Implementation of 3D Stereo Image Capture System Based on Multi-Segmented Method

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ABSTRACT

In this paper, we suggest a new modeling of CMOS camera by using combinations of several pinhole camera models and check its validity by using synthesized stereo images based on OpenGL software. We introduce 3D image capturing hardware system built in my laboratory which consists of 5 motor controller and two CMOS camera module based on S3C6410 processor. We choose 9 segmentations and propose the method to find optimal alignment and focusing based on the measure of alignment and sharpness and propose the synthesizing fusion with the optimized 9 segmentation images for the best 3D depth feeling. From the experimental results concerning disparity values in each 9 segments, we can assure that the multi-segment method proposed in this paper may be one of good methods which improve the better feelings of 3D depth in stereo image.

Keywords: Pinhole, Segmented Image, Multi-segment, Disparity, CMOS camera module

1. INTRODUCTION

3D reconstruction from 2D images is an active research topic in the computer vision community. Some recent works are focused on interactive 3D reconstruction algorithms. The CMU 3D room propose an algorithm for view-dependent nonuniform sampling for image-based rendering. This algorithm may be needed for making a good 2D image for many viewers when each of them has his own different geometric view plane[1]. A taxonomy and evaluation system proposed by D. scharstein [2] is widely used in evaluating the disparity accuracy in stereo matching algorithms with a set of benchmark image data sets. There has been many researches for estimation of optical flow especially for estimating of an object by using 2D images under the assumption that the light source is invariant with respect to movement of the object which is not true in real life. Fleet and Weiss provide a tutorial introduction to gradient based optical flow [4] [5] under a image constraint equation which is not always true in 2D image. The perceived depth seen in a stereoscopic images varies not only with many geometric parameters but also with the many parameters with human eye such as separation between two eyes and focusing of each eye. It is well known fact that there is a limit to the range of perceived depth. Human can not detect the depth difference between two objects if two objects are located beyond 350m from the viewer. So it is useless to consider the scene depth of object if its distance is very far from the viewer. This is the reason why the research should be done concerning relationship and optimal mapping between scene depth and perceived depth for the best implementation of stereoscopic image. N.Hollman address this problem and propose multi-region algorithm and this algorithm allows different regions of the scene to be mapped to the different ranges of perceived depth on a target 3D display [6]-[8].

Fig. 1. Image capturing system

We also proposed new mapping algorithm between scene depth and perceive depth [9]. In this paper, we propose a theoretical and technical ideas for developing a 3D stereo video camera system based on previous research works. We comments on the important geometric parameters for synthesizing fusion with the multi-captured images. We simulate our research with OpenGL software to obtain 9 segmentation of the scene with the assumption that human do not rotate his head and just rolling his eye to watch the scene. We calculate and decide geometric parameters based on this assumption for obtaining virtual 9 segmentations of the scene. We introduce the 5 degree of freedom(DOF) stereo camera system which is the first version of our laboratory, as shown in figure 1. We use 4 DC servo motor and one stepper motor for mechanical control. We also develop a control algorithm to align the two left and right camera capture system by measuring the offset distances. We begin with a brief review and mathematical preliminary for the technology and theory for 3D image processing and propose an decision algorithm whether an object is within the trapezoidal region or not and also comment on the projection theory. In section 3, we discuss the technical issue for calibration and suggest a simple control law for adjusting the focus and alignment for capturing several segmentations of image. We also propose a new performance index measure for focus and alignment problem in capturing the left and right images. In section 4, we suggest simple fusion algorithm to make a whole 3D stereo image from the several segments of image which are captured by stereo camera system operating with the proposed control algorithm. In section 5, we simulate our proposed algorithm with the virtual objects synthesized on circular polarized LCD screen by using OpenGL programming and we also introduce the hardware system and comment on the disparity. We conclude with a summary of this paper and a discussion of planned future work.

2. Mathematical Preliminary

In this section, we introduce the mapping theory that is necessary to understand and design the parameters for the 2D projection view of 3D object. In stereo vision signal processing, we should synthesize the 3D object into the 2D circular polarized LCD screen. The key idea is that planar mapping function is dependent on the geometric parameters between LCD and the eyes of human who is sitting in front of LCD. This is the reason why we comments on the geometric parameters between object and camera. We insist that this geometric parameters play very essential role for synthesizing a good quality of 3D stereo image. Now we introduce the mathematics for projection process from the 3D image space to 2D image plane for synthesizing 3D stereo image into 2D polarized LCD screen. We also propose the algorithm whether or not a point is inside of trapezoidal region to decide whether a point should be considered or not in synthesizing a 3D stereo image.

A. Geometric Parameters

The geometric coordinate relation between the eye of the viewer and virual LCD screen can be expressed as follows.

$$T_{se}\begin{pmatrix} x_s \\ y_s \\ z_s \end{pmatrix} = \begin{pmatrix} x_e \\ y_e \\ z_e \end{pmatrix} \quad (1)$$

where

$$T_{se} = R_{(x,-\theta_x)}R_{(y,\theta_y)}T_{(y,-d_y)}T_{(x,-d_x)}T_{(z,-d_z)} \quad (2)$$

In this paper, the virtual LCD denotes the 2D screen window through which a viewer watch the objects and we should synthesize this virtual scene into real LCD screen located at with the same orientation and position as those of virtual LCD. The scene synthesized with this suggested method is the the optimized scene under the assumption that a person is going to watch this scene with the same geometric relation with real LCD screen. In there, (x_s, y_s, z_s) denotes the coordinate of the virtual LCD screen coordinate system and (x_e, y_e, z_e) denotes the coordinate of the eye coordinate system of the viewer as shown in figure 2. The main problem to solve in this paper is to obtain the equation that makes the objects which is behind the virtual LCD to be projected onto the virtual LCD screen in the the direction of the eye view point of viewer. We define the trapezoidal region $\Re$ which will be projected onto the virtual LCD by using the 4 corner points p_1, p_2, p_3, p_4 and the range of scale k as follows in the eye coordinate system.

$$\Re = trapezoidal(p_1, p_2, p_3, p_4, k) \quad (3)$$

The trapezoidal region $\Re$ is shown in figure 3. In the next subsection, we propose an algorithm whether a point is within the trapezoidal or not.

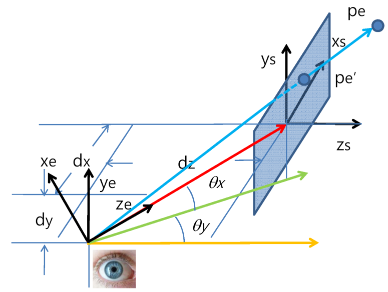

Fig. 2. Geometric Parameters

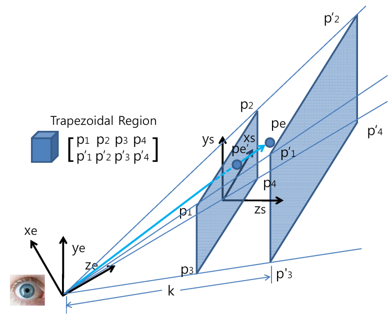

Fig. 3. Trapezoidal Region

B. Belonging Decision Algorithm

In this subsection, we propose an algorithm whether or not a point is inside of trapezoidal region to decide whether a point should be considered or not in synthesizing a 3D stereo image. This algorithm is needed to make a stereo 3D image from the synthesized scene and objects made by OpenGL software. Let a point in side of trapezoidal be P_0 and its coordinate in eye coordinate system be (x_0, y_0, z_0). We try to find 6 planar equations for the trapezoidal with its value at P_0 be positive. The equation of each plane S_n is determined by any arbitrary three corner points of the corresponding surface of the trapezoidal. Let (a_n, b_n, c_n, d_n) be the parameter vector of each surface. Then the equation of each surface can be expressed as follow.

$$S_n(x, y, z) = a_n x + b_n y + c_n z + d_n = 0, \quad n = 1 \cdots 6 \quad (4)$$

Then we propose an algorithm whether a point is inside of trapezoidal or not as a theorem 1.

Theorem 1: If all the values of $S_n(x, y, z)$ at a point P are positive, then the point P is located inside of trapezoidal.

C. Projective Mapping Function

We propose a projective mapping as a theorem as follow under the assumption that a point is inside of trapezoidal region we are interested in. In here, we only consider a object which lie in side of the trapezoidal characterized by 4 vertex which denote the virtual LCD screen in the eye coordinate system and scale factor k expressed in equation (3).

Theorem 2: For a given 4 vertex p_1, p_2, p_3, p_4 with the scale factor k, the projective point p'_e of the a point p_e which is located

TABLE I
DYNAMIC RANGE OF CAMERA MODULE(UNIT: DEGREE)

θ_{LM}	θ_{RM}	θ_{MU}	θ_{MD}	θ_{LU}	θ_{RD}
-27.3	27.3	22.1	-22.1	33.3	-33.3

in the corresponding trapezoidal can be expressed as follow.

$$p_e' = P_{roj} p_e \tag{5}$$

Let p_s' is the corresponding coordinate of p_e' with respect to the coordinate system of virtual LCD screen. Then we obtain

$$p_s' = {P_{roj}}' p_s \tag{6}$$

where

$$P_{roj}{}' = T_{se}^{-1} P_{roj} T_{se} \tag{7}$$

and P_{roj} is the projective operation in the eye coordinate system with respect to trapezoidal region.

Proof: From the definition of T_{se} expressed in equation (2), we have

$$\begin{aligned} p_s' &= T_{se}^{-1} p_e{}' \\ &= T_{se}^{-1} P_{roj} p_e \\ &= T_{se}^{-1} P_{roj} T_{se} p_s \end{aligned} \tag{8}$$

Therefore, we prove equation(7). ■

3. EXPERIMENTAL ENVIRONMENT

We build the stereo camera system using advanced embedded system based on the ARM1176 MPU core and we use MS WinCE as a operating system for developing camera device driver and application program based on USB OTG for sending image data file to the host computer system that is operating under the Windows XP and we use the OpenGL as a software tool and implement the 3D stereo image on the circular polarized 17 inch LCD Screen. We use the OV3640 CMOS camera module as key element for stereo image capture system. The main feature of the CMOS camera module is that the depth of field(DOF) is enough to have all the objects in the scene to be in focus when the objects are located 20cm far from the CMOS camera. We try to obtain the geometric parameters and the relations between camera capture system and 3D circular polarized LCD display system to make comfortable 3D real time video play. We assume that only one person is watching at center and 50cm in front of LCD which is 33.5cm width and 27.0cm height. We also assume the distance of the left eye and right eye of a person is 6.0 cm. In our camera capture system, we set the distance between the right and left camera as 6cm. The following table I shows the dynamic range of the view angle of OV3640 CMOS camera module which we find by analyzing the standard captured image set in our laboratory. Its dynamic range is enough to capture the left and right camera images for synthesizing its stereo 3D image on the 3D circular polarized LCD by using image processing and OpenGL programming.

A. Calibration of Pinhole Camera

In this paper, we briefly discuss about the calibration of pinhole under the assumption that the eye mechanism of human and the camera module we use in experiment are very similar to the pinhole camera[10]. The geometric relation among world

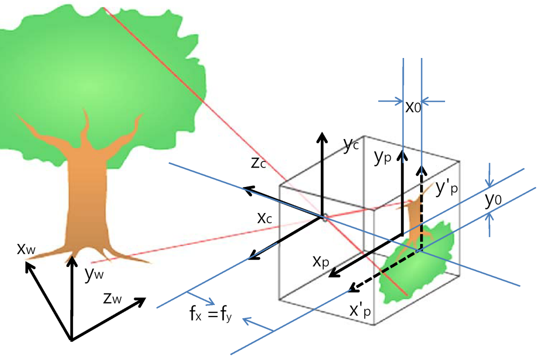

Fig. 4. Geometric Parameters of Pinhole Camera

coordinate system, camera coordinate system and pixel image coordinate system are shown in figure 4. Usually the focal length f_x and f_y of real camera module are not exactly the same and has a asymmetric optical property which is expressed by parameter γ between x and y axis in camera coordinate system. Also there exist a little planar offset (x_0, y_0) in pixel image coordinate system because of the misalignment between camera coordinate system and pixel image coordinate coordinate system. Let the 2D position in pixel image coordinate system and the 3D position in world coordinate system be $(u\ v\ 1)^T$ and $(x_w\ y_w\ z_w\ 1)^T$ by using notation of Homogeneous coordinate. Then we obtain following equation.

$$\begin{pmatrix} u z_c \\ v z_c \\ z_c \end{pmatrix} = A_{cp} A_{wc} \begin{pmatrix} x_w \\ y_w \\ z_w \\ 1 \end{pmatrix} \tag{9}$$

where

$$A_{cp} = \begin{pmatrix} f_x & \gamma & x_0 \\ 0 & f_y & y_0 \\ 0 & 0 & 1 \end{pmatrix}, \quad A_{wc} = (R : T) \tag{10}$$

and R and T are 3×3 rotational matrix and 3×1 translational vector between world coordinate system and camera coordinate system. The calibration problem in pinhole camera is to find the parameters for matrix A_{cp} and A_{wc}. The number of parameters of A_{cp} and A_{wc} are 5 and 6 respectively. Therefore the calibration problem in pinhole camera is to find or estimate these 11 parameters. In general case, CMOS camera module is designed and manufactured so that the values of f_x equals to f_y and γ, x_0 and y_0 should be near to zero. In this paper, we assume that the values of f_x equals to f_y and x_0 and y_0 s are zero. In this case, the calibration problem is to find and calculate f_x and the 6 parameters of A_{wc}. Therefore, we try to control a camera system such that

$$\begin{aligned} A_{wc}^L &= \begin{pmatrix} 1 & 0 & 0 & +3 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \\ A_{wc}^R &= \begin{pmatrix} 1 & 0 & 0 & -3 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \end{aligned} \tag{11}$$

where A_{wc}^L and A_{wc}^R denote the A_{wc} for left and right camera module and 3 means 3cm in above matrices.

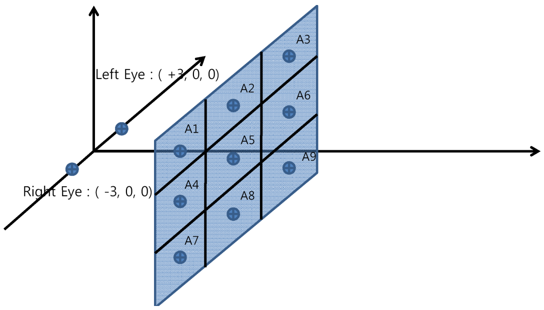

Fig. 5. Segmentation of Image

TABLE II
ANGLE PARAMETERS OF HUMAN EYE. UNIT : DEGREE

Segmentation	θ_{L1}	θ_{L2}	θ_{R1}	θ_{R2}
LT	11.7	11.1	18.1	10.8
CT	-3.4	11.3	3.4	11.2
RT	-18.1	10.8	-11.7	11.1
LM	11.7	0	18.1	0
C	-3.4	0	3.4	0
RM	-18.1	0	-11.7	0
LB	11.7	-11.1	18.1	-10.8
CB	-3.4	-11.3	3.4	-11.3
RB	-18.1	-10.8	-11.7	-11.1

B. Zooming and Alignment

We try to obtain and use 9 images from each left and right camera capture system for synthesizing fusion 3D image for the more comfortable 3d depth feeling. The geometric view of each segmentation of 9 image can be shown in figure 5. Each image is a captured projected image of left or right camera which is adjusted optimally with alignment and focusing of corresponding segmentation. In later, this 9 segmented images are synthesized for making one whole image. By considering the dynamic range of the rotation of human eye shown in table II, we choose the following pairs of dynamic range of each image shown in table III and we developed a control algorithm for finding the exact optimal capturing angles based on the sharpness of stereo images for each segmentation images and record the angle and distance offset parameters for rendering later. The angle parameters of human eye can be expressed as follows under the assumption that human right and left eyes are located at $(-3,0,0),(3,0,0)$ respectively.

$$\begin{aligned} \theta_{R1} &= atan2(x+3,z) \quad (12) \\ \theta_{R2} &= atan2(y,\sqrt{(x+3)^2+z^2}) \\ \theta_{L1} &= atan2(x-3,z) \\ \theta_{L2} &= atan2(y,\sqrt{(x-3)^2+z^2}) \end{aligned}$$

Segmentation symbols of each images are left-top(LT), center-top(CT), right-top(RT), left-middle(LM),center (C), right-middle(RM), left-bottom(LB), center-bottom(CB),right-bottom(RB) respectively. In the above table, $\theta_{L1},\theta_{L2},\theta_{R1},\theta_{R2}$ denote the left-right, up-down rotating angle of the left and right camera capture system respectively. In this paper, we assume that a person who watches the synthesized LCD screen does not move his neck and just make rolling his eyes only. For more details, refer to [11].

TABLE III
DYNAMIC RANGE OF SEGMENTATION. UNIT : DEGREE

Segmentation	θ_{L1}	θ_{L2}	θ_{R1}	θ_{R2}
LT	(10,13)	(10,13)	(17,20)	(9,12)
CT	(-5,-2)	(+10,+13)	(2,5)	(10,13)
RT	(-20, -17)	(9,12)	(-13,-10)	(10,13)
LM	(10,13)	(-2,+2)	(17,20)	(-2,+2)
C	(-5,-2)	(-2,+2)	(+2,+5)	(-2,+2)
RM	(-20,-17)	(-2,+2)	(-13,-10)	(-2,+2)
LB	(10,13)	(-13,-10)	(17,20)	(-12,-9)
CB	(-5,-2)	(-13, -10)	(2,5)	(-13,-10)
RB	(-20,-17)	(-12,-9)	(-13,-10)	(-13,-10)

4. FUSION BASED ON INTERPOLATION

In this subsection, we propose a simple fusion method that make a whole stereo 3D image with the 9 segmented/captured images from the left and right camera module. The simple method is to crop each segmented image with the same size, such as 1/9 of whole LCD image area, based on the angle data which are acquired when the corresponding segmented image is captured. Under the assumption that the angle data are the same as those of eyes of person who watch the real LCD screen, we just union the same pixel size of each segmentation to make a whole image for left and right stereo images as follows.

$$I_w = \bigcup_{i=1,\cdots,9} Crop(I_{seg,i}) \quad (13)$$

where $I_{seg,i}$ denotes each captured segmented image and I_w denotes whole synthesized image. For example, let assume that the LCD Screen size is 1280×1024. Then we crop each segmented image into $(1280/3) \times (1024/3)$ size image around its center and then combine these 9 cropped images into a whole 1280×1024 image. We do this operation twice for obtaining left and right whole image. If the above assumption concerning the angle data is not satisfied, we should do adopt a filtering and smoothing signal processing with the captured images. In this case, we first calculate the geometric position vector $p_v = (x_v, y_v, z_v)$ of center pixel of each captured segmented image in virtual LCD screen based on the capturing angle data and also calculate the corresponding position $p_L = (x_L, y_L)$ in the real LCD screen. Then we crop the image as shown in figure 6 by considering this position p_L for each corresponding segmentation. In next future work, we try to find more advanced algorithm for interpolation of segmentation images for fusion.

5. SIMULATION AND EXPERIMENTAL RESULTS

We simulate our proposed algorithm based on the virtual objects made by programming with OpenGL software tool. We synthesize a 3D stereo image from the 9 segments of image captured by virtual left and right camera which is separated 6cm with each other. This separation length is the same length of distance between two left and right eyes of average person. We choose several cube as objects located around 1m behind of virtual LCD screen. In this simulation, we assume that a person who watch the synthesized image does not move and rotate his neck and moves only his eye balls. We use the angle parameters of human eye shown in table II for obtaining 9 segmentations of image. We also suggest a camera model for general CMOS camera. Camera model of general CMOS camera can be approximated as an image sum of several/many ideal pinhole cameras. Let I_{CMOS} and be the image of CMOS camera and let $I_{pin}(x,y,z)$ be the image

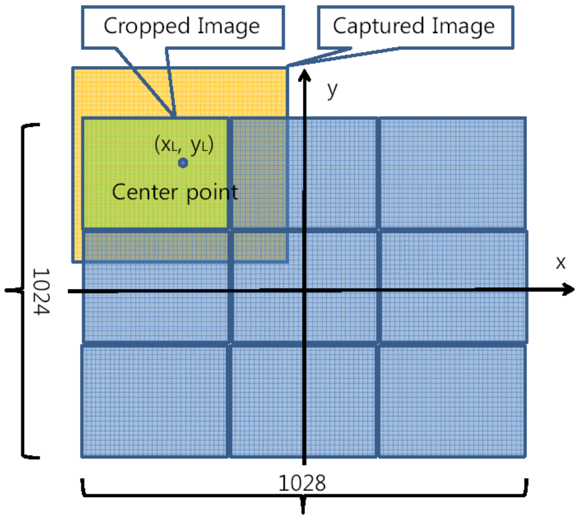

Fig. 6. Cropping and Union for Fusion

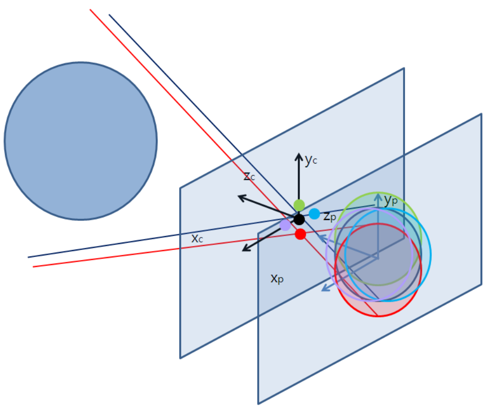

Fig. 7. CMOS Camera Model

of pinhole camera whose aperture is located at (x, y, z) from the center. We can approximate I_{CMOS} as follows by using several images obtained from the ideal pinhole cameras as shown in figure 7.

$$I_{CMOS} = \frac{1}{N} \sum_{i=1,N} I_{pin}(x_i, y_i, z_i) \tag{14}$$

For the simplicity of simulation, we assume that all the ideal pinhole cameras have the same focal length $f_{x0} = f_{y0}$ and share the same image plane and have the same aperture plane, that is, z components of aperture are the same. We obtain camera parameters of each pin hole camera as follows.

$$A_{cp,i} = \begin{pmatrix} f_{x0} & \gamma & x_{i0} \\ 0 & f_{y0} & y_{i0} \\ 0 & 0 & 1 \end{pmatrix}, A_{wc,i} = \begin{pmatrix} 1 & 0 & 0 & -x_{i0} \\ 0 & 1 & 0 & -y_{i0} \\ 0 & 0 & 1 & 0 \end{pmatrix} \tag{15}$$

From the above equation, we can see the above transformation is not linear with respect to aperture offset x_{i0} and y_{i0}. This kind of nonlinear effect makes it difficult to find a good preprocessing method for the captured CMOS camera image. In this paper, we set N as 5 for the simplicity of simulation and $(x_i, y_i), i = 1, \cdots, 5$ be center point and 4 corner points of rhombus around the center of aperture. We set the distance of a vertex of rhombus d from the center as 0.1[mm] in this paper. We set the focal length f_{x0} as 5[mm]. Therefore the percentage of the aperture offset compared with focal length is about 2 % in this simulation. We use the OpenGL real time graphics as a software tool. The test scene consists of same size of 19 cubes and 2 axes. The width, length and height of cube are 8cm each and surrounding 8 cubes are located 12cm far from the centered cube on each axis. We assume that distance between 3D LCD screen and human viewer is 50cm and the distance between the centered cube and human viewer is about 100cm. So we set the near and far clipping planes into the z-axis as follows.

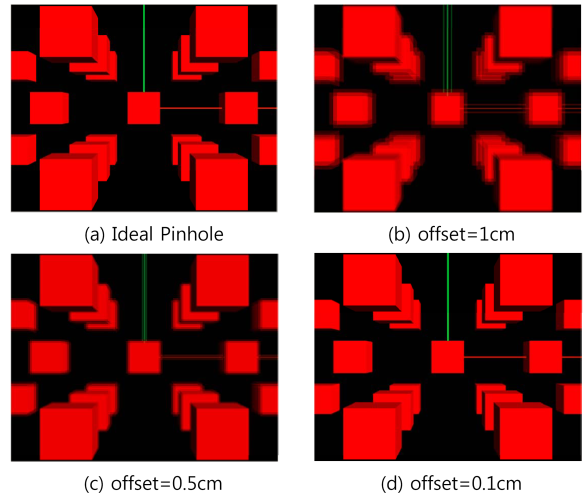

Fig. 8. Performance of pinhole models

$$z_n = -50cm \quad z_f = -200cm$$

Next we move the cubes 100cm in the direction of negative z-axis by using glTtranslatef() API function of OpenGL. Figure 8 shows the image captured by using one ideal pin hole camera and the image synthesized by using 5 ideal pin hole camera model proposed above when the distance of a vertex of rhombus d from the center are 10.0, 5.0, 1.0[mm] respectively. We also calculate the difference of the image in region of interest $R_{ROI}$by using the following equation.

$$I_d = \sum_{(i,j) \in R_{ROI}} |I_{d,RGB}(i,j)| \tag{16}$$

where $I_{d,RGB}(i,j)$ means the absolute sum of difference of RGB color components in pixel $p(i,j)$ between two images. We select R_{ROI} as one segmentation (about 420×330 pixel size window patch) around the center of synthesized images. The simulation results in this region of interest are shown in table IV. From the data in table IV, we can see that the proposed CMOS camera module can be used for synthesizing general CMOS camera whose characteristics are very similar to the ideal pinhole camera. From the simulation results, we can simulate the general CMOS camera by choosing appropriate number of pinhole camera model and selecting appropriate offset value. We found that 1.0[mm] is appropriate for offset value in simulating CMOS camera model. Also another important characteristic of general CMOS camera is that the resolution of image with respect to the solid angle is nonlinear. Its image resolution at solid angle zero is better and

TABLE IV

SIMULATION RESULTS OF CMOS CAMERA MODEL

offset [mm]	I_d	offset [mm]	I_d
10	2,502,362	2	645,503
5	1,365,189	1	300,149

Fig. 9. Centered segment

bigger than at any other angle. This is the same reason why we should control and focus our eye on an object to see more clearly. When our eye is focused at an object, we can get larger image by rotating eye with the same amount of linear angle. It means that the sensitivity of our eye with respect to rotating angle is relatively high when it is focused at an object. Therefore the disparity of the left and right captured images depends on the alignment of the left and right camera module with respect to an object which we are interested in. The disparity d_L of the left and right image for some region of interest can be decided such that the two left and right images match as closely as possible as follow.

$$I_L(i,j) \approx I_R(i-d_L,j) \ for \ (i,j) \in R_{ROI} \qquad (17)$$

where $I_L(i,j)$ and $I_R(i,j)$ is the left and right captured images respectively. Figure 1 shows the experimental environment of capturing system. We use 1 step motor and 4 DC servos for control the left and right CMOS camera by using ATCAN1280 micro-processor. We develop a main embedded board by using S3C6410 which was designed by Samsung electronic company based on ARM1176 main CPU core and we added some hardware circuit for multiplexing its CMOS capturing function. Figure 9 shows synthesized 480x800 sized images of combined left and right images for a sample environment which has 1 box object in each 9 segment of LCD screen where ROI is the centered segment. The values of d_L in each segment are shown in table V. From the data shown in the table, we can see that the segment alignment method between camera module and object is very important for the realization of 3 D depth synthesizing. These are the main key experimental results. From the analysis of experimental results, multi-focusing image capturing system may improve the depth quality in 3D image processing.

TABLE V

DISPARITY TABLE OF CENTERED SEGMENT

(x,y)	d_L	(x,y)	d_L	(x,y)	d_L
(50,120)	-12	(50,400)	-11	(50,680)	-16
(220,120)	4	(220,400)	2	(220,680)	4
(390,120)	64	(390,400)	64	(390,680)	55

6. CONCLUSION

In this paper, we analyze the real experimental results obtained by using a fusion method to combine a whole stereo image from the 9 captured images. We also comment on the importance of the projective mapping for handling signal processing. We suggest real time 5 degree of freedom motor control system for capturing stereo images based on the measure of alignment and sharpness which is needed for calibrating camera module. In the next version, we will try to add 1 more DOF to each left and right camera module for zooming calibration by using voice coil motor. It is needed to have good knowledge concerning the geometric parameters not only in capturing a left and right image but also in synthesizing stereo image for designing of a good stereo vision system. We introduce mathematical preliminary which is needed to analyze and synthesize stereo image. We do simulate by using OpenGL software and get some results that verify the validness of our proposed algorithm. We have real experimental results based on ARM11 core embedded system. We capture nine segment stereo images and analyze the disparity parameters in each segment. From the analysis of 9 stereo segment images, we can see that this segmented method will be one of good methods for realization of the 3 D depth in stereo vision system. We will try to expand this method to more multiple segments than 9 segments for obtaining human-like vision capability.

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