PAPER

A Segmentation-Based Multiple-Baseline Stereo (SMBS) Scheme for Acquisition of Depth in 3-D Scenes

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SUMMARY This paper presents a new scheme to estimate depth in a natural three-dimensional scene using a multi-viewpoint image set. In the conventional Multiple-Baseline Stereo (MBS) scheme for the image set, although errors of stereo matching are somewhat reduced by using multiple stereo pairs, the use of square blocks of fixed size sometimes causes false matching, especially, in that image area where occlusion occurs and that image area of small variance of brightness levels. In the proposed scheme, the reference image is segmented into regions which are capable of being arbitrarily shaped, and a depth value is estimated for each region. Also, by comparing the image generated by projection with the original image, depth values are newly estimated in a top-down manner. Then, the error of the previous depth value is detected, and it is corrected. The results of experiments show advantages of the proposed scheme over the MBS scheme.

key words: *multiple-baseline stereo, region segmentation, stereo matching, error correction, interpolated viewpoint*

1. Introduction

Recently, there are increasing needs for obtaining three-dimensional (3-d) information from two-dimensional (2-d) images in computer vision. Stereo is a useful technique to acquire the 3-d information. In this scheme, 3-d distance or depth is determined by identifying corresponding features between two images from different viewpoints. However, finding the corresponding features has been the most difficult problem. The usual approach is to use edge points, particularly zero crossing points obtained by Laplacian filtering, as the corresponding features [1]. However, it is difficult to obtain enough accuracy and efficiency since the corresponding features are found for point by point. Similar approaches have also been proposed: some approaches use edge segments [2]–[4], and another one uses isoluminance contours [5].

In these schemes, there is a possibility of false matching since the depth value is estimated from only two images. In the Multiple Baseline Stereo scheme [6], where multiple images are used, accuracy of stereo matching is improved. In this scheme, by evaluating the whole of stereo matching in multiple stereo pairs, the cases that false matching occurs are reduced. However, it still has a problem that the depth value often has errors since matching is performed for square blocks of the same size. To reduce these errors, the matching block is to be changed depending on the shape of objects in the scene.

In this paper, we propose a new scheme to estimate depth values from a multi-viewpoint image set. In our scheme, an input image is segmented into regions and we employ them as matching blocks [7]. However, at the occlusion part the error of depth is sometimes remained. Then, we introduce a scheme of correcting these errors [8]. By using the original images and the acquired depth values, a projection image is generated at the viewpoint of another original image. By comparing the projection image with the original image, depth values are newly estimated for occluded regions in a top-down manner. Then, the error of the previous depth value is detected and it is corrected.

In the next section, we describe the conventional and proposed schemes to acquire the depth values. The advantage of the error correction is explained in Sect. 3. In Sect. 4, we show some experimental results, and compare the proposed scheme with the conventional scheme. In Sect. 5, we discuss region segmentation in terms of estimation errors and also, errors remaining in the estimation result. Finally, Sect. 6 concludes this paper.

2. Acquisition of Depth Information

2.1 Stereo Scheme

In the stereo scheme, the depth is calculated from the disparity d, which is the difference between the corresponding points of left and right images. Using the disparity d shown in Fig. 1, the depth z is given as

$$z = \frac{BF}{d}, \tag{1}$$

where B and F are the baseline and focal length, respectively. Both of the following two schemes, Multiple-Baseline Stereo scheme and the proposed scheme, are based on the Stereo scheme.

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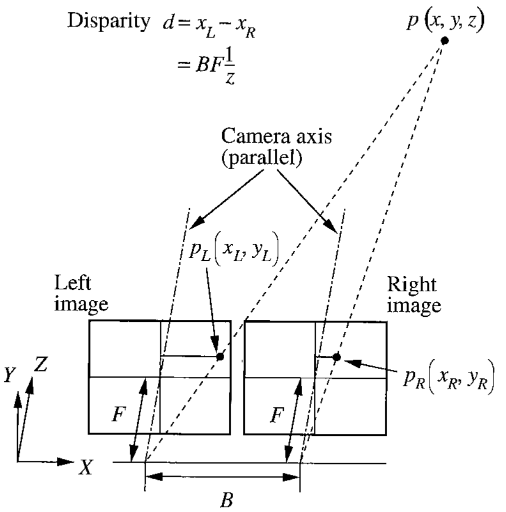


Fig. 1 Disparity in a stereo pair of images.

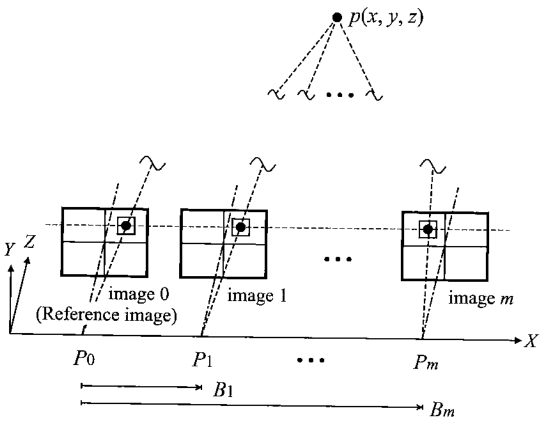


Fig. 2 Multiple-Baseline Stereo scheme.

2.2 Multiple-Baseline Stereo Scheme

In the Multiple-Baseline Stereo (MBS) scheme, the multiple images with different baselines are used, which are obtained either with a set of cameras arranged on a straight line while their optical axes are kept perpendicular to the line, or by sliding a camera along a straight line. In stereo matching, we need to search only along the epipolar lines in the other image for the corresponding point. As shown in Fig. 2, let the locations of m viewpoints be $P_0, P_1, \ldots, P_m$ on the X-axis. The baseline B_i $(i = 1, 2, \ldots, m)$ is the distance between the image 0 and the image i and defined as P_i minus P_0. Given $\{B_i\}$, the disparity d_i between the image 0 and the image i is obtained from d_m by

$$d_i = \frac{B_i}{B_m} d_m. \tag{2}$$

Here, the image 0 is taken as the reference image. To evaluate d_i from the stereo pair of the image 0 and the image i, the sum of squared difference (SSD) is used, which is defined as

$$SSD_i(x,\ d) = \sum_{x' \in W} \{f_0(x + x') - f_i(x - d + x')\}^2. \tag{3}$$

Here, $f_i(x)$ denotes the value of the image i along the local X-axis and W is the matching block region with its own local coordinates. The shape of the matching block is square here. By adding the SSD, d_m can be evaluated from multiple stereo pairs. The evaluation function of d_m is the sum of SSD (SSSD) written as

$$SSSD_{1,m}(x,\ d) = \sum_{i=1}^{m} \sum_{x' \in W} \left\{ f_0(x + x') - f_i\left(x - \frac{B_i}{B_m} d + x' \right) \right\}^2. \tag{4}$$

Here, the suffixes of SSSD denote the range of summation. The value of d that gives the minimum of SSSD is determined as the estimate of the disparity d_m at x. If the minimum values appear successively, the mean of the d's giving them is used.

The use of SSSD makes the estimation of disparity more reliable than the use of SSD. For example, suppose the cases that the images include regions of periodic patterns. The preliminary experiment has shown that SSSD has the only one minimum in the most cases, while SSD reveals minimum values at two or more different disparities.

2.3 Proposed Scheme

In the MBS scheme mentioned in the previous section, the acquired depth values often have errors since all the matching blocks have the same size. To reduce the errors, we propose a Segmentation-Based Multiple-Baseline Stereo (SMBS) scheme, where the disparity is estimated for each segmented region, that is, for each object area in the scene.

In the SMBS scheme, the reference image is segmented into regions. In this segmentation, we use the K-means algorithm [9]. The center points of the clusters are located in the two-dimensional plane, and the intensity and location are used as parameters. By this algorithm, isolated parts belonging to a region are split and the small regions are merged. By repeating this process, a set of the segmented regions is obtained. The depth value is calculated for each region.

Furthermore, we use $(2n + 1)$ images as a multi-viewpoint image set in the proposed scheme. These images are labeled from the image $-n$ to the image n, from left to right as shown in Fig. 3. In the MBS scheme, the first image in the multi-viewpoint image set is selected as the reference image, and the disparity is calculated sequentially through the image set. In this scheme, some regions which exist in the reference image disappear in

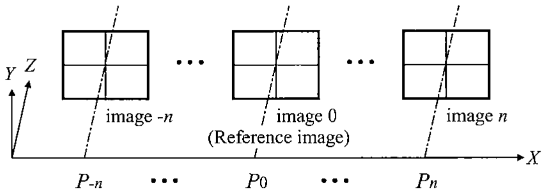


Fig. 3 A multi-viewpoint image set used in the proposed scheme.

other images of multi-viewpoint image set, and these states cause matching errors. In the SMBS scheme, to reduce this region disappearance, the center image in a multi-viewpoint image set, the image 0 at the position P_0, is taken as the reference image. By searching the SSSD toward bidirections, right and left, the disparity is calculated more correctly.

By rewriting Eq. (4) and altering the range of summation to the both sides of the image 0, the evaluation function SSSD to calculate the disparity of W_{label} is given as

$$SSSD_{-n,\,n}(label,\,d) = \sum_{i=-n,\,i\neq 0}^{n} \sum_{x\in W_{label}} \left\{ f_0(x) - f_i\left(x - \frac{B_i}{B_n}d\right)\right\}^2. \quad (5)$$

Here, W_{label} is a segmented region in the reference image, and *label* denotes the region number. The value of d that gives the minimum of SSSD is determined as the estimate of the disparity d_n of W_{label}.

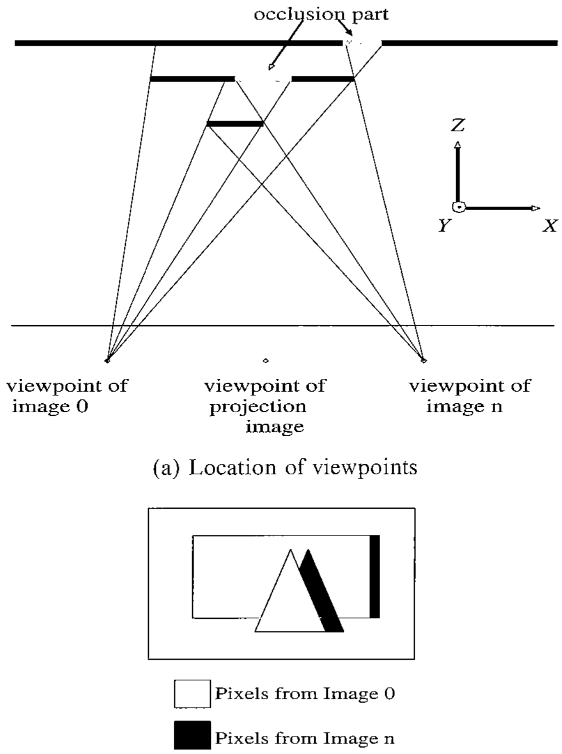
In the proposed scheme, because of the segmentation and the bidirectional search, the accuracy of the acquired depth values is improved.

3. Error Correction of Depth Information

3.1 Outline

When an object is located behind another object in the scene, some parts of that object are visible at some viewpoints, but hidden at other viewpoints. This state is called occlusion. If an occlusion occurs in the multi-viewpoint image set, some region which is included in the reference image is to be missing or lack in other images. Consequently, the occlusion causes false stereo matching. In the proposed scheme, considering occlusion effects, the errors of the depth values are corrected.

For each region of the reference image, a disparity value, or equivalently a depth value, has been obtained by the stereo matching scheme described in the previous section, which is one of so-called bottom-up processing. Although the estimated depth values may be incorrect, by using them we can distinguish those regions where some occlusion occurs. Also, disparity values are capable of being estimated this time by one of so-called top-down processing: By using an assumed disparity value of the target region and the already obtained disparity values of other regions, the projection image is generated, and the degree of correspondence between this image and the original image is measured. By repeating this procedure with varying the assumed value, the disparity of the region is estimated. Compared with this newly obtained value, the previously obtained value is corrected. In the rest of this section, we describe the error correction scheme in detail.



(a) Location of viewpoints

(b) Projection image

Fig. 4 Projection for error correction.

3.2 Projection Method

In the error correction, by using the estimated depth values and the original images, the projection image is produced at another viewpoint. In this section, we describe the procedure to project the image.

To generate a projection image i' at the same viewpoint as that of the image i, we use two original images: the center image and the rightmost image, the image 0 and the image n, if $0 < i < n$, or the center image and the leftmost image, the image 0 and the image $-n$, if $-n < i < 0$. Figure 4 depicts the case of $0 < i < n$. In this case, the image 0 has the depth values. If the image 0 includes an occlusion part as shown in Fig. 4, we supplement this part of the image 0 with that of the image n. The supplement prevents the lack of pixel at the occlusion part.

The projection image i' is generated by the following procedure.

Step 1: Using the regions of the image 0 and the depth value of each region, the image is projected at the viewpoint of the image n.

Step 2: The lack pixels of the projection image are supplemented with those of the image n.

Step 3: The depth value of the region supplemented in the previous step is set equal to that of the neighboring region.

Step 4: The regions including the supplemented regions are projected onto a plane at the viewpoint of the image i to generate the projection image i'.

We can also use this projection method to produce those images which interpolate any viewpoints in a multi-viewpoint image set.

3.3 Error Correction Method

Since a depth value is obtained for each region, the procedure of error correction is applied to every region. The procedure consists of three main parts: selection of a region including occlusion, estimation of a disparity value by top-down processing, and decision of error correction. For a target region W of the previously estimated disparity D, we describe below the steps of the procedure of error correction.

Step 1: Examine if any occlusion occurs on the target region or not, by using the depth values. More precisely speaking, examine if the target region is located behind at least one of left and right adjacent regions and also if the length of the border between these two regions is relatively larger than a threshold. If so, go to the next step. If not so, the procedure is skipped and the disparity value is left unchanged.

Step 2: Select an original image between two images, the image $\lfloor n/2 \rfloor$ and the image $-\lfloor n/2 \rfloor$, where $\lfloor r \rfloor$ denotes the integer part of r. Here, the viewpoint from which the target region is more visible is selected. More precisely speaking, if the adjacent region located in front of the target region (one located apart farther from the target region when both left and right adjacent regions are in front of it) is the left one, the image $\lfloor n/2 \rfloor$ is selected, or if it is the right one, the image $-\lfloor n/2 \rfloor$ is selected. Let the image c denote the selected image, and let P_c denote the viewpoint of the image c.

Step 3: Assume a disparity value d of the target region, and then, generate the projection image $W(d)$ of the region W from the viewpoint P_c by the method described in Sect. 3.2.

Step 4: Measure the difference between $W(d)$ and the image c. In more detail, by calculating the absolute difference of brightness levels between each pixel inside of $W(d)$ and the corresponding pixel of the image c, obtain the average of the differences in $W(d)$ as the projection error $E(d)$.

Step 5: Repeat Step 3 and Step 4 with varying the value of d, and then, obtain the value of d minimizing $E(d)$ as the new estimate of the disparity, denoted by d_c, of the target region.

Step 6: If the absolute difference between D and d_c is larger than a threshold, and also if d_c is derived from the distinctive minimum of projection error, determine that D is incorrect, and then, replace D by d_c. If otherwise, the disparity of the target region is left unchanged.

In the processing of the target region, it is assumed that the regions located in front of it have correct disparity values. To keep the correct front-to-back relation between regions, the procedure of error correction is carried out in the order from the region of the largest disparity toward the regions of the smaller disparity. Furthermore, the procedure is carried out sequentially. in the processing of the target region, the previously modified values of disparity are used in the top-down processing.

4. Experiments

4.1 Methods

In the experiments, we use nine images, whose specifications are listed in Table 1, as a multi-viewpoint image set. These images are taken by sliding a camera straight at equal intervals of 1 cm, and they are labeled from image −4 to image 4 in order. Figure 5 shows the image 0, namely, the center image in this multi-viewpoint image set.

We obtain the depth values by the conventional scheme using blocks of 5×5 pixels. Also, we carry out the proposed scheme for the image set. In the proposed scheme, the error correction is performed for the estimated depth values, and interpolation images between viewpoints are generated.

4.2 Results

Figure 6 shows the regions segmented from the image

Table 1 Specification of a multi-viewpoint image set for experiments.

number of images	9
image size	720×486 pixels
pixel color	8 bits monochrome
maximum disparity	about 50 pixels

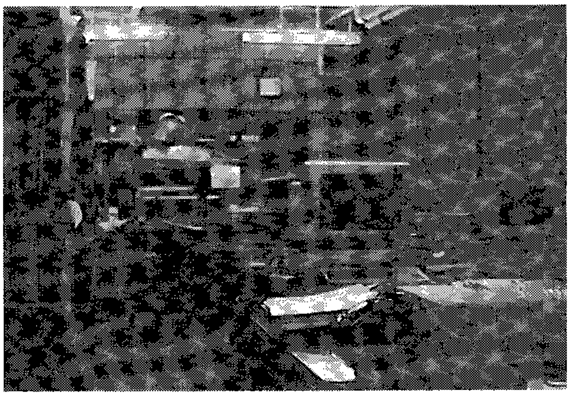


Fig. 5 An example image in a multi-viewpoint image set used in experiments (the center image).

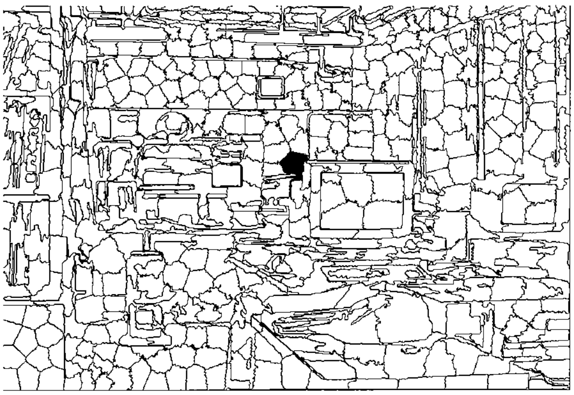
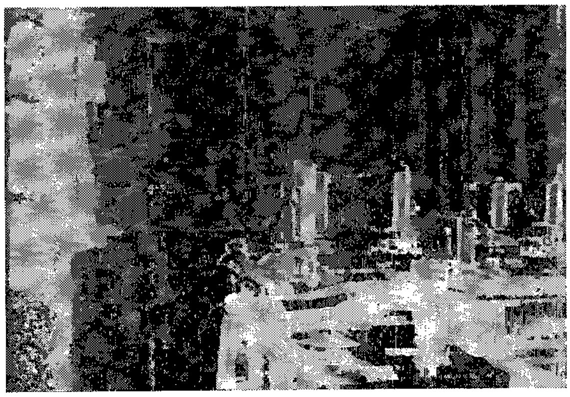


Fig. 6 Result of region segmentation for the image of Fig. 5.



(a) By Multiple-Baseline Stereo scheme

(b) By the proposed scheme before error correction

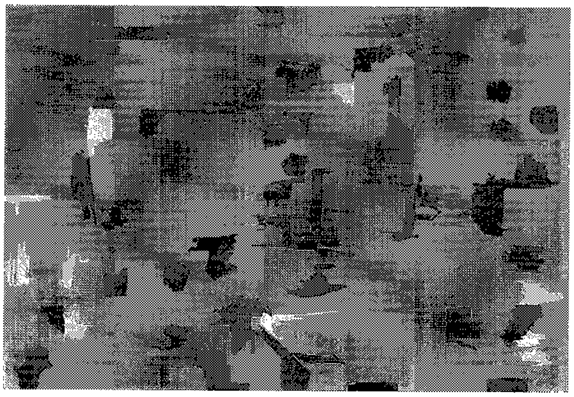
Fig. 7 Spatial distribution of disparity obtained from the image of Fig. 5.

of Fig. 5. The region filled in black in this figure is referred later. The depth values obtained with the MBS scheme and with the SMBS scheme without error correction are shown in Figs. 7 (a) and (b), respectively. In these figures, intensity denotes the value of estimated disparity. Disparity of 50 pixels is expressed by the intensity of 255 (brightest) in 256 levels. Comparing these two figures, in the MBS scheme there occur the cases that the pixels which belong to different objects in the scene and, hence, which should have different disparity are fused. On the contrary, in the SMBS scheme most of these errors of disparity are reduced since the disparity is calculated for every segmented region.

Error correction is carried out for the disparity of Fig. 7 (b). Figure 8 (a) shows the regions whose disparities have been changed by error correction. In this figure, black regions are ones whose disparities have been changed smaller, white regions are ones whose disparities have been changed larger, and gray regions are unchanged ones. Spatial distribution of disparity after error correction is shown in Fig. 8 (b). Comparing Fig. 7 (b) with Fig. 8 (b), it is seen that some errors of disparity are corrected particularly at the left "fluorescent lamp attached on the ceiling" and the upper left side of "the TV monitor" in the image.

To see how error correction performs, let us now pay attention to the region which is shown as the black area in Fig. 6. In Fig. 7 (b), this marked region has an error of the depth value, since occlusion occurs between "the TV monitor" and "the blackboard on the wall." The comparison between SSSD of the marked region and that of the right neighboring region inside of "the monitor" area is shown in Fig. 9. It is seen that both curves have similar dependence on disparity. However, measured manually in the image plane, the actual disparity of the marked region is about 3 pixels. This means that the disparity of the marked region is strongly influenced by that of the region inside of "the TV monitor" because of occlusion. Hence, by performing block matching with SSSD, the acquired depth value is subject to an error.

Because the marked region is adjacent along the long range of its right border to "the side of TV monitor" region whose estimated depth value is smaller than that of the marked region, the error correction procedure is applied to it. The values of projection error of the marked region are shown in Fig. 10. Compared with Fig. 9, this figure indicates that the distribution of the projection error is hardly influenced on the right



(a) Regions of modified disparity (Black region: Disparity is changed smaller. White region: Disparity is changed larger. Gray region: Disparity is unchanged.)

(b) Spatial distribution of disparity

Fig. 8 Results of error correction.

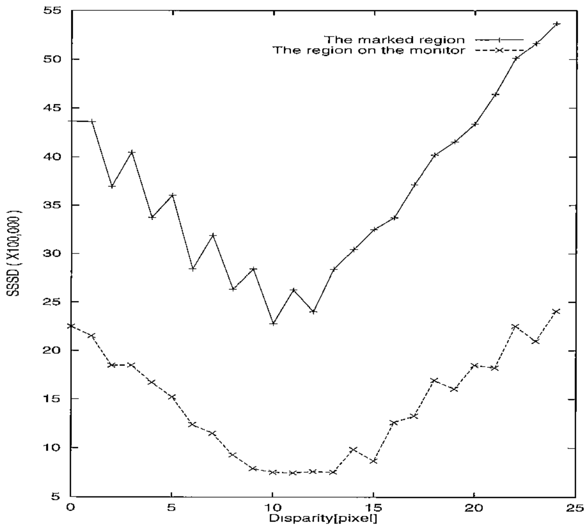


Fig. 9 Comparison between SSSD of the marked region and that of the right neighboring region inside of the monitor area of Fig. 6.

neighboring region. Then, by performing the error correction procedure with projection errors in the front-to-

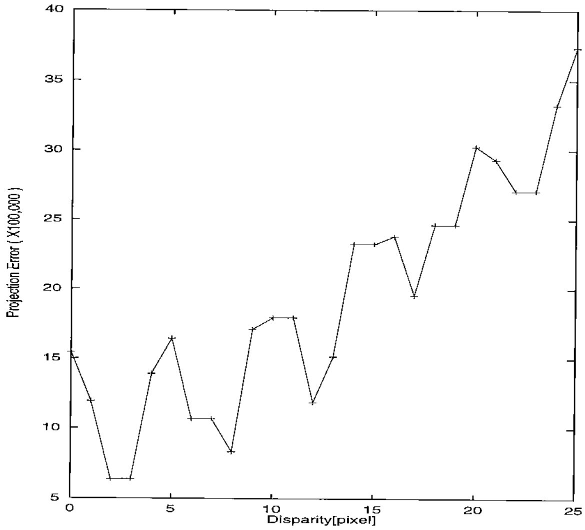


Fig. 10 The values of projection error of the marked region of Fig. 6.

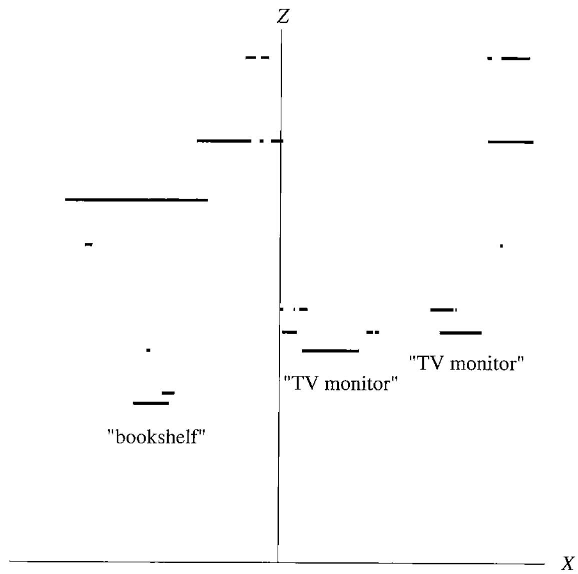


Fig. 11 The XZ-plane of the reconstructed 3-d scene.

back order, the correct depth value of the marked region is acquired.

The 3-d scene is reconstructed from the regions with the XY-coordinates in the reference image and the acquired depth values. Because a depth value is estimated for the whole of a region in our scheme, the regions are reconstructed as plates located parallel to the XY-plane in the 3-d space. Figure 11 shows the XZ-plane, where each axis is suitably scaled for convenience and the origin corresponds to P_0. The X-axis corresponds to the centered horizontal line in the reference image. In this figure, the regions are to be depicted with horizontal line segments. Here, the rightmost region on the X-axis has very small disparity as seen in Fig. 8 (b). This disparity value is obviously wrong, and hence, that re-

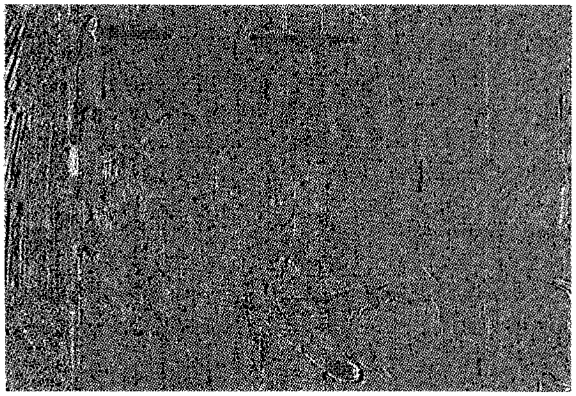


Fig. 12 Difference image between the original image and the projected image at the viewpoint of the image 2 (Difference values multiplied by 16).

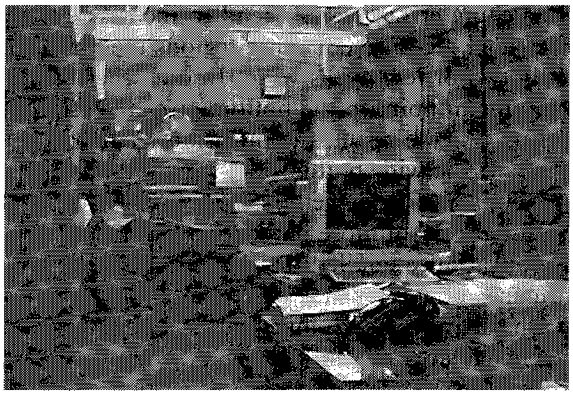


Fig. 13 An example image at interpolated viewpoint.

gion is removed from Fig. 11. Also, extremely short line segments represent the fractions of those regions touching the XZ-plane. From this figure, it is seen that the relative relation of locations in the Z-direction among the objects located at the middle height of the image, "bookshelf" on the left hand, two "TV monitors," and so on, is correctly obtained.

Next, we examine the correctness of the acquired values by comparing between an original image and a projection image at the identical viewpoint. By the projection scheme described in Sect. 3.2, with the segmented regions and the acquired disparities, the projection image is generated at the same viewpoint as that of the image 2 from the image 0 and the image 4. Figure 12 shows the difference image between the original image 2 and the projection image. Here, difference values are multiplied by 16 and biased at 128 to be displayed in 256 brightness levels. From this figure it is seen that although the brightness levels inside regions are different between these two images, most of regions except those located at the ends of the image are projected almost at correct locations. Consequently, the acquired disparities are considered to have enough precision to generate interpolated images with.

Using the acquired depth values, we can generate the images at any interpolated viewpoints. Figure 13 shows the projection image seen from the viewpoint centered between the viewpoint of the image 2 and that of the image 3. The interpolation image seems to look so natural.

5. Discussions

5.1 Effects of Region Segmentation

In the proposed scheme, image segmentation is performed by the clustering method using the K-means algorithm. A segmented region consists of those pixels which have similar brightness levels and it is capable of being arbitrarily shaped. We can obtain various results of segmentation by changing the initial clusters in the K-means algorithm. We applied the SMBS scheme to each of various sets of segmented regions. Comparing the results of disparity estimation, we have considered the effects of region segmentation on disparity estimation as follows:

1. If an image area of small variance of pixel levels is segmented into many small regions, wrong disparities are liable to be deduced for these regions from false matching inside of that area.
2. In the image area including brightness edges, small regions rather than large ones have more tendency to be given correct disparities.
3. An excessively large region is liable to cause matching errors, even if it is included in a projection of a scene object.

The first effect holds true for the MBS scheme using small square blocks in matching. In the SMBS scheme, it is important to segment an image so as to improve the effects of the use of arbitrarily shaped regions on reduction of estimation errors. As described above, region size especially affects the performance of estimation. For the scene used in the experiments, we examined several sets of regions in terms of the correctness of the disparities estimated from them. The set of region shown in Fig. 6 is selected as one that relatively acceptable disparities are obtained from.

5.2 Remaining Estimation Errors

In the estimation of disparity by region matching, the curve of SSSD tends to reveal somewhat wide bottom, that is, to have successive small values in a range including the minimum point. This bottom is mainly caused by stereo matching errors, which probably occur in calculation of SSD, because a scene object looks of different shape and also, of different reflection levels of illumination according to viewpoints. In our experiments, the matching errors of SSD tend to increase especially in occluded regions. For other regions the bottoms are usually two or less pixels wide. In our scheme, simply, the minimum point in the bottom gives the estimate of disparity. As the result, the precision of disparity may be degraded in wide bottoms. The precision is expected to be improved in a method, for instance, where the center of gravity of those points on a SSSD curve in the range of variance smaller than a threshold including the minimum point is taken as the exactly minimum point.

On the other hand, matching of a region included in an image area of similar brightness levels occasionally fails to estimate the correct disparity. For example, in Fig. 8 (b) there are seen some regions of extremely small and, therefore, wrong disparity, which are shown as dark regions in the figure, at the top and bottom frames of the "TV monitor," at the "floor" and so on. Each of these regions is adjacent in both left and right sides to those regions which have the brightness levels similar to those of the region. Hence, the SSSD of the region hardly shows so distinctive curve as to estimate disparity. Furthermore, matching of those regions which are truncated at the left or right end of the image hardly deduces correct disparity, because the range of matching is limited.

The evaluation function used in our error correction algorithm, projection error, probably suffers from the same errors as those described above, because it, as well as SSSD, uses difference values. Hence, in the algorithm, only if the value obtained on the basis of the projection errors seems to be reliable, the disparity value previously estimated is to be replaced by it. As the result, however, the wrong disparity may remain unchanged.

On the other hand, error correction is carried sequentially by using the depth values already processed, under the assumption that the smaller depth values than that of the target region are correct. This sequential processing improves the reliability of the top-down processing. However, the previous errors are possibly propagated.

6. Conclusions

We have proposed a segmentation-based multiple-baseline stereo scheme for the acquisition of depth values in a 3-d natural scene, and showed its advantages. The proposed scheme consists of three steps: region segmentation, stereo matching, and error correction. The use of regions in stereo matching between multiple-baseline stereo images reduces the cases of false matching, and hence, improves the accuracy of estimated depth values. Also, the error of depth value of each region is corrected by comparing the projection image with the original image. By using the acquired depth values, the images of natural looks are synthesized at any viewpoints interpolated in a multi-viewpoint image set.

On the other hand, in the proposed scheme all pixels consisting of a region are assumed to have the same depth value. However, in some cases the depth value varies inside the region. This problem is also left in the future study.

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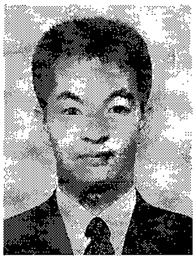

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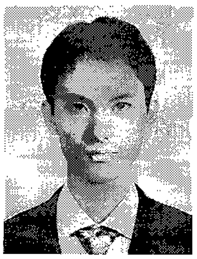

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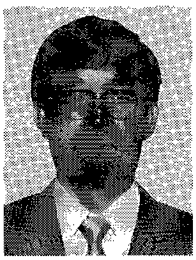

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