3D Reconstruction: Novel Method for Finding of Corresponding Points using Pseudo Colors

Libor BOLEČEK, Václav ŘÍČNÝ, Martin SLANINA

Dept. of Radio Electronics, Brno University of Technology, Purkyňova 118, 612 00 Brno, Czech Republic

xbolec01@ stud.feec.vutbr.cz, ricny@feec.vutbr.cz, slaninam@feec.vutbr.cz

Abstract. *This paper deals with the reconstruction of spatial coordinates of an arbitrary point in a scene using two images scanned by a 3D camera or two displaced cameras. Calculations are based on the perspective geometry. Accurate determination of corresponding points is a fundamental step in this process. The usually used methods can have a problem with points, which lie in areas without sufficient contrast. This paper describes our proposed method based on the use of the relationship between the selected points and area feature points. The proposed method finds correspondence using a set of feature points found by SURF. An algorithm is proposed and described for quick removal of false correspondences, which could ruin the correct reconstruction. The new method, which makes use of pseudo color image representation (pseudo coloring) has been proposed subsequently. By means of this method it is possible to significantly increase the color contrast of the surveyed image, and therefore add more information to find the correct correspondence. Reliability of the found correspondence can be verified by reconstruction of 3D position of selected points. Executed experiments confirm our assumptions.*

Keywords

3D reconstruction, features points, image correspondence, pseudo color.

1. Introduction

This paper deals with reconstruction of spatial model of a scene. The creation of spatial model of a scene is a very actual topic in computer vision. Results of reconstruction are three spatial coordinates in a selected coordinate system (Fig. 1c). An associated task is the creation of a depth map of a scene. The depth map is represented by a grayscale image. Intensity of each pixel is equivalent to the relative depth (Fig. 1b). Some interesting methods for creation of depth map have been published in [1] and [2], where the authors proposed a hybrid method for dense matching. The reconstructed model can be used

a) b) c)

Fig. 1. a) Scene obtained by camera FUJIFILM W3. b) Depth map of the same scene. c) Reconstruction of the scene spatial model calculate by freeware

in many areas – especially in civil engineering, robotics, medicine, etc. Depth map is used mostly in 3DTV.

In order to build the model, we have to carry out several fundamental, i.e.

- Localization of corresponding points,
- interior calibration,
- exterior calibration.

The process can be described by a flowchart shown in Fig. 2. Methods used for the reconstruction of three-dimensional model scenes (determining spatial coordinates) are well-known and well described in the literature – for example in [14], [15], [16]. To achieve highly accurate reconstruction, it is necessary to find the most accurate corresponding points in the two partial images of the analyzed scene captured with varying parallax. There are many publications dealing with this task, for example [24]-[28].The main content of this paper is devoted to this area.

Section 2 contains the necessary mathematical apparatus for reconstruction. The next section describes the proposed method. At first, we propose a method for finding a concrete selected point based on the relation of feature points. Subsequently, we propose a modification of the method for elimination of false correspondences. Moreover, we investigate the possibility of using false colors in the process of finding the corresponding points. This is a new approach. An image is converted from grayscale to false colors using a process called pseudo coloring. Section 4 provides results of the executed experiments. Finally, Section 5 summarizes the contribution of the proposed approach.

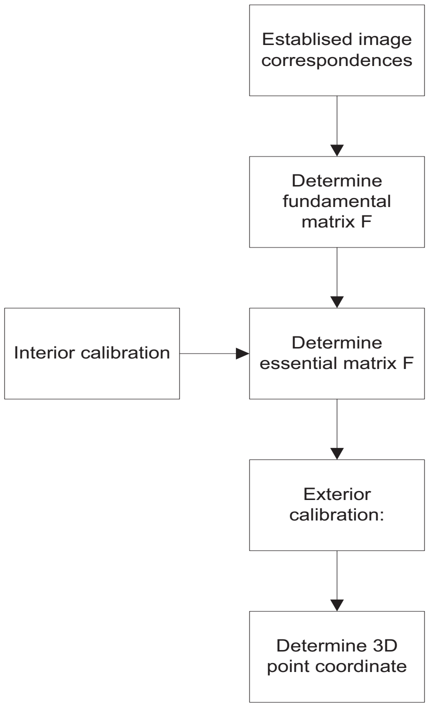


Fig. 2. A general flowchart of the designed system for reconstruction of 3D model.

2. Related Work

The most important step that needs to be done in order to create a depth map is to acquire image correspondences. The image correspondences are then used in all subsequent operations in the reconstruction. At first, the feature points in the left and right images need to be found. Feature points are pixels with salient properties which can be detected in both images. It is necessary to find the corresponding pixel in each image. Algorithms for this task are often examined and many compact studies of this problem exist [6], [7]. Nowadays descriptors are often used to find the corresponding points. Descriptors are functions, which describe points by using properties of their neighborhood. SURF (Speeded Up Robust Feature) [9] is apparently the most widely used.

When the set of corresponding points is found, the interior and exterior orientation of camera must be obtained. The interior orientation represents the properties of camera (f, u_0, v_0, s) and its distortion. Interior camera parameters are expressed by the calibration matrix K as

$$\mathbf{K} = \begin{bmatrix} f_u & s & u_0 \\ 0 & f_v & v_0 \\ 0 & 0 & 1 \end{bmatrix} \quad (1)$$

where f_u and f_v represent the focal lengths in pixels, (u_o, v_o) represent the coordinates of principal point, s represents the skew. Many methods have been proposed for camera calibration [3], [4], [5].

The exterior orientation represents the relation between camera positions given by rotation matrix **R** and translation vector **T**. Exterior calibration is calculated based on the knowledge of the interior matrix **K** and corresponding points. Finally, (2) expresses the calculation of 3D coordinates [16].

$$\begin{bmatrix} \mathbf{P}_3 \cdot x_i - \mathbf{P}_1 \\ \mathbf{P}_3 \cdot y_i - \mathbf{P}_2 \\ \mathbf{P'}_3 \cdot x'_i - \mathbf{P'}_1 \\ \mathbf{P'}_3 \cdot y'_i - \mathbf{P'}_2 \end{bmatrix} \cdot \mathbf{X} = 0 \quad (2)$$

where $\mathbf{P}_1$, $\mathbf{P}_2$, $\mathbf{P}_3$ and $\mathbf{P'}_1$, $\mathbf{P'}_2$, $\mathbf{P'}_3$ are rows of the projection matrix **P**, **P'**. The projection matrix is obtained as **P** = [**I** | 0] and **P** = [**R** | T]. Further x_i, y_i, x'_i and y'_i are image coordinates of corresponding points. Vector **X** contains the resulting spatial coordinates of points. The system of equations can be solved with a linear least squares solution [16]. This paper deals especially with localization of corresponding point. Therefore, we do not describe the process of the reconstruction of spatial coordinates in detail, specifying the form of fundamental or projection matrix.

The above described procedure can be used only if we know image coordinates of the reconstructed point in both images. In general it is a very difficult problem to detect image coordinates in both images for an arbitrary point if it lies in an area with regular textures or in "white region" without features and contrast. We have proposed and tested a method based on relation between arbitrary **selected points** (by user) and **feature points** in its neighborhood. The main idea uses a hypothesis that small areas in an image lie in the same depth. In consequence, points from the same area are transformed identically between images. Therefore, when we know the positions of some points in the given area in both images and the position of the selected point in the first image, we can deduce position of the selected point in the second image. In the first stage of research published in article [23], we tested the usability of the basic idea. In this paper, we examine the possibilities of position refinement for the point in the second image.

3. Proposed Method

The main aim of our work is to propose a fast method to obtain spatial coordinates of an arbitrary point in a scene. Our approach is based on statistics and probability. A flowchart of the whole system is shown in Fig. 3. All the algorithms that have been used work with grayscale images. We can divide the system into several separate parts. At first, two images together with the calibration matrix are loaded. The capture positions of images can be in general relation. This means that the sensing cameras can have different viewing angles, different distances from the scene and arbitrary displacement in horizontal and even vertical direction. The only condition is visibility of the same objects. In the usual case of stereo sensing, the situation is simplified by using horizontal displacement only. In this work, we call the input images left and right, although they do not necessarily need to be classic stereo images. Subsequently, the significant points are detected and correspondences are established. In the next step, we use the proposed algorithm to eliminate false correspondences. Then, 3D coordinates of feature points are calculated using a system of equations (2). At this point, we have all the required information to use the proposed method for reconstruction of spatial position of a selected point. Position of the point in the left image is selected. Subsequently, we can use the proposed algorithm to find its position in the right image. Through the knowledge of point positions in both images, we can calculate its spatial position. In some steps open source algorithms have been used. In the following, our suggested approaches are described.

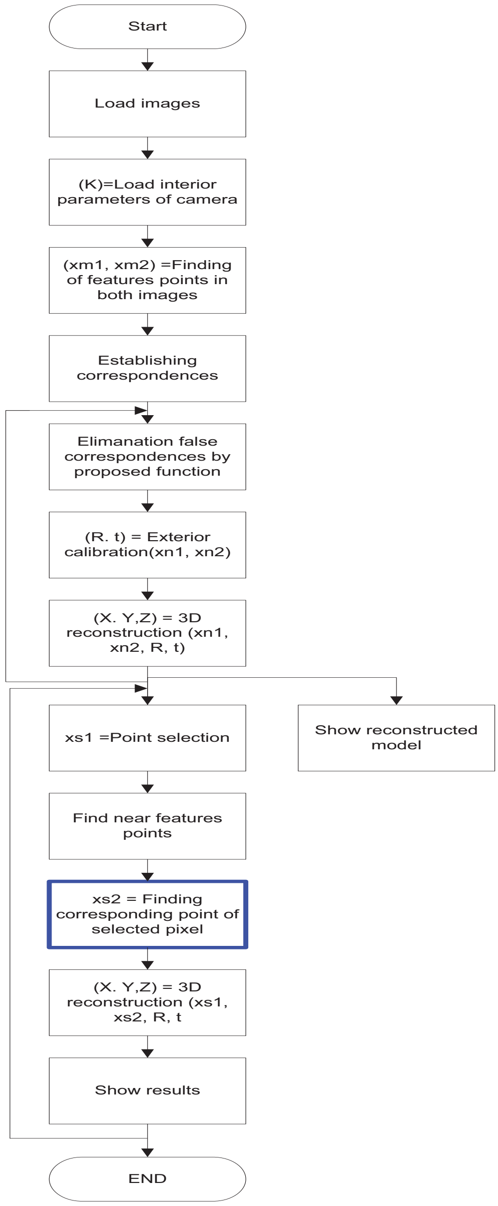


Fig. 3. Flowchart of the designed system for the reconstruction of 3D model.

3.1 False Correspondence Elimination

A common approach based on the use of epipolar geometry and Random Sample Consensus (RANSAC) algorithm [11] is often used. Our method draws on the method published in [10]. We exploit rules which combine constraints for horizontal parallax, extremities in angle and similarity of neighborhoods. At first, we determine angles ß, formed between each straight line connecting the corresponding points and the horizontal axis. Subsequently, we calculate the confidence interval of the angle. There can be a number of different correct angles depending on the position point in space. Consequently, the correspondence points are evaluated as false if the appropriate angle ß does not fall within the specified confidence interval. Further, the correspondence is marked as false even if the horizontal displacement between pixel positions is bigger than the determinate threshold. The threshold is derived from image size and average horizontal movement of a set of corresponding points. Moreover, we use limitation of the color deviation in defined neighborhood, if correspondences are found in pseudo color. First, we calculate the average deviation of reliable correspondences in the true color image. Based on the average deviation, threshold is determined for false correspondences. Subsequently, we calculate the difference between the neighborhoods of corresponding points found in the false colors. The difference is calculated from the values in true color image. If the difference exceeds threshold, then the relevant correspondence is evaluated as false. Due to the use additional constraint, we can detect false correspondences that the original method does not reveal.

3.2 Finding the Position of a Point in the Right Image

The main topic of this paper is the method proposed for spatial coordinate reconstruction of an arbitrary point using its relation with close feature points. This procedure is the most important block in the implemented system (see Fig. 3). The input data for the 3D reconstruction algorithm are the coordinates of the corresponding points in both images. Coordinates of a selected point in the left image are selected by user. The obtained coordinates of the corresponding point in the second image is a difficult task which is commonly executed using different similarity measures (Sum of Absolute Differences - SAD, Sum of Squared Differences - SSD, Ratio Image Uniformity - RUI, Mutual Information - MI). In the case that a point belongs to texture or to coherent area without contrast, the discovered correspondences have low reliability.

In the first part of the procedure, we make a decision whether it is necessary to supplement the set of points with extra points. Decision is made by a trained artificial neural network, whose inputs are the depths of near feature points and their distances from the selected point. In the instance that the point lays in dangerous area (too few correspondences found by SURF), adding extra information is necessary for obtaining accurate results. During the first test, the information has been added using manual determination of auxiliary correspondences. In the next phase of research, we decided to use conversion to pseudo color for finding new correspondences (see Section 3.3).

The proposed procedure to determine coordinates of a point in the second image is described by a flowchart shown in Fig. 4. The method is based on calculation of the position of a selected point in the right image using the known positions of feature points in both images. Therefore, at first, we have to find a set of the feature points. Feature points are found by the algorithm SURF. In the second step, we want to assess the differences in positions of the points found in the right (*SURF_pos_r*) and the left image (*SURF_pos_l)*. Subsequently we use this difference to deduce position of the selected point in the right image. However, we are interested in the difference in positions of points which are spatially close to the selected point only. Therefore, we calculate the Euclidean distances between the position of the selected point and the positions of points found by SURF in the left image. Pursuant Euclidean distance we determine five closest feature points. This quantity of points was determined experimentally. In case that we would use a larger count of points, the risk is increasing that some points belong to another object, in depth different from the selected point. On the contrary, if we use too few points, then we increase the danger of probabilistic error.

In the next step we calculate the potential positions of the selected points in the right image, which forms the input to the last step of the algorithm for determining corresponding points, together with the position in the left input image. Potential position (*Pot_pos*) is calculated using following equation.

$$Pot\_pos = SURF\_pos\_l - SURF\_pos\_r\ . \quad (3)$$

Subsequently we calculate the difference in color of the selected point (in the left image) and of its potential position (in the right image).

$$coldiff = \sqrt{\left(R_{sel} - R_j\right)^2 + \left(G_{sel} - G_j\right)^2 + \left(B_{sel} - B_j\right)^2}\ . \quad (4)$$

We eliminate the points whose difference exceeds a threshold. This rule eliminates all potential pixels whose color is not sufficiently similar to the color of the selected pixel (in the left image). In case that after this operation only one potential position remains in the right image, we decide that just this position is correct and we can calculate the spatial coordinates of this point using (3). If more than one point remains, we continue with next steps to obtain a reliable corresponding point. In the next step we calculate differences between individual potential positions using the following equation.

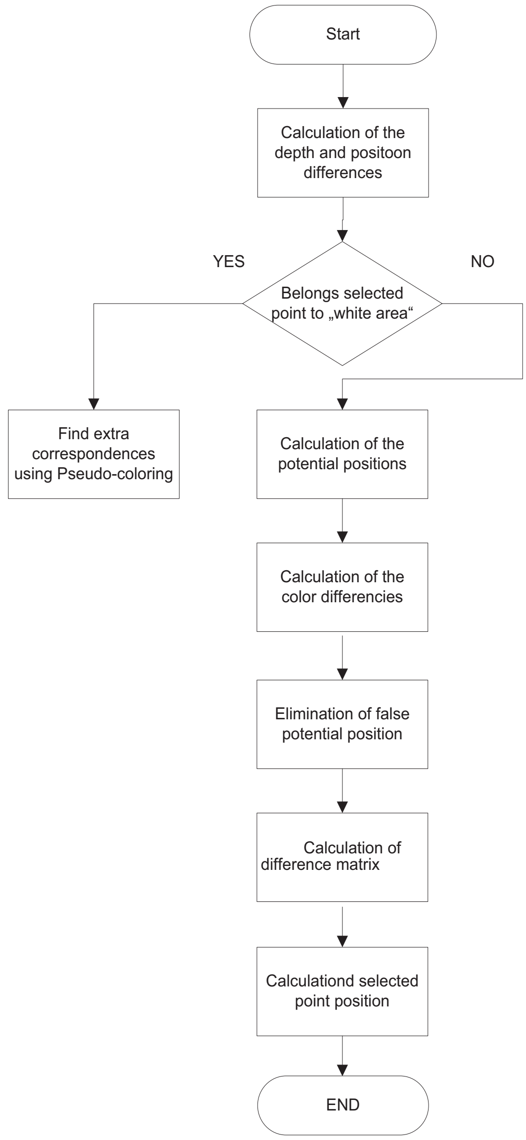


Fig. 4. Flowchart of the proposed algorithm determining the image coordinates for a selected point in the second image.

$$dif(i,j) = \sqrt{\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2} \quad (5)$$

where i, j are indices of potential positions and x, y are image coordinates. Consequently we obtain the Difference Matrix containing differences as

$$\begin{vmatrix} dif(1,1) & dif(1,2) & .. & dif(1,j) \\ dif(2,1) & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots \\ dif(i,1) & \dots & \dots & dif(i,j) \end{vmatrix}. \quad (6)$$

Based on the matrix, we can determine the layout of the points. Depending on the situation, we calculate the final position of the selected point in the right image. Illustrative image in Fig. 5 shows different possible situations. We can define three basic situations:

A) Two points remain: final position is given by the average of their positions;

B) Two close points and one farther point remain: firstly, average position from nearby points is calculated, then weighted average with farther point is calculated (farther point has smaller weight);

C) Two pairs of points remain: firstly, average position from the nearby points is calculated. Then, weighted average from the averaged positions of both pairs of points is calculated. The pair with smaller distance between the points has greater weight.

The mentioned weight is given by the ratio of distances from the selected point. Using the procedure described above, we obtain better results than using simple averaging of possible positions and using simpler rule proposed in [23] (see Section 3 for results). The process of finding corresponding point by using simple averaging is briefly described in the following paragraph.

The first two steps are the same as in the previous procedure. We find a set of corresponding points by SURF and we select five near points using calculation of Euclidian distance. Subsequently, we calculate differences between depths of individual near points and their distances from the selected point. In case that ratio of depths exceeds a chosen threshold, the position of a selected pixel point in the right image is calculated only from two closest points. Influence of each point is given by the ratio of its distance from selected point. Otherwise, the position of the point is obtained by averaging displacements of five nearest points.

3.3 Method Using Pseudo Colored Surveyed Scenes

Pseudo-coloring is a technique for converting gray scale images to false colors (pseudo colors), that do not correspond to the real colors of the scene. This method allows for a significant increase of resolution details in the scene. The main use of false (pseudo) color is for analysis by human viewers, because humans recognize more color levels than grayscale degrees. A pseudo-colored image is described by three color components, as well as true RGB images (with true colors) or HSV. This Section deals with the possibility to use pseudo-coloring for finding corresponding points in areas without contrast. In the previous research, we investigated the possibility of using pseudo color space for image registration [24]. Its drawback is in increased computational complexity.

Different methods for converting image to pseudo coloring were published [19], [20], [21]. We can find a survey some of them in [22]. In this work we use the method proposed in [21], which defines conversion using parametric equation of curve in RGB space. The method can be described by following math equations.

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \frac{1}{2\cdot\sqrt{3}} \begin{pmatrix} 1+\sqrt{3} & 1-\sqrt{3} & 2 \\ 1-\sqrt{3} & 1+\sqrt{3} & 2 \\ -2 & -2 & 2 \end{pmatrix} \cdot \begin{pmatrix} r(t)\cdot\sin(\omega\cdot t+\varphi) \\ r(t)\cdot\cos(\omega\cdot t+\varphi) \\ z(t) \end{pmatrix} \quad (7)$$

where φ defines the initial color (color of pixel with zero brightness) and ω specifies the dynamics of color changes. These parameters are inputs to conversion. Through change of these parameters, we can affect the conversion; hence we can affect the output image. Consequently, we can influence the search of correspondence. Particularly the dynamics of changes ω has a significant impact.

Fig. 6 shows that with pseudo-color, it is possible to find corresponding points in image areas where it was impossible in grayscale image. The search for corresponding points works perfect in pseudo colors when corresponding pixels have exactly the same brightness value in both grayscale images. Such condition is ensured if both images (picture, photograph) have been captured in the same time with the same light conditions and with the same CCD sensor. If this is not the case, a problem appears, because differences in pixel values increase due to the process of pseudo coloring. Here, pixel value is the brightness level in grayscale images and R, G, B components in false color images.

To solve this problem, we use two approaches. First of them is elimination of false correspondences using constraints defined by a reliable correspondence obtained in grayscale image. Elimination is based on the algorithm described above in Section 2.1. We can obtain constraints from the restricted neighborhood of a point. The second approach uses the methods for image enhancement in grayscale for better results. In this method, we transform the scale from one picture to another with the aim to eliminate the difference between the pixel values (brightness) in corresponding pictures before converting them to pseudo color. Therefore these methods may be combined with methods for image enhancement in grayscale for better results.

Practically, in our method we use pseudo coloring only in case we do not have enough information for estimation of corresponding points from the grayscale analysis (by method described above in Section 3.2). In such case we do not have sufficiently close points (found by SURF) for reliable results and we need to add some extra information. Then, we convert only the neighborhood of the selected point. Subsequently, we can find correspondences using SURF in pseudo-color image. Finally, we use the algorithm to estimate the position of the selected point in the right image using the revealed correspondences.

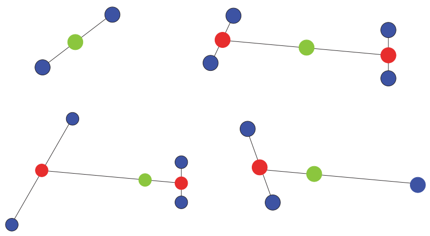


Fig. 5. Possible scatter of points and process calculation of the final position of the point in the right image. Blue marks represent initial positions, red marks represent interim results and green marks represent the final position of point in the right image. Final position is calculated as progressive weighted average of initial positions. Weight is given by distance between points in pairs.

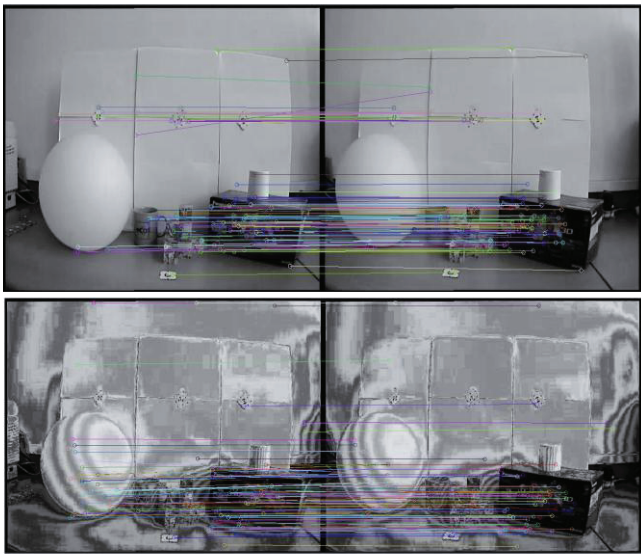


Fig. 6. Finding the correspondence in grayscale (top) and in pseudo-colored image (bottom), displayed as grayscale.

4. Results of Experiment

The system for fast reconstruction of spatial coordinates was designed in MATLAB and tested on a set of images. The set contains images with various properties:

- Varying mutual position of the sensing cameras;
- Varying content of the scene;
- Various cameras.

The calibration matrices have been obtained by a MATLAB toolbox [13] inspired mainly by Zhengyou Zhang [4]. Feature points were found by the SURF algorithm [17]. Various methods were tested, however SURF achieved the best results. We have used the algorithm SURF with these basic parameters: Hessian threshold: 0.0002, number of octaves: 5, length of SURF descriptor: 64. In order to calculate the spatial coordinates

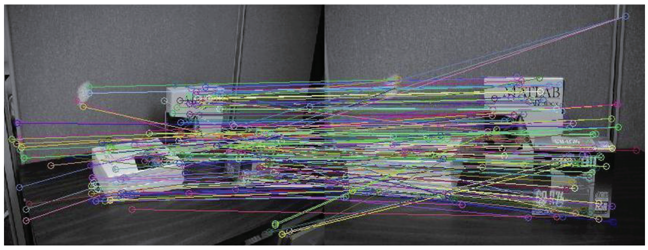


Fig. 7. Image correspondences before use algorithm for elimination false correspondences (picture is taken from [16]).

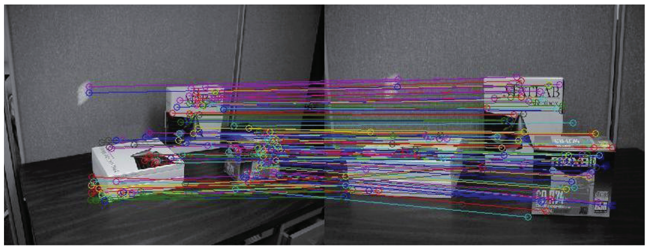


Fig. 8. Image correspondences after use algorithm for elimination false correspondences (picture is taken from [16]).

of feature points, triangulation. We proposed a modification in elimination of false correspondence. Fig. 7 shows the initial correspondents. Obviously, some of the correspondents are false. Fig. 8 shows correspondents after application of the proposed method for elimination of false correspondents. The improvement is evident.

Further, we have tested a novel approach for finding a point corresponding to the selected point. Fig. 9 and Fig. 10 show the results of using the proposed method to find the point position in the right image. For clarity, figures show only a part of the scene with neighborhood ofthe selected point. The first figure represents a simple situation when the closed feature points have similar depths. Obviously, in this case, the position of the point is found correctly (Fig. 9). As a consequence, reconstruction is executed correctly as well (see Fig. 12a). In the second case, the selected point belongs to the dangerous area. This means that close feature points have significantly different depths or are distant from the selected point. Fig. 10b shows that even in this situation, we have obtained better results if an improvement of the basic idea described in Section 3.2 was used. We have proved that we can reach additional improvement if pseudo coloring is used. The tests confirmed that the SURF algorithm finds feature points with reliable correspondences even in areas where they could not be found in true colors (see Fig. 6).

The resulting reconstructions are shown in Fig. 12 for scenes in Fig. 11. Due to the limited extent of the paper, we present just a limited number of figures with results (see Fig. 12). For clarity and lucidity, accurate manual correspondences were established, which are used for modeling of objects in the scene (blue objects in Fig. 12).

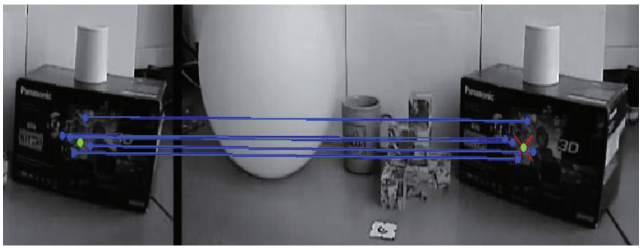


Fig. 9. Finding the position of selected point in the second image using the proposed method (simple situation). Blue marks represent the nearby salient points. Red marks represent possible positions of the selected point in the second image. Green marks represent positions of the selected point in both images.

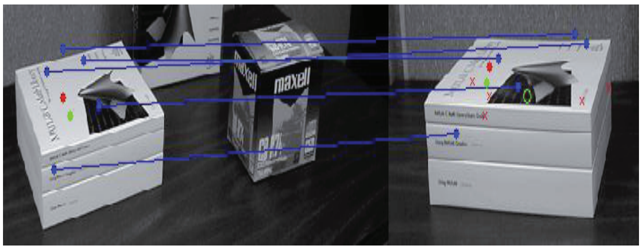


Fig. 10. Finding the position of selected point in the second image using the proposed method (simple situation). Blue marks represent the nearby salient points. Red crosses represent possible positions of the selected point in the second image. Red dots represent extra points. Green marks represent positions of selected points in both images.

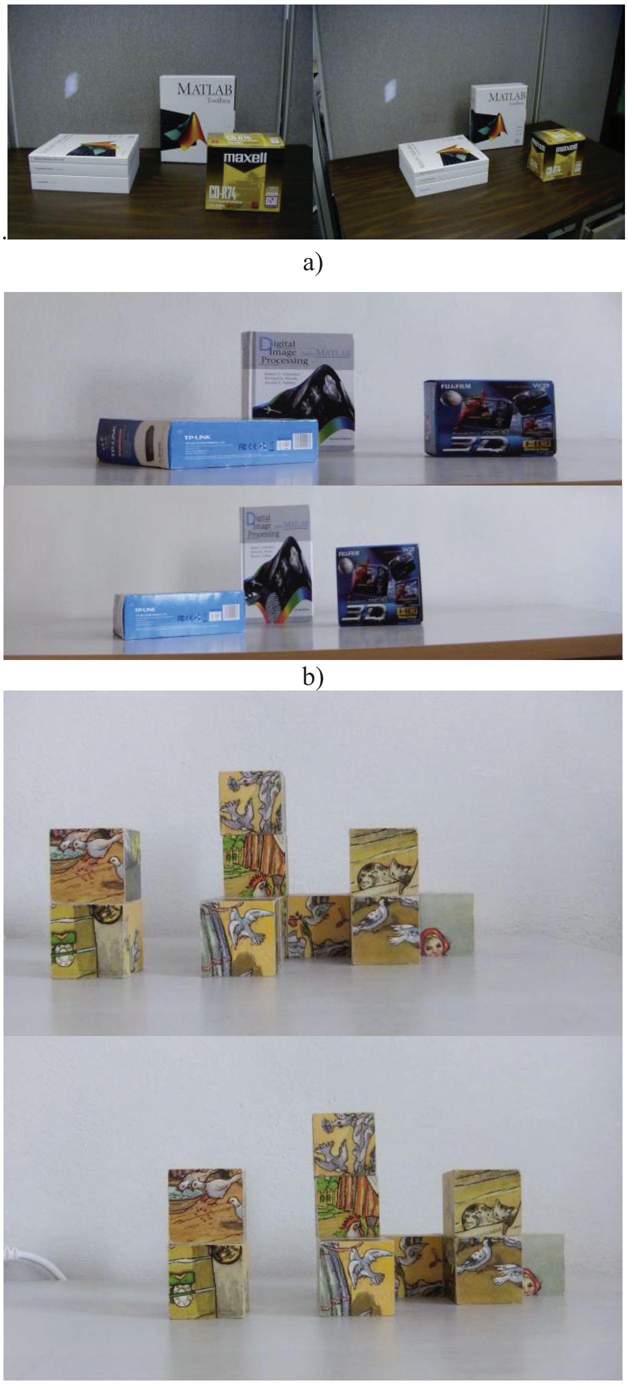
These correspondences have no function in the proposed algorithms and serve only for graphical representation of results.

For the purpose of quantitative expression of the results, we performed calculation of spatial coordinates of several points. The required correspondences of points were obtained by four different methods: averaging from five near points (Five Points Method), averaging from two near points (Two Points Method), proposed method described in detail in Section 2.2 – Elimination Ratio Method(ER) and SAD as a representative of regularly used local methods. Besides that, we determined the true spatial positions of points. Subsequently, we calculated the differences between the computed positions and the true spatial positions as Euclidian distances.

$$differ = \sqrt{\left(X_{true} - X\right)^2 + \left(Y_{true} - Y\right)^2 + \left(Z_{true} - Z\right)^2}\ . \tag{9}$$

We executed this test for two images. The results are summarized in Tab. 1. From the results, it is obvious that the use of the proposed method is advantageous. On the other hand, it is necessary to mention that SAD method works well in case of points with relatively significant surroundings.

The test was executed on PC with processor Intel Core 2 Duo 2 GHz and 2 GB RAM memory. The method contribution is particularly its speed, due to the fact that we do not examine certain vicinity of image for each selected



a)

b)

c)

Fig. 11.Tested scenes used in test. a) MATLAB scene obtained from web [16]. b) Boxes scene by camera FinePix REAL 3D W1. c) Cubes obtained by camera FinePix REAL 3D W1.

Method	differences	
	boxes	cubes
Five Points Method	0.4619	0.6260
Two Points Method	0.5451	0.6677
ER method	0.1941	0.6752
SAD	1.4341	134.2489

Tab. 1. Summary of differences in the computed spatial positions.

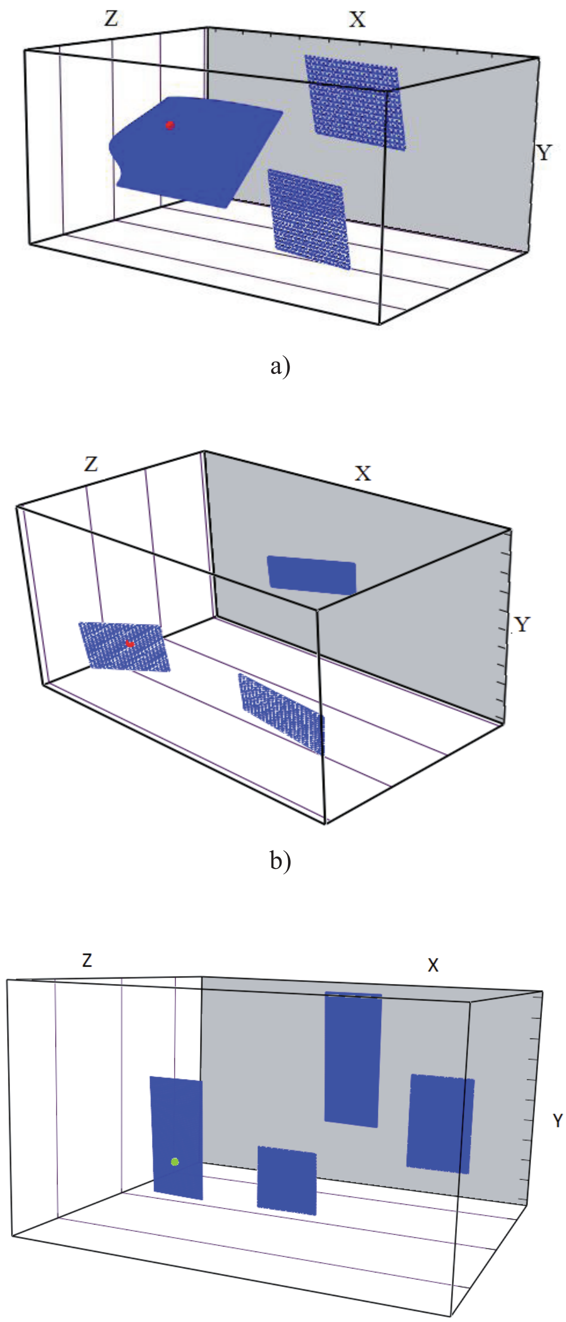


Fig. 12. Resulting reconstruction position of selected points. Color marks represent locations of selected points in space. Blue objects are pictured only for clarity. Model of a) MATLAB scene b) Boxes scene c) Cubes scene.

point. Algorithm for determination of pixel position in second image, which is the core of the proposed method, is performed in around 7 milliseconds. The proposed algorithm is faster than search using SAD (or similar metrics). In case that the position of the pixels differs only in the column, the execution time is approximately the same as for SAD with these properties: window size: 9, range of parallax: 120 pixels. However, time demand of SAD will largely increase when we search in a larger neighborhood or use a larger window. For example, in case we need to search in a large range of horizontal parallax (from 0 to 600 pixels) and take into consideration even the vertical parallax, because images are in general positions (for example in range 100 pixels), then the computation time of SAD is approximately 5 s.

5. Conclusion

We have proved the usability of the proposed method estimating the position of selected (by user) point in right image, based on relationship with correspondences found by SURF. In the first tests, we confirmed that for more reliable results, it is often required to add extra information to a certain area with lack of suitable cor-responding points (for example area with rapid change of depth). We mentioned that this information can be added in the form of targets in the scene or as manually added correspondences during image processing.

In connection with these findings, we propose using a conversion to pseudo colors. This conversion brings an increase of contrast and in consequence a possibility of finding new correspondences. The performed tests confirm that this approach is usable. However, a problem with false correspondences is raised. This problem can be solved using transform of grayscale before the conversion and elimination of false correspondences through a set of reliable correspondences. Obviously, use of pseudo color for this purpose is entirely new. Use of pseudo color allows for creation of denser network of corresponding points, which is helpful for reconstruction of spatial coordinates and for creation of quality depth map. We are aware of no other work using pseudo colors for these purposes, therefore there are no comparable results.

Moreover, we proposed an improvement of the algorithm for estimation of the selected point position in the right image. Adjustment of the algorithm allows for more reliable and more precise results. Improvement is based on the assumption that not all feature points around the selected points belong to the same depth and we need to identify them and utilize this information in the right way. The Difference Matrix and calculation of color differences ensure this request.

Limitation of false correspondences is an important task too, therefore setting the right correspondences allows for finding the correct exterior calibration and sub-sequently precise reconstruction. Our approach provides fast and reliable results.

Most methods deal with finding correspondences in significant points. They not solve finding correspondence for a concrete point selected by the user. Therefore direct comparison is impossible. We compared our method with some methods based on similarity measures such as SAD, SSD and so on. Comparison with SAD is summarized in Tab. 1.

Acknowledgements

This work was supported by the grant projects of the Czech Science Foundation no. 102/10/1320, MEYS of the Czech Republic no. LD12005 and no. CZ.1.07/2.3.00/20.0007 and finally by the BUT project no. FEKT-S-11-12. The described research was performed in laboratories supported by the SIX project; no. CZ.1.05/2.1.00/03.0072, the operational program Research and Development for Innovation.

References

[1] LIANG, Y., TAM, W. J. Stereoscopic image generation based on depth images for 3D TV. *IEEE Transactions on Broadcasting*, 2005, vol.51, no.2, p. 191 – 199.

[2] KAMENCAY, P., BREZNAN, M., JARINA, R., LUKAC, P. Depth map computation using hybrid segmentation algorithm. In *34th International Conference on Telecommunications and Signal Processing (TSP)*. Budapest (Hungary), 2011, p. 584 - 588.

[3] GRUEN, A., HUANG, T. S. (Eds.) *Calibration and Orientation of Cameras in Computer Vision*. Berlin (Germany): Springer, 2001.

[4] ZHANG, Z. Flexible camera calibration by viewing a plane from unknown orientations. In *The Proceedings of the Seventh IEEE International Conference on Computer Vision.* Kerkyra (Greece), 1999, p. 666 - 673.

[5] MENDONCA, P. R. S., CIPOLLA, R. A simple technique for self-calibration. In *IEEE Computer Society Conference on Computer Vision and Pattern Recognition.* Ft. Collins (CO, USA), 1999.

[6] TUYTELAARS, T., MIKOLAJCZYK, K. Local invariant feature detectors: a survey. *Foundations and Trends in Computer Graphics and Vision*, 2008, vol. 3, no. 3, p. 177 - 280.

[7] STEFFEN, G., HOLLERER, T., TURK, M. Evaluation of interest point detectors and feature descriptors for visual tracking. *International Journal of Computer Vision*, 2011, vol. 94, no. 3, p. 335 - 360.

[8] KALIA, R., KEUN-DONG, L. SAMIR, B. V. R., SUNG-KWAN, J., WEON-GEUN, O. An analysis of the effect of different image preprocessing techniques on the performance of SURF: Speeded up robust features. In *17th Korea-Japan Joint Workshop on Frontiers of Computer Vision (FCV)*. Ulsan (Korea), 2011.

[9] BAY, H., TUYTELAARS, T., GOOL, L. V. SURF: Speeded up robust features. In *Proceedings of the 9th European Conference on Computer Vision*. Graz (Austria), 2006, p. 404 - 417.

[10] CHUAN, L., JINJIN, Z., CHUANGYIN, D., HONGJUN, Z. A. Method of 3D reconstruction from image sequence. In *2nd International Congress on Image and Signal Processing (CISP).* Tianjin (China), 2009., p. 1 - 5.

[11] FISCHER, M. A., BOLLES, R. C. Random sample consensus: A paradigm for model fitting with applications to image analysis and automated cartography. *Communication of the ACM*, 1981, vol. 24, no. 6, p. 381 - 395.

[12] LOWE, D. Distinctive image features from scale-invariant keypoints. *International Journal of Computer Vision*, 2004, vol. 60, no. 2, p. 91 - 110.

[13] BOUGUET, J.-Y. *Camera Calibration Toolbox for Matlab,* open source software. [Online] Cited 2010-07-09. Available at: http://www.vision.caltech.edu/bouguetj/calib_doc/.

[14] MIKHAIL, E. M., BETHEL J. S., MCGLONE, J. CH. *Introduction to Modern Photogrammetry*. New York: Wiley, 2001.

[15] KRAUS, K. *Photogrammetry: Geometry from Images and Laser Scans,* 2nd ed. Berlin: Walter de Gruyter, 2007.

[16] MA, Y., SOATTO, S., KOSECKA, J., SASTRY, S. S. *An Invitation to 3-D Vision: From Images to Geometric Models*. New York: Springer, 2004.

[17] KROON, D.-J. *OpenSURF,* open source software. [Online] Cited 2010-09-06. Available at: http://www.mathworks.com/ matlabcentral/fileexchange/28300-opensurf-including-image-warp

[18] STANČÍK, P. *Optoelectronic and Photogrammetric Measurement Systems*, Ph.D. thesis. Brno (Czech Republic): Brno University of Technology, 2008. In Czech.

[19] YOUVAN, D. *Pseudocolor in Pure and Applied Mathematics: A Free on-Line e-Book with Source Code.* [Online] Cited 2011-04-18. Available at: http://www.youvan.com/ .

[20] LU, X-J., DING, M-X., WANG, Y-K. *A New Pseudocolor Transform for Fibre Masses Inspection of Industrial Images.* [Online] Cited 2011-4-11. Available at: http://www.aas.net.cn/ qikan/manage/wenzhang/2007-1284.pdf .

[21] LEHMAN, T., KASER, A., REPGES, R. A Simple Parametric Equation for Pseudocoloring Grey Scale Images Keeping Their Original Brightness Progression. [Online]. Cited 20011-4-11. Available at: http://ganymed.imib .

[22] BOLEČEK, L. *Displaying Grayscale Images in False Colors*, diploma thesis. Brno (Czech Republic): Brno University of Technology, 2009.

[23] BOLEČEK, L., ŘÍČNÝ, V., SLANINA, M. Fast method for reconstruction of 3D coordinates. In *35th International Conference on Telecommunications and Signal Processing*. Prague(Czech Republic), 2012, p. 740 - 744.

[24] FANG-HSUAN, C., TZU-HAO, K., YEA-SHUAN, H. Fast depth estimation method from a pair of retified images. In *Eighth International Conference on Intelligent Information Hiding and Multimedia Signal Processing (IIH-MSP)*. Piraeus-Athens (Greece), 2012, p. 375 - 378.

[25] MOALLEM, P., FAEZ, K. Search space reduction in the edge based stereo matching by context of disparity gradient limit. In *Proceedings of the 2nd International Symposium on Image and Signal Processing and Analysis (ISPA)*. Pula (Croatia), 2001, p. 164 - 169.

[26] FOURIE, J., GREEN, R., MILLS, S. Directed correspondence search: Finding feature correspondences in images using the Harmony Search algorithm. In *24th International Conference Image and Vision Computing (IVCNZ)*. Wellington (New Zealand), 2009, p. 102 - 107.

[27] GONG-JIAN, W., JIN-JIAN, L., WEN-XIAN, Y. A high-performance feature-matching method for image registration by combining spatial and similarity information. *IEEE Transactions on Geoscience and Remote Sensing*, 2008, vol. 46, no. 4, p. 1266 - 1277.

[28] MACIEL, J., COSTEIRA, J. P. A global solution to sparse correspondence problems. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 2003, vol. 25, no. 2, p. 187 - 199.

About Authors…

Libor BOLEČEK was born in Šternberk, Czech Republic in April 1985. He graduated from the Faculty of Electrical Engineering and Communication (FEEC), Brno University of Technology (BUT), in 2010. The field of his interest includes image processing, quality evaluation and photo-stereometric systems.

Václav ŘÍČNÝ was born in 1937. He is emeritus professsor at the Faculty of Electrical Engineering and Communication, Brno University of Technology. His research interest includes, in particular, video and television technology, analog and digital signal processing and measurement.

Martin SLANINA was born in 1982. He received the Master's degree in 2005 and the Ph.D. degree in 2009, both in Electronics and Communication from the Brno University of Technology (BUT), Czech Republic. Currently he is an assistant professor at the Department of Radio Electronic, BUT. His research interests are in no reference video quality metric design, subjective video quality methodologies and video technology. He serves as a GOLD AG chair in the IEEE Czechoslovakia Section.