Comparison of 3D models of an object placed in two different media (air and water) created on the basis of photos obtained with a mobile phone camera

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Abstract. Photogrammetry is one of the contactless geodetic techniques that provide reliable information about objects and their surface properties. Traditional photogrammetric methods require specialized equipment, such as metric cameras, which are very expensive and difficult to access, and the processing of the data obtained from them requires a significant investment of time. An alternative to this solution are generally available non-metric cameras, which can replace professional photogrammetric devices. Currently, consumer-grade digital cameras are enjoying the increase of popularity among photogrammeters thanks to the interchangeable lenses, good image sensor quality and the ability to manually set all camera parameters. However, due to the high costs of purchasing and maintaining such equipment, mobile phone digital cameras are increasingly used, the parameters of which are beginning to match many professional digital SLRs. The newest smartphones are also waterproof, so they can have potential applications in underwater photogrammetry.

This article presents the possibilities of using mobile phone cameras in close-range photogrammetry and shows the beginning of research on the use of smartphones in underwater photogrammetry. Three-dimensional models of the gear wheel were made on the basis of photos obtained in two media: in the air and underwater. The two point clouds were then compared, obtaining an average distance difference of ±0.3 mm.

1. Introduction

Digital technology has developed rapidly in recent years, also in the case of mobile phones. Smartphones, currently classified as low-cost devices, are popular not only among average consumers, but also more and more often among photogrammeters. It has been proven many times in the literature that mobile phone cameras in terms of cost, accuracy and flexibility are a viable option to be used in close-range photogrammetry [1, 2]. This recently established field of photogrammetry using smartphones is called mobile photogrammetry.

Waterproofness is a significant advantage of mobile phone cameras over traditional photogrammetric devices. Smartphones, in contrast to, for example, digital cameras, do not require an expensive underwater housing. This major advantage means that mobile phones can possibly be used for inventorying underwater objects.

The main objective of this paper was to assess the photogrammetric capabilities of mobile phone cameras in close-range measurements for an object located in two different media: in the air and underwater.
2. Methodology
Mobile photogrammetry and underwater photogrammetry are the fields of photogrammetry that, due to the measurement specifications and the limited measurement range, qualify for close-range photogrammetry. The main goal of photogrammetric research is to determine the geometry of an object (shape, size, position) in three-dimensional space based on the measurement and analysis of two-dimensional images. Below, an attempt is made to describe areas by characterizing, inter alia, the measuring devices used, the existing problematic issues, and the prevailing applications and trends, according to the current literature.

2.1 Mobile photogrammetry
Mobile photogrammetry is a rapidly growing field of close-range photogrammetry that uses the potential of mobile phone cameras to create three-dimensional models. In contrast to digital cameras, mobile phones are handy, lightweight and much cheaper. The largest manufacturers of smartphones are competing in the selection of the best functions and features of devices, including the parameters of cameras. The most modern smartphones have several lenses located on the back of the device (e.g. four in the Samsung Galaxy S20 Ultra) and on the front (e.g. two in the Realme X50 Pro) with a resolution of up to several dozen MPx (e.g. the main lens of Xiaomi Mi Note 10 has 108 Mpx). These features make mobile phones interesting devices for image data acquisition.

One of the fundamental problems with mobile photogrammetry is the accuracy of the mobile phone camera. The specification of the camera structure, in particular optical and electrical elements, affect the geometric distortions of images, which results in low quality of photos. In order to eliminate image distortions, a calibration process is carried out in which the elements of the camera's internal orientation and imaging errors are determined. Depending on the adopted criterion, different methods of calibration are distinguished. In [3], the connection of the calibration process with the target measurement was differentiated as the basic criterion. The first method of this criterion, referred to as "self-calibration" or "on the job calibration", involves performing a calibration using photos for the actual measurement. The second method is an independent calibration, performed as a separate measurement, on a so-called test field. An example of such a solution in mobile photogrammetry is presented in papers [4-6]. Calibration can also be distinguished by the amount of photos used to calculate the calibration parameters. Then the calibration process itself is carried out on the basis of specific models. The most popular is the "physical" model created by Brown [7], in which the image points are defined as follows:

\[
\begin{align*}
    x' &= x + \bar{x}(K_1 r^2 + K_2 r^4 + K_3 r^6 + \cdots) + \left[ P_1 \left( r^2 + 2x^2 \right) + 2P_2 x y \right] \left[ 1 + P_3 r^2 + \cdots \right] \\
    y' &= y + \bar{y}(K_1 r^2 + K_2 r^4 + K_3 r^6 + \cdots) + \left[ 2P_1 x y + P_2 \left( r^2 + 2y^2 \right) \right] \left[ 1 + P_3 r^2 + \cdots \right]
\end{align*}
\]

with:

\[
\begin{align*}
    \bar{x} &= x - x_p \\
    \bar{y} &= y - y_p \\
    r &= \sqrt{\left( x - x_p \right)^2 + \left( y - y_p \right)^2},
\end{align*}
\]

where:

- \( x, y \) - image coordinates of the point,
- \( x_p, y_p \) - interior orientation parameters,
- \( K_1, K_2, K_3 \) - radial distortion coefficients,
- \( P_1, P_2, P_3 \) - tangential distortion coefficients.
One of the directions of current research in mobile photogrammetry is research aimed at automating the process of obtaining images. For example, [8] presents an integrated system that allows remote control of multiple mobile phones to support a long-term project that requires a continuous monitoring process. In [9] the authors proposed to combine a mobile phone with a centralized server plus an annex cloud for online 3D reconstruction. This solution provides immediate visual feedback, allows to optimize the results of the reconstruction, enables simultaneous operation of the system by multiple users, and ensures reasonable use of resources (mobile phone battery, memory availability). A similar approach in the development of mobile photogrammetry can be found in [10], which presents a 3D reconstruction system based on images obtained from smartphones and tablets.

2.2 Underwater photogrammetry

Underwater photogrammetry is another field of close-range photogrammetry, in which the main goal is to determine the technical condition of the research object through vision research [11], while the object is located under water. One of the most popular instruments used in underwater photogrammetry is the digital camera. However, the majority of digital cameras require a special underwater housing with an appropriate lens port in order to be fit for the underwater inquisitions [12]. For this reason, low-cost devices, such as the GoPro camera, are gaining popularity, providing relatively high resolution in relation to low acquisition and maintenance costs [13]. Both, more expensive digital cameras and cheaper GoPro cameras, require professional divers during the underwater inventory. Due to the dangerous specification of measurements (long exposure of divers, difficult measurement conditions), unmanned aerial vehicles such as drones [14] or underwater robots [15] are increasingly used. They can be controlled completely remotely or with little involvement of divers.

In underwater photogrammetry, there are many factors that affect the quality and accuracy of the measurements taken. One of the most important environmental factors is the clarity of the water. In the case of areas at shallower depths, in order to avoid sunlight reflecting off the water surface and the research object, it is recommended to measure in the late afternoon [16]. When the inventoried object is located at considerable depth, it is recommended to use additional lighting in the form of LED flash lamps. Depending on the visibility conditions, the photographing distance also changes. Insufficient transparency of the water reduces the contrast of the image and requires the camera to be closer to the object when acquiring images. Particles floating in cloudy water are also a source of problems during the image processing.

An important aspect of the underwater photogrammetry is the camera calibration. The light beam refracts when passing through various media (water, glass, air), which in turn causes a refractive error that must be taken into account in the calibration process. Two solutions to this problem were proposed in [16], the first one is the use of a collinearity model modified with a geometric interpretation of light in multimedia (camera housing-water). The second solution involves the use of standard system calibration software consisting of a camera and a waterproof housing device.

The process of georeferencing photos in underwater photogrammetry is a problematic aspect due to the more complex logistics under water than in the air. Georeferencing can be performed in various ways depending on the target frame of reference. In the local system, the easiest way to georeference photos is to place a linear scale on or next to the research object [17]. A slightly more complicated method of georeferencing is to create a grid of points, which is placed on the tested surface [16]. The points then should be measured, which usually is performed by trilaterational measurement (linear measurement carried out using a system of triangles or quadrilaterals). In the case of assigning a global reference system, it is required to bind the grid points to points with known coordinates, which is possible through the GNSS survey [18].

The present application of underwater photogrammetry is very wide. The research is carried out both in laboratory conditions and in natural waters at depths from several to several dozen meters [17]. Underwater photogrammetry is used primarily in archeology [19-20] to inspect sunken objects (such as shipwrecks and prehistoric settlements), in marine biology [21, 22], e.g. to research surface and other
morphological features of corals. Other applications include bathymetric and hydrographic measurements and research and the maintenance of underwater cables and pipelines.

2.3 Mobile photogrammetry in underwater photogrammetry
Mobile photogrammetry in the context of underwater inquisitions has not yet been presented in the literature in practical application. This is mainly due to the environmental limitations of mobile phones. Each waterproof smartphone has an individual degree of water resistance, which is defined by the IP standard (International Protection Ratings). The depth of immersion of the mobile phone is usually up to several meters for a period of time lasting several dozen minutes. On the other hand, the most common use of underwater photogrammetry, i.e. archaeological or marine biology measurements, requires measurements at a depth up to several dozen meters, which excludes this type of use of mobile photogrammetry. However, there is a potential application in the study of objects located at shallower depths, e.g. dams, or in the study flooded small mines.

3. Results

3.1 Instruments
The photos were taken using the Huawei P40 Pro + mobile phone with 5 cameras (one in the front and four in the back - Figure 1). The description of the apparatus parameters is presented in Table 1.

![Figure 1. Description of the cameras of the Huawei P40Pro + mobile phone.](image)

| Camera placement | Resolution | Lens            | Focal length | Sensor                | Aperture value | Pixel size |
|------------------|------------|-----------------|--------------|-----------------------|----------------|-----------|
| front            | 32 MPx     |                 | 26 mm        | CMOS BSI              | f/2.2          | no data   |
| back             | 50 MPx     | Wide Angle      | 23 mm        | CMOS 1/1.28”          | f/1.9          | 2.44 µm   |
| back             | 40 MPx     | Ultra-Wide Angle| 18 mm        | CMOS BSI 1/1.54”      | f/1.8          | 4.48 µm   |
| back             | 8 MPx      |                 | 240 mm       | no data               | f/4.4          | 1.22 µm   |
| back             | 8 MPx      |                 | 80 mm        | no data               | f/2.4          | 1.4 µm    |
3.2 Research object
The research object for which the 3D model was made is the gear (Figure 2). In order to maintain the same frame of reference for both models, the gear was attached to a wooden plate on which reference points were also placed and fixed.

![Figure 2. The gear is placed in two media: in the air (on the left) and under the water (on the right).](image)

3.3 Frame of reference
Due to the unknown coordinates of the camera position, it was necessary to design a reference system consisting of GCPs (ground control points), the so-called markers, that will be used to align photos. The developed reference system consists of 12 markers located around the measuring object. They were generated in the Agisoft Photoscan software, which allowed for their automatic detection during photo processing. The points were measured linearly (66 observations) by the peer-to-peer measurement. The obtained observations were strictly aligned in the C-GEO software using the method of least squares. The position error of the worst determined point did not exceed ± 0.001 m.

3.4 The measurement
The photos were taken in similar weather conditions: the sky was cloudy, the temperature was around 25°C. Underwater photos were taken in a fold-out backyard pool with a diameter of 5.5 meters and a height of 1.2 m. During the acquiring images, the water temperature was approx. 24°C, the photos were taken at a depth of approx. 0.9 m. 139 photos were obtained from the "in the air" measurement series, while from the series "under water" 152 photos. The photos overlapped by about 60-80%.

3.5 Processing in Agisoft PhotoScan

![Workflow of image processing in Agisoft Photoscan software.](diagram)
The first stage of processing in Agisoft Photoscan software started with importing a series of photos. The next step involved the alignment of the photos: based on the detected tie points (common points in the photos), the program created a sparse point cloud model, determined the position of the camera position for each photo and estimated the internal and external parameters of the camera. These parameters are:
- $f$ - focal length,
- $cx, cy$ - principal point coordinates,
- $b1, b2$ - Affinity and Skew (non-orthogonality) transformation coefficients,
- $k1, k2, k3, k4$ - radial distortion coefficients,
- $p1, p2, p3, p4$ - tangential distortion coefficients.

Subsequently, markers were automatically detected, their coordinates were loaded, four scale bars were created and re-aligned images using GCPs to georeference the cloud of points. In the last step, camera alignment optimization was performed, in which the estimated camera parameters and coordinates of the cloud points were adjusted based on the reference coordinates. The distribution of the residual components is shown in Figure 4.

![Image residuals obtained after the self-calibration of the camera for data "in the air" (left) and "under water" (right).](image)

The average distortion errors presented in the above photos are arranged in characteristic circles with increased values in the frame corners and in the center of the image. The distortions in the corners (over 1 pix) may be the result of the image sharpenings function when taking pictures. In turn, the round shape of the distortions may be caused by the use of varifocal lenses in which the mobile phone camera used for inquisition is equipped [23]. The root mean square reprojection error (Table 2) obtained as a result of the processing was 1.68 pixels for photos obtained "in the air", and 2.30 pixels for the photos obtained “under water”. The relatively high value of the projection errors may result from the change in the illumination of the subject when taking photos from different angles. The reference points are matched in the photos with an accuracy of approximately 8 mm.

|                       | air       | water     |
|-----------------------|-----------|-----------|
| RMS reprojection error | 1.68 pix  | 2.30 pix  |
| GCPs total error      | 0.00808952 m | 0.00817667 m |
The last stage of processing in Agisoft Photoscan was the creation of the "dense cloud" based on the sparse point cloud model. The obtained 3D models are presented in the figures below.

![3D models of the gear made on the basis of photos acquired "in the air" - model no. 1 (on the left) and "under water" - model no. 2 (on the right).](image)

**Figure 5.** 3D models of the gear made on the basis of photos acquired "in the air" - model no. 1 (on the left) and "under water" - model no. 2 (on the right).

### 3.6 Comparison of the air and the underwater models

The comparison of the obtained point clouds was carried out in the CloudCompare software using the "Cloud to Cloud" (C2C) method. The greatest value of the difference in the distance of points was ±7 mm for the points located in the upper part of the gear wheel and in the places of the ring roads of the districts. The average distance between the two models was ±0.3 mm. These differences resulted mainly from the loss of points in these places of the model no. 1, which resulted in the selection of wrong pairs of points when determining the distance.

![Comparison of 3D models of a gear made on the basis of photos acquired "in the air" (reference model) and "under water" (model compared).](image)

**Figure 6.** Comparison of 3D models of a gear made on the basis of photos acquired "in the air" (reference model) and "under water" (model compared).

### 3.7 Comparison of individual lengths of elements of the tested object

At the end of processing the acquired 3D models, the lengths of individual elements of the gear were compared with the actual dimensions. The measurement results are shown in the figure below. The average difference between the actual measurements and the measurements from the model no. 1 was ±0.8 mm, while the difference between the actual measurements and the measurements from the model no. 2 was ±0.7 mm.
4. Discussion and conclusions

This paper presents the steps of processing photos obtained from two different media (water and air). Then two 3D models were made and both point clouds were compared using the "Cloud to Cloud" method. The average distance of points obtained as a result of the comparison was ±0.3 mm, which proves that the model created on the basis of photos taken "under water" is almost identical to the model generated on the basis of photos taken "in the air". The greatest differences in the distance of the points reached ± 7 mm. However, after careful analysis of the models, it was found that these values resulted from the insufficient number of points in model no. 1 in various places, and this in turn resulted in an incorrect selection of pairs of points when determining the distances. The actual dimensions of individual elements of the gear were also compared with the dimensions of the elements in models no. 1 and no. 2. The average differences did not exceed ±0.8 mm, which also proves the faithful representation of the research object in 3D.

The research model presented in this paper confirms the possible use of mobile phone cameras in close-range photogrammetry and it is the beginning for further research in the context of underwater photogrammetry. In the case of researching the object "in the air", mobile phone cameras ensure high accuracy and precision of the obtained results while maintaining a short processing time. Regarding underwater photogrammetry, the first tests were carried out under the following conditions: a shallow immersion depth (up to about 1 meter) and very good environmental conditions (no water turbidity and good lighting), to give faithfully imaged object model. However, to determine the potential use of smartphone cameras in underwater photogrammetry, further research should be carried out at greater depths, taking into account the environmental constraints that existed at that time, such as poor lighting and reduced water transparency. The use of mobile phones deeper than a few meters also requires a specialized waterproof case, which is another variable that needs to be analyzed.

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