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AN ATTEMPT TO OPTIMIZE THE PROCESS OF AUTOMATIC POINT MATCHING FOR HOMOGENEOUS SURFACE OBJECTS

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ABSTRACT: In recent years the progress in algorithms optimization has resulted in many solutions in the area of fully automatic reconstructing of 3D model of any object from a sequence of non-metric images. An important step in the formation of a 3D model is so-called matching process of homologous points in the sequence of images. This stage is still a bottleneck for the reconstruction of objects consisting of uniform surfaces, such as sculptures, reliefs, or even the human body. The solution may be to apply an artificial variety to surfaces by covering them with a random texture pattern. A wide range of multimedia projectors, with increasingly higher resolutions and luminosities, enables us to perform the projection of any texture on the object, and then to register it. In this article, we present the idea of creating an artificial pattern, a structure that will provide significant improvement of automatic point identification stage, and the proper mapping of homologous points in the sequence of images. While creating a pattern allowing easy feature extraction does not present much of a problem, assurance of its uniqueness for the whole object for matching purposes, requires a deliberate idea. Statistical formulation of the problem demonstrates the high efficiency of the method.

1. INTRODUCTION

1.1 Motivation

During our studies on the topic of 3D reconstruction from non-metric images with photogrammetric methods we encountered a problem related to detection of the conjugate points between adjacent images that presented very uniform surfaces. Usually the features are extracted by the Harris operator and the corners detected in stereo-pairs or in sequence of images make input for tie point's detection procedure. There is no problem with finding a sufficient number of tie points for regular surfaces with plenty of natural or artificial features. The problem may occur on uniform surface or on surface with no enough number of features. Lack of tie points results in appearing empty holes in 3D model cloud, what may be serious obstacle in further proceeding. Uniform texture of homogeneous surface may be rearranged to suit matching process by projecting an artificial pattern (D'Apuzzo, 2002;Chang, 2008).

1.2 3D reconstruction process

There are many scenarios to calculate 3D coordinates of conjugate points which form the object that is being reconstructed. One preferable (Chang, 2008) is first to normalize stereo-image pairs using epipolar geometry. Then interest points are extracted followed by matching process to identify the conjugate points. The matched tie points are tracked through captured neighbouring images and then multiple light ray intersection is performed to finally calculate coordinates of all points belonged to reconstructed surface. Next all the surfaces are combined simultaneously using the homogeneous points on reconstructed surfaces in a least square adjustment procedure. In testing procedure several artificial patterns will be tested to decide on their suitability in the process of point matching. The concise introduction of Harris detector and normalized cross-correlation (NCC) concepts are needed, as crucial elements of testing procedure.

Matching process requires a detection of the conjugate points what may be automated by identifying surface features. Features can be extracted using the Harris corner detector (Harris and Stephens, 1988), which is a popular interest point detector based on the local auto-correlation function of a signal, what is indeed the sum of squared differences (SSD) similarly to Moravec algorithm (Moravec, 1980). SSD given by equation (1) is calculating between an image patch over the area (u,v) and its shift by (x,y).

$$S(x,y) = \sum_u \sum_v w(u,v)\big(I(u+x,v+y) - I(u,v)\big)^2 \tag{1}$$

In the equation, the weighted sum of squared differences between two patches is denoted as $S(x,y)$. The lower number indicates more similarity in the image and local maximal value of the number indicates that a feature of interest is present. The advantage of the Harris detector over the Moravec method is to replace shifted patches with the differential of the corner score with respect to direction directly what produces the approximation (2).

$$S(x,y) \approx \sum_u \sum_v w(u,v)\big(I_x(u,v)x - I_y(u,v)y\big)^2 \tag{2}$$

In the equation (2) the partial derivatives of I are denoted as I_x and I_y. This improvement hugely reduced the calculation complexity of the algorithm. If we apply a circular window or circularly weighted window (Gaussian blur) the response will be isotropic, what is another huge advantage over Moravec method. Finally in (3) eigenvalues of the Harris matrix (A) are replaced with *determinant(A)* and *trace(A)* what makes next computational improvement in terms of time complexity.

$$M_C = \lambda_1\lambda_2 - \kappa(\lambda_1 + \lambda_2)^2 = det(A) - \kappa\, trace^2(A) \tag{3}$$

The normalized cross-correlation (Lewis, 1995) is well-known area-based matching method for assessing the image similarity Small windows composed of grey values are used as matching primitives to perform comparisons over uniform zones of images until the best correspondence is reached. Lewis has demonstrated superiority of NCC over the traditional cross-correlation and other matching methods. Cross-correlation term $c(u,v)$ in (4)

$$c(u,v) = \sum_{x,y} f(x,y)t(x-u,y-v) \tag{4}$$

is a measure of the similarity between samples. Serious drawback of cross-correlation was requirement to maintain the regular lighting conditions between image sequences. Another disadvantage was that the correlation between exact samples might be smaller than the correlation between the feature and for instance a bright spot.
Normalized cross-correlation, given by equation (5)

$$\gamma(u,v) = \frac{\sum_{x,y}[f(x,y)-\bar{f}_{u,v}][t(x-u,y-v)-\bar{t}]}{\left\{\sum_{x,y}[f(x,y)-\bar{f}_{u,v}]^2 \sum_{x,y}[t(x-u,y-v)-\bar{t}]^2\right\}^{\frac{1}{2}}} \tag{5}$$

significantly reduces the above disadvantages. Lewis proved supremacy of NCC over the other matching methods in typical applications.

2. TESTING PROCEDURES

2.1 Setup of the hardware.

As sample material a standard mannequin that can be found in any textile shop was used. To reduce time consuming proceedings only face area images were acquired. For testing purposes sequence of photos was reduced to stereo-pairs. Pictures were taken in two series. At first, the ‘normal case’ pictures were taken, where the axes of two photos were perpendicular to the baseline. Next, the convergent pictures were taken, where the axes of photos were directed towards one point on the dummy torso. Distance from the camera tripod to the dummy was fixed to 2 meters and baseline also was fixed to 0.8 m (Figure 1).

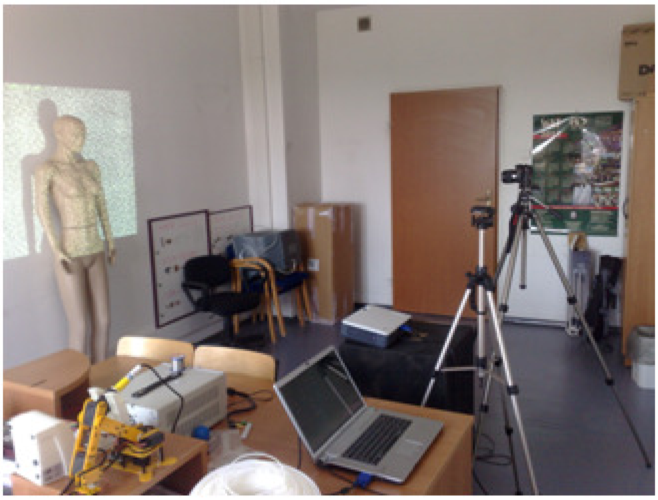


Fig. 1. The setup up of the hardware.

2.2 Examined patterns

To investigate the efficiency of the identification of the conjugate points on homogeneous surface photos were taken at regular day light without any pattern and then with seven different types of patterns.
First pattern (Fig.ure 2) was generated by MATLAB function image = rand([rows columns]) and consisted of squares in various shades of gray.

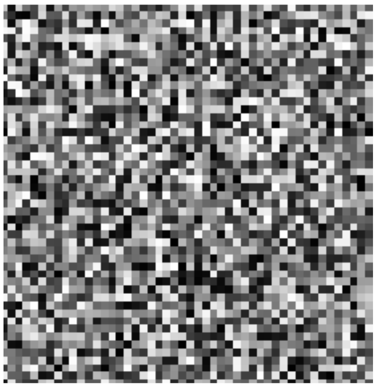


Fig. 2. Pattern with fifty-by-fifty matrix of various shades of gray.

Second pattern (Figure 3) was produced with Yuki Kamitani's Matlab Image Tools randomly generating black and white squares
http://www.cns.atr.jp/~kmtn/imageMatlab/index.html).
The ratio of black squares to white squares was set up as 0.5.

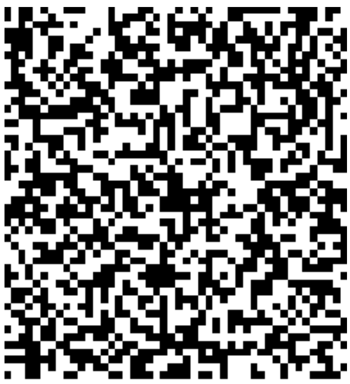
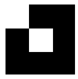
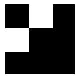
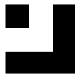
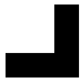


Fig. 3. 50 by 50 matrix consisting of black and white squares

Tab. 1. Examples of Chang's three-by-three sub-blocks.

Sub-block ID	Encoded pattern	Corresponding image
3	1 0 0 0 1 0 0 0 0	
4	0 1 0 1 0 0 0 0 0	
8	0 1 0 1 1 0 0 0 0	
11	1 1 0 1 1 0 0 0 0	

Third pattern (Figure 4) was designed by Yu Chuan Chang (Chang, 2008) and consisted of three-by-three sub-blocks (Table 1), arranged in pattern in a random way.
Originally much more sub-blocks were constructed, but finally, after many tests, only eleven were chosen as the most distinguished one from another.

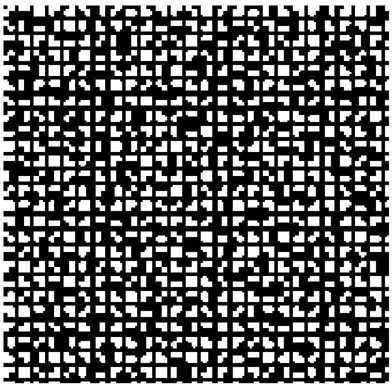
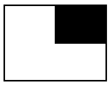
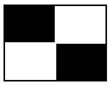
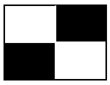


Fig. 4. Chang's pattern consisting of 9 randomly arranged blocks.

For the purpose of this study Chang's pattern was redesigned to a unique pattern consisting of ten blocks, two-by-two (Tab**. 2** 2) and tree-by-tree squares.

Tab. 2. Two-by-two blocks used in testing procedure

Sub-block ID	Encoded pattern	Corresponding image
0	0 1 1 1	
1	1 0 0 0	
2	0 1 0 0	
3	1 0 1 1	
4	0 0 0 1	
5	1 1 1 0	
6	1 1 0 1	
7	0 0 1 0	
8	0 1 1 0	
9	1 0 0 1	

Two-by-two blocks were designed to allow the Harris detector to discover as many corners as it is possible, inside and outside of the block edges. An option with three-by-three blocks is actually a copy of the two-by-two blocks. The only distinction is white stripe left at the bottom and on the left to prevent sub-blocks touch each other. Because the sub-blocks are arranged automatically, the black dots from neighbouring blocks may form black spots. Blurring white and black spots may result in poor feature detection. For test purposes, white colour of the stripe was applied, as opposed to Chang' version, who had used in his pattern black one.

Fig. 5. Random pattern consisted of 2-by-2 blocks.

Fig. 6. Pi-random pattern consisted of 2-by-2 blocks.

Fourth and fifth pattern (Figure 5, Figure 6) is arranged from blocks selected randomly. Last two types of patterns (Figure 6, Figure 8) are arranged from blocks selected in a special way.

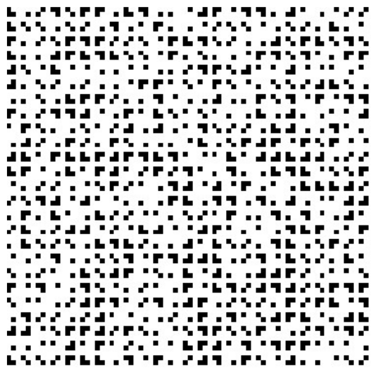


Fig. 7. Random pattern consisted of 3-by-3 blocks

For a long time scientists have been investigating the uniqueness of the digit of π (Berggren, 2004). However the question if the π is random remains still unanswered. Certainly the most elementary mathematical hypothesis will continue to intrigue people in coming years. Mathematicians are still exploring the most modern algorithms and mathematical formulas to prove randomness of π (Bailey, 2006). Based on the latest research (Bailey, 2011) we decided to use the digit of π to arrange ten blocks to form artificial π-random pattern.
Data used in our function was downloaded from the site of the Yasumasa-Kanada-Laboratory (www.super-computing.org). It holds the decimal representation of the first 4.2 x 109 digits of Ludolph's number.

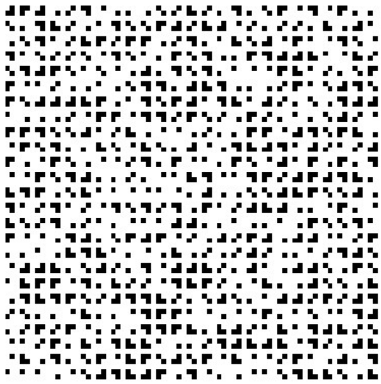


Fig. 8. Pi-random pattern consisted of 3-by-3 blocks.

We assigned each block one decimal digit as ID (Table 2). Started from decimal point, we're walking along the π reading digits and inserting corresponding blocks into pattern matrix (Figure 6, Figure 8). The result seems to be very similar to the regular random matrix.

2.3 The procedure

Firstly points of interest were detected (Figure 9) in the pictures with the Harris corner detector (Table 3 and Table 4 – left and right picture)**Tab. 3**

Then matching process (Figure 10) was performed with normalized cross-correlation (Table 3 and Table 4 – putative matches).
In the next step the output was filtered and outliers were eliminated (Table 3 and Table 4 - filtered matches).
Only for pictures taken for plain object, without any projected pattern, local contrast enhancement was applied. Wallis filter was utilised (Remondino, 2003) to improve performance of the matching process.

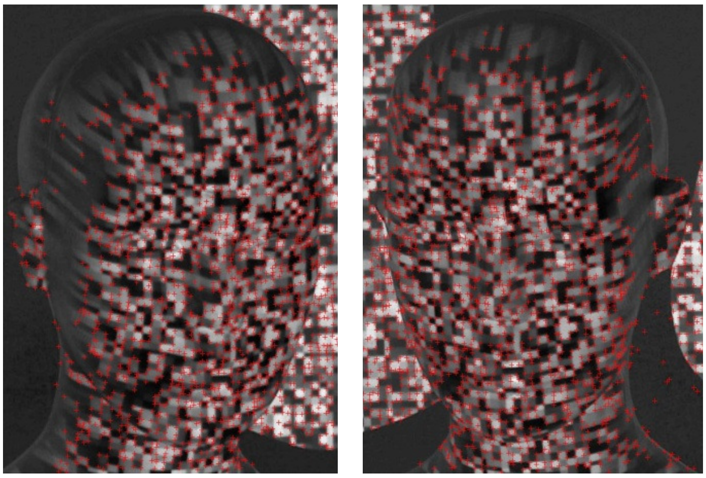


Fig. 9. Red crosses indicate the detected corners.

All pictures were converted with Matlab function rgb2gray to grayscale intensity image. The κ, a tuneable sensitivity parameter, was set at the value 0,04 suggested in literature.
The searching window parameter of the normalised cross-correlation process was set to value 31.

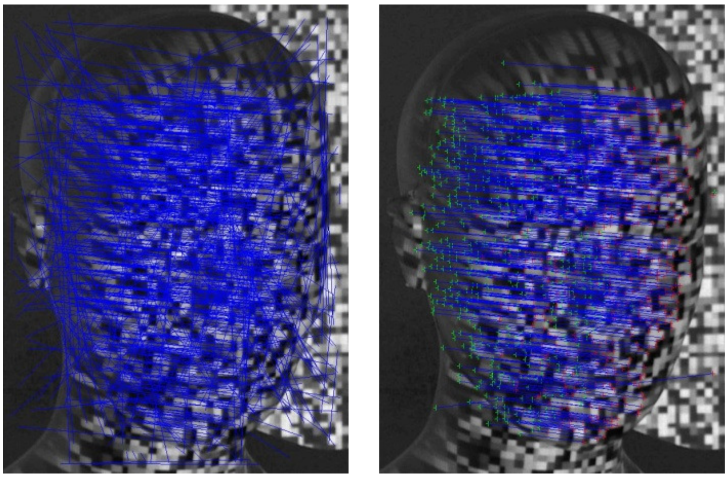


Fig. 10. Blue lines show linked points before and after filtering.

The pictures were cropped to show only the face, what helped to improve performance of tests and at the same time the results were no affected.

3. RESULTS

Tab. 3. The result of matching on the convergent pictures.

convergent pictures					
pattern	left pic.	right pic.	putative matches	filtered matches	efficiency gain [%]
1	1350	1573	670	412	1004
2	1255	1358	592	392	956
3	2497	2724	871	500	1219
4	1305	1539	617	429	1046
5	951	961	286	147	358
6	1420	1551	682	475	1158
7	900	977	279	171	417
no pattern	395	416	87	41	0

Comparing the number of matched points from all the columns we can clearly see how efficient the method with pattern projection is.

There is no doubt that the influence of an artificial pattern enriched homogenous surface in much more than significant way. The mean value of efficiency gain (Table 3 and Table 4 – efficiency gain) for both series is on the level of 1000 %, which demonstrates a very considerable improvement. In the research, the high efficiency of Chang's pattern has been confirmed and also the comparable effectiveness of patterns number 1, 4 and 6 was observed.

Tab. 4. Result of matching on the 'normal case' pictures.

'normal case' pictures					
pattern	left pic.	right pic.	putative matches	filtered matches	efficiency gain [%]
1	2151	2360	874	631	1660
2	1894	1943	656	384	1010
3	2427	2709	843	570	1500
4	1970	2159	694	433	1139
5	1819	2088	580	352	926
6	1976	2117	693	422	1110
7	1799	2075	571	348	915
no pattern	381	403	81	38	0

4. CONCLUSIONS

As it has been proved, matching stage of the reconstruction process of homogenous surface may be significantly improved with the help of artificial pattern. However, a weakness of the method is caused by a limitation of projector luminosity. Significant drawback may be still limited by a range of projection offered by the projectors. During the day, difficulties connected with outdoor conditions, like direct sunlight or weather conditions, may occurred. Therefore, the method may be rather limited to indoor conditions. It should be also emphasized, that creation of proper illumination conditions would not be enough to make a perfect picture. To take a good quality pictures in regularly lighted scene there is need for a very experienced camera operator.

Further development of encoded patterns would be desirable. Because of the fact that the pattern layout is known, it is possible to track the location of features in the picture, which may not only improve the timing, but even totally redesign matching process.

Another future challenge is to utilise genetic programming to automatically synthesize image operators that can detect interest points (Trujillo, 2008).

Parallel computing is the next step in developing feature extraction and matching algorithms. Proper method should enable split a computational task into subproblems, each one assigned to its own processor unit.

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