

Efficient Stereo Matching Method using Elimination of Lighting Factors under Radiometric Variation

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Abstract: Many stereo matching methods show quite accurate results from depth estimation for images captured under the same lighting conditions. However, the lighting conditions of the stereo image are not the same in the real video shooting environment. Therefore, stereo matching, which estimates depth information by searching corresponding points between two images, has difficulty in obtaining accurate results in this case. Some algorithms have been proposed to overcome this problem and have shown good performance. However, those algorithms require a large amount of computation. For this reason, they have a disadvantage of poor matching efficiency. In this paper, we propose an efficient stereo matching method using a color formation model that takes into account exposure and illumination changes of captured images. Our method changes an input image to a radiometric invariant image and also applies a local binary patch, which is robust to lighting changes, to the transformed image according to exposure and illumination changes to improve the matching speed.

1 INTRODUCTION

Many researchers have studied techniques for providing more realistic video content to the public. This effort led to the development of high-resolution digital imaging technologies such as high definition television (HDTV) and ultra high definition television (UHDTV). In addition, since the late 2000s, three-dimensional (3D) movies have been popular all over the world, and various types of 3D video content have been produced. Recently, techniques for creating immersive video content such as super multi-view images and 360° images are also being studied. Various image processing and computer vision theories are used to create such realistic and immersive video content, and depth information of the object plays an important role in adding realism to the two-dimensional (2D) image. The more accurate the depth information of the object, the more realistic 3D video content can be produced. Therefore, until recently, research to obtain accurate depth information has been actively conducted.

One of the methods for depth estimation is an active-sensor based method. This method uses an infrared-ray or a laser to measure the distance between the sensor and the object. The other method is a passive-sensor based method. This method estimates depth information based on geometric theory and human visual system from single or binocular images. One representative passive-sensor based method is stereo matching that uses the characteristic of binocular disparity. It compares brightness values of pixels between two images having different viewpoints. Then, corresponding points are found and the disparity value between them is calculated. According to the characteristic of binocular disparity, the disparity value is interpreted as depth information of that pixel.

There are several ways to estimate disparity values using stereo matching. A local stereo matching method defines a cost function between a reference patch and a target patch in the stereo image. After that, the principle of winner-takes-all (WTA) is applied to the matching cost calculated for all disparity candidates to determine the optimal disparity value of the current pixel. This is the basic

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method for disparity estimation from the stereo image. Recently, a method for improving the performance of local stereo matching by aggregating the matching cost calculated according to the disparity candidates has been proposed (Zhang et al., 2014). Another type of stereo matching is a global stereo matching method. This method models an energy function for the disparity estimation. The energy function includes a data term and a smoothness term. Each of the terms calculates the matching cost and checks the disparity continuity among neighboring pixels, respectively. This function is optimized by some optimization algorithms such as belief propagation (Sun et al., 2002) and graph cuts (Boykov et al., 2001) to determine the final disparity value. Generally, the global stereo matching method shows better performance than the local stereo matching method. However, due to the process of optimization that compares the disparity continuity among pixels, this method usually requires more computation than the local stereo matching method.

Recently, many researchers are interested in deep learning, and since the appearance of AlexNet (Krizhevsky et al., 2012), researches on image processing and computer vision using convolutional neural networks (CNNs) such as VGGNet (Simonyan et al., 2014) and ResNet (He et al., 2016) have increased. Those networks have been applied to various fields in computer vision and shown better performance than conventional methods. At a similar time, deep learning began to be used for stereo matching. MC-CNN calculates the matching cost by extracting the same sized patch from the left and right viewpoint images according to disparity candidates. Then, it trains the learning model to have the optimal matching cost at the actual disparity value (Žbontar et al., 2015). Similarly, an algorithm was proposed that improves the performance of MC-CNN by increasing the size of the target patch according to disparity candidates and then training the probability distribution of the matching cost (Luo et al., 2016). Those two methods applied deep learning only to the part that calculates the matching cost in stereo matching. Unlike those methods, a method of applying deep learning to all the processes of stereo matching was proposed (Mayer et al., 2016).

Although many stereo matching papers have been published so far, most stereo matching algorithms have been tested to stereo images taken under the same lighting conditions. In a real stereo image shooting environment, it is difficult for two viewpoint images to have the same lighting conditions and it causes errors in the result of stereo matching. An

adaptive normalized cross-correlation (ANCC) that calculates the matching cost between two images by eliminating lighting factors in the color formation model was proposed (Heo et al., 2010). This method shows a stereo matching result that is robust to lighting changes. However, in calculating the matching cost, there is a disadvantage that it is inefficient because of too much computational complexity. Various methods have been proposed to solve the computational complexity problem of ANCC. Those methods have less computational complexity than that of ANCC. However, they show unstable stereo matching results compared with ANCC. Therefore, we propose an efficient stereo matching method that shows fast and stable matching results for various lighting changes.

2 RELATED WORKS

In general, the result of stereo matching is poor when images are captured under different lighting conditions. Fig. 1 shows results of stereo matching with various methods. We tested conventional stereo matching methods using *Aloe* from Middlebury stereo datasets (Scharstein et al., 2007).

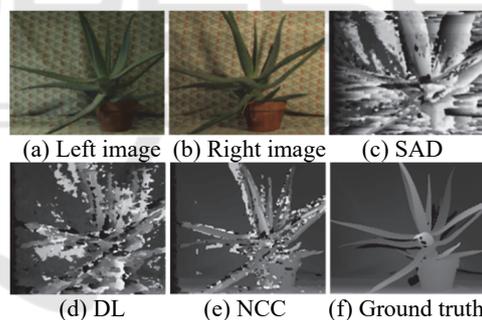


Figure 1: Stereo matching with various methods.

In Fig. 1, Fig. 1(a) and (b) represent a left viewpoint and a right viewpoint images. Both images are captured under different illumination conditions. Fig. (c) - (e) show stereo matching results using the sum of absolute differences (SAD), deep learning (Luo et al., 2016), and normalized cross-correlation (NCC), respectively. Fig. (f) is a ground truth disparity map of the left viewpoint image. All results in Fig. 1 were optimized by graph cuts (Boykov et al., 2001). As shown in Fig. 1, it is difficult to obtain a good disparity map with general matching methods. Even the stereo matching method using deep learning shows a poor disparity map. In this section, we introduce some algorithms proposed to solve this

problem and also explain disadvantages of each method.

2.1 Adaptive Normalized Cross-Correlation (ANCC)

The ANCC method (Heo et al., 2010) uses a color formation model that is defined by (Finlayson et al., 2003) to remove lighting factors from captured images. The color formation model in the left viewpoint image is defined in (1). In the process of storing a digital image, the actual color values are distorted by lighting factors as shown in (1).

$$\begin{aligned} \begin{pmatrix} R_L(p) \\ G_L(p) \\ B_L(p) \end{pmatrix} &\rightarrow \begin{pmatrix} \widetilde{R}_L(p) \\ \widetilde{G}_L(p) \\ \widetilde{B}_L(p) \end{pmatrix} \\ &= \begin{pmatrix} \rho_L(p) a_L R_L^{\gamma_L}(p) \\ \rho_L(p) b_L G_L^{\gamma_L}(p) \\ \rho_L(p) c_L B_L^{\gamma_L}(p) \end{pmatrix} \end{aligned} \quad (1)$$

In (1), where $\rho_L(p)$ is a brightness factor that represents the lighting geometry at the current pixel p , γ_L is a gamma exponent, and a_L , b_L , and c_L are scale factors. The ANCC removes $\rho_L(p)$ using log-chromaticity normalization. As a result, $\widetilde{R}_L(p)$ is changed to (2).

$$R_L''(p) = \log \frac{a_L}{\sqrt[3]{a_L b_L c_L}} + \gamma_L \log \frac{R_L(p)}{\sqrt[3]{R_L(p) G_L(p) B_L(p)}} \quad (2)$$

There are still scale factors and the gamma exponent in (2). ANCC uses a $N \times N$ sized patch for elimination of scale factors. It also applies a bilateral filter to the patch (Tomasi et al., 1998) for preserving depth information of object boundary. An equation for removing scale factors is defined in (3).

$$R_L'''(t) = R_L''(t) - \frac{\sum_{t \in W(p)} w(t) R_L''(t)}{Z(p)} \quad (3)$$

In (3), where $W(p)$ is the kernel at current pixel p , w represents the kernel of bilateral filter, and Z means the sum of weights in the bilateral kernel. The last lighting factor, the gamma exponent, is removed using an equation of NCC as shown in (4).

$$\begin{aligned} &ANCC_{logChrom_R}(f_p) \\ &= \frac{\sum_{i=1}^M w_L(t_i) w_R(t_i) [R_L'''(t_i)] \times [R_R'''(t_i)]}{\sqrt{\sum_{i=1}^M |w_L(t_i) R_L'''(t_i)|^2 \times \sum_{i=1}^M |w_R(t_i) R_R'''(t_i)|^2}} \end{aligned} \quad (4)$$

The equation (4) is used as a cost function of ANCC. In (4), where $ANCC_{logChrom_R}$ means the cost function of log R channel and f_p is a set of disparity candidates at the current pixel. This cost function shows robust results in lighting changes. Authors of

ANCC define an additional cost function from the original RGB image to compensate the information loss due to the process of log-chromaticity normalization. The cost function of original R channel is defined in (5). In (5), where $\widehat{R}_L(t_i) = \widetilde{R}_L(t_i) - \frac{\sum_{t \in W(p)} w_L(t) \widetilde{R}_L(t)}{Z(p)}$.

$$\begin{aligned} &ANCC_R(f_p) \\ &= \frac{\sum_{i=1}^M w_L(t_i) w_R(t_i) [\widehat{R}_L(t_i)] \times [\widehat{R}_R(t_i)]}{\sqrt{\sum_{i=1}^M |w_L(t_i) \widehat{R}_L(t_i)|^2 \times \sum_{i=1}^M |w_R(t_i) \widehat{R}_R(t_i)|^2}} \end{aligned} \quad (5)$$

Both cost functions in (4) and (5) are applied to the energy function for the global stereo matching, and it is optimized by graph cuts.

The ANCC method using both log-chromaticity and original RGB cost functions shows stable results under different lighting conditions as depicted in Fig. 2(a). However, since the bilateral filter is applied to all the pixels, the computational complexity becomes high depending on the kernel size.

2.2 Normalized Cross-correlation in Log-RGB Space

To reduce the computational complexity of ANCC, a stereo matching method in log-RGB space using NCC was proposed (Li, 2012). Unlike ANCC, which requires the bilateral filter for all pixels in the image to remove scale factors, this method has less computational complexity than ANCC because it only requires calculating the average of all the pixel values in the log-RGB image. Therefore, the equation of (3) is changed to (6). In (6), where I_{log} is a set of pixels in the log-RGB image having the left viewpoint and M is the number of pixels in the image.

$$R_L'''(t) = R_L''(t) - \frac{\sum_{t \in I_{log}} R_L''(t)}{M} \quad (6)$$

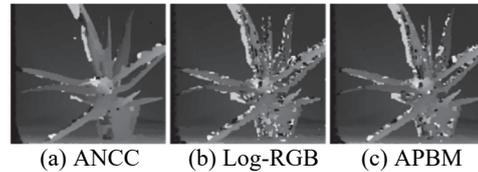


Figure 2: Results of ANCC, Log-RGB, APBM methods.

The removal of the remaining lighting factor is the same as that of ANCC. We implemented this method and tested it using the same image used in Fig. 1. The result of this method is shown in Fig. 2(b). Compared with the ANCC result in Fig. 2(a), the result of this method looks worse. On the contrary, compared with

the results of Fig. 1(c), (d), and (e), Fig. 2(b) shows a better result than them.

2.3 Adaptive Pixel-wise and Block-wise Matching (APBM)

An adaptive pixel-wise and block-wise matching (APBM) is another stereo matching method that has lower computational complexity than ANCC and is robust to lighting changes (Chang et al., 2019). This method removes scale factors using the average of the all the pixel values in the log-RGB image and eliminates the gamma exponent using an equation of hue transformation. Through this process, the input image is converted into an independent image from the lighting factors.

The APBM method uses the equation of pixel-wise matching based on the transformed input image to speed up the process of stereo matching. Subsequently, the equation of block-wise matching is also used for compensation of the matching inaccuracy caused by using the pixel-wise matching. This method is faster than ANCC. However, when we compare the APBM result with the result obtained using both log-chromaticity and original RGB cost functions, the result of APBM looks worse than that of ANCC as depicted in Fig. 2(c).

3 PROPOSED METHOD

3.1 Analysis of Conventional Methods

In Section 2, we introduced ANCC that showed robust stereo matching results in various lighting conditions and also introduced Log-RGB and APBM methods that solve the computational complexity problem of ANCC. However, those algorithms did not show better results than ANCC in terms of stereo matching accuracy. For the objective evaluation of each algorithm, we estimated disparity maps by applying each algorithm to *Aloe* images captured under various exposure and illumination. After that, the error rate between the obtained disparity map and the ground truth was calculated and summarized in Table 1 and Table 2.

Table 1 shows an error rate comparison under different exposure levels and Table 2 represents the error rate comparison under different illumination levels. Each first column in the two tables means the exposure and the illumination levels of the left and right images, respectively. In Table 1, where GC means that the energy function is optimized by graph cuts. ANCC, Log-RGB, and APBM methods show

lower error rates than SAD when the two images have different exposure levels. However, when compared to NCC, those methods show higher error rates than NCC. In particular, at dark exposure levels (e.g. 0-0, 0-1, and 0-2), those methods show very poor results than NCC.

On the other hand, it can be seen that ANCC, Log-RGB, and APBM methods show better error rates for most illumination levels than SAD and NCC. Especially, those methods perform better than other methods when the illumination level differences between the left and right images are large (e.g. 1-3 and 2-3).

Table 1: Error rate comparison (exposure).

	SAD +GC	NCC +GC	ANCC (7×7)	ANCC (31×31)	Log- RGB+GC	APBM +GC
	Error rates (%)					
0-0	13.9	13.05	12.27	10.74	18.32	15.3
0-1	97.87	10.96	16.24	13.6	17.94	15.32
0-2	97.93	10.75	19.55	15.48	16.73	14.33
1-1	12.01	10.23	6.6	5.42	12.46	9.19
1-2	97.55	10.13	6.22	4.99	11.19	7.62
2-2	11.09	9.94	5.37	4.5	9.99	5.51

Table 2: Error rate comparison (illumination).

	SAD +GC	NCC +GC	ANCC (7×7)	ANCC (31×31)	Log- RGB+GC	APBM +GC
	Error rates (%)					
1-1	12.01	10.26	6.6	5.29	12.43	9.42
1-2	77.43	12.75	9.78	7.97	15.65	11.68
1-3	82.99	23.01	16.35	11.81	17.44	13.8
2-2	11.97	10.72	5.98	4.55	10.9	7.2
2-3	72.25	17.93	12.91	9.73	16.28	13.02
3-3	11.9	11.42	7.24	5.2	11.9	8.59

Both Table 1 and Table 2 show that ANCC, Log-RGB, and APBM are generally stronger than SAD and NCC for illumination changes, but are more vulnerable to exposure changes. In the case of the NCC method, it shows robust results in exposure changes without removing lighting factors of input images. Therefore, ANCC, Log-RGB, and APBM methods, which remove lighting factors from input images based on the color formation model, are rather inefficient compared to NCC.

The purpose of proposed method is to create an efficient stereo matching algorithm that uses basic and simple cost functions to reduce computational complexity and is also robust to exposure and illumination changes.

3.2 Image Transformation

We analyzed that APBM performed worse than ANCC because it did not consider the problem of discriminability caused by the log-chromaticity normalization, which was mentioned in the original paper of ANCC. Therefore, the proposed method transforms the input image to the independent image from lighting factors based on color formation models divided into two cases to solve this problem.

The first case is that the stereo image is captured with a fixed camera exposure. In this case, we assume that scale factors in (1) are all the same. According to this assumption, (1) is rewritten as (7).

$$\begin{pmatrix} R_L(p) \\ G_L(p) \\ B_L(p) \end{pmatrix} \rightarrow \begin{pmatrix} \widetilde{R}_L(p) \\ \widetilde{G}_L(p) \\ \widetilde{B}_L(p) \end{pmatrix} = \begin{pmatrix} \rho_L(p)R_L^{YL}(p) \\ \rho_L(p)G_L^{YL}(p) \\ \rho_L(p)B_L^{YL}(p) \end{pmatrix} \quad (7)$$

In the same way with ANCC, the log transform is applied to (7). After that, the log-chromaticity normalization is performed for eliminating the brightness factor. Therefore, an equation (2) is changed to (8).

$$R_L^a(p) = \gamma_L \log \frac{R_L(p)}{\sqrt[3]{R_L(p)G_L(p)B_L(p)}} \quad (8)$$

The second case is that the stereo image is captured with a fixed lighting geometry. In this case, the brightness factor $\rho_L(p)$ may be omitted from (1). Therefore, we assume that the color formation model in (1) is transformed to (9).

$$\begin{pmatrix} R_L(p) \\ G_L(p) \\ B_L(p) \end{pmatrix} \rightarrow \begin{pmatrix} \widetilde{R}_L(p) \\ \widetilde{G}_L(p) \\ \widetilde{B}_L(p) \end{pmatrix} = \begin{pmatrix} a_L R_L^{YL}(p) \\ b_L G_L^{YL}(p) \\ c_L B_L^{YL}(p) \end{pmatrix} \quad (9)$$

In (9), there are scale factors a_L , b_L , and c_L . We apply log transform to (9). The scale factors are removed by subtracting the average pixel value of each color channel from all the pixels in the log image. Those processes are defined in (10) and (11). The equation (11) is also summarized in (12).

$$\log(\widetilde{R}_L(p)) = \log a_L + \gamma_L \log R_L(p) \quad (10)$$

$$R_L^b(p) = \log(\widetilde{R}_L(p)) - \frac{\sum_{t \in I_{\log}} \log(\widetilde{R}_L(t))}{M} \quad (11)$$

$$R_L^b(p) = \gamma_L \log \frac{R_L(p)}{\sqrt[M]{\prod_{t \in I_{\log}} R_L(t)}} \quad (12)$$

The proposed method uses the average sum of (8) and (11) to solve the problem of discriminability. This is because the equation (8) has the log-chromaticity

normalization problem, but (12) is free from this. The combination of (8) and (11) is defined in (13).

In (13), there is a gamma exponent. To remove the gamma exponent, we apply the log transformation again to (13). After that, the gamma exponent is removed in the same manner as in (11). This is defined in (14). If the result value of (13) has a negative value, the log transformation in (14) cannot have real value. Therefore, in the actual implementation process, we add the positive constant value to (13) and apply this value to (14).

$$R_L^c(p) = 0.5 * \gamma_L \log \frac{R_L^b(p)}{\sqrt[3]{R_L(p)G_L(p)B_L(p)} * \sqrt[M]{\prod_{t \in I_{\log}} R_L(t)}} \quad (13)$$

$$R_L^d(p) = \log R_L^c(p) - \frac{\sum_{t \in I_{\log}} \log R_L^c(t)}{M} \quad (14)$$

Based on color values converted so far, the final transformed color channels are shown in (15). We change the result of (14) to an exponential value. This is because the result of (14) may have a negative number because of the logarithmic value. In the actual implementation process, we also multiply the positive constant value to (15) for making 16bit integer value. In (15), where R_L^F , G_L^F , and B_L^F represent transformed color channels using the proposed method.

$$\begin{pmatrix} R_L^F(p) \\ G_L^F(p) \\ B_L^F(p) \end{pmatrix} = \begin{pmatrix} e^{R_L^d(p)} \\ e^{G_L^d(p)} \\ e^{B_L^d(p)} \end{pmatrix} \quad (15)$$

We applied our new color model to the stereo image that was used in Fig. 1 to test. As a result, images in Fig. 1 was changed to new images that have similar color distributions as depicted in Fig. 3.

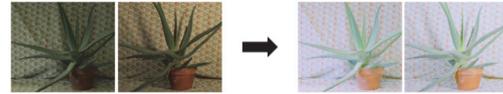


Figure 3: Image transformation using proposed method.

3.3 Cost Computation

The proposed method calculates the matching cost using the transformed images in Fig. 3. For the cost computation, we apply a census transform that uses a local binary patch for the similarity measure between left and right images (Zabih et al., 1994). The census transform calculates color differences between the center pixel and its neighboring pixels in the patch. Subsequently, if the difference is larger than 0, the

neighboring pixel value is changed to 1. In the opposite case, that pixel value is set to 0. This process is applied to both left and right patches. Binary values from two patches are listed in numeric sequences as shown in Fig. 4 to calculate the matching cost by measuring Hamming distance.

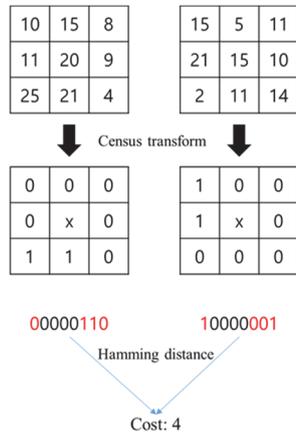


Figure 4: Example of census transform.

The cost function calculating Hamming distance between two patches is used as a data term $D_p(f_p)$ of the energy function defined in (16).

$$E(f) = \sum_p D_p(f_p) + \sum_p \sum_{q \in N(p)} V_{pq}(f_p, f_q) \quad (16)$$

In (16), where q is a set of neighboring pixels in the patch and V_{pq} is a smoothness term that checks the disparity continuity among pixels. The energy function is optimized by graph cuts and all parameters used in this process are the same as those used in (Heo et al., 2010).

Table 1 shows that robust stereo matching methods in various lighting conditions have worse error rates than those of NCC when the exposure level of input image is low. In addition, some algorithms in Table 1 show worse results than NCC even under the same exposure levels. It means that stereo matching using the original input image shows better results than stereo matching using the transformed image in those situations. To solve this problem, we use average pixel values of the left and right images and also calculate the absolute difference between two average values. If the average value of the left or the right image is lower than 50, or the absolute difference between the two average values is lower than 7, original color images are used as inputs for stereo matching. If not, transformed images are used. An overall scheme of our method is shown in Fig. 5.

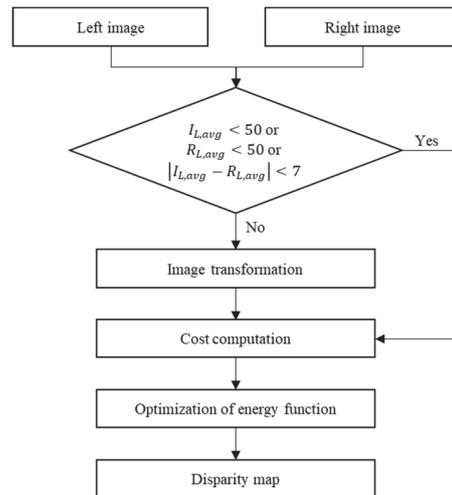


Figure 5: Flowchart of proposed method.

4 EXPERIMENTAL RESULTS

We tested the proposed method using Middlebury stereo datasets: *Aloe*, *Dolls*, and *Moebius* (Scharstein et al., 2007). To evaluate whether the stereo matching result is robust to lighting changes, the exposure and illumination levels of the left and right images were classified into 6 cases, respectively. Fig. 6 shows disparity maps acquired through stereo matching methods when the illumination level of the left and right images is 1 and 3, respectively. ‘GT’ in Fig. 6(i) means the ground truth.

For quantitative evaluation, we measured the error rate of the stereo matching result according to the exposure and illumination conditions. The error rate means that the ratio of the number of error pixels to the total number of pixels in the image. The error pixel refers to a pixel having the difference between the actual disparity value and the experimentally obtained disparity value is greater than 1. Those are summarized in Table 3 and Table 4.

The ANCC results in Fig. 6, Table 3, and Table 4 are estimated using a 7×7 sized patch. The original ANCC paper used a 31×31 sized patch for stereo matching. Therefore its matching speed is slower but results performs better than ANCC with the 7×7 sized patch. However, in this paper, the 7×7 sized patch was used for the proposed method and other methods such as SAD and NCC. For this reason, the 7×7 sized patch was used for ANCC for fair comparison of execution time and error rates.

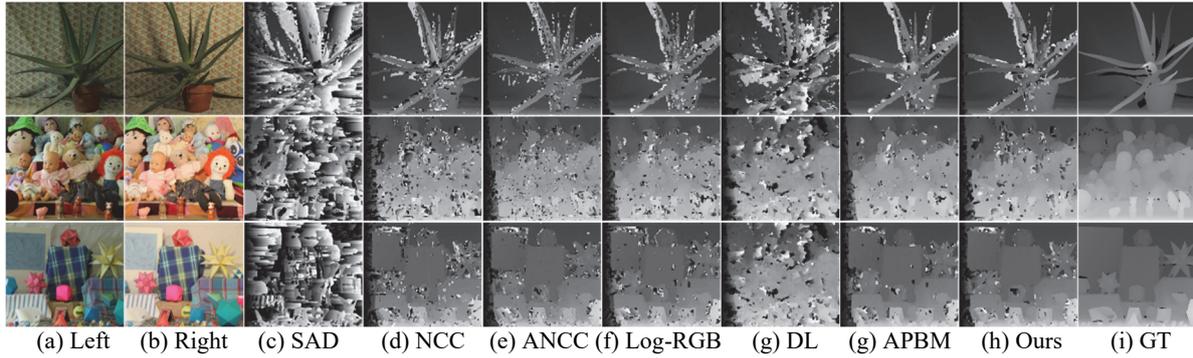


Figure 6: Disparity maps of datasets having the illumination level of the left and right image 1 and 3, respectively.

Table 3: Error rate comparison between the proposed method and other methods (exposure).

	SAD+GC	NCC+GC	ANCC (7×7)	Log-RGB+GC	DL	APBM+GC	Ours
Error rates (%)							
0-0	20.33	14.55	16.48	26.06	24.25	23.88	10.03
0-1	97.93	12.71	17.82	23.51	31.11	21.07	9.17
0-2	97.99	14.6	22.3	24.64	47.17	21.96	10.63
1-1	18.14	11.56	9.46	15.86	23.56	12.31	7.04
1-2	97.47	13.22	10.34	16.63	34.79	12.25	9.13
2-2	17.23	11.66	8.03	13.2	24.94	8.63	7.19
Avg.	58.18	13.05	14.07	19.98	30.97	16.68	8.87

Table 4: Error rate comparison between the proposed method and other methods (illumination).

	SAD+GC	NCC+GC	ANCC (7×7)	Log-RGB+GC	DL	APBM+GC	Ours
Error rates (%)							
1-1	18.15	11.6	9.41	15.81	23.56	12.41	7.06
1-2	77.63	13.77	11.23	17.89	35.32	14.16	9.57
1-3	87.88	28.1	21.14	23.31	59.59	18.92	20.12
2-2	18.66	11.61	8.62	14.51	24.41	10.64	6.93
2-3	80.07	22.68	16.54	20.12	52.06	15.96	14.88
3-3	18.69	11.63	8.5	14.29	25.23	10.43	6.75
Avg.	50.18	16.57	12.57	17.66	36.7	13.75	10.89

Error rates in both Table 3 and Table 4 mean that in the non-occluded region. In Table 3, where DL means stereo matching using CNNs (Luo et al., 2016). The proposed method shows the best results for all exposure conditions compared to other methods. In the case of illumination, our method performs better in all other illumination conditions except for '1-3' than other methods as shown in Table 4.

The running time for the cost computation is summarized in Table 5. In Table 5, the deep learning based method shows the fastest running time. However, as shown in Table 3 and Table 4, deep learning-based method shows poor results for various exposure and illumination levels. On the contrary, the

proposed method performs more robust results under various lighting conditions than other methods. In addition, our method shows faster cost computation time than ANCC. Considering the error rate and the speed of cost computation, the proposed method shows more efficient performance than ANCC and other methods even with the small sized patch.

Table 5: Cost computation time.

SAD+GC	NCC+GC	ANCC (7×7)	Log-RGB+GC	DL	APBM+GC	Ours
Time (sec.)						
24.14	38.45	117.86	38.72	7.72	74.81	39.77

5 CONCLUSIONS

In this paper, we proposed a method for efficient stereo matching that is robust to lighting changes and has a fast matching speed. The proposed method transforms the input image into the independent image from lighting factors. After that, the matching cost is calculated using the concept of census transform. Besides, we also calculate average pixel values from the left and right images. Those values are applied to selecting whether to use the original color image or the transformed image as an input for stereo matching before the cost computation. As a result, the proposed method showed three times faster speed for the cost computation than that of ANCC and also showed 5.2% and 1.68% lower errors than ANCC in exposure and illumination conditions, respectively.

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