correct proportions of the reproduced objects.
2. Correct scaling of the point cloud based on reference dimensions is fundamental for reliable use for measuring other distances.
3. For micro-scale objects, it is possible to correctly reproduce details, but when measuring small distances, one should bear in mind the possibility of a large relative error caused by the limited image resolution.
4. When taking photos of objects at a macro or intermediate scale, the shape of small details may not be reproduced. This problem can be solved by treating them as micro-scale objects and taking a series of additional photos
5. A macro-scale point cloud (part of the road) created by photographic scanning and proper scaling recreates the road with an accuracy far exceeding the typical requirements in road accident reconstruction. The measurement uncertainty on the tested cloud did not exceed a few centimeters over a distance of 125 m.
6. The obtained uncertainties in the mapping of real objects are smaller the larger the object being mapped and do not exceed 7% in the case of micro-scale objects, 1.5% in the case of intermediate-scale objects and much less than 1% in the case of macro-scale objects.
7. Relatively large measurement uncertainties in the case of objects on a micro and intermediate scale result from the system limitations of the software, and not from the inaccuracies of the obtained point clouds.
8. Photographic scanning is an excellent alternative to expensive methods requiring laser scanning or structured light scanning, and the accuracy of the method used in relation to those mentioned will be the subject of further research work.
9. Obtaining satisfying results allows the authors to focus their attention on conducting research and analysis, on searching for a method that guarantees even greater accuracy in reproducing real objects.

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