International Conference on
Electronics, Electrical Engineering, Computer Science

EEECS 2016

2016 in Phuket, Thailand, January 20 – 22

International Association of Science & Engineering Researcher IASER

KCCTA Korea Culture&Contents Technology Association 한국문화콘텐츠기술학회

MBRC

1st EEECS 2016

11:10-11:40 **KENOTE ADDRESS**
Aquamarine

Speak: Prof. Minho Jo, Korea University, Korea

11:40-12:20 **INVITED TALKS**
Aquamarine

Speaker:

Prof. Sergei Gorlatch, University of Muenster, Germany

Prof. Sasalak Tongkaw, Songkhla Rajabhat University, Thailand

12:20-14:00 **LUNCH**
Hotel Novotel Phuket Vintage Park Resort

14:00-15:40 **SESSION III Oral Presentation**
Pearl

Chair: Prof. Chompoo Suppatoomsin, Prof. Jeong-Sik Park

01EEECS344
Using Multi-view to Identify Factors that Affect their Use in Electronic Learning Course
Sasalak Tongkaw, Chothitam Tamrak, Jaksit Olarikchat [Songkhla Rajabhat University, Thailand]

01EEECS374
Hybrid Driver Fatigue Detection System Based on Data Fusion with Wearable Sensor Devices
QuanZhe Li, Juan Wu, Shin-Dug Kim [Yonsei University, Korea], Cheong Ghil Kim [Namseoul University, Korea]

01EEECS368
An Accumuation-Based Rectification and Distortion Correction Method
Hyeon-Sik Son, Byungin Moon [Kyungpook National University, Korea]

01EEECS382
Evaluating the Overhead of Data Preparation for Heterogeneous Multicore System
Songwen Pei, Junge Zhang, Linhua Jiang [University of Shanghai for Science and Technology, China], Myoungseo Kim, Jean-Luc Gaudiot [University of California, Irvine, USA]

An Accumuation-Based Rectification and Distortion Correction Method

Hyeon-Sik Son and Byungin Moon*
School of Electronics Engineering
Kyungpook National University
Daegu, Korea
soc_shs1984@ee.knu.ac.kr, bihmoon@knu.ac.kr

***Abstract*—Rectification is an essential pre-processing step for simplifying disparity extraction of all stereo matching algorithms. However, rectification imposes a high computational burden because its process entails complex matrix calculations and distortion correction. Thus, this paper proposes an efficient rectification method that simplifies computation by replacing the complex matrix computations and distortion correction of conventional rectification with simple accumulations. The experimental results show that compared with the conventional method, the proposed method generates well-rectified images with reduced computation.**

Keywords—rectification; stereo vision; stereo matching;

I. Introduction

A stereo vision system calculates 3D distances by finding disparities between a stereo image pair captured by a stereo camera. The 3D distances acquired by a stereo vision system can be applied to various applications such as autonomous vehicles, intelligent robots, and 3D multimedia content [1-3]. One of pre-processing steps for stereo matching is rectification, the process of removing vertical mismatches between stereo images input by the stereo camera. Because rectification reduces the disparity search range from 2D to 1D, it is commonly required for all stereo matching algorithms [4]. However, because it requires complex matrix calculations for coordinate translation and high-degree equations for distortion correction, it increases latency and slows down the entire stereo matching process. Thus, this paper proposes an efficient rectification method that reduces computational overhead by replacing the complex matrix computation and distortion correction process with simple accumulations.

II. Conventional Rectification Algorithm

To create a rectified image, the process of rectification finds the pixel coordinates of the input image corresponding to the pixel coordinates of the rectified image and fills the pixel values of the image by interpolation [5]. A widely used camera calibration and rectification program is the camera calibration toolbox in MATLAB [6], the algorithm of which we refer to as the conventional rectification algorithm.

To map the (X_r, Y_r) rectified image coordinates onto the (X, Y) coordinates of the acquired raw image according to the camera calibration toolbox, the conventional rectification method uses the following equations:

$$X_n = \frac{X_c}{Z_c}, Y_n = \frac{Y_c}{Z_c}, \text{ and } \begin{bmatrix} X_c \\ Y_c \\ Z_c \end{bmatrix} = R^T \times KK_{new}^{-1} \begin{bmatrix} X_r \\ Y_r \\ 1 \end{bmatrix}, \quad (1)$$

where KK_{new} is the intrinsic parameter matrix of the rectified image, R is the rectification rotation matrix, and

$$R^T \times KK_{new}^{-1} = \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix}, \quad (2)$$

and

$$\begin{bmatrix} X \\ Y \end{bmatrix} = KK \times \begin{bmatrix} X_{dist} \\ Y_{dist} \end{bmatrix} = \begin{bmatrix} f_x \times X_{dist} + cc_x \\ f_y \times Y_{dist} + cc_y \end{bmatrix}, \quad (3)$$

where KK is the intrinsic parameter matrix of the camera, f_x and f_y are the focal length parameters, cc_x and cc_y are the principal points parameters in KK, and

$$\begin{aligned} X_{dist} &= (1 + kc_1 \times q^2 + kc_2 \times q^4 + kc_5 \times q^6) \times X_n \\ &+2 \times kc_3 \times X_n \times Y_n + kc_4 \times (q^2 + 2 \times X_n{}^2) \\ Y_{dist} &= (1 + kc_1 \times q^2 + kc_2 \times q^4 + kc_5 \times q^6) \times Y_n \\ &+kc_3 \times (q^2 + 2 \times Y_n{}^2) + 2 \times kc_4 \times X_n \times Y_n \end{aligned}, \quad (4)$$

where $q^2 = X_n{}^2 + Y_n{}^2$ and kc_1 ~ kc_5 are the distortion parameters. The parameter matrices and distortion parameters can be calculated using the process of stereo camera calibration. Camera distortion can be decomposed into two factors: radial and tangential distortion. Tangential distortion, which is calculated by terms of (4) with kc_3 and kc_4, is commonly neglected [7] and kc_5 is almost equal to zero. Thus, (4) can be simplified as

$$\begin{aligned} X_{dist} &= (1 + kc_1 \times q^2 + kc_2 \times q^4) \times X_n \\ Y_{dist} &= (1 + kc_1 \times q^2 + kc_2 \times q^4) \times Y_n \end{aligned}. \quad (5)$$

This research was supported by the MSIP (Ministry of Science, ICT and Future Planning), Korea, under the C-ITRC (Convergence Information Technology Research Center) (IITP-20 15-H860 1-15-1 002) supervised by the IITP (Institute for Information & communications Technology Promotion). This investigation was financially supported by Semiconductor Industry Collaborative Project between Kyungpook National University and Samsung Electronics Co. Ltd.

*Corresponding author: Byungin Moon

As shown in the above equations, rectification entails the calculation of complex matrices, and radial distortion correction requires the calculation of fifth-degree equations. To reduce computational overhead, [8] proposed a compact rectification algorithm, and [9] used a reverse mapping rectification method that computes the transformation matrix, which presents corresponding relationships between pixels in the original images and those in the rectified images using

$$X = \frac{X_m}{Z_m}, Y = \frac{Y_m}{Z_m}, \text{ and } \begin{bmatrix} X_m \\ Y_m \\ Z_m \end{bmatrix} = KK \times R^T \times KK_{new}^{-1} \begin{bmatrix} X_r \\ Y_r \\ 1 \end{bmatrix}. \quad (6)$$

These rectification methods, unfortunately, cover only coordinate translation and rotation, and they do not address distortion correction. Furthermore, as they still require complex matrix calculations, [10] proposed a simplified rectification method that uses accumulations instead of matrix multiplications; however, it neglects distortion correction. Thus, this paper proposes a rectification method with radial distortion correction that simplifies computation using arithmetic accumulations.

III. Proposed Rectification Algorithm

When a camera outputs an $M \times N$ resolution image, pixel values are transmitted sequentially, shown in Fig. 1, and commonly processed in the same order. That is, while the x coordinate of the rectified image increases by 1 for every calculated pixel, the y coordinate is fixed during rectification through one row, and the y coordinate of the rectified image increases by 1 when only the row changes. In addition, (1) can be rewritten as

$$\begin{aligned} X_c &= c_{11} \times X_r + c_{12} \times Y_r + c_{13} = c_{11} \times X_r + f(Y_r) \\ Y_c &= c_{21} \times X_r + c_{22} \times Y_r + c_{23} = c_{21} \times X_r + g(Y_r). \\ Z_c &= c_{31} \times X_r + c_{32} \times Y_r + c_{33} = c_{31} \times X_r + h(Y_r) \end{aligned} \quad (7)$$

Because Z_c in (1) and q^4 in (5) are empirically almost equal to 1, (5) is approximated as

$$\begin{aligned} X_{dist} &= (1 + kc_1 \times q^2 + kc_2) \times X_c \\ Y_{dist} &= (1 + kc_1 \times q^2 + kc_2) \times Y_c \end{aligned}. \quad (8)$$

During rectification processing in the x-direction, $f(Y_r)$ and $g(Y_r)$ are constants because Y_r is fixed. Using this feature, (3), (7) and (8) can be rewritten as

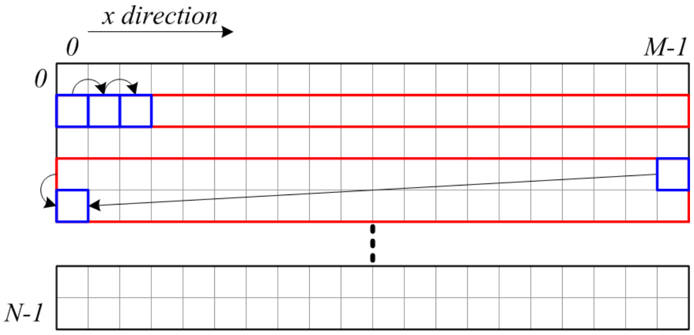

Fig. 1. Pixel-processing sequence.

$$\begin{aligned} X &= a_x \cdot X_r^3 + b_x \cdot X_r^2 + c_x \cdot X_r + d_x \\ Y &= a_y \cdot X_r^3 + b_y \cdot X_r^2 + c_y \cdot X_r + d_y \end{aligned}, \quad (9)$$

$$\begin{aligned} a_x &= f_x \cdot (\alpha_1 \cdot c_{11}{}^3 + \alpha_1 \cdot c_{11} \cdot c_{21}{}^2) \\ b_x &= f_x \cdot (\alpha_1 \cdot c_{21}{}^2 \cdot A + 2\alpha_1 \cdot c_{11} \cdot c_{21} \cdot B + 3\alpha_1 \cdot c_{11}{}^2 \cdot A) \\ c_x &= f_x \cdot (c_{11} + \alpha_2 \cdot c_{11} + 2\alpha_1 \cdot c_{21} \cdot A \cdot B + 3\alpha_1 \cdot c_{11} \cdot A^2) \\ d_x &= f_x \cdot (A + \alpha_1 \cdot A \cdot B^2 + \alpha_1 \cdot A^3 + \alpha_2 \cdot A) + cc_x \end{aligned}, \quad (10)$$

$$\begin{aligned} a_y &= f_y \cdot (\alpha_1 \cdot c_{21}{}^3 + \alpha_1 \cdot c_{21} \cdot c_{11}{}^2) \\ b_y &= f_y \cdot (\alpha_1 \cdot c_{11}{}^2 \cdot B + 2\alpha_1 \cdot c_{11} \cdot c_{21} \cdot A + 3\alpha_1 \cdot c_{21}{}^2 \cdot B) \\ c_y &= f_y \cdot (c_{21} + \alpha_2 \cdot c_{21} + 2\alpha_1 \cdot c_{11} \cdot A \cdot B + 3\alpha_1 \cdot c_{21} \cdot B^2) \\ d_y &= f_y \cdot (B + \alpha_1 \cdot B \cdot A^2 + \alpha_1 \cdot B^3 + \alpha_2 \cdot B) + cc_y \end{aligned}, \quad (11)$$

and

$$\begin{aligned} A &= f(Y_r) = c_{12} \cdot Y_r + c_{13} \\ B &= g(Y_r) = c_{22} \cdot Y_r + c_{23} \end{aligned}. \quad (12)$$

During rectification through one row, because the y pixel coordinate in the rectified image is fixed, A and B are constants, so, all of the coefficients such as a_x, b_x, c_x, d_x, a_y, b_y, c_y, and d_y are also fixed. On the other hand, when the y coordinate increases as a result of row increment, A and B change as defined in

$$\begin{aligned} A_n &= A_{n-1} + c_{12} \\ B_n &= B_{n-1} + c_{22} \end{aligned}. \quad (13)$$

When A and B increase, the coefficients must be recalculated because they depend on A and B.

According to (9), the proposed rectification computes a third-degree equation that can be regarded as a kind of difference sequence as shown in Fig. 2. Thus, the proposed method performs rectification using simple accumulation as defined in

$$\begin{aligned} X &= h_{n+1} = h_n + \Delta h_n, h_0 = d_x \\ Y &= g_{n+1} = g_n + \Delta g_n, g_0 = d_y \\ \Delta h_{n+1} &= \Delta h_n + \Delta^2 h_n, \Delta h_0 = a_x + b_x + c_x \\ \Delta g_{n+1} &= \Delta g_n + \Delta^2 g_n, \Delta g_0 = a_y + b_y + c_y \\ \Delta^2 h_{n+1} &= \Delta^2 h_n + 6a_x, \Delta^2 h_0 = 6a_x + 2b_x \\ \Delta^2 g_{n+1} &= \Delta^2 g_n + 6a_y, \Delta^2 g_0 = 6a_y + 2b_y \end{aligned}, \quad (14)$$

where the coefficients should be recalculated after every row change.

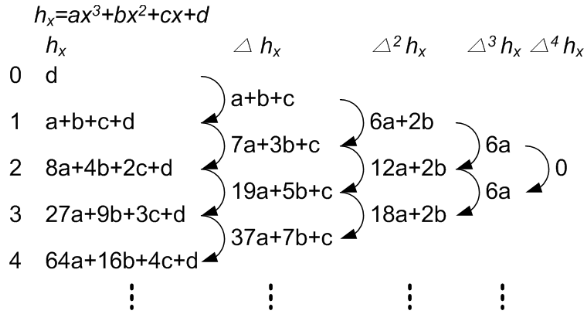

Fig. 2. Difference sequence for a third-degree equation.

IV. Experimental Result

To evaluate the results of the proposed rectification method, we modeled four rectification methods, described in Table I, using MATLAB R2013a and used the image sets of BoofCV [11] as inputs. We also extracted the camera calibration parameters for rectification using the camera calibration toolbox of Caltech, as shown in Fig. 3. The figure shows that tangential distortion parameters kc_3 and kc_4 are negligible and that radial distortion parameter kc_5 is usually zero.

TABLE I. Rectification Methods for The Experiments

Method	Rectification Methods	
	Description	***Use of Equations***
1	Rectification with distortion correction	(1), (2), (3), (4)
2	Rectification with radial distortion correction	(1), (2), (3), (5)
3	Rectification without distortion correction	(6)
4	Proposed rectification	(10), (11), (13), (14)

```
Intrinsic parameters of left camera
Focal length:      [ 524.36523  526.37302 ]
                   [ 313.03006  249.04865 ]
Skew:              [ 0.00000 ]
Distortion:        [ -0.35955  0.16956  0.00048  -0.00038  0.00000 ]

Intrinsic parameters of right camera
Focal length:      [ 525.74556  527.57744 ]
                   [ 318.78038  245.47857 ]
Skew:              [ 0.00000 ]
Distortion:        [ -0.35941  0.17397  0.00033  -0.00109  0.00000 ]

Intrinsic parameters of left rectified image
Focal length:      [ 417.00000  417.00000 ]
                   [ 313.93555  247.79603 ]
Skew:              [ 0.00000 ]

Intrinsic parameters of right rectified image
Focal length:      [ 417.00000  417.00000 ]
                   [ 315.06720  247.79602 ]
Skew:              [ 0.00000 ]

Left rotation matrix
                          1    0.00597   -0.002713
R_L =              -0.00597          1     0.00034
                    0.00271  -0.000327           1

Right rotation matrix
                          1    0.00411     0.00383
R_R =              -0.00411          1   -0.000343
                   -0.00383   -0.00033           1
```

Fig. 3. Camera calibration parameters for the experiments.

Fig. 4 shows the rectified images using proposed rectification method 4 and conventional rectification methods 1, 2 and 3. Methods 1, 2, and 4 produced well-rectified images, but method 3 produced a rectified image with some vertical mismatches in the boundary areas caused by distortion. Although the proposed rectification, like method 3, lost pixels in the boundary area of the images, it corrected distortion and finely aligned stereo images. In addition, the rectified images of methods 1 and 2 only slightly differ, confirming that tangential distortion can be disregarded.

Fig. 5 illustrates the results of extracting depth maps from the rectified images. To extract the depth maps, we used semi-global matching (SGM) [12]. According to the figure, although the proposed rectification method lost boundary pixels, it removed the depth errors caused by the vertical mismatches of method 3.

Table II shows the number of operations according to the image resolution. The proposed rectification method reduced the number of operations dramatically by replacing the complex matrix calculation with simple accumulation based on the feature of the difference sequence and by skipping the division operation of (1), which negligibly affected the rectification results.

TABLE II. Number of Operations

Model	Image Resolution	Number of Operations		
		Addition	***Multiplication***	***Division***
1	640x480	7,065,600	11,980,800	614,400
	1280x720	21,196,800	35,942,400	1,843,200
	1920x1080	47,692,800	80,870,400	4,147,200
2	640x480	4,608,000	7,065,600	614,400
	1280x720	13,824,000	21,196,800	1,843,200
	1920x1080	31,104,000	47,692,800	4,147,200
3	640x480	2,764,800	2,764,800	614,400
	1280x720	8,294,400	8,294,400	1,843,200
	1920x1080	18,662,400	18,662,400	4,147,200
4	640x480	1,855,680	36,480	-
	1280x720	5,548,320	54,720	-
	1920x1080	14,284,800	82,080	-

V. Conclusion

This paper proposed a new rectification method for stereo matching that simplifies computational complexity using two approaches. First, we replaced the complex matrix computation of conventional rectification with simple accumulation using the feature of difference sequence. Then we used empirical approximations to simplify the rectification computation. The proposed rectification method generated almost the same rectified images as conventional rectification methods with radial distortion correction, but it dramatically reduced computation complexity.

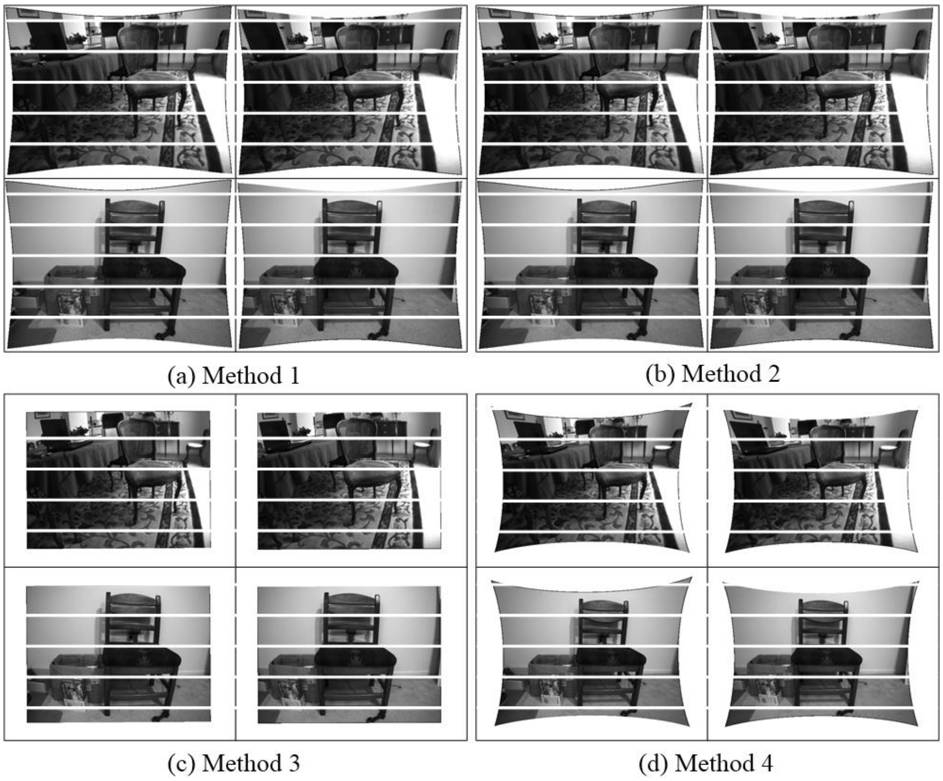

Fig. 4. Rectified images of the proposed and conventional rectification methods.

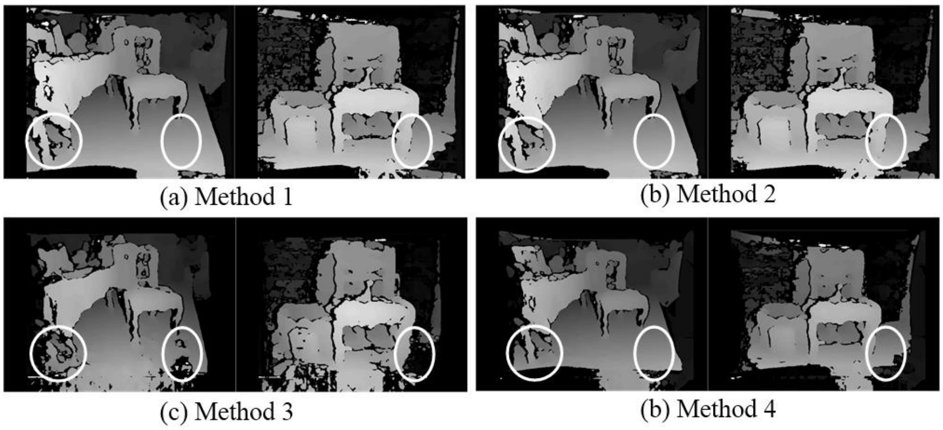

Fig. 5. Depth maps from the rectified images of the proposed and conventional rectification methods.

REFERENCES

[1] K. Sabe, M. Fukuchi, J.-S. Gutmann et al., "Obstacle Avoidance and Path Planning for Humanoid Robots using Stereo Vision," in Proc. of International Conference on Robotics and Automation (ICRA), 2004.

[2] A. Chilian and H. Hirschmuller, "Stereo Camera based Navigation of Mobile Robots on Rough Terrain," in Proc. of International Conference on Intelligent Robots and Systems (IROS), 2009.

[3] N. Kaempchen, U. Franke, and R. Ott, "Stereo Vision based Pose Estimation of Parking Lots using 3D Vehicle Models," in Proc. of Intelligent Vehicle Symposium (IV), 2002.

[4] J. Gluckman and S.K. Nayar, "Rectified Catadioptric Stereo Sensors," IEEE Trans. Pattern Anal. Mach. Intell., vol.24, pp. 224-236, February 2002.

[5] K. Jawed, J. Morris, T. Khan et al., "Real Time Rectification for Stereo Correspondence," in Proc. of International Conference on Computational Science and Engineering (CSE), 2009.

[6] http://www.vision.caltech.edu/bouguetj/calib_doc/

[7] R.Y. Tsai, "A versatile camera calibration technique for high-accuracy 3D machine vision metrology using off-the-shelf TV cameras and lenses" IEEE J. Robot. Autom., vol. 3, pp.323-344, August 1987.

[8] A. Fusiello, E. Trucco, and A. Verri, "A compact algorithm for rectification of stereo pairs," Mach. Vis. Appl., vol. 12, pp. 16-22, March 2000.

[9] S. Jin, J. Cho, X. D. Pham et al., "FPGA Design and Implementation of a Real-Time Stereo Vision System," IEEE Trans. Circuits Syst. Video Technol., vol. 20, pp. 15-26, January 2010.

[10] J. Hyun and B. Moon, "A Simplified Rectification Method for Efficient Hardware Implementation," in Proc. of International Workshop on Advanced Computing and Multimedia Technology (ACMT), 2015.

[11] http://boofcv.org/

[12] H. Hirschmuller, "Stereo Processing by Semiglobal Matching and Mutual Information," IEEE Trans. Pattern Anal. Mach. Intell., vol. 30, pp. 328-341, February 2008.