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ANALYSIS OF OPERATORS FOR DETECTION OF CORNERS SET IN AUTOMATIC IMAGE MATCHING

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ABSTRACT: Reconstruction of three dimensional models of objects from images has been a long lasting research topic in photogrammetry and computer vision. The demand for 3D models is continuously increasing in such fields as cultural heritage, computer graphics, robotics and many others. The number and types of features of a 3D model are highly dependent on the use of the models, and can be very variable in terms of accuracy and time for their creation. In last years, both computer vision and photogrammetric communities have approached the reconstruction problems by using different methods to solve the same tasks, such as camera calibration, orientation, object reconstruction and modelling. The terminology which is used for addressing the particular task in both disciplines is sometimes diverse. On the other hand, the integration of methods and algorithms coming from them can be used to improve both.

The image based modelling of an object has been defined as a complete process that starts with image acquisition and ends with an interactive 3D virtual model. The photogrammetric approach to create 3D models involves the followings steps: image pre-processing, camera calibration, orientation of images network, image scanning for point detection, surface measurement and point triangulation, blunder detection and statistical filtering, mesh generation and texturing, visualization and analysis. Currently there is no single software package available that allows for each of those steps to be executed within the same environment. For high accuracy of 3D objects reconstruction operators are required as a preliminary step in the surface measurement process, to find the features that serve as suitable points when matching across multiple images. Operators are the algorithms which detect the features of interest in an image, such as corners, edges or regions.

This paper reports on the first phase of research on the generation of high accuracy 3D model measurement and modelling, focusing upon the application of different operators for accurate feature point extraction. The implementation of those operators is discussed and performance of different operators is analysed. The optimal operator for high accuracy close range object reconstruction is then highlighted. This research has facilitated a development of the feature extraction and image measurement process that will be central to the development of an automatic procedure for high accuracy point cloud generation in multi image networks where robust orientation and 3D point determination will facilitate surface measurement and modelling within a single software system.

1. INTRODUCTION

3D modelling of objects is a complete process, which starts from data acquisition and ends at a virtual 3Dmodel on the computer display. This term is often understood only as processing of a measured cloud of points into a triangularised network or a texturised

surface, while, in fact, it describes a more general and complete process of the entire object reconstruction.
Requirements of many applications, including digital archiving, contain the high geometric accuracy, photo realistic results and the possibility to model details, as well as low costs, automation of processing and mobility and flexibility of technology. Due to those all requirements, selection of an appropriate 3D modelling technique is not always a simple task .
Photogrammetric, close range measuring systems, which are currently available, are based on digital technology and they are used to reconstruct object surfaces or to apply a point-base method. Characteristic features of those systems are universality of applications, the high accuracy and reliability of results and the highly advanced level of measurements automation. Each of such systems is characterised by a defined construction and ways of operations, objectives of utilisation, software applied, as well as by detailed technical parameters [Remondino, 2003].
The presented paper discusses the first phase of research concerning the implementation of highly accurate measurements of 3D objects and their modelling. Basing on performed tests [Zawieska, 2010], analysis of possibilities to apply two selected detection operators, applied in order to accurate point (corner) detection of an object, has been discussed. Utilisation of Harris and Susan operators has been presented for digital images of diversified resolution and then, results of application of those operators, basing on combining successive images (stereogrammes) have been discussed. Those tests allowed for selection of such an operator, which will enable to select and measure such image points, that the basic process aiming at development of a procedure of automated detection of clouds of points, with the high accuracy, in networks consisting of many images will be performed, when the reliable image orientation and determination of the 3D location of points is required. The performed tests have mainly focused on automated detection of image points of the good quality, which will be used for image orientation. The issue of automatic combination of photographs, basing on a detected group of points (corners) on digital images, will be analysed in successive experiments.
Digital images acquired with the use of two cameras, Canon EOS 20D and Hasselblad H4D50, the matrix of which is not equipped with an IR filter, have been used in order to achieve the above objectives. A cardboard solid (an icosehedron) with a diversified texture on its walls, was the object of investigations. The solid was placed on a rotating platform, which was rotated during acquisition of successive photographs. The software tools, developed in Delphi, were utilised for detection of points on a photograph and for combination of stereo-pairs. In order to verify results obtained, the utilised networks of photographs was processed with the use of the PhotoModeler Scanner.

2. CORNER DETECTION OPERATORS

Since the first corner detector, the Moravec operator [Moravec, 1977], was developed, several other corner detectors have been proposed. However, a universal corner detector does not exist. For that reason in this paper two corner detectors, characterised by different features, are compared.
The first one, the Harris operator, is inspired by the Moravec operator. The operator bases on an autocorrelation method. The operator determines a local change of intensity resulting

from shifting a window placed around the considered point by a small distance in all directions.
The operator may be used in the matching task when the original image is compared with its transformed projection, because it is independent on affine transformation and allows to obtain satisfactory results for scaled objects. Besides, the operator has a fair robustness to noise.
The second algorithm, the SUSAN operator, has a definitely different approach. The algorithm is based on brightness comparison within a circular mask. Objects from the image should have a uniform brightness inside a relatively small circles. In other case a point is located on an edge.
The SUSAN operator is not satisfactory in case of an affine transformation. However, it allows to obtain good results for scaled objects. Additionally, the operator has an excellent robustness to noise.
In the next sections detailed information about both operators are presented together with their mathematical description.

HARRIS Operator

The Harris operator calculates an autocorrelation matrix *M* for each pixel (*x, y*) from an original picture:

$$M = \begin{bmatrix} A & C \\ C & B \end{bmatrix}, \tag{1}$$

where:

$$\begin{aligned} A &= \left(\frac{\partial I}{\partial x}\right)^2 \otimes w \, , \\ B &= \left(\frac{\partial I}{\partial y}\right)^2 \otimes w \\ C &= \left(\frac{\partial I}{\partial x}\frac{\partial I}{\partial y}\right) \otimes w \quad , \end{aligned} \tag{2}$$

Where I is an individual grey value of original picture points, $\otimes$ is the convolution operator, and w is the Gaussian window.
Next, the cornerness map is calculated by the corner measure $C(x, y)$, which determines that a point is a corner :

$$C(x, y) = det(M) - k\big(trace(M)\big)^2, \tag{3}$$

as an difference between the determinant of the matrix M and the trace of this matrix taken with a coefficient k.
Finally, all points with value $C(x, y)$ less than the determined threshold T are zeroes and the suppression is done to eliminate nearest corners.

SUSAN Operator

The SUSAN operator works on greyscale images. For each pixel $r_0 = (x, y)$ a circle mask is generated with a given radius. For each pixel r inside the mask the value $c(r, r_0)$ is calculated as:

$$C(r, r_0) = e^{\frac{-(I(r)-I(r_0))^6}{t}}, \quad (4)$$

where I is an individual grey value for the pixel and t is the given coefficient.
From the equation (5) the value $n(r_0)$ is calculated as:

$$n(r_0) = \sum_r c(r, r_0) \quad (5)$$

The value $n(r_0)$ allows to estimate a number of pixels in the neighbourhood of r_0, which intensity I(r) is similar to the intensity of the central point $I(r_0)$.
If the number of points with a similar intensity in the neighbourhood of r_0 is small then the point r_0 may be considered as a corner. The decision function for that is given as:

$$C(r_0) = \begin{cases} g - n(r_0), n(r_0) < g \\ 0, n(r_0) \geq g \end{cases} \quad (6)$$

The threshold g used in the equation (6) may be estimated as a fractal of the maximum of $n(r_0)$.

3. MATCHING

In the matching task an equivalent of one image is find on the second image. The origin point is determined by the corner detector. The projected point from the second image should be also detected by the operator. When the geometry of the camera system is known then a possible location of the projection may be limited by a rectangle.
However, more than one point can be detected in the limited rectangle. In such case the best match has to be found. For that purpose the method of area based matching may be used.
The area based matching algorithm is dedicated for matching of aerial photographs, which may be threatened as photographs of plain objects. However, matching of photographs taken with a narrow angle between cameras and a modelled object, also seems possible.
The algorithm is based on a comparison of intensity of area around a detected point and an intensity of area around potential projections. The details are presented in the next section.

Area Based Matching

In the matching process the area based matching [Lang, Förstner, 1998] may be used. The area based matching aims to find the best fit to the intensities between two images for a limited area.
For a square window, which is determined by the detected corner an intensity map is generated. On the second image a space, which may contain a projection of the window, is analyzed for the best intensity fit.

The best fit is detected basing on a cross correlation. The cross correlation coefficient between the original window and the window, which may be the projection, is computed according to equation:

$$\rho = \frac{\sum_{\xi=1}^{m}\sum_{\eta=1}^{n}\left((f(\xi,\eta)-\mu_1)*(g(\xi,\eta)-\mu_2)\right)}{\sqrt{\sum_{\xi=1}^{m}\sum_{\eta=1}^{n}\left((f(\xi,\eta)-\mu_1)\right)^2*\sum_{\xi=1}^{m}\sum_{\eta=1}^{n}\left((g(\xi,\eta)-\mu_2)\right)^2}} \quad (7)$$

$$-1 \le \rho \le 1$$

where
$f(\xi,\eta)$= individual grey values of a reference window
μ_1 = average grey value of a reference window
$g(\xi,\eta)$ = individual grey values of corresponding part of a search window
μ_2 = the average grey value of the corresponding part of a search window
m, n = the numbers of rows and columns of a reference window

4. EXPERIMENT ASSUMPTIONS

The performed tests had two major objectives. The first one was to assess the utilization of different corner detectors in an image matching process. Detailed information about various aspects of the assessment are presented below. The second objective was to compare matching of photographs with different values of angles in the space determined by cameras and a modelled object. A significance of the angle value will be also discussed later in this section.

Assessment of Corner Detectors

In the matching process two corner detection operators were considered. The first one, the Harris operator [Harris, Stephens,1988], has strong invariance to rotation and scale as well as image noises. The second one, the SUSAN operator [Smith, Brady,1977], is described as one of the most effective corner detection algorithm of the methods based on geometry. Both methods have been compared in the paper [Jun Jie Liu, et al, 2009] with respect to the corner detection for single photographs.

In this paper both methods are compared in the image matching task. For that purpose corners were detected on a pair of images. In the next step corners from both images are matched basing on a similarity of a value calculated by the corner detector.

There are three main aspects, which influence the quality of the matching process. The first one is a number of detected points. When a 3D model is created, eight points are necessary to place two-dimensional points in a three-dimensional space. When the bigger number of points is known, an additional validation of the model is possible. On the other hand, a huge number of detected points influences the time required for triangulation in the model creation process.

The second aspect, which is related to the number of corners, is a point location. Corners are the most important points of the modelled object. The corner detector is dedicated to detect such points. However, false corners may be also detected on the object texture elements. Because a plane is determined by three points, extra points usually do not give

any additional information about the object geometry. As it was mentioned, the time of modelling will be increased and such points may be modelled as artefacts on the surface.
The last aspect concerns the possibility to detect the same point on different images. In a discussed case the object revolves around the single axis. For small angles such rotation may be described locally as translation. However, transformation will change the corner's neighbourhood. For an appropriate matching the revolved point has to be detected and described in a similar way that the original one.
Those three aspects will be discussed for both, the Harris and the SUSAN operators. Firstly, on the basis of single images and then, on the basis of pairs of images.

Matching for Different Angles

Matching between pairs of images is usually done for a system with a narrow angle between cameras and the object. One of the main advantages of the narrow angle is a reduction of a rotation as a source of differences between images to a translation. This approach should bring better matching results, since differences in the intensity map are smaller. Additionally, calculations for the construction of a 3D model are significantly simpler.
However, in the case of the narrow angle, the detection of the third co-ordinate of points in the 3D space is calculated with a strongly propagated error. Because distances in the geometry of photographs between matched points are rather small, a minor error in a distance calculation influences a major error in the calculation of the third co-ordinate.
The solution is to utilise a wider angle. Then the distances in the photograph geometry are bigger and the minor error in the distance calculation brings only the minor error in the calculation of the third co-ordinate. However, the number of matching points will be reduced on photographs acquired by the system with the wide angle between cameras and the object. Matching will be more difficult, because variation of the intensity map will be higher.
This problem may be partially eliminated by an indirect matching. Points are paired between a pair of photographs taken with the narrow angle between cameras and the object. Next, the second pair of photographs is analysed. In the new pair the left picture is the same as the right picture in the first pair. When a point from the first picture is detected on the second one and then, once again, the projection of the point from the second picture has a detected equivalent on the last photograph, the connection between the first and the last photograph is established.
Such connection gives a point, which is represented on two photographs taken with the wide angle between cameras and the object. So, the point may be used in the modelling of a 3D object, without a significant error precession.
At the same time the connection was established in two steps between photographs taken with the wide angle between cameras and the object. That brings lower variation of the intensity map and better matching results.
Both techniques of matching for the wide angle: the direct and the indirect one will be mutually compared; their results will be also compared with the results of matching with the use of narrow angles.
All described techniques were implemented in the Delphi environment.

5. TESTS ON SINGLE IMAGES

For the tests two series of photographs were used. The first one was taken with Canon amateur camera. The second series was taken with the Hasselblad H4D50 camera. For each series three photographs have been taken. Then the photographs were ordered in series. On the second photograph the object was rotated by 15 degrees, comparing to the first photograph.
Detailed data about the number of detected corners for both series and operators are listed in Table 1. This Table presents a number of detected points for each photograph. Additionally, the average number of detected points is calculated for each series. Basing on those calculations, stability of detection may be analysed. The object is rather regularly shaped and the number of detected points should be similar for all photographs in both the series. The stability may be estimated by the standard deviation, which determines an average difference between the average number of points and the number of detected points on the photographs. The same value is given also as a percentage.
The results for the Harris operator are presented in Figure 1. In case of the amateur camera, the entire object is covered with detected points. In case of the professional camera the majority of results are located on edges. Only one side is marked with false corners.

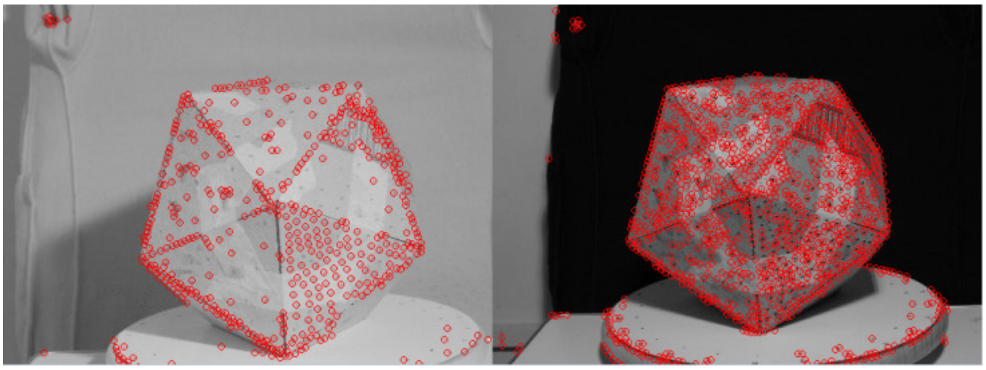

Fig.1. Results of the Harris corner detector: on the left a photograph taken with the Hassleblad H4D50 camera; on the right a photograph taken with the Canon 20D camera. (The example was generated for low resolution images).

In case of the Harris operator results from the amateur camera are rather stable. The difference between the number of detected points on the following photographs is less than 6 percent. This value increases for the high resolution image acquired by the professional camera.
The results for the SUSAN operator are presented in Figure 2. The number of recognized corners is significantly less than in case of the Harris operator. Only for the amateur camera a detection of false corners on the sides of the object is noticed. But even in this case the number of recognized corners, as well as their location, are similar to the results of the Harris operator for the professional camera.

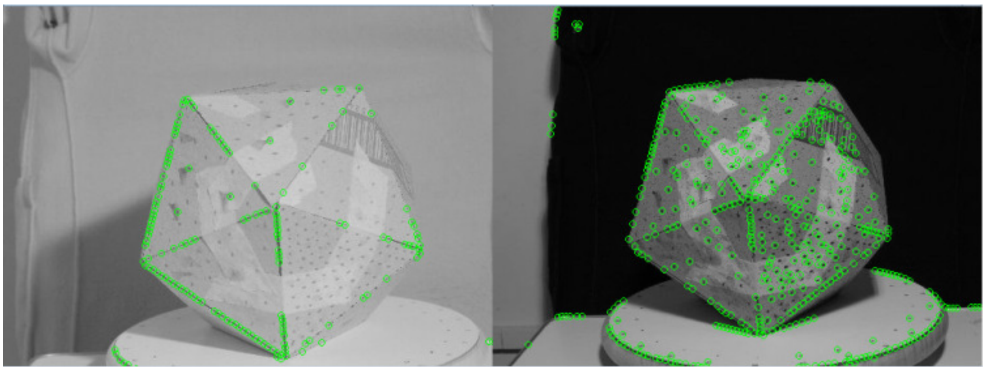

Fig. 2. Results of the Susan corner detector: on the left an image taken with the Hasselblad H4D50 camera; on the right an image taken with the Canon 20D camera. (The example was generated for low resolution images).

In the case of the professional camera a number of detected points is strongly reduced. Moreover, nearly all of them are placed on the edges.
The stability of the results is good in both cases, for the professional and the amateur camera. In the case of the professional camera the standard deviation is increased, but this is not the significant (Tab.1).
Tests show that the Susan operator detects less points than the Harris operator for the professional camera (for the amateur camera those numbers are similar). However, those points are better localized. The same concerns the professional camera, which improves the location of the points.
As a conclusion of the test it may be said that the SUSAN operator used for the photographs taken with the professional camera brings the best location of the points.

Tab. 2. Corner detection stability. The table presents a number of detected corners on each image.

Camera	Operator	Image 1 [k]	Image 2 [k]	Image 3 [k]	Average Number of Points [k]	Standard Deviation [k]	Standard Deviation [%]
Canon 20D	Harris	6.6	6.9	7.4	7.0	0.4	5.8
	Susan	9.0	8.8	8.3	8.7	0.4	4.7
Hasselblad H4D50	Harris	12.2	11.6	15.8	13.2	2.3	17.2
	Susan	5.1	4.9	5.5	5.1	0.3	6.3

6. TESTS ON PAIRS OF IMAGES

Each series of photographs, for both, the amateur and the professional camera, contains three photographs. That gives also three pairs of photographs. The difference between a view of the object on the first photograph and the second one is 15 degrees. The same concerns the second photograph and the last one. The difference between the first and the last view is 30 degrees.
When the neighbouring photographs (such as 1st-2nd or 2nd-3rd) are matched directly, matching with a gap (such as 1st-3rd) may be done in two ways: directly or indirectly.
In the case of direct matching points from the first photograph are matched with the points from the last photograph. The percentage of the matched points should be lower in this case than when the neighbouring photographs are matched, because the number of identical points on both pictures will be lower.
The indirect matching technique has two steps. Detection of pair of points between the first and the second photograph and detection of equivalents of the paired points from the second photograph on the last one. In this case the percentage of the matched points will be still lower than for the neighbouring photographs. However, narrow angles between views will improve the ability to find paired points and the percentage should be higher for the indirect technique than for the direct one with the use of a wider angle. Both techniques will be compared.

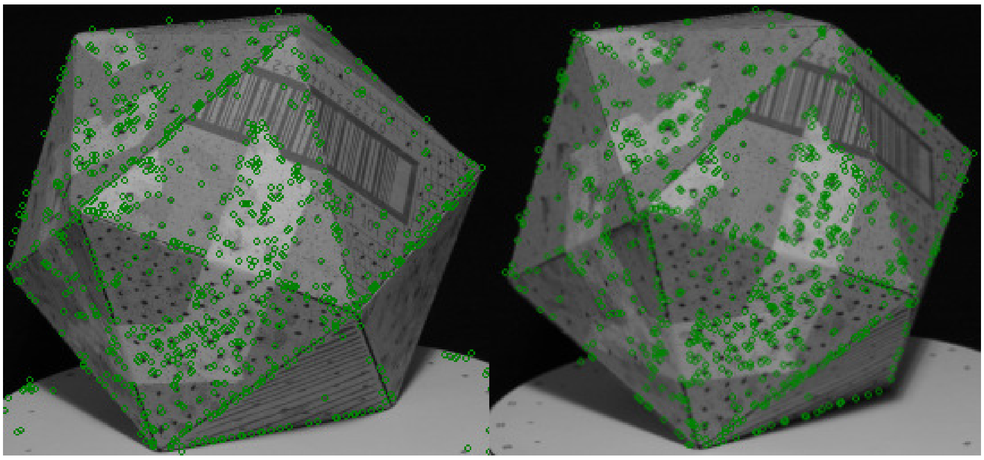

Fig. 3. Points detected by the Harris operator and matched on two images (1-2) taken with the Canon 20D camera.

In the first test the Harris operator was used. Photographs taken with the amateur camera were analysed. The matched points are presented in Figure 3. The average percentage of points, which were used in the matching process, was 10.35 for the neighbouring photographs. The direct technique for far images gives only 5.88 percent. Better results are obtained for the indirect technique: 8.18 percent. The detailed data are given in Table 2.

Tab. 2. Statistics for matching with the Harris operator on photographs taken with the Canon camera.

Pair	Number of points		Number of paired points	Percentage of paired points	
	Left	Right		Left	Right
1-2	6630	6881	618	9.32	8.98
2-3	6881	7416	825	11.99	11.12
1-3	6630	7416	412	6.21	5.56
1-2-3	6630	7416	573	8.64	7.73

In the second test the Harris operator was used. Photographs taken with the professional camera were analysed. The matched points are presented in Figure 4. The average percentage of points, which were used in the matching process, was 13.37 for the neighbouring photographs. The direct technique for far images gives only 5.43 percent. Better results are obtained for the indirect technique: 6.04 percent. The detailed data are given in Table 3.

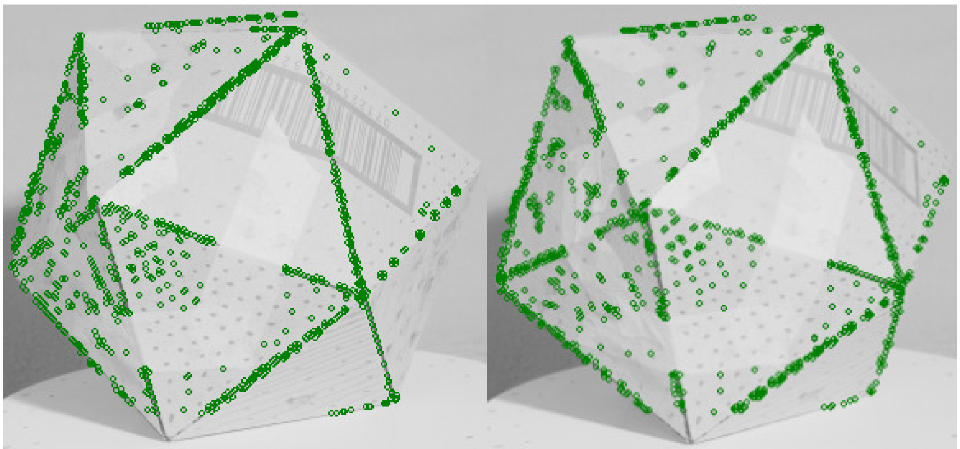

Fig 4. Points detected by the Harris operator and matched on two images (1-2) taken with the Hasselblad H4D50 camera.

In the next test the SUSAN operator was used. Photographs taken with the amateur camera were analysed. The matched points are presented in Figure 5. The average percentage of points, which were used in the matching process, was 10.49 for the neighbouring photographs. The direct technique for far images gives only 7.18 percent. Better results are obtained for the indirect technique: 9.103 percent. The detailed data are given in Table 4.

Tab. 3. Statistics for matching with the Harris operator on photographs taken with the Hasselblad camera.

Pair	Number of points		Number of paired points	Percentage of paired points	
	Left	Right		Left	Right
1-2	12175	11600	1664	13.67	14.34
2-3	11600	15794	1702	14.67	10.78
1-3	12175	15794	745	6.12	4.72
1-2-3	12175	15794	830	6.82	5.26

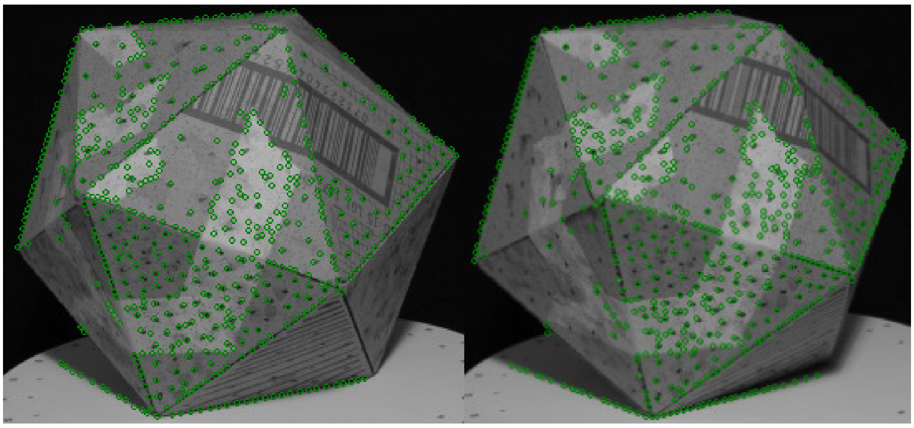

Fig. 5. Points detected by the SUSAN operator and matched on two images (1-2) taken with the Canon 20D camera.

In the last test the SUSAN operator was used. Photographs taken with the professional camera were analysed. The matched points are presented in Figure 6. The average percentage of points, which were used in the matching process, was 17.46 for the neighbouring photographs. The direct technique for far images gives only 12.42 percent. Better results are obtained for the indirect technique: 13.26 percent. The detailed data are given in Table 5.

Tab. 4. Statistics for matching with the SUSAN operator on photographs taken with the Canon 20D camera.

Pair	Number of points		Number of paired points	Percent of paired points	
	Left	Right		Left	Right
1-2	9055	8799	863	9.53	9.81
2-3	8799	8259	964	10.96	11.67
1-3	9055	8259	620	6.85	7.51
1-2-3	9055	8259	780	8.61	9.44

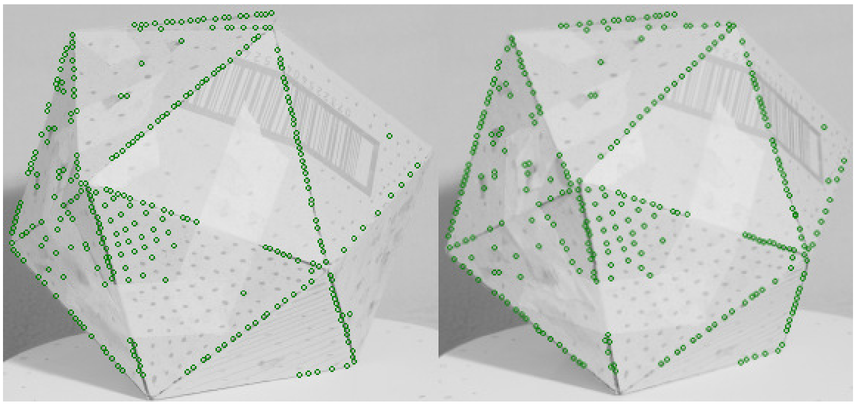

Fig 6. Points detected by the SUSAN operator and matched on two images (1-2) taken with the Hasselblad H4D50 camera.

Tab. 5. Statistics for matching with the SUSAN on the photographs taken with the Hasselblad H4D50 camera.

Pair	Number of points		Number of paired points	Percent of paired points	
	Left	Right		Left	Right
1-2	5078	4897	942	18.55	19.24
2-3	4897	5526	832	16.99	15.06
1-3	5078	5526	660	13.00	11.94
1-2-3	5078	5526	702	13.82	12.70

As a conclusion of the test it may be said that utilization of a professional camera brings better results in matching of neighbouring photographs. However, if the Harris operator is used the results are worse for the high resolution photographs in the indirect matching technique. For that reason the professional camera should be used in connection with the SUSAN operator. Then the results are the best both, for direct and indirect techniques.
It may be also noticed that the indirect technique gives better results than the direct technique for far photographs.
The presented pictures show that the Harris operator gives worse location of points. In case of the amateur camera the majority of points are located on the sides instead of the edges. For the professional camera the location is better, however edges are still blurred.

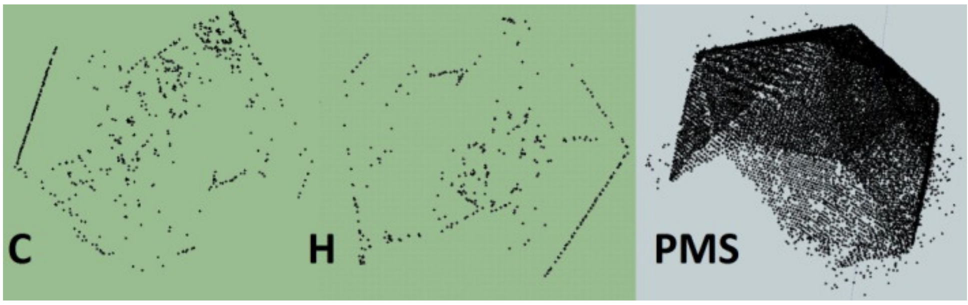

Fig 7. A cloud of points for the model created with the SUSAN operator from two photographs taken with the Canon 20D - (C) and Hasselblad H4D50 - (H). For comparison a model created by the PhotoModeler Scanner - (PMS) is presented.

The SUSAN operator gives good location in both cases, for the amateur and for the professional camera. For that reason points detected by this operator were used in modelling the object. The results are presented in Figure 7. The results are not so clear as results of the PhotoModeler Scanner, however a part of edges is very well detected and the number of additional points is at an acceptable level. Moreover, artefact points, which are located outside the model, have not been detected.
The presented models are only a draft, only two pictures were used in the modelling process, but they allow to assume that presented techniques will bring satisfactory results in future works.

7. CONCLUSIONS

In this paper an issue of matching photographs has been discussed. Two corner detection algorithms: the Harris and the SUSAN operators, were tested. Both operators were tested on photographs taken with the amateur and the professional camera.
Firstly, the operators were tested on single photographs. Tests proved that - despite the reduction of the number of detected points - the SUSAN operator, which works on the photographs from the professional camera brings the best point location.
In the second series of the test the detected points were analysed with respect to the matching procedure. The results for the neighbouring photographs confirmed conclusions from the preceding tests. In case of the photographs from the professional camera over

17 percent of points detected by the SUSAN operator were matched. This presents the best results of the discussed variants.

In the case of photographs that are not direct neighbours, two matching techniques, the direct and the indirect one, were tested. For all variants the indirect technique brought better results. Once again, the best results were obtained when the professional camera and the SUSAN operator were used.

The first steps in the 3D modelling were also presented. The results allow to hope for satisfactory results in the future.

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