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STUDY OF THE CAPABILITIES OF MOBILE PHONES WITH CAMERAS TO OBTAIN GEOMETRIC DATA

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Abstract

Mobile phones with cameras enable us to take photos of any objects at any time. The question arises whether this new device of communication can play a role in obtaining geometric data and what accuracy demands can still be satisfied by this device.

Our series of experiments essentially involve taking photos of a geometrically defined area and examining the degree of likelyhood of the photogrammetric solution to the known geometry. This study was extended to various cameras, the number of points with known co-ordinates, the number of shots, and the object distance which has a decisive impact on picture scale. Furthermore, we compared the accuracy values of the results yielded by the processing of images taken by mobile phones with cameras and by other cameras.

Numerical results are disclosed in a tabular format and the conclusions to be drawn from the numbers are summarized.

Keywords: mobil phone, digital close range photogrammetry, precision, direct linear transformation.

1. Introduction

Mobile phones equipped with cameras are not a novelty any longer. Phones with cameras of VGA resolution produce suitable quality, but there are ones in the megapixel range. In the course of a rapid development, prices of handsets are going down, and this communication device, nearly always with us, enables us to take a photo of anything, anywhere. In this situation, experts involved in photogrammetry are to study the capabilities of these devices in terms of obtaining geometric data.

Two different types of mobile phones with cameras were applied in our experiments. The cheaper, SAMSUNG SGH-X640 type set allowing $f = 3.35$ mm fourfold digital zoom has a CMOS, VGA (300 k) digital camera. The other phone set used was of the SAMSUNG SGH-D600E type, with a camera of $f = 3.35$ mm focus, allowing fourfold digital zoom and with a CMOS 2M sensor. The cameras are shown in *Fig. 1.*

In the first phase of our investigations, we built test-fields where we specified points and accurately determined their co-ordinates. Some of the points were used for photogrammetric orientation (control points), and the co-ordinates of the other points were specified as unknown points for a photogrammetric processing. Our

Fig. 1. The mobile phones applied

conclusions were drawn from the differences between the co-ordinates of each point as measured and as determined by photogrammetry.

2. Producing Spatial Data from Images by Mobile Phones

2.1. The Test-fields Used

In the field of close range photogrammetry, where objects of some tens of centimetres or smaller are surveyed, the usual survey procedure is to build a precise network of high stability, to measure it precisely, and then to place various small-sized objects into this pre-fabricated network and to specify the geometric parameters required. In the first phase of determination, the images are located in the field using the known test-field points, then the already orientated images are used for determining the geometric data of the object from the image co-ordinates. One of the first such networks were built by BURCH and FORNO in 1984; [13] this network is the miniature copy of skyscrapers in Manhattan (*Fig. 2*). Such a test-field – termed frequently in the literature as a Manhattan-type test field – was built at the Department of Photogrammetry and Geoinformatics at BUTE. The test-field itself consists of cylinders of various heights mounted on a stainless steel plane of 45 X 35 cm, where the points specified are represented by the holes located on the cover circles of the cylinders (*Fig. 3*).

The geometric features of the test-field were determined by a Zeiss Opton 3D co-ordinate measuring instrument. The instrument specifies the co-ordinates of points with a resolution within the 0.1 micron range and a median error of less than one micron. *Fig. 4* shows the test-field measurements.

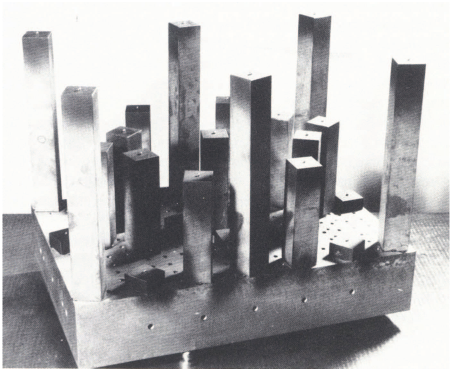

Fig. 2. Burch's test-field

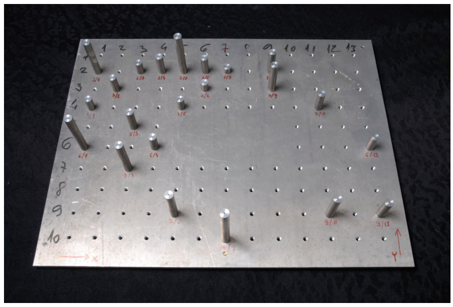

Fig. 3. The test-field used

Fig. 4. Test-field measurement

Fig. 5. Ground test-field

The ground test-field intended for studying photography of greater distances is illustrated in *Fig. 5*. Here 6 to 8 m of shooting distances were examined. This test-field, set up in the yard of BUTE, was orientated by geodetic means, that is, the points previously specified were provided with 3D co-ordinates. The location of the points enables us to select and assign control points of appropriate number and accuracy and proper differences in depth, spread evenly in the images.

2.2. Determination of Image Co-ordinates

Photogrammetric measurements are not performed on the object itself but on the images taken thereof. The images generated by mobile phones with cameras are handled as digital files by the computer. 2D measurements of digital files are mainly performed on a computer display. Today's measurement technologies allow that the determination of image co-ordinates are not equal to specifying pixel indices, more accurate ones are also feasible. Measurements under pixel accuracy can be performed by displaying the image by an appropriate software in an enlargement where an image pixel is displayed by several pixels (e.g. 64) on the monitor. The degree of greyness or colour of the pixels displayed on the monitor are calculated by the computer using a mathematical process, whose solutions are discussed in digital image processing. The measurement must be associated with the original pixel as a real number. In order to increase measurement accuracy, literature references (FRASER) [12] emphasize the importance of point specifications. In the event of a manual evaluation, the standard deviation of a measurement was examined using wedge-shaped marking in the course of our experiments. Having used images produced from several distances and several directions, this value always remained under 0.3 pixel, therefore this value is going to be used when qualifying image co-ordinates.

2.3. Determination of Object-side Co-ordinates

2.3.1. Connection between the Image Co-ordinates and Object Co-ordinates

The mathematical model of photogrammetric mapping is central projection. In its sense, the field point, the center point of projection, and the image point are collinear, lying along the same straight line. The equation for this spatial straight line is usually specified in the following form:

$$
\begin{aligned}
x_k &= -c\frac{(X-X_0)r_{11}+(Y-Y_0)r_{21}+(Z-Z_0)r_{31}}{(X-X_0)r_{13}+(Y-Y_0)r_{23}+(Z-Z_0)r_{33}}\\
y_k &= -c\frac{(X-X_0)r_{12}+(Y-Y_0)r_{22}+(Z-Z_0)r_{32}}{(X-X_0)r_{13}+(Y-Y_0)r_{23}+(Z-Z_0)r_{33}}
\end{aligned}
\qquad (1)
$$

where

x_k, y_k	are image co-ordinates in the co-ordinate system of the image;
X, Y, Z	are co-ordinates of the object point in the object-side co-ordinate system;
X_0,Y_0,Z_0	are co-ordinates of the projection center point in the object-side co-ordinate system;
M	is the scale;
$r_{i,j}$	are elements of the rotation matrix between the co-ordinate systems of the image and the object side;
c	is the focal distance.

Equations in the form of (1) provide a basis for the adjustment of ray bundle to process images produced by photogrammetric measurement cameras, hence the image co-ordinates in them refer to the co-ordinate system of the image, which does not exist in mobile phones with cameras. In the event of using non-metric cameras, such as mobile phones with cameras, these co-ordinates can be substituted by some of their plane transformed variations (FEKETE) [10]:

$$a_1 + a_3 x_m + a_5 y_m = -c \frac{(X - X_0)r_{11} + (Y - Y_0)r_{21} + (Z - Z_0)r_{31}}{(X - X_0)r_{13} + (Y - Y_0)r_{23} + (Z - Z_0)r_{33}}$$
$$a_2 + a_4 x_m + a_6 y_m = -c \frac{(X - X_0)r_{12} + (Y - Y_0)r_{22} + (Z - Z_0)r_{32}}{(X - X_0)r_{13} + (Y - Y_0)r_{23} + (Z - Z_0)r_{33}} \tag{2}$$

Equations in the form of (2) enable adjustment of ray bundle to process images produced by non-metric cameras since the image co-ordinates figuring here may be in any discrete co-ordinate system. Of course, this has a price as well: we have six new unknown quantities per image in our equations.

Another solution for optical mapping was provided by (ABDEL-AZIZ and KARARA) [1]. Similarly to equations in the form of (1), a direct connection was established between the image co-ordinates of object points specified in a discretionary co-ordinate system and the co-ordinates of the object side. They noted the method as Direct Linear Transformation and is generally referred to as DLT in the special literature on photogrammetry. The DLT method is based on the following equations:

$$x = \frac{L_1 X + L_2 Y + L_3 Z + L_4}{L_9 X + L_{10} Y + L_{11} Z + 1}$$
$$y = \frac{L_5 X + L_6 Y + L_7 Z + L_8}{L_9 X + L_{10} Y + L_{11} Z + 1} \tag{3}$$

If photos are taken of more than six points of known co-ordinates in an image and their image co-ordinates are measured, then the parameters L_i referring to this image can be calculated. And if these parameters are known in at least two images, then by measuring the image co-ordinates of an unknown new point in these images object-side co-ordinates can be calculated. Of course, these calculations are not broken down in such a way, but by solving extensive equation systems with reference to the entire photogrammetric network.

2.3.2. The DLT Software Developed at the BUTE Department of Photogrammetry

The software mentioned in the headline was written in the Turbo Pascal language; it runs under DOS and it has a graphical user interface (GUI), which highly facilitates its operation. The program is not suitable for image evaluation; a suitable CAD or image processing software must also be used for determining image co-ordinates. The program is suitable for obtaining the co-ordinates of the points measured from the DXF format widespread in CAD softwares, that is, to determine image co-ordinates. The DLT calculates the object-side co-ordinates of unknown points from the image co-ordinates already specified using the list of co-ordinates for points with known co-ordinates, and specifying the results both in the form of a list of co-ordinates and a DXF file suitable for further processing by a CAD program.

3. Processing the Results Received

3.1. Qualification of Photogrammetric Networks

Close range photogrammetric networks are substituted by their points. Determination of the network involves the determination of the co-ordinates of these points. Network qualification is linked to point co-ordinates. Special literature on photogrammetry (e.g. KARARA, 1989) [13] uses three characteristics for this purpose: accuracy, precision, and reliability.

This interpretation of precision represents the difference of the final result of a calculation from the 'real' value. If there are enough points on the object side which can be deemed perfect from the photogrammetric point of view, then the standard deviation of co-ordinate differences will provide a global picture of the procedure applied:

$$\sigma_X^2 = \frac{\sum_{i=1}^{n_X} \Delta X_i^2}{n_X}; \qquad \sigma_Y^2 = \frac{\sum_{i=1}^{n_Y} \Delta Y_i^2}{n_Y}; \qquad \sigma_Z^2 = \frac{\sum_{i=1}^{n_Z} \Delta Z_i^2}{n_Z} \tag{4}$$

where

$\sigma_X^2, \sigma_Y^2, \sigma_Z^2$ are variances,
ΔX, ΔY, ΔZ are co-ordinate differences,
n_X, n_Y, n_Z are number of differences.

Accuracy estimation originates from the examination of the co-variance matrix of the point co-ordinates yielded from adjustment by least sqares, used in general and for the whole. In the matrix, diagonal components provide parameter variances, and those outside the main diagonal line provide co-variances. The co-variance matrix can be used to produce a correlation matrix. Its main diagonal line includes median errors and the components outside the main diagonal line will be the correlation coefficient factors between parameters. The degree of accuracy is usually associated with the location of the system of co-ordinates.

The internal reliability of measurements is characterized by the value of the smallest gross error still possible to be indicated. This quantity is directly proportional to the a priori median error of the measurement and is inversely proportional to the portion of redundant measurements falling to each measurement. If the impact on the co-ordinates of this smallest gross error still possible to be indicated is examined, the so-called external reliability will be evaluated.

Furthermore in our study, our networks are to be qualified primarily by the precision data in the meaning above.

3.2. Experiments Performed, Conclusions

In the course of our experiments, five pictures were taken of the Manhattan-type test-field presented in chapter 2 by both mobile phones with cameras, in the arrangement illustrated in *Fig. 6*. Precision was examined in this arrangement in function of the number of images and the control points included in the calculation. Finally, the results were compared with the results yielded from images produced by other cameras of higher quality.

The ground test-field was photographed in the arrangement shown in *Fig. 7*, from two different measured distances. Our studies were extended to the number of control points, the number of images, and the measured distance. Comparisons were made with other cameras in this case as well.

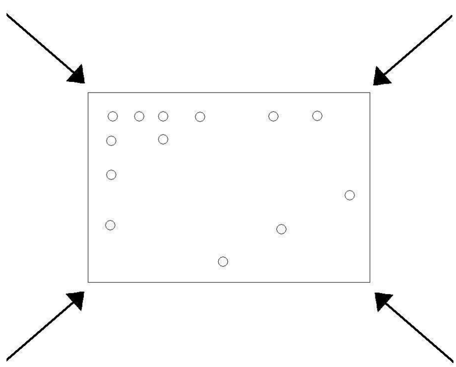

Fig. 6. Locations of taking photographs Manhattan-type test-field

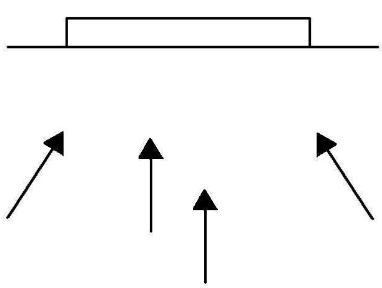

Fig. 7. Locations of taking photographs ground test-field

There are 22 indicated and measured points on the Manhattan-type test-field presented. A minimum of 6 points must be included as control points in the DLT process. In the course of our experiments, the number of control points was set between 7 and 10 and the number of images ranged between 2 and 5. When processing the images, the co-ordinates of the points not included in orientation were calculated as new points, so it was made possible to qualify our network with the formulas (4). The precision indices are included in a table, with n indicating the number of images, r representing the number of control points included in the calculation, and σ standard deviations are in mm.

Table 1. Samsung SGH-X640

n	r	σx	σy	σz
2	7	1.38	2.35	2.75
	8	1.37	1.53	2.05
	9	1.02	1.50	2.04
	10	1.04	0.96	1.55
3	7	0.40	0.62	0.97
	8	0.41	0.50	0.88
	9	0.40	0.47	0.82
	10	0.42	0.48	0.83
4	7	0.34	0.32	0.55
	8	0.32	0.25	0.41
	9	0.22	0.25	0.27
	10	0.18	0.22	0.24
5	7	0.19	0.24	0.25
	8	0.19	0.20	0.26
	9	0.20	0.19	0.22
	10	0.19	0.20	0.20

Table 2. Samsung SGH D600E

n	r	σx	σy	σz
2	7	0.37	0.64	1.53
	8	0.38	0.64	1.54
	9	0.36	0.51	1.47
	10	0.37	0.50	1.46
3	7	0.33	0.40	0.99
	8	0.31	0.38	0.66
	9	0.30	0.37	0.64
	10	0.30	0.37	0.65
4	7	0.34	0.32	0.55
	8	0.31	0.28	0.36
	9	0.23	0.24	0.26
	10	0.19	0.18	0.23
5	7	0.21	0.22	0.25
	8	0.19	0.23	0.23
	9	0.18	0.19	0.21
	10	0.17	0.18	0.20

The following conclusions can be derived from the analysis of the data in the tables:

- Object side data of relatively high and homogeneous precision can be obtained from images taken from a distance of several tens of centimetres by mobile phones with cameras, even if simpler mobile phones with cameras are used.
- Homogeneity is only achieved by introducing the fourth image providing a proper geometric arrangement and the appropriate redundancy of control points.
- When using a simpler camera, standard deviations may be as much as five-fold of the minimum possible to be achieved if only two pictures are taken. In case of higher-quality cameras, this value is only three-fold.

- In order to increase precision, it is more important to use a fourth image than to increase the number of control points ($n = 3$ and $r = 10$ are always worse than $n = 4$ and $r = 7$).
- As redundancy is increased, the growth of precision slows down considerably at a certain limit. In our case, this limit is at $n = 4$ and $r = 10$.

In the course of our experiments, data obtained from the processing of images by a high-quality digital camera (Sony Cybershot DSC F707), from a similar measured distance were also compared to the data obtained from images produced by mobile phones with cameras. In the arrangement of four standing points, which is considered to be ideal by us, about 10 to 15% improvement was achieved using ten control points as opposed to processing by mobile phones. So in the aggregate it can be established that in case of a measured distance below 30 cm, results nearly similar to high-performance digital cameras can be yielded by even lower-quality mobile phones with cameras.

According to the literature (FRASER, 1996) [11], the following correlation can be specified between the object-side co-ordinates of close range photogrammetric networks and the precision of image co-ordinates:

$$\bar{\sigma}_c = \frac{q}{\sqrt{k}} S\sigma = \frac{q}{\sqrt{k}} d\sigma_a \tag{5}$$

where

$\bar{\sigma}_c$ is the experimental error of object-side co-ordinates X, Y, Z;
S is the scale of the image;
d_a is the object distance,
σ_a is the average error of image co-ordinates;
σ_a is the average error of angle measurement,
q is the design factor characteristic of the network,
k is the ratio of independent perceptions and the number of images

If the value of σ is expressed from *Eq.* (5), a real number is arrived at for the precision of image co-ordinates. This value should not be confused with the pixel value below 0.3 as described in section 2.2, because this value only indicates the standard deviation of repeated measurements, while the value calculated here characterizes the precision of the entire recording and evaluation system. In our network, the values $k = 1$ and $q = 0.5$ taken from experience in literature [17, 11, 18] result in a root mean square error of image co-ordinates $\sigma = 0.004$ mm. However, if it is taken into consideration in *Eq.* (5) that $S = d/c$, where d is the measured distance and c is the value of the camera constant, and the measured distance is expressed from this, the resulting correlation will be as follows:

$$d = \frac{\bar{\sigma}_c \sqrt{k}^c}{q\sigma} \tag{6}$$

This measured distance can be considered as the maximum measured distance, because if the camera is taken farther away, the median errors of object-side points will also increase. This problem can usually be solved in photogrammetry by increasing the camera constant; however, this is not feasible yet in the case of mobile phones with cameras. Calculating d will result in a value around 40 cm, what means that in case of a larger measured distance the precision value will be inferior to the one to be forecasted by formula (5).

By processing images photographed from larger measured distances, we actually intended to find out how much worse the result will be if the measured distance is not several tens of centimetres but several metres. The results are shown in the tables below:

Table 3.

n	r	σx	σy	σz
2	8	0.253	0.334	0.421
	10	0.256	0.300	0.398
3	8	0.163	0.137	0.221
	10	0.159	0.128	0.202
4	8	0.102	0.091	0.126
	10	0.095	0.087	0.124

Table 4.

n	r	σx	σy	σz
2	8	0.190	0.301	0.264
	10	0.184	0.303	0.257
3	8	0.153	0.195	0.187
	10	0.148	0.188	0.205
4	8	0.098	0.105	0.108
	10	0.089	0.086	0.099

Following the previous train of thought, one of the most important issues for us is the precision values arrived at. As the table indicates, the previous average median error of 0.2 is replaced here by an average of 10 cm. However, it is not the most important number; the most important one is the average error of image co-ordinates. Taking correlation [5] as a starting point and setting $k = 1$ and $q = 0.8$ will result in $\sigma = 0.069$ mm, which is more than seventeen times the previous value. At the second network, the value $q = 0.8$ was also specified on the basis of experience from the literature. The following conclusions were drawn from the results yielded:

- Our assessment of the number of images and control points did not change as the object distance was increased.
- The median errors of image co-ordinates were actually multiplied at the same rate as the object distance was multiplied.

In case of recordings by other cameras, the results are much better. Using a Kodak DCS 420 digital camera in the best arrangement, the average mean error of co-ordinates will be 0.49 cm (DETREKŐI) [7]. This shows that mobile phones with cameras can only be used with limited geometric precision in case of larger object distances. Another interesting observation is that in the best arrangements, the results with 2 megapixel cameras are not much better, while it is also true that no such conspicuously bad results were yielded when using less images and less control points as in the case of using a VGA camera.

4. Summary

This publication studied the capabilities of mobile phones with cameras for use in photogrammetry. The following most important statements were made on the base of the field-test, which can be generalized:

- Even mobile phones with cameras equipped with a VGA monitor are suitable for photogrammetric processing in case of small object distances of several tens of centimetres if the appropriate network geometry is established and the image redundancy corresponding to the network is also given. These values are specified for a certain network type.
- In our judgement, one of the best properties to characterize network precision, the errors of image co-ordinates derived from network errors, are to increase at the same rate in function of the object distance, what means that the mean errors of object-side points will also increase. In case of larger object distances, users must decide whether the precision capability of a mobile phone with a camera is appropriate in the case concerned.

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