Three-dimensional Shape Recovery from Focused Image Surface

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Abstract

A new method for the three-dimensional shape recovery from image focus is proposed. The method is based on approximation of the Focussed Image Surface (FIS) by a piecewise curved surface which tracks the realistic FIS in image space. The piecewise curved surface is estimated by interpolation using the Lagrangian polynomial. The new method has been implemented on a prototype camera system. The experiments and their results are provided and discussed. The experimental results show that the new method gives more accurate results than the previous methods.

Keywords: CCD camera, focus measure, Focused Image Surface (FIS), shape recovery

1. Introduction

Three dimensional shape recovery of objects is very important in image processing and computer vision. Many methods of 3-D shape recovery have been proposed for the past few decades in the literature. Among these methods, Shape from Focus (SFF) method is challengeable because it has good properties in terms of the correspondence problem and camera calibration.

Traditionally, a focus measure at each pixel position is computed in a small window around the pixel over image frames sensed by planar image detector [1][2][3][4][5]. Once the best focused image frame is found from focus measure, the object distance can be computed by using the lens formula equation. The traditional methods do not consider the fact that an image of 3-D object is also three dimensional in image space. This means that in order to increase the accuracy of shape recovery, a focus measure should be computed over realistic focused image surface in image space rather than over planar image frames. In 1995, Subbarao and Choi proposed an accurate SFF method based on Focused Image Surface (FIS) [6]. The method called SFF.FIS used a piecewise planar approximation for the shape recovery of simulated and real objects. The SFF.FIS method yielded more accurate results than the traditional method. In fact the SFF.FIS method gave some hints to extend our thought from 2-D plane to 3-D space. However, it still has some shortcomings in accuracy and computation. There are two main reasons for this. The first one is that the piecewise planar approximation causes errors in computation of the focused image from the lens plane because the actual FIS using the piecewise planar surface is not well approximated. The shape of a realistic FIS is arbitrarily curved rather than planar even in a small window around a target pixel. The second reason is that its computation cost is high because the whole cubic volume in image space is searched by each piecewise planar surface in order to compute focus measures.

In this paper, we propose a new method to improve the accuracy of depth estimation of a physical object surface. Our new method is based on approximation of the FIS by a piecewise curved surface, which tracks the realistic FIS in image space. The contribution of this method is that the accuracy of depth estimation of a physical object surface is increased as compared to the previous methods. The new method has been implemented on a prototype CCD camera system. A number of experiments were carried out to evaluate our method. The experiments and their results are provided and discussed. The experimental results show that the new method gives more accurate results than the previous methods.

2. Shape from Focus (SFF)

2.1 Focused Image Surface(FIS)

<Figure 1>

The Focused Image Surface (FIS) was defined in Subbarao and Choi’s paper [6]. According to paraxial-geometric optics, there is a one-to-one correspondence between the shape of an object and the shape of its FIS [6]. Figure 1 shows an object surface and the corresponding image surface of the object in image space. This surface is defined to be the FIS and the image points where FIS and image detector meet are completely focused. The geometry (i.e., the shape) and the radiance distribution of the object surface are uniquely determined by the FIS and the focused image. Therefore, the problem of shape recovery can be posed as the problem of finding the accurate shape of FIS.

In practice, we estimate the continuous FIS from the discrete sequence of image frames. So the step size between an image frame and the next one should be small enough to find the best focused position. But small step size causes the increase in the number of required images. It requires large memory space and computational costs. Note that this image step size problem is similar to the sampling theorem in signal processing.

2.2 Previous SFF Method (SFF.FIS)

The SFF.FIS method [6] that was previously proposed can be described as two phases. In the first phase of the SFF.FIS method, a traditional SFF method is used to find a rough estimate of FIS. An accurate FIS is found by using three-dimensional piecewise planar window for computing focus measure in the image sequences. It can be summarized as follows.

1) The image detector is first moved to $z = z_0$. An image, $g_i(x, y)$, is recorded by moving the image detector to positions $z_i = z_0 + i*d$ where d is a small displacement for $i = 0,1,2,\cdots,I-1$, $x = 0,1,2,\cdots,X-1$, and $y = 0,1,2,\cdots,Y-1$. Usually, $z_0 =$ focal length f, X and Y are the number of rows and columns respectively in each image frame, and I is the number of image frames

2) Compute the Laplacian operator at every point (x, y) on each image frame and record the

Laplacian image $L_i(x, y)$ for ith image frame. We call the sequence of Laplacian image $L_i(x, y)$ for all i as the Laplacian image sequence. Note that $L_{i_0}(x_0, y_0)$ is the Laplacian value at the image point (x_0, y_0) of the i_0th image frame. That is, the coordinate of the image sequence and the Laplacian image sequence are corresponding.

3) To get a rough estimation, a traditional SFF method is used. In this method Laplacian values on overlapping windows of size $(2N+1)\times(2N+1)$ (N is about 7) centered at point (x, y) of the Laplacian image $L_i(x, y)$ are used to compute the focus measure of image point (x, y) of the ith image frame position. For each window, the image frame number for which the sum of Laplacian values is a maximum over all the image frames is determined. So the image frame number thus found determines a rough estimate of FIS.

4) In the second phase of the algorithm, the initial estimate of FIS is refined as follows. In this phase, the entire original image sequence g_i containing I image frames is used. For every window in which the FIS was estimated in the first step, a small cubic volume (about the size of $(2N+1)^3$) image space is considered in the image sequence. The volume is centered at the initial estimate of FIS in that window. Now, in this volume, a search is made for a planar window, which is closest to the actual FIS, by maximizing the focus measure computed over the planar search window. The initial estimates of position and orientation of the FIS are used as starting values during the search process.

<Figure 2>

In SFF.FIS method, piecewise planar window in image sequences, which estimates the actual FIS, is used to compute focus measure (see Figure 2). However the piecewise planar approximation of FIS does not give accurate result when the surface of the object has complex geometry. Because the shape of an object and it's FIS are arbitrarily curved (not plane) even in a relatively small window around a target pixel. In addition, if the window size is decreased to fit for piecewise planar approximation of FIS, the window does not contain sufficient information to compute focus measure. Determining the window size also has close relationship with the texture strength of an image.

3. New Method Using Piecewise Curved Surface

In this section we will propose a new SFF method which is based on approximation of FIS by a piecewise curved window that tracks the realistic FIS in image space. The idea of the new SFF method came from FIS concept like as SFF.FIS, but piecewise curved windows are used to estimate FIS because the piecewise planar approximation is not suitable for objects with complex geometry.

<Figure 3>

To find the piecewise curved window that tracts the shape of FIS in an appropriate window range, various shape functions can be considered – e.g. Spline, Bezier, etc. But in our shape recovery problem the shape of the object in real world can not be measured exactly. So we only find numerical expressions which approximate the overall trend of the FIS surface very well in a given small window area. Through considerate inspection of FIS, we can find the fact that the curvature of FIS shape in a concerned window area is not of a high order. It means that piecewise curved window determined by some low order surface function is suitable for small patches of FIS. So in this paper we simply adapted second order Lagrange Polynomial equation [7]. Consider a small window in the image space centered around (x, y). If we select nine points $(x+p, y+q, i_{x+p,y+q})$ where $p = -N, 0, N$ and $q = -N, 0, N$ obtained by rough depth estimation $i_{j,k}$ on the window as shown in Figure 3, we can interpolate a piecewise curved window $S(p, q; x, y)$ centered at (x, y). The algorithm that computes curved window $S(p, q; x, y)$ to calculate focus measure by using Lagrange Polynomial [7] can be realized as below:

$p_{-1} = -N, \quad p_0 = 0, \quad p_1 = N$

$q_{-1} = -N, \quad q_0 = 0, \quad q_1 = N$

for $p = p_{-1}$ to p_1 do /* for x coordinate */

$P_{-1} = \{(p - p_0)\times(p - p_1)\}/\{(p_{-1} - p_0)\times(p_{-1} - p_1)\}$

$P_0 = \{(p - p_{-1})\times(p - p_1)\}/\{(p_0 - p_{-1})\times(p_0 - p_1)\}$

$P_1 = \{(p - p_{-1})\times(p - p_0)\}/\{(p_1 - p_{-1})\times(p_1 - p_0)\}$

$s_{-1} = P_{-1}\times i_{x+p_{-1},y+q_{-1}} + P_0\times i_{x+p_0,y+q_{-1}} + P_1\times i_{x+p_1,y+q_{-1}}$

$s_0 = P_{-1}\times i_{x+p_{-1},y+q_0} + P_0\times i_{x+p_0,y+q_0} + P_1\times i_{x+p_1,y+q_0}$

$s_1 = P_{-1}\times i_{x+p_{-1},y+q_1} + P_0\times i_{x+p_0,y+q_1} + P_1\times i_{x+p_1,y+q_1}$

for $q = q_{-1}$ to q_1 do /* for y coordinate */

$Q_{-1} = \{(q - q_0)\times(q - q_1)\}/\{(q_{-1} - q_0)\times(q_{-1} - q_1)\}$

$Q_0 = \{(q - q_{-1})\times(q - q_1)\}/\{(q_0 - q_{-1})\times(q_0 - q_1)\}$

$Q_1 = \{(q - q_{-1})\times(q - q_0)\}/\{(q_1 - q_{-1})\times(q_1 - q_0)\}$

/* piecewise curved window by Lagrange polynomial */

$S(p,q;x,y) = Q_{-1} * s_{-1} + Q_0 * s_0 + Q_1 * s_1$

end /* y loop */

end /* x loop */

Note that changing $i_{x+p_a,y+q_b}$ can make various curved windows.

The rough estimate of FIS from the traditional SFF method is used as the initial position of nine control points. By changing the initial position of nine control points about ±1 or ±2, curved windows for search of FIS are estimated. The focus measure is then computed by summing the Laplacian values on these curved windows. Finally the center depth position of curved window which gives the maximum focus measure is the accurate FIS position of each image point. Note that, since the piecewise window becomes planar window when all nine control points are on one plane, so our new method inherently includes SFF.FIS method.

4. Implementation and Experiments

The proposed algorithm was implemented on a camera system called KACS (K-JIST Active Camera System). Figure 4 shows the block diagram of KACS. As shown in Figure 4, KACS consists of a CCD camera, a motorized lens, DC motor driver, PC I/O interface board, image grabber board, and SUN Ultra SPARC-1. The grabber board receives image signal from CCD camera. Then the image frames are processed and stored in Pentium PC and transferred to SUN Ultra Spac-1 for further processing. I/O interface board is used to control DC motor control unit. The image step, numbered 0 to 96, is controlled through the motor interface by the program residing in the PC. Step number 0 corresponds to focusing an object at far distance and step number 96 corresponds to focusing a nearby object at a distance of about 1m from the principal plane of camera lens so that the whole FIS of the object lies in the image sequence. The camera settings with those objects were as follows: focal length=51mm, F-number=1.2. The image size used in the experiments was 256 by 256 in pixel.

<Figure 4>

For good experiments, following factors should be considered:

- Sufficient edge information on image.
- Depth of field (DOF) of camera
- Image step interval

Two experiments were conducted for a simulated cone object and a real cone object. The simulated cone object is necessary to verify our new SFF algorithm. For the real cone object, the point of comparison is the tip of the cone. The sharper is the better, because the tip of the real cone is sharp. Here we present the results for the objects. Figure 5 shows the ideal tip and surface of the simulated cone.

<Figure 5>

<Figure 6>

<Figure 7>

The images of simulated cone object at various steps are shown in Figure 6. Figure 7 (a) and (b) show the results for a simulated cone object to compare our new method and the SFF.FIS method. As shown in Figure 7 (a) and (b), the tip of the cone is shaper and the surface of the cone is smoother in case of our new SFF method as compared to the SFF.FIS method. To compare the results from two methods, smoothness and RMS error have been considered. The smoothness of surface is compared by using norm of surface that is defined as

$$e_{st} = E\left[\sum_x \sum_y \left\{ \begin{array}{l} \left(S(x+1,y) - 2S(x,y) + S(x-1,y)\right)^2 \\ + 2\left(S(x+1,y+1) - S(x,y+1) - S(x+1,y) + S(x,y)\right)^2 \\ + \left(S(x,y+1) - 2S(x,y) + S(x,y-1)\right)^2 \end{array} \right\}\right] \tag{1}$$

where $S(x,y)$ is the estimated depth and $E[\cdot]$ is the expectation.

The norm of surface is commonly used as the constraint for smoothness in curve fitting analysis. The equation (1) looks like sum of various second-order derivatives. If the roughness of surface, i.e. geometric change of $S(x,y)$, is increased, e_{st} is increased. So we can infer that smooth surface has small norm of surface. Table 1 shows that the surface of depth estimate from our new method is smoother than that from SFF.FIS method. The RMS errors from two methods for a simulated cone are shown in Table 2.

From these results we can see that our new method gives more accurate results than the SFF.FIS method.

<Table 1>

<Table 2>

The real cone object of length 90cm and base diameter 14cm is made by hardboard. Black and white strips were drawn on it so that dense textures of ring patterns are viewed. Each picture of Figure 8 was taken at different lens steps. As shown in the pictures, only a part of cone surface is in focus and elsewhere it is out of focus. The sharply focused area in the picture moves as the step changes forward or backward.

<Figure 8>

Figure 9 (a) and (b) show the results for the real cone object. Particularly the tip of the cone is sharper and closer to the original shape of the object in the case of the new method as compared to the previous one.

<Figure 9>

5. ACKNOWLEDGEMENTS

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6. Conclusions

A general form of search window for SFF method based on a piecewise curved surface has been proposed. Especially the Lagrange Polynomial has been used to estimate the piecewise curved surface for finding a depth map of cone objects. The experimental results indicate that our new SFF method provides more accurate results than the previous one.

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Figure Captions

Figure 1. Focused Image Surface (FIS) in image sequences.

Figure 2. An example of planar window in image sequences.

Figure 3. Nine control points in image space.

Figure 4. KACS: K-JIST Active Camera System.

Figure 5. A simulated cone object.

Figure 6. Simulated cone images at (a) step 20, (b) step 40, (c) step 60, and (d) step 80.

Figure 7. 3-D Depth maps for a simulated cone object by (a) the previous method (SFF. FIS) and (b) the new method.

Figure 8. Real cone images at (a) step 20, (b) step 40, (c) step 60, and (d) step 80.

Figure 9. 3-D Depth maps for a real cone object by (a) the previous method (SFF.FIS) and (b) the new method.

Figures

Figure 1

↑ up

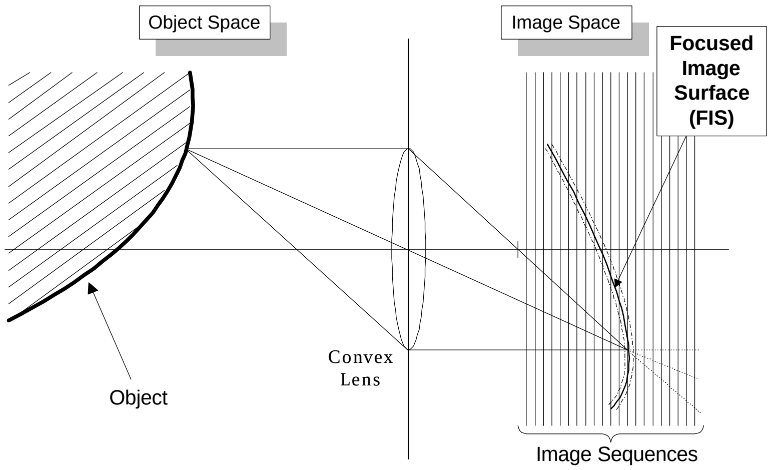
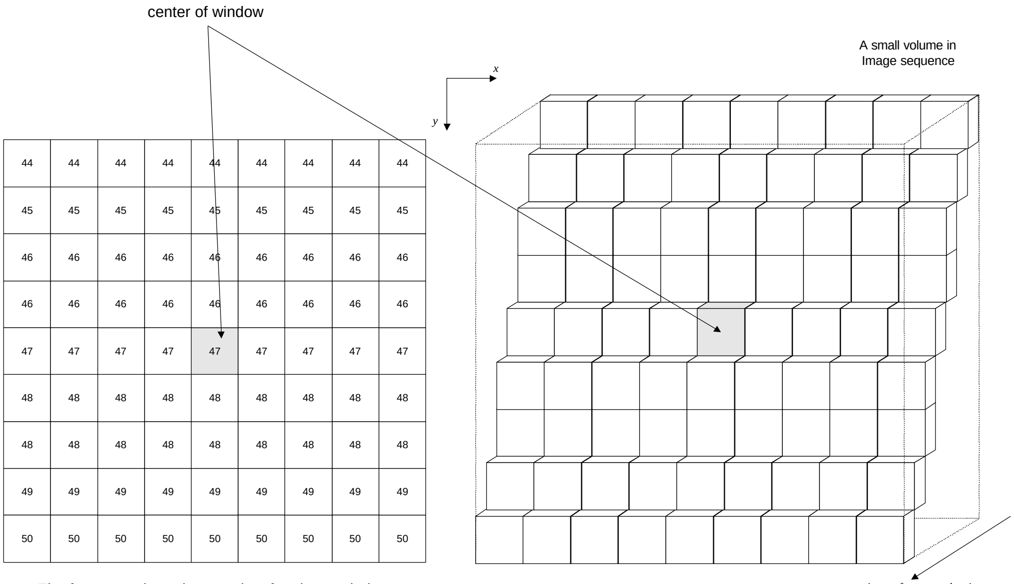


Figure 2

↑ up



The frame numbers that consist of a planar window in the image sequence

planar window in the image sequence

Figure 3

↑ up

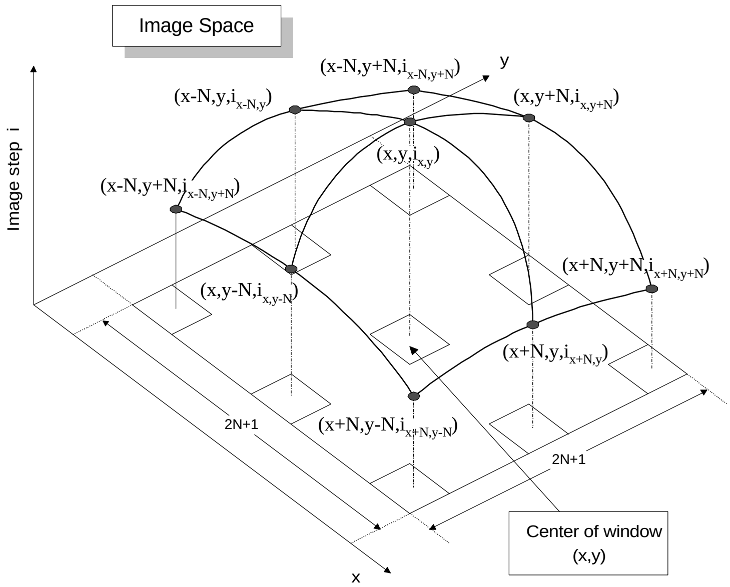


Image Space
Image step i
y
x
(x-N,y+N,i_{x-N,y+N})
(x-N,y,i_{x-N,y})
(x,y+N,i_{x,y+N})
(x,y,i_{x,y})
(x-N,y+N,i_{x-N,y+N})
(x+N,y+N,i_{x+N,y+N})
(x,y-N,i_{x,y-N})
(x+N,y,i_{x+N,y})
(x+N,y-N,i_{x+N,y-N})
2N+1
2N+1
Center of window
(x,y)

Figure 4

↑ up

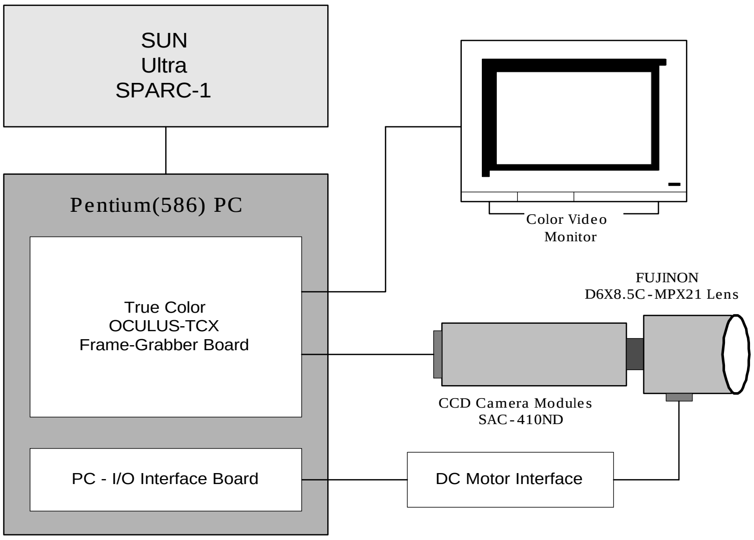

SUN
Ultra
SPARC-1
Pentium(586) PC
True Color
OCULUS-TCX
Frame-Grabber Board
PC - I/O Interface Board
Color Video
Monitor
FUJINON
D6X8.5C-MPX21 Lens
CCD Camera Modules
SAC-410ND
DC Motor Interface

Figure 5

↑ up

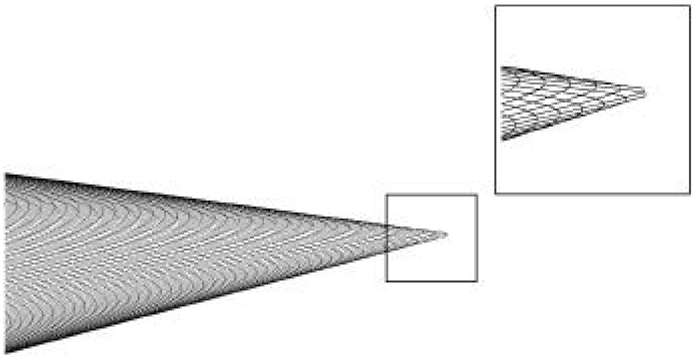


Figure 6

↑ up

(a)

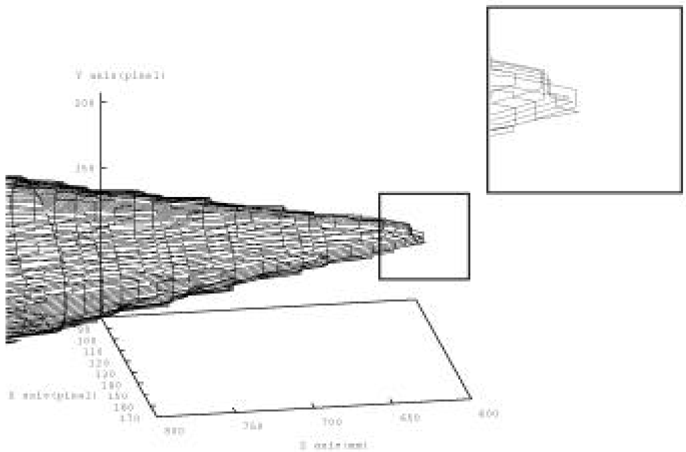
(b)

(c)

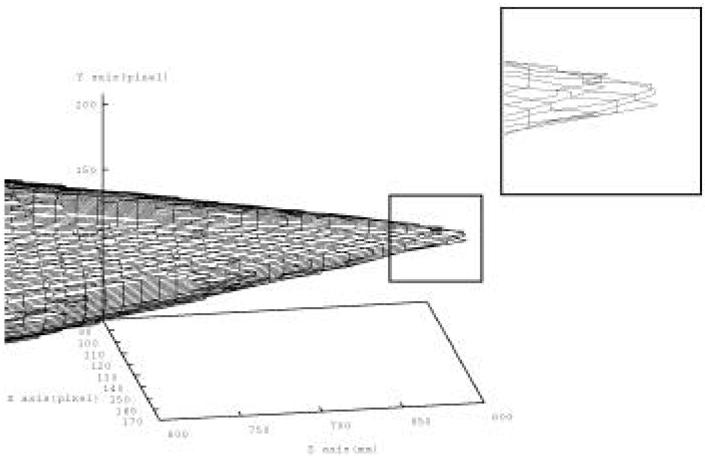
(d)

Figure 7

↑ up



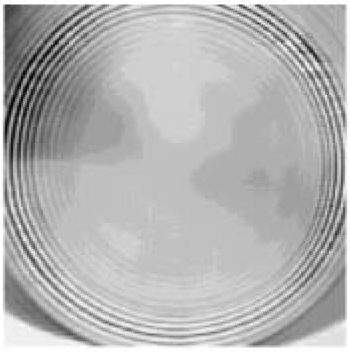
(a)



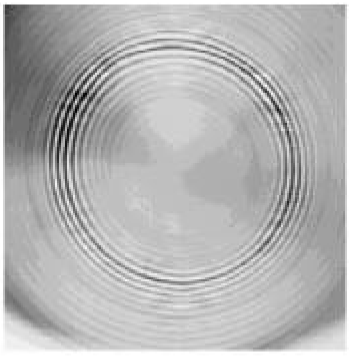
(b)

Figure 8

↑ up



(a)



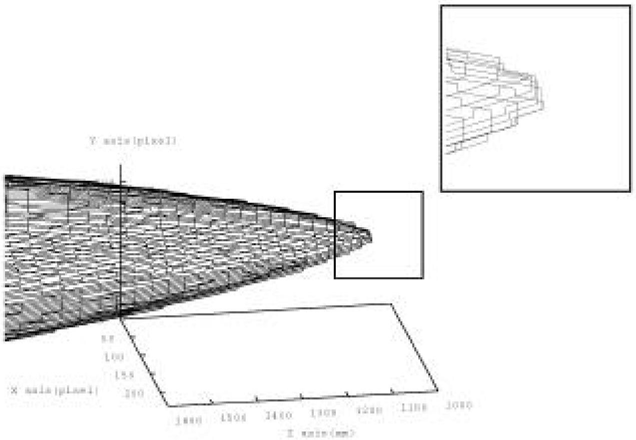
(b)

(c)

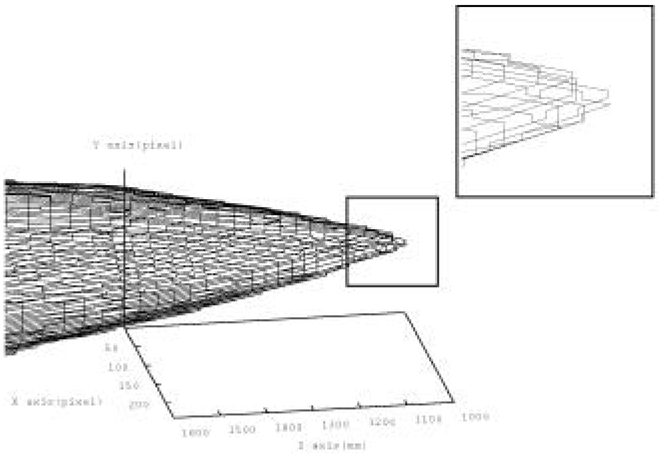
(d)

Figure 9

↑ up



(a)



(b)

Table Captions

Table 1. Smoothness of depth map results.

Table 2. RMS Error of depth map results

Tables

Table 1

	SFF.FIS Method	New Method
Smoothness e_{st}	5.342	2.417
Number of test points: 2209 pixels		

Table 2

	SFF.FIS Method	New Method
RMS Error	0.379 step	0.241 step
Number of test points: 2209 pixels		

Biographies and Photographs

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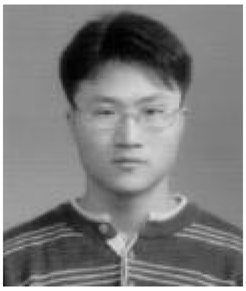

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