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DEPARTMENT OF RADIOCOMMUNICATION

SELECTED PROBLEMS IN PHOTOGRAMMETRIC SYSTEMS ANALYSIS

VÝBRANÉ PROBLÉMY ANALÝZY FOTOGRAMMETRICKÝCH SYSTÉMŮ

ZKRÁCENÁ VERZE DIZERTAČNÍ PRÁCE
SHORT VERSION OF DOCTORAL THESIS

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1 INTRODUCTION

1.1 Problem formulation

Photogrammetry is a scientific discipline which deals with reconstructing three-dimensional objects from two-dimensional photographs. Photogrammetry allows the reconstruction of an object and analysis of its characteristics without physical contact with them [1]. This work deals with multiple frame photogrammetry allowing to determine three spatial coordinates. Designation stereogrammetry is used in the situation when two cameras with parallel optical axes are used and their spatial positions differ only in horizontal direction. The first use of analog photogrammetry is dated approximately to the second half of the 19th century. The input to photogrammetry are two or more photo images acquired by a camera system. All principles discovered and described during the origin of this method are still in force. The new age of photogrammetry began after the coming of digital photography. Digital photogrammetry uses a digital camera to obtain an image of the scene. Subsequently, a personal PC is used for data processing. In recent years, digital photogrammetry and stereophotogrammetry have become a dynamicly developing scientific area. This fact relates with rapid expansion of 3D technology. We can observe the development of new sensing and displaying systems. This development was influenced by increasing performance of computers. The performance of current PCs allows to execute computationally difficult operations. Due to this fact, many operations can be executed even in real time.Image processing is used in every step of obtaining information about spatial coordinates. Finding corresponding points is a crucial method used during proper reconstruction.

Reconstructing spatial coordinates and obtaining depth maps is a problem, which have wide applications in many areas. The depth of a point can be represented in two various ways. The first way is creating a model with discrete points $P(X, Y, Z)$. The second way is an expression using a depth map. The depth map is an image with the same size as the input image. The value of the individual pixel of the depth map is given by the relative depth of the scene, where depth means the distance of the point from the camera.

Civil and mechanical engineering industries are typical representatives of the fields which use a 3D model of the scene. Other disciplines using spatial reconstruction are for example medicine, robotics, reconstruction of traffic accidents and the entertainment industry. Nowadays, 3D TV is becoming more popular and more used. The first standards about 3D TV have already been formed.

The basis of stereoscopic displays is using two images of the same scene. These images are called stereo images (left and right). Each eye sees a slightly different image of the same scene. The images are shifted in a horizontal direction. The resulting spatial image is formed in the brain. The depth map plays an important role during the creation of stereo images and transmission of the data for 3D imaging. The quality of the depth map is of fundamental importance for spatial perception.

The main topic and aim of my dissertation is obtaining information of spatial coordinates by using two digital images. The dissertation deals with both representation of spatial information (depth map and spatial coordinates). The first section deals with metric reconstruction of the spatial model and it contains a proposal of the new approach for finding corresponding points in the images. Another part of the dissertation also analyses the impact of various aspects on the precision of the reconstruction. The dissertation also deals with the estimation of depth maps. The last part of the dissertation deals with the quality of experience in 3D video.

1.2 Aim of the work

The aims of my dissertation were established after studying scientific literature and analyses of the state of the art. Notwithstanding many detectors of the significant points and algorithms for finding corresponding points, there are issues which need to be solved. The analyzing of the precision of the executing reconstruction logically follows the study and research in this area. Estimating the depth map and evaluating the spatial effect of the watcher is a very perspective area at this time of dynamic development of commercial 3D imaging. The solution of described issues can be summarized to the following aims:

1. Proposal of novel fast methods for matching points in images. The proposal will be supported by an analysis of the currently used methods. Software implementation of the proposed methods to the system for determining spatial coordinates of the points in the scene.
2. Analysis of the achievable accuracy of determining spatial coordinates in the 3D model of the scene. The quantification of the aspects affecting accuracy (especially the aspects related with parameters of the sensing system and its calibration).
3. Proposal of the system (algorithm) for estimating the depth map from the two images of the scene.
4. The realization and evaluation of the subjective tests of the spatial effect and quality in a 3D TV. The examination of the dependency of spatial perception on the various parameters: sensing parameters, content of the sequence, viewing conditions during reproduction on TV displays using various 3D systems.

2 3D METRIC RECONSTRUCTION

The spatial metric reconstruction of the spatial model of an analyzed scene using photogrammetry (location of the spatial coordinates) is the central topic of my dissertation. The fundamental ideas of photogrammetry are described for example in books [1]. The fundamental task in this reconstruction is finding corresponding points in both input images of the analyzed scene. Finding corresponding points is a great problem especially in automatic and semi-automatic systems. A high quality solution of this problem is very difficult especially in an image area with regular texture or small brightness variation.

The chapter 2.1 contains comparison of the some methods frequently used for finding corresponding points. Two novel approaches for finding corresponding points are proposed in this chapter. The first proposed method is based on the presumption that if the depth of few points in the neighborhood of the selected point is known, then position of the corresponding point can be found. This method is primary designed to reconstruction of individual points selected by user. The using of the conversion gray scale images to the pseudo-colors is next new proposed approach to the problem of the finding corresponding point.

2.1 Comparison of commonly used methods for finding corresponding points

The finding corresponding points can be divided into two steps. Firstly, we need to find significant points in both images. Subsequently, we have to determine which points represent the same point in the scene (matching). Finding significant points is executed by detectors. A significant point is a point which can be found repeatedly. The most frequently used methods were tested. The investigation of the influence of the objective parameters of the image on the finding corresponding points was aim of the experiment.

2.1.1 Experiment and results

In the test, images from the Middlebury stereo dataset were used [2]. The database contains true depth map of the images. The true depth maps are important in evaluating the correctness of the determined correspondences. The images even depth maps have resolution 1310 x 1112. The calculation of the objective parameters of the image was included in the test. We investigated the impact of the following properties of the image to the correctness of the correspondences: Structural Similarity Index Measure (SSIM)[3], spatial Activity (SA), frequency Activity (FA), correlation coefficient(CC),standard Deviation (SD), EDGE, local Entropy (LE), local Range (LR), contrast (CO). The process of the test can be described by the following steps

1. Assignment of the set of corresponding points and calculation of the horizontal disparity for each pair of corresponding points.
2. Comparison of the horizontal disparity with the value of the appropriate pixel in the true disparity map and calculation of the reliability.
3. Calculation of the objective parameters of the images.
4. Final evaluation of the obtained data.

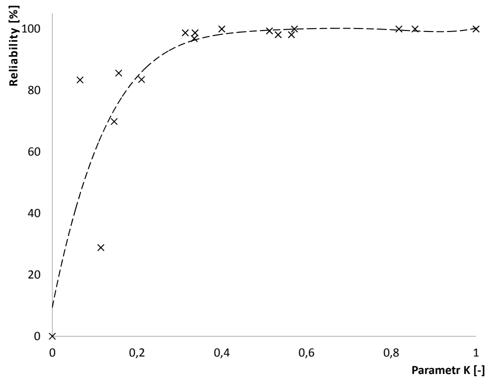
The main aim is mutual comparison of algorithms. The average reliability was calculated. Obviously, SIFT provided the best results. The average reliability and standard deviations are in Tab. 2.1. We reveal that reliability is dependent on selected parameters. However, the dependency on the individual parameters is weak. The level of the significance was improved by combining relevant parameters. We designed the parameter K_r which is given by the following relation

$$K_r = \frac{\mathrm{SA} \cdot \mathrm{LE} \cdot \mathrm{Edge}^{0.25}}{\mathrm{FA} \cdot \mathrm{LR}}. \tag{2.1}$$

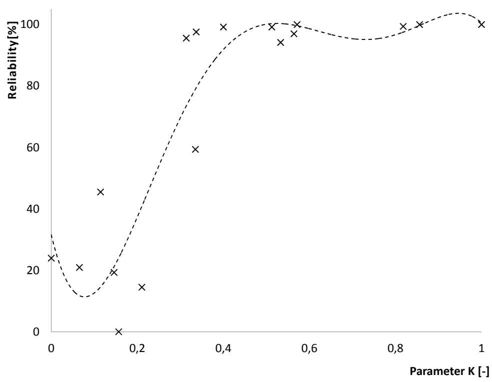
This relation was obtained experimentally. Parameter K_r serves to describe the images. We can estimate the probability of good reliability of finding corresponding points. When the value of K_r increases, then the probability of good reliability also increases. This fact is obvious from Fig.2.1.1, where parameter K is on the horizontal axis and the reliability of finding corresponding points is on the vertical axis. Parameter K_r is normalized to a range from 0 to 1 for a better illustrative nature.

Method	**HARRIS**	**SURF**	**SIFT**
Average reliability [%]	80.72	82.80	97.43
Standard deviation [%]	12.57	18.18	4.11

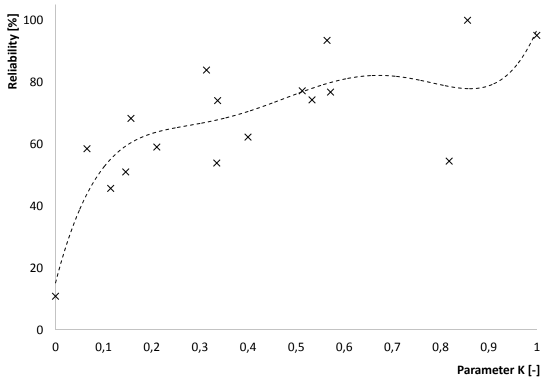
Table 2.1: Comparison of reliability of finding corresponding points by commonly used methods SURF, SIFT, Harris detector for the used set of images [2].



a)



b)



c)

Figure 2.1: The dependency of the reliability of finding corresponding points on the parameter K_r for individual images from the used database by a) SIFT, b) SURF, c) HARRIS .

2.2 Proposed new method for correspondence of the selected point

Finding the corresponding point $p_{2,sel}\,(x_{2,sel}, y_{2,sel})$ in the right (second) image I_2 for selected point $p_{1,sel}\,(x_{1,sel}, y_{1,sel})$ in the left (first) image I_1 presents the main actual problem.

The basic principle of the method is using the following hypothesis.**If selected point P_{sel} is located in image area $A_i m$, which has certain depth $depth_{A_{im}}$, then there exist a high probability that point P_{sel} has equal depth $depth_{P_{sel}}$ $=depth_{A_{im}}$** . We will specify this fundamental assumption consecutively. **If we reliably know the depth of a few points in the selected point P_{sel} neighborhood, then we can determine the depth of the selected point with certain reliability**.

The flowchart of the algorithm is shown in Fig. 2.2. The inputs are image coordinates of the selected point $x_{1,sel}, y_{1,sel}$ in the left image. In the first step, the significant points $p_{1,SURF}$ are found by algorithm SURF in a restricted neighborhood of the selected point in left image and their corresponding point $p_{2,SURF}$ in right image are determined.

In the instance that the point lays in a dangerous area (too few correspondences found by SURF), adding extra information is necessary for obtaining accurate results. In the case that a point does not belong to a danger area, then the algorithm continues by calculating of the potential positions of the selected point in the right image. The calculation of the potential positions is based on the knowledge of M_{SURF} and the position of the selected point in the left image $x_{1,sel}, y_{1,sel}$. The movement M_{SURF} represents the change of the position of the significant points between left and right images. Then, potential positions $p_{2,potential}(x_{2,potential}, y_{2,potential})$ are calculated by using following equation

$$p_{2,potential}(x_{2,potential}, y_{2,potential}) = p_{1,sel}\,(x_{1,sel}, y_{1,sel}) - M_{SURF}. \qquad (2.2)$$

The aim of following step is identifying of the unreal (wrong) potential position. This procedure eliminates all potential pixels whose color is not sufficiently similar to the color of the selected pixel (in the left image). In case that only one potential position remains in the right image after this operation. We determined that just this position is correct and we can calculate the spatial coordinates of the selected point. If more than one point remains, we continue with the next steps to obtain a reliable corresponding point. The rule based on the weighted averaging is subsequently used. We can obtain better results than using simple averaging of possible positions. Used procedures are detailed described in [24].

2.2.1 Experiments and results

The experimental verification of the the proposed algorithm was executed by using application (system) described in chapter 2.4. Finding the corresponding point was executing in the 6 six different images during the test. The three parameters of selected point's neighborhood 3x3 was calculated: entropy, correlation and standard deviation. Subsequently, we evaluated the influence of the objective properties on the results. The obtained results were compared with results obtained using the method SAD (sum of absolute differences). The obtained results are assessed by the divergence from the positions determined accurately by the operator. The strongest impact on the results has standard deviation. Accuracy is directly proportional to standard deviation. The influence is less significant for our proposed methods. The dependency is plotted in Fig. 2.3. The results of the experiment confirm our assumptions and feasibility of the proposed method. Obviously, the common method failed when the neighborhood of the selected points is dull and featureless (small standard deviation). The proposed method allows to obtain better results in this situation. The average euclidian distance from the true positions is for our proposed method 4.69 pixels whereas for method SAD is 32.99 pixels.

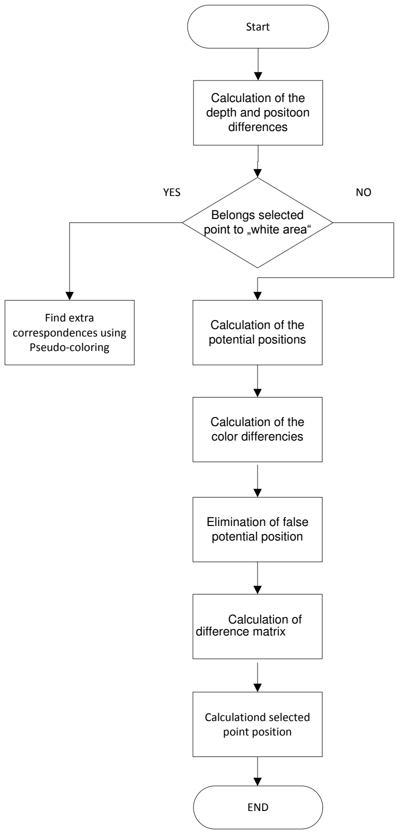


Figure 2.2: The flowchart of the proposed system for finding corresponding point for selected point.

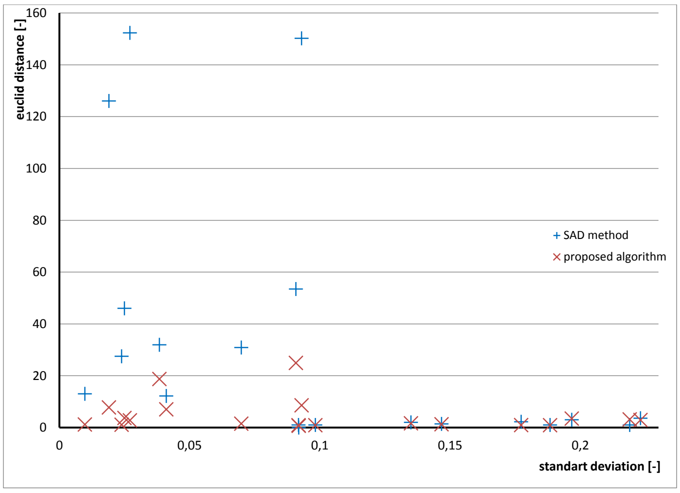


Figure 2.3: Dependency of the accuracy (represented by euclidean distance from the accurate results) of finding corresponding points on the standard deviation.

2.3 Utilizing the image in pseudo-color

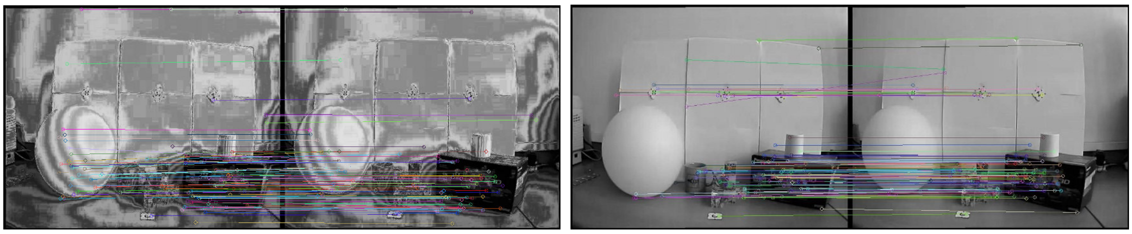
Finding correspondences by the commonly used method based on similarity is problematic in areas with regular texture or with monotone brightness. This problem can be partly solved by the method proposed in chapter 2.2. Another possibility is making an effort to increase the contrast in problematic areas without correspondences. The use of pseudo colors is one of the ways to perform this.

Pseudo-coloring is a technique for converting gray scale images to false colors (pseudo colors), that do not correspond to real colors of the scene. This method allows a significant increase of contrast in the scene. A pseudo-colored image is described by three color components. The process of pseudo coloring combines increasing space dimension and scale transformation. The parameters of the conversion can be adjusted based on this analysis. The disadvantage is the increase of computational complexity caused by multidimensional space. We implemented two various methods for conversion in our experiment. The first used method defines conversion using parametric equation of curve in RGB space [4] (further called Color Curve (CC)). The second method is based on the conversion to color space HSV [5].

Subsequently, we need to investigate applicability of the idea in various scenarios with various level of the reality. Fig. 2.3 shows that with pseudo-color imaging, it is possible to find corresponding points in image areas where it was impossible in grayscale image (see Fig. 2.3). The search for corresponding points works perfectly in pseudo colors when corresponding pixels have exactly the same brightness value in both gray scale images. Such a condition is ensured if both partial images (picture, photograph) have been captured at the same time with the same light conditions and with the same CCD sensor. Otherwise, a problem appears, because differences in pixel values increase due to the process of pseudo coloring. Two approaches can be used for solving this problem.

The first approach is eliminating false (wrong) correspondences using some restrictions which are deduced from reliable correspondences found in a monochromatic image. The proposed algorithm for elimination was created as an extension of the algorithm published in [6]. The rules combine the restrictions of the horizontal parallax, extreme in the angles of the line connecting corresponding points and similarity of the neighborhood of the examined image point.

The second approach uses 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 the corresponding pictures before converting them to pseudo color. A suitable transformation can be deduced from the relation of the brightness value of the corresponding points found in the gray scale image.



a) b)

Figure 2.4: a) The correspondences found in the pseudo-color image (shown in gray scale for better clarity). b) The correspondences found in the monochromatic image.

2.3.1 Results

The greatest advantage of conversion to pseudo color is finding corresponding points in areas where it is impossible to find them in a gray scale image. Few correspondences (less than in pseudo colors with a higher threshold) in gray scale were found only after extremely decreasing the decided threshold (from 1000 to 50). This decreasing of the threshold decreases the reliability of the correspondences too. Increasing the reliability is possible by the approach described above. The procedure of the tests was the following: converting images to the pseudo- color, finding corresponding points in various image representations, calculating of the parallax, comparing parallax with disparities of the particular pixel true depth map. The test was executed with nineteen images from the Middbury Stereo Database [2]. The resolution of the images is 1110x1350. The results are summarized in Tab 2.2. Conversion to pseudo color by various methods and with various parameters was used in the experiments. The average reliability of the correct correspondences found in pseudo color is comparable with the reliability of finding correspondences in grayscale. The best results (reliability 91.37%) were reached when correspondences were found in the grayscale image obtained by the sum of individual component of pseudocolored images.

Representation	**Method**	**Parameter**	**Reliability [%]**
Gray scale	origin	-	84.53
Pseudo Color	Color curve	$\omega = 5°$, $\phi = 5°$	79.33
Pseudo Color	Color curve	$\omega = 15°$, $\phi = 5°$	86.14
Pseudo Color	Color curve	$\omega = 30°$, $\phi = 5°$	84.61
Pseudo Color	based on HSV	k=1.4	80.48
Pseudo Color	based on HSV	k= 14	85.83
Gray scale	sumed based on HSV	k=4	91.37

Table 2.2: Average reliability of finding corresponding points in various representations of an image in a set of images from database [2].

2.4 Designed software: Implementation of the proposed approach

In previous chapters were described the proposed methods for finding corresponding points in two images of the same scene captured by cameras located in the various location. In another section, we investigate achievable precision of the reconstruction and a method for estimating the depth map. Designing an application was suitable. The application served for research. However, a graphical user- friendly interface was designed, therefore the application can be used for practical purposes or as an educational tool. The advantage of the application is the possibility of selecting from more methods in the most offered procedure. In the application, some known approaches and open source solutions are used, besides the proposed methods. The application allows the following procedures: finding corresponding points, image rectification, interior and exterior calibration of the camera, calculation spatial coordinates of the select point, reconstruction of the spatial model of the scene, generation depth map of the scene from two or more image.

3 ACCURACY OF THE METRIC RECONSTRUCTION ANALYZE

Various aspects affecting precision of the reconstruction are discussed in this chapter. The theoretical part was supported by executed experiments. We have to distinguish between two various situations. In normal situations, the calculation of space coordinates is executed using basic photostereogrammetry equations [1]. In the general case, the procedure based on the camera calibration and finding corresponding points is used. The errors of the spatial coordinates are different in these two situations due to various mechanisms of the calculation. Therefore, these situations will be solved separately. Incorrect determination of corresponding points position is investigated in section 3.1. The section 3.2 deals with the incorrect camera alignment (calibration).

3.1 The influence of correspondence error

Some error always occurs even if accurate camera calibration is assumed. The error is caused by small errors in determining corresponding points. Firstly, the stereo case is briefly described. The equations for error of spatial coordinates assuming correctly determined focal length and stereo base are deduced from basic photostereogrammetry equations in [1]. The resulting error also depends on, besides error in correspondences, the two ratios $\frac{Z}{f_c}$ and $\frac{Z}{B}$. Consequently, the errors increase with increasing depth Z of the point.

The error in the general case is a more complex problem. Therefore, the estimation of the error is obtained directly by calculating the error in a particular situation. The images from database [7] were used. The calibration matrix $\mathbf{K}$, rotation matrix $\mathbf{R}$, translation vector $\mathbf{T}$ and correct spatial positions of the 2675 corresponding image pairs are known. The analysis of the precision of the reconstruction was executed for three various camera alignments. The errors increase with increasing depth. This fact is consistent with the situation in the stereo case parallel optical axes. However, the curve of the dependencies is not constantly increasing, because the error depends on more conditions. The full version of dissertation contains figures with dependencies and more detailed analysis this problem.

3.2 The influence of inaccurate cameras alignment

The precision of the reconstruction depends on the geometry of the cameras, especially on the correctness of its determination. The geometry is determined by the exterior calibration of the cameras. The calibration can be wrong and then the angles represent error in the calibration. The influence of the error of camera rotation represented by error angles α, β and γ are executed in this work. The situation is shown in Fig. 3.1. There are two various practical situations which can be represented by these errors. In the first case, the cameras were originally in normal positions with parallel optical axes. In the second case, the cameras were originally in the general positions and were transformed to the stereoscopic state by using the projective matrix obtained during exterior calibration. We determine exterior calibration of the camera using found corresponding points. Therefore, wrongly determined corresponding points cause wrong determination of exterior calibration. Subsequently, wrong exterior calibration causes wrong reconstruction of space coordinates.

We analyzed the effect of various errors in camera alignment on the system accuracy. This topic is based on article [8] and dissertation [9].

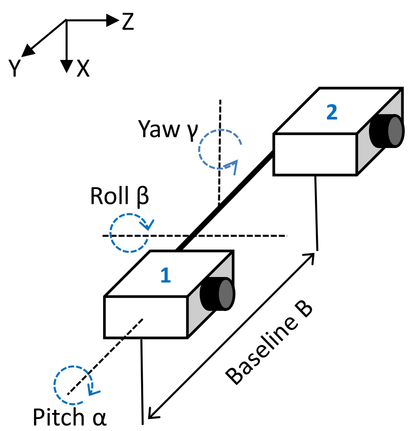


Figure 3.1: Normal scanning system with two cameras (possible fault angles α, β, γ are marked). .

3.2.1 Errors in stereo positions of the cameras

At first, we deduce a general formula for calculating errors in all spatial coordinates in dependency on the incorrectly determined image coordinates. The relation for error in depth ΔZ is deduced in [8]. Formulas for errors in the other two dimension ΔX and ΔY are deduced in this chapter. In the next step, the relations for incorrectly determined image coordinates x_2' and y' are found. The relations are deduced from geometrical situations by using trigonometric functions. Subsequently, this relation is substituted into the general relation. The following equations were obtained by using formulas describing simple stereophotogrammetry [8]

$$Z_{error} = f_c \cdot \left(\frac{B}{x_2 - x_1} - 1\right) \simeq f_c \cdot \left(\frac{B}{x_2 - x_1}\right), \tag{3.1}$$

$$Z_{real} = f_c \cdot \left(\frac{B}{x_2' - x_1} - 1\right) \simeq f_c \cdot \left(\frac{B}{x_2' - x_1}\right), \tag{3.2}$$

where Z_{error} is the observed absolute depth from image plane to the object. Z_{real} is the real(true) absolute depth, f_c is the focal length of both cameras (we assume the simple case, where cameras are the same), B is stereo base (length of the base line), x_1 is the correct (true) position of the measured point in the first image obtained by the first camera, x_2 is the true position of the measured point in the second image obtained by the second camera and x'_2 is the error (observed) position of the particular pixel in the second image captured by the real second camera.

The error is calculated as the difference of the real Z_{real} and observed depth Z_{error} of the point. After execution mathematical operation we obtained final formula

$$\Delta Z = Z_{real} \left(\frac{x_2' - x_2}{x_2' - x_1}\right). \tag{3.3}$$

The formula (3.3) represents the general error of the spatial coordinate Z. The coordinate x_2' is substituted in the next step. The formula for coordinate x_2' is derived for each situation (error in three various angles).

Subsequently, we deal with the derivation of the general formula for ΔX and ΔY. The procedures are very similar to the derivation formula for ΔZ. The deduced formulas are presented in dissertation. At this moment, all general equations necessarily required for expressing the errors have been expressed. Firstly we will deal with error in roll with rotation angle α between two cameras. The geometric situation is shown in Fig. 3.2. Author in [8] derived substitution $x'_{2,Z} = x_2 \cdot cos(\alpha)$ and substituted it to (3.3).

However, the error in the expression of $x'_{2,Z}$ can be proved. This formula is valid only if point P lies on the x axis. From Fig.3.2, it is obvious that x_2' is equivalent to abscissa $\overline{RS}$ while expression $x_2' = x_2 \cdot cos(\alpha)$ used in [8] is equivalent to abscissa $\overline{RY}$. Obviously, $x_2' = \overline{RY} - \overline{SY}$ and from triangle OSY $\overline{SY} = y \sin\alpha$ and therefore

$$x'_{2,P} = X\cos\alpha - Y\sin\alpha. \tag{3.4}$$

Similarly, y' can be deduced from triangle OSY, where $y = \bar{OY}$ is its hypotenuse and from triangle RPY, where $x_2 = \bar{PY}$ is its hypotenuse. Therefore

$$y'_{2,P} = Y\cos\alpha + X\sin\alpha. \tag{3.5}$$

The correctness of our deduced formulas was proved experimentally. Consequently, formula (3.4) is successively substituted into formula (3.3) and formulas for ΔX and ΔY. The final equations for errors in all spatial coordinates are obtained and after mathematical modification have forms

$$\Delta Z_T = Z_{real} \frac{X_2\left(cos\alpha - 1\right) - Y \sin\alpha}{B}, \tag{3.6}$$

$$\Delta X_T = \frac{BX}{X + B\cos\alpha - X\cos\alpha + Y\sin\alpha} - X, \tag{3.7}$$

$$\Delta Y_T = -\frac{XY + B^2\sin\alpha + Y^2\sin\alpha - BX\sin\alpha - XY\cos\alpha}{X + B\cos\alpha - X\cos\alpha + Y\sin\alpha}. \tag{3.8}$$

Subsequently, theoretical and practical errors are compared. These errors are equal. Therefore, the obtained relations can be used for estimating the error caused by the roll of the camera.

Figure 3.3 illustrates relative error in depth (coordinate Z) in dependency on space coordinate X of the object. The error angle of the roll is a parameter of the curves. The error is related to depth (space coordinate Z). The error calculated by the formula proposed in [8] is plotted with dashed lines. The error calculated by the newly proposed formulas are plotted with solid lines.

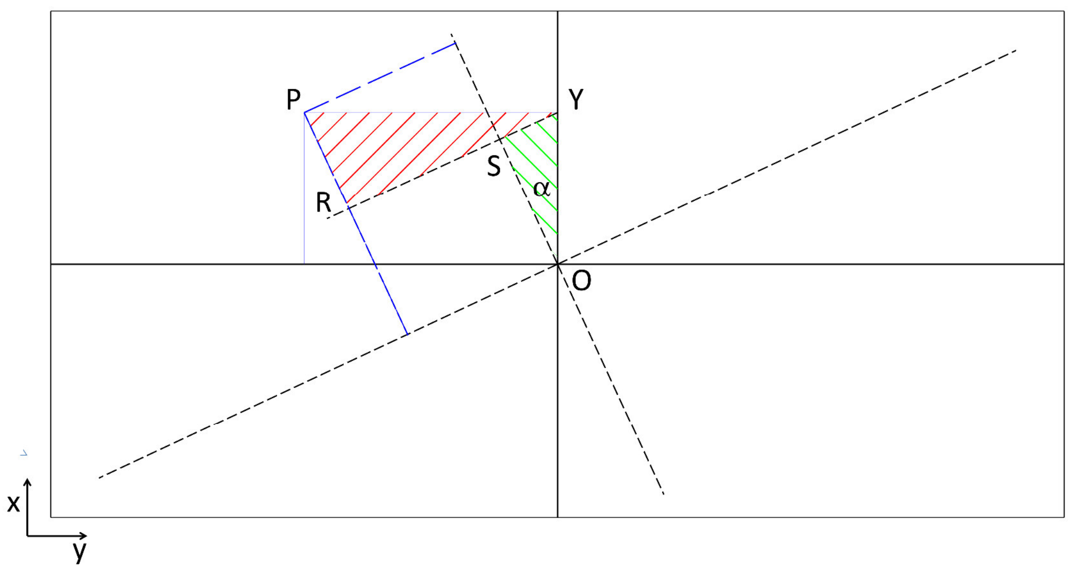


Figure 3.2: The geometric situation for the roll error (error angle α).

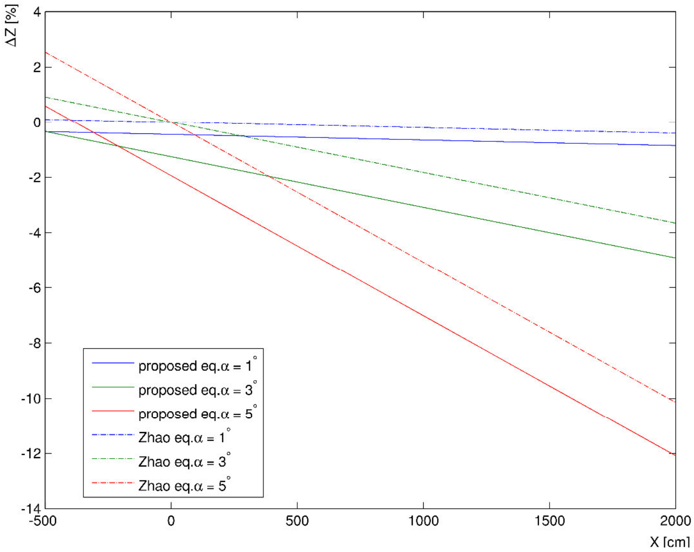


Figure 3.3: The dependency of the relative error ΔZ of the coordinate Z on the roll angle α and space coordinates X. Used sensing system parameters B=75mm, f=8.5mm.

Subsequently, we assume that calibration of the second camera is perfect except for a certain rotation angles β or γ (see Fig. 3.1. Spatial models of the situations were used for derivation (see Fig. 3.4). The following procedure of the derivation is common for both situations. The basic of the derivation is finding the point of intersection of the plane ϑ and abscissa $\bar{u}$ (denoted in Fig. 3.4a). After mathematical operations, the simplified formulas for image coordinates are obtained a) for rotation angle β

$$x'_{2,P} = \frac{X f_c}{Z \cos\beta - f_c + Y \sin\beta} \tag{3.9}$$

$$y'_{2,P} = -\frac{Y f_c \cos\beta^2 - Z f_c \cos\beta \sin\beta}{Z \cos\beta - f_c + Y \sin\beta} \tag{3.10}$$

b) for rotation angle γ

$$x'_{2,P} = -\frac{X f_c \cos\gamma^2 - Z f_c \cos\gamma \sin\gamma}{Z \cos\gamma - f_c + X \sin\gamma}, \tag{3.11}$$

$$y'_{2,P} = \frac{Y f_c}{Z \cos\gamma - f_c + X \sin\gamma}. \tag{3.12}$$

Consequently, these derived formulas are successively substituted to formulas (3.3) and formulas for ΔX and ΔY. The final equations for errors in all spatial coordinates are obtained.

The differences between spatial coordinates in an ideal camera stereoscopic system and a system with error in alignment were calculated and compared with the theoretical error obtained by the newly derived formulas. Theoretical errors and real differences are equal, therefore the derived formulas are verified.

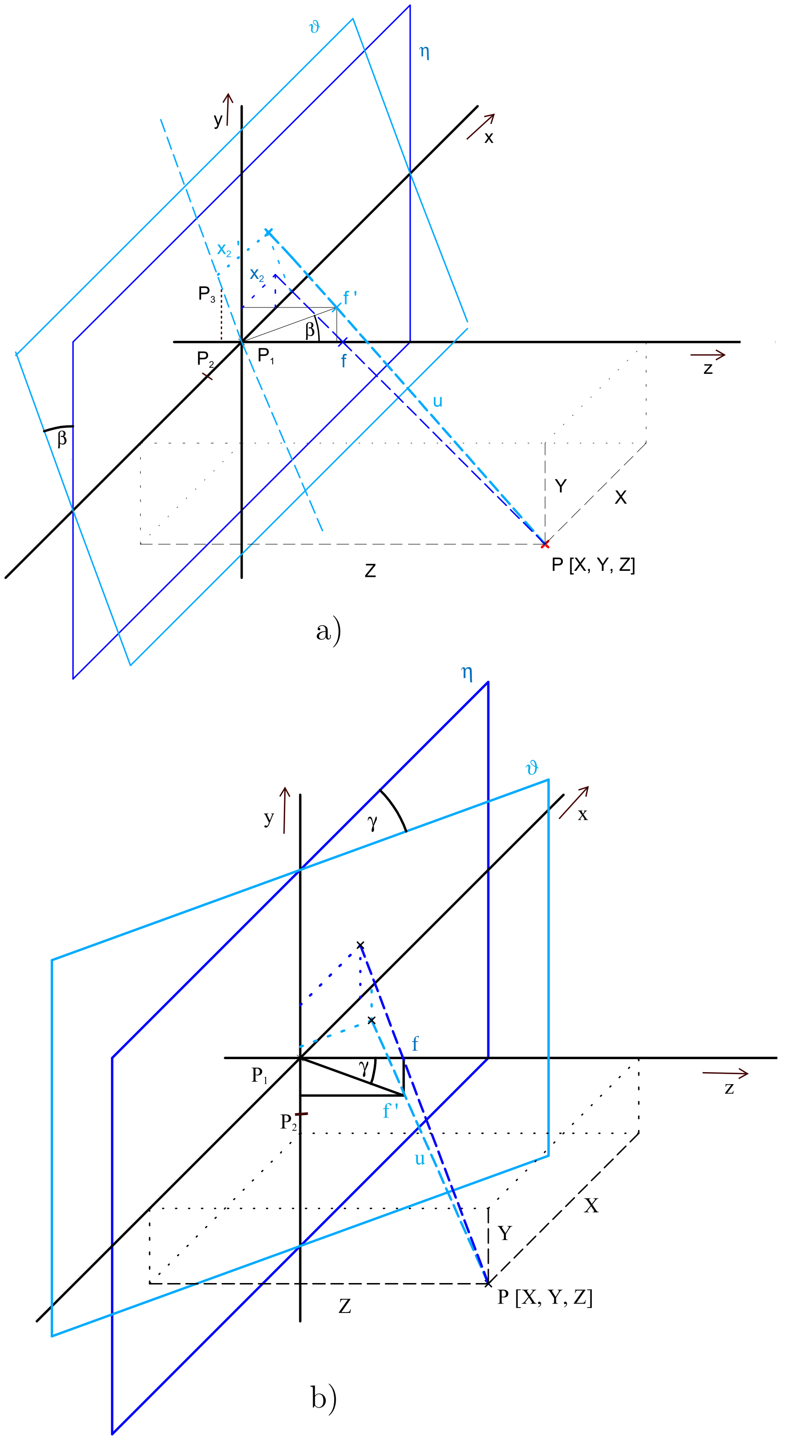


Figure 3.4: a) The space model of the error at angle a) β b) γ. The dark blue plane represents the plane of the image without error. The skyblue plane represents the plane of the image with error.

3.2.2 Errors in general positions of the cameras

The cameras of the 3D sensing system can generally have arbitrary positions in space. Then, the error in camera alignment is equal to the error in rotation matrix **R**. The coordinate system center is usually located at the optical center of the first camera. Therefore, the rotation angles ϕ,κ, ω and matrix **R** represent the relation between both cameras and between the coordinate system and the second camera. Assuming that we know rotation angles ϕ,κ, ω between the optical axis of the camera and axes of the coordinate system, then the theoretical rotation matrix of the camera **R** can be obtained by using relation (3.13) [10]

$$\mathbf{R} = \begin{bmatrix} \cos\phi\cos\kappa & -\cos\omega\sin\kappa + \sin\omega\sin\phi\cos\kappa & \sin\omega\sin\kappa + \cos\omega\sin\phi\cos\kappa \\ \cos\phi\sin\kappa & \cos\omega\cos\kappa + \sin\omega\sin\phi\sin\kappa & -\sin\omega\cos\kappa + \cos\omega\sin\phi\sin\kappa \\ -\sin\phi & \sin\omega\cos\phi & \cos\omega\cos\phi \end{bmatrix} \tag{3.13}$$

On the contrary, the rotation angles can be determined from rotation matrix **R**. The rotation matrix **R** is obtained by using an 8- point algorithm from the set of corresponding points. Therefore, errors in determining corresponding points cause an error in the rotation matrix **R**. The resulting error of the rotation matrix is given by the combination of the error in each corresponding point. Therefore, the influence of the error in a particular correspondence to the results is affected by the error in other correspondences. The next aspect is mutual camera positions. All of the following experiments are statistical sensitive analysis. The received results are valid only for specified conditions. However, some general hypothesis and conclusions can be deduced.

In the first experiment, the additive white Gaussian noise with various Signal Noise Ratio SNR is added to all accurately found corresponding points. SNR is in the range from 40dB to 60dB. The method Monte Carlo was used. A thousand repetitions of reconstruction with a particular level of noise was executed. Subsequently, the average value, standard deviation and worst case were determined. The experiment is based on the comparing angles determined from rotation matrixes obtained from correct and incorrect set of corresponding points.

The results are shown for two various images in Tab. 3.1. The some conclusions can be deduced from the obtained results. The error of angle ϕ is most sensitive to errors in correspondences. The number of correspondences has crucial importance. The errors significantly increase with decreasing number of correspondences. It is obvious that the error of the rotation matrix is considerable even for a very small error in correspondences. Therefore, the importance of correct correspondences is obvious from the results. The executed experiments and obtained results serve for demonstration of the importance of correctly finding corresponding points and for design process for estimating possible error.

In the second experiment, only one point is debased by an accurately defined error. Other correspondences are accurate. The worst case analysis is executed again. The most sensitive point and most affecting point of other point are found.

SNR	Image1						Image2					
SNR	Worst case [°]			Average value [°]			Worst case [°]			Worst case [°]		
	$\Delta\phi$	$\Delta\kappa$	$\Delta\omega$	$\Delta\phi$	$\Delta\kappa$	$\Delta\omega$	$\Delta\phi$	$\Delta\kappa$	$\Delta\omega$	$\Delta\phi$	$\Delta\kappa$	$\Delta\omega$
40	35.4	13.7	9.9	12.4	6.2	2.9	1.5	0.2	1.2	1.5	0.1	1.1
45	19.9	9.7	4.8	4.8	3.3	1.1	1.4	0.1	1.0	1.4	0.1	0.9
50	10.1	6.0	2.6	2.2	1.6	0.5	1.4	0.1	0.8	1.4	0.0	0.8
55	4.8	3.7	1.3	1.2	0.9	0.3	1.3	0.1	0.7	1.3	0.1	0.7
60	3.1	2.0	0.7	0.7	0.5	0.2	0.5	0.2	0.1	0.3	0.1	0.1

Table 3.1: Results of the Monte Carlo experiment testing influence of the error in the finding corresponding points on the error in rotation matrix for two scenes .

4 DEPTH MAP GENERATION

This chapter describes two proposed methods for depth map generation. The first method addresses the passive system for generating the depth map. The fundamental idea use of the space continuity of the depth map. The second method is based on combining passive and active methods for estimating the depth map.

4.1 Algorithm based on similarity measurements and space continuity

The aim of stereo matching is to compute the disparity (mutual spatial shift) of two input images(called left and right image) for each pixel. **The images differ only by horizontal parallax**,which is various for various pixels. Subsequently, the depth of the point in the scene is given by the parallax between points which represent this point in both images, these points are called corresponding points.

The proposed method consists of the two fundamental steps. In the first step, the initial depth map is obtained by implementing SAD (Sum of Absolute Differences) and CGRAD (Cost from Gradient of Absolute Differences) [11]. This process is based on the algorithm implemented by Shaun Lankton [12]. The initial disparity map has many discontinuities and errors. We proposed approach for improvement of the initial depth map. The approach is based on the assumption of continuity of the depth map in rows and utilizes information about edges in images.

In the initial depth map remain areas with undefined depth and some errors. We proposed a solution of this problem. At firstly, we executed post processing of the depth map and zero area are found. The zero area are pixel without determined depth. Edge representation of the image is obtained by implementing the Canny detector. The core of the approach follows. We find the depth on both rims of the zero regions (*depth_Rborder* and *depth_Lborder*) and length of the region (*length*). Subsequently, difference of these depth is calculated. In the subsequent step we use edge representation. There are four various cases possible (see Fig 4.1b). The depth is determined depending on what case of situation occurred.

We implemented the proposed method in MATLAB. The method has a working designation of Depth Continuity Method DCM. Subsequently, we performed some tests of the applicability of the method. For this purpose, we used images from the open database Middlebury Stereo Datasets [2]. This database contains stereo images and a true depth map of the scene. The used images have a size of 370x465 pixels. The obtained results are compared to results obtained by other ways:

- CSAD+belief propagation BP,
- commercial software Stereo tracer ST.

The obtained depth maps were compared with true depth maps which are part of the used database [2]. The results are summarized in Tab. 4.1. Resulting depth maps and detailed description is not in short version of the PhD thesis.

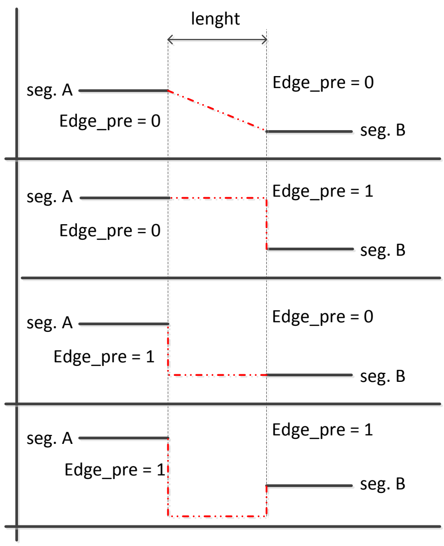


Figure 4.1: Diagram of the four possible alternatives in process using edges. A, B are two segment with well determine depth. Zero segment lies between them. Result depth is depict by red line.

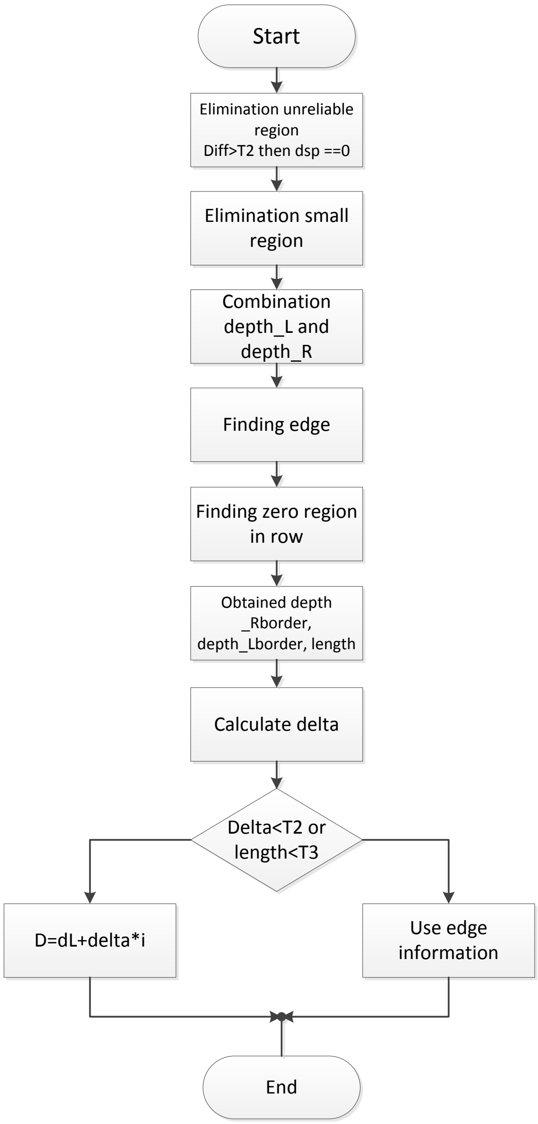


Figure 4.2: Flowchart of the improvement depth map based on space continuity.

image	Reliability [%]			Average error in depth [pixel]		
	ST	BP	DCM	ST	BP	DCM
Tsukuba	66.8	40.8	20.6	28.1	10.0	8.6
Rock2	60.2	65.1	8.1	39.9	43.8	2.2
Baby1	57.8	22.9	13.8	16.4	20.1	8.4
Cloth3	59.0	50.2	5.6	25.9	22.3	2.76

Table 4.1: The reliability and average error of the depth map estimated by various methods.

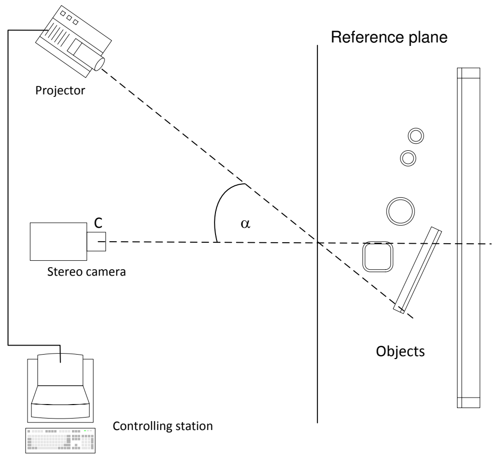
4.2 Precise map using combination of the passive and active method

The utilization of combining passive and active approaches is other way of how to acquire a more accurate estimation of the depth map. I cooperated on this topic with ing. Kaller. The active method is incoherent profilometric scanning [13] based on the projection of the fringe pattern on a scene. In our method we implemented phase shifting profilometry (PSP) which is very easy to implement [15]. The output of scanning is phase in the range $\langle -2\pi, 2\pi \rangle$. The wrapped phase contains sudden changes (wraps) between edge values. We need to eliminate these wraps [16]. The unwrapping is executed by implementing the open source code of the method published in [17]. During the experiment, a problem with the shadows had to be solve. The algorithm for shadow detection and elimination its influence was proposed [25].

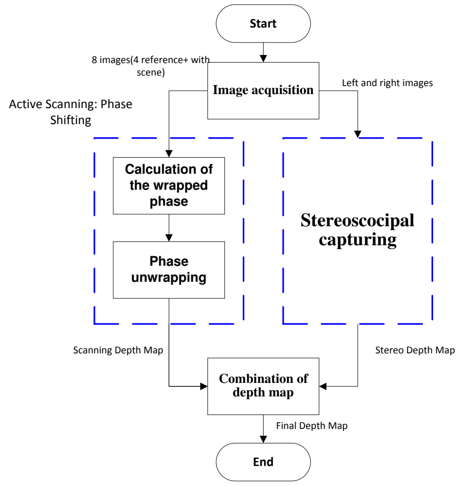
The obtaining depth from the stereo image is passive method used in the combination [18]. In final version of the method, we implemented original proposed method described in section 4.1. The fundamental idea is utilization of the good properties of the both component methods. On the contrary disadvantageous features of the used method will eliminated by using in combination. The advantage of the incoherent profilometric scanning is continuous and accurate depth profile for individual object in a scene. On the contrary, disadvantageous of active method is failure to maintain of the relation between depth of the individual object in a scene. On the other hand, we can easily obtain distance between individual objects in a scene by using stereo method. However, the disadvantage of the passive method is inaccurate profile of the individual object. This error is caused by matching problem.

The schematic plan of the workplace for obtaining the depth map by combining the passive and active methods is in Fig. 4.3a. The work place contains a DLP projector, which projected a fringe pattern on a scene. The scene is captured by a stereo camera. Subsequently, the image processing part of the method can be executed when we have captured the required images.

Fig. 4.3b shows a flowchart of the image processing. In the first step, the depth maps are obtained from the profilometric and stereo images. The combination of both depth maps is the last step in our method for generating depth map. The process of the combination is based on advantages of each depth map. Therefore we want obtain profile of each objects from profile map and transform it to range given by stereo map. The proposed procedure is based on objects detection and subsequently finding the range of the depth for each object in the depth map obtained by passive method (*stereo_depth_map*). The found range is used for transforming the depth map obtained by the active method. The final depth map is shown in Fig. 4.4. (*profilometric_depth_map*). The proposed procedure used besides known principles (FPP, unwraping, stereo visions) also two original algorithms for executed component task: shadow detection and synthesis of the two depth map.

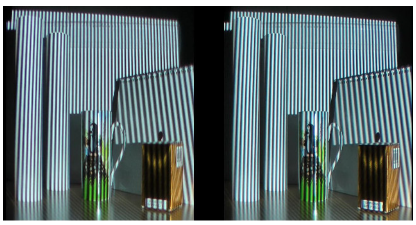


a)

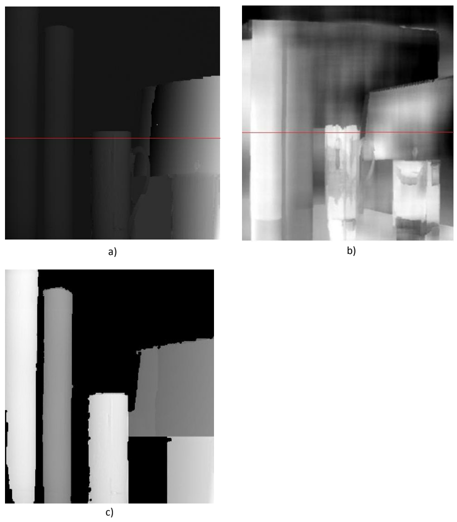


b)

Figure 4.3: a) Schematic plan of workplace for combinations of the passive and active sensing. b) he flowchart of the process of combination active and passive method for estimation depth map.



a)



b)

Figure 4.4: a) The input image of the scene with projected pattern b) The depth map obtained by profilometry. c) The depth map obtained by stereo vision d) The resulted depth map.

5 QUALITY OF EXPERIENCE IN 3D

The topic of 3D video is closely connected with the depth map estimation and its precision. The proper definition of the QoE appeared in White Paper [19] which was created by the consortium Qualinet. The aim of many researchers is to create objective metrics for determining QoE. Subjective tests are powerful tool used for this purpose. The determination of QoE is a difficult problem, because QoE is affected by various aspects. Among the key ones include: viewing conditions, content of the sequence, sensing system, 3D imaging system and its parameters, technology and technical parameters of the display, observer's physiological and psychological features. At the subjective evaluation of these effects cannot be separated.

The aim of executed subjective test was to compare and evaluate the directional dependency of the viewer's spatial perception and 3D image quality on three of today's 3D TVs. Therefore, research focusing on the viewing angle was performed and the results are described. Tests were performed separately on three types of TV displays with different technologies (LCD, plasma) and different 3D displaying methods. Currently, the most commonly 3D imaging method and their representatives are used:

- Eclipse (active) method (3D TV Panasonic TX-P42GTT20E with Full HD plasma display and active controlled LCD glasses).
- Polarization method (42LW570S LG 3D TV with Full HD LCD display).
- Auto-stereoscopic display (3D monitor Toshiba Qosmio F-750 with 15 " LCD).

5.1 Measuring workplace

Objective measurements of photometric parameters and subjective testing of spatial perception and quality of 3D images reproduced by different displays were realized for different visual angles. Arrangement of the workplace is in Fig. 5.1. Visual angle (α) is changed by 10°. Observer positions are placed on a circle. The optimum viewing distance is maintained in all test positions. Subjective tests and the previous measuring of objective photometric parameters were carried out in a partially darkened room in order to reduce the effect of external lighting.

5.2 Measurement of photometric parameters of tested displays

Objective measurements of the directional dependence of photometric parameters (saturation S and brightness B) of all three displays, which were used for 3D imag-

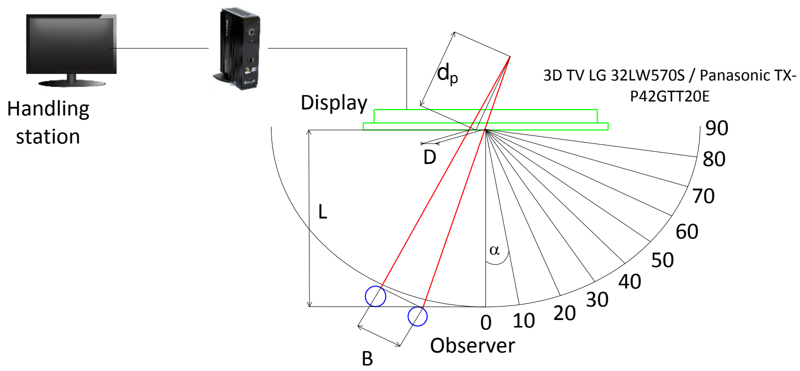


Figure 5.1: Schematic arrangement of the workplace.

ing, were also a component part of these tests. This, at least, enables a partial evaluation of the impact of display technology on the subjectively assessed viewer's spatial perception. Electronic signals of four test patterns generated by the TV generator, were used for measuring. The results confirm the known fact that the directional dependence of color reproduction of plasma displays is less than LCD displays. However, it is apparent, that for the small visual angles α in the horizontal direction (up to the 20%) degradation of color reproduction for all three display types is approximately similar and relatively small.

5.3 Testing methods and videosequences used in the test

An observer evaluates perceived quality of displayed 3D images and spatial effect. The evaluator's visual abilities were verified by special check tests. For testing, we selected a group of 28 observers within an age range of 15 -70 years. Two different methods for the evaluating perception were used. First of them used evaluation without reference and discrete scale and second one used evaluation with reference and continuous scale. Because the test results obtained by these two methods differ a little for statistical processing and final graphic display, their average is used. The results obtained by these various ways of evaluations were equal. This fact is one of the important findings of this experiment.

Three 3D video sequences with a duration of about 15 seconds, containing a scene with different depth were selected for testing. Three 3D still images selected from these video-sequences were also evaluated. Evaluators had approximately 5 seconds for each evaluation. All 3D image tests were obtained mainly from Blu Ray discs and played by the media player X-streamer Ultra in native Full HD resolution (1080 x1920 pixels) and in the "Side by Side" format.

5.4 Results of the subjective tests and their statistical processing

Subjective test results of directional dependence of 3D image quality and spatial perception are shown in Fig. 5.2. The color resolution is used in this figures: red: Panasonic with active glasses, green LG with passive glasses, blue: Toshiba autostereoscopic display.

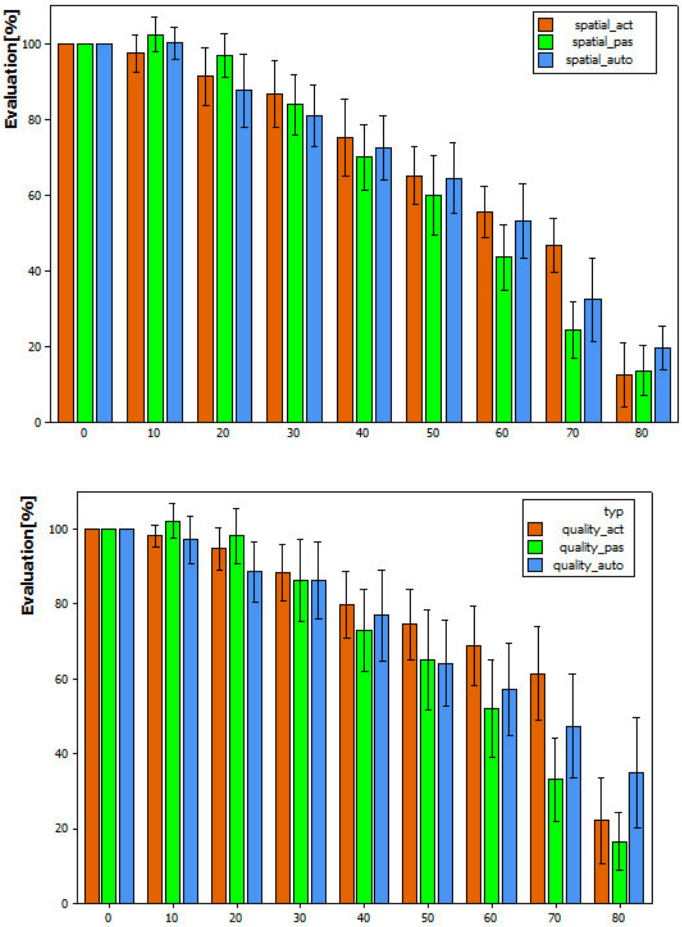


Figure 5.2: Subjective test results of directional dependence of 3D images a) spatial percept b) quality.

Subsequently after performing the subjective tests, we executed a statistical analysis of the obtained results. One of the most important tasks was detecting outliers (odd results)[20]. In this work, outliers are respondents whose evaluation distinctly deviates from the mean value in most viewing angles. The various methods were used for outlier detection: Grubbs test [21], cluster analysis and Principal Component Analysis PCA [22]. The results indicate that eliminating outliers does not distinctly improve the confidence interval of results in spatial effect. This fact is proof that evaluating spatial perception in 3D TV is individual in certain scales and we cannot obtain results with a minimal confidence interval. Hence, there will always be some variance of evaluation of individual respondents.

However, the main aim of PCA is to condense information, which is contained in a great number of original variables. We can sufficiently describe a set of evaluations from individual respondents by three components. This fact implies that the evaluation of respondents is mutually very similar. Great similarity is a mark that the results of subjective tests have good reliability. We confirmed reliability of the tests by using the analysis ANOVA (Analysis of Variance)[23]. ANOVA is a statistical method for comparing the similarity of two or more sets of data. In our case, the evaluations of individual respondents are similar and therefore the results of the test are reliable. ANOVA proved similarity of the respondents' answer to questions about spatial perception. On the contrary, the result of ANOVA refutes similarity of the respondents' answer to questions about quality. This situation can be caused by inaccurate definition of quality to respondents.

5.5 Conclusion

The influence of the viewing angle on the resulting spatial perception and quality of the 3D images and video were evaluated using objective measurements and subjective tests. Tests were performed on three TV sets with different displays and methods of 3D displaying. The purpose of the objective measurements was to determine the dependency of the relative color saturation S and brightness B on the viewing angles for all three TV systems used and assess the relationship between this dependency and subjective evaluations. The objective measurement confirmed the known fact, that the plasma display has a wider viewing angle. It was shown that different testing methods have negligible effect on the results. The evaluation of both parameters (spatial effect and image quality) is almost identical for small viewing angles. Subsequently, the evaluation begins to differ for higher angles and an active system is evaluated better than a passive system. This fact is in accordance with the results of the objective measurement.

6 SUMMARY CONCLUSION

The new method for detecting a corresponding point for a specific selected point was proposed in section 2.2. The proposed method is based on the model of probability of the movement of the points in the examined area of the image. The new approach can be used with an advantage especially for finding a corresponding point for points selected by the user in an area with small contrast. The algorithms was published in paper [26]. The proposal of the method for finding corresponding points by converting to pseudo colors is an important innovation described in section 2.3. The executed tests confirmed the usability of this method especially with an image area without contrast. This approach was published in paper [27]. Both proposed methods were implemented to the designed software for reconstructing the model of the scene and calculating the depth maps (see section 2.4).

The next research area was the accuracy of model scene reconstruction. First aim was to extend previous work in the area of investigation of the effects of camera alignment errors on estimating depth by a stereoscopic camera system. The practical experiment revealed that the previously derived equation for error in depth due to errors in camera rotation are incorrect. Therefore, a new equation for error in depth estimation was derived and its correctness was proven by experiment. Subsequently, the equations for estimation error in the remaining two spatial coordinates were derived and their correctness was proven. The second part deals with the impact of inaccurate determination of corresponding points. This impact is investigated in both camera systems: stereo alignment and even universal arrangement. The error is expressed directly for a stereo system. The investigation of the universal arrangement connects the error in corresponding points with the error in camera alignment. The impact of various errors in finding corresponding points on the error of the exterior calibration is a very complex problem with a large number of degrees of freedom. Therefore, the statistical probabilistic analysis is the sole solution.

The creation of the depth maps closely relates to the reconstruction of the model of the scene especially with finding corresponding points. I proposed three methods for generating depth maps. Two of them are based on using stereo images (see section 4.1). The initial depth map obtained by using commonly used method is improved by two various methods. The first method is based on edge representation and using spatial continuity of the depth map. The second one is based on image segmentation and using correspondences of the significant points found by the algorithm SURF. These methods were published in paper [28]. The third approach is a system based on using the combination of a passive stereoscopic method and an active optical incoherent active scanning method(see section 4.2). The two maps are generated and subsequently transformed to one. This method was published in paper [29].

The last important aim was executing and evaluating subjective tests of the spatial effect of the stereoscopic 3D videosequence on the technologically different 3D displays with different 3D systems. The influence of changing the viewing angle in both directions was examined. The measurement of the objective parameters of the displays was executed. For executing the tests, a methodology for testing was proposed. The results were published in the papers [30], [31].

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Curriculum Vitae

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Languages	Czech – mother tongue English – proficient user (C1)

Abstract

This dissertation deals with selected topics of digital photogrammetry. The problem is defined and the state of the art is described in the first part of the dissertation. Four specified aims are solved. The proposal of the method for finding corresponding points is the first topic. Two new methods were proposed. The first method uses conversion of an image to pseudo- colors. The second method used a probabilistic model obtained from the known pairs of the corresponding points. The analysis of the accuracy of the reconstruction is the second solved topic. The influence of the various aspects to the accuracy of the reconstruction is analyzed. The most attention is paid to incorrect camera alignment and errors in finding corresponding points. The third topic is estimation of the depth maps. The two method were proposed. The first method is based on the combination of the passive and active method. The second wholly passive approach uses continuity of the depth map. The last investigative topic is quality of experience of the 3D videos. The subjective tests of the perception of 3D content for the various 3D displaying systems were performed. The dependency of the perception on the viewing angle was also investigated.

Abstrakt

Disertační práce se zabývá vybranými partiemi digitální fotogrammetrie. V první části práce je definované téma a popsán současný stav poznání. V následujících kapitolách jsou postupně řešeny čtyři dílčí navzájem navazující cíle. První oblastí je návrh a ověření metody pro hledání souhlasných bodů v obraze. Byly navrženy dvě nové metody. První z nich používá konverzi stereo snímků do nepravých barev a druhá využívá pravděpodobností model získaný ze známých párů souhlasných bodů. Druhým tématem je analýza přesnosti výsledné rekonstrukce prostorových bodů. Postupně byl analyzován vliv různých faktorů na přesnost rekonstrukce. Stěžejní oblastí je zkoumání vlivu chybného zarovnání kamer a chyby v určení souhlasných bodů. Třetí téma představuje je tvorba hloubkových map. Byly navrženy dva postupy. První přístup spočívá v kombinaci pasivní a aktivní metody druhý přístup vychází z pasivní metody a využívá spojitosti hloubkové mapy. Poslední zvolenou oblastí zájmu je hodnocení kvality 3D videa. Byly provedeny a statisticky vyhodnoceny subjektivní testy 3D vjemu pro různé zobrazovací systémy v závislosti na úhlu pozorování.