

# Correcting for the Gain Difference of the Cameras in the Intensity—Based Parallax Estimation

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**Abstract** In this paper an intensity-based method to estimate the parallax between the left and the right image of a stereo pair is studied. Since the simplest intensity-based method, i. e. block matching, is sensitive to noise, when small block sizes are required (as e. g. for computer vision purposes), a new method, improved block matching, based on the non-linear diffusion process, was recently developed. It was shown that this new method has better noise suppressing properties than traditional block matching. Here, it is investigated how the new method reacts to a difference in average luminance and contrast of the left and the right image, caused by a gain difference in the left and the right camera. First, it is shown that improved block matching is less sensitive to these differences than traditional block matching. Secondly, a correcting mechanism, called gain control, based on the statistics of the left and the right image of the stereo pair, is shown to improve the performance of the parallax estimating algorithm.

**Keywords** Image analysis, Stereovision, Parallax field, Gain control.

## 1 Introduction

There are two fundamentally different approaches to estimate the parallax field between the left and the right image of a stereo pair: the intensity-based and the feature-based methods. The intensity-based method is the method of choice, if a dense parallax field is required, i. e. if a parallax value for every point, not just some feature points, is needed.

Block matching, the simplest intensity-based method, is a well-known technique to estimate the parallax field. It is e. g. used in the multi-view profile of MPEG-2, currently under development [1]. The parallax field resulting from block matching is of high enough quality for coding purposes, since in coding it is only important to try to make a good prediction. For computer vision appli-

cations block matching produces parallax fields of too low a quality. Since block matching assumes that the parallax field is constant over a block, in computer vision smaller blocks than the usual macroblocks (defined in MPEG) of size  $16 \times 16$  are preferred. However, the smaller the block size, the larger the fraction of false matches. Therefore, an additional smoothness constraint has to be introduced. In other words, the parallax samples can no longer be estimated block by block, each block separate from the other, but neighboring estimates have to influence each other. Based on these ideas the improved block matching method was introduced in [2, 3]. This method for estimating the parallax field is under investigation in this paper. More particularly, its robustness against a gain difference between the left and the right camera is studied.

The gain of the left and the right camera usu-

ally are set independently, causing the average luminance and the contrast of the left and the right image to differ. Since at the heart of every intensity-based method lies the assumption that the luminance of corresponding points is equal, the difference in gain may thoroughly perturb the estimation of the parallax field. This paper first deals with the influence of the gain difference on the parallax field estimated with the improved block matching method, and then proposes a way to compensate for the influence of this gain difference.

In section 2, the intensity-based method to estimate the parallax field is described (see also [3]). Next, in section 3, it is shown that the new method is less sensitive to a difference in gain than traditional block matching. Nevertheless, the difference in gain still has an influence. In section 4, a method to compensate for the gain difference is proposed. Finally, in the last section some conclusions are drawn.

## 2 Improved Block Matching

### 2.1 Outline of the algorithm

All intensity-based methods to estimate the parallax field  $d(x, y)$  of a stereo pair consider the energy in the displaced frame difference [2]:

$$D[d(x, y)] = \int dx dy [L(x + d(x, y), y) - R(x - d(x, y), y)]^2 \quad (1)$$

in which  $L(x, y)$ , resp.  $R(x, y)$ , is the left, resp. the right, image. A parallax field that minimizes this functional is searched for. This ensures that this parallax field is such that the shifted intensity patterns differ as little as possible. However, not all parallax fields are allowed to take part in the minimization process. The allowed parallax fields have to obey certain constraints, e. g. a smoothness constraint.

Taking the parallax field of the form:

$$d(x, y) = \sum d_{ij} f(x - j\Delta, y - i\Delta) \quad (2)$$

in which  $f(x, y)$  is an interpolation function  $f(x, y) = 1$  for  $|x| < \frac{\Delta}{2}$ ,  $|y| < \frac{\Delta}{2}$  and  $f(x, y) = 0$

elsewhere), and  $\Delta$ , the block size, is an integer multiple of the pixel distance, the functional (1) reduces to a multidimensional function of the samples  $d_{ij}$  of the parallax field. Remark that the parallax field of eq. (2) is constant over blocks of size  $\Delta \times \Delta$ . This introduces (rigid) smoothness in the parallax field.

It can easily be shown that finding the samples  $d_{ij}$  of the parallax field that minimize the energy in the displaced frame difference (see eq. (1)) separately, by an exhaustive search is equivalent with traditional block matching: every sample of the parallax field is estimated on its own, without influence of its neighbors. For small block sizes (e. g.  $\Delta = 4$ ), necessary for computer vision purposes, traditional block matching does not perform well. The smaller the blocks, the less diverse the intensity patterns within the block, and the harder to discriminate between different candidate blocks. The way to solve this ambiguity problem is to allow for neighboring estimates of parallax samples to influence each other. A smoothness constraint has to be introduced.

In [2] a new method based on the multi-dimensional Newton-Raphson technique to find the minimum of a function, was developed. In [3], it was proven that this method is equivalent with the iterative improving of an initial estimate obtained by traditional block matching: given an initial estimate for the parallax field  $d_{ij}^0$  a better one  $d_{ij}$  can be obtained by:

$$d_{kl} = \sum_{i,j} \gamma_{kl ij} \left[ d_{ij}^0 - (1 - g(M_{ij})) \frac{V_{ij}}{M_{ij}} \right]. \quad (3)$$

The definition of the fields  $V_{ij}$  and  $M_{ij}$ , the function  $g$  and the tensor  $\gamma$  are given below. The process (3) is iterated. The part between the brackets is called the samplewise update. The multiplication with the tensor  $\gamma$  is a linear filtering. Their effect is described in the following.

The fields in eq. (3) depend on derivatives of the functional (1) to the parallax field samples  $d_{ij}$ :

$$V_{ij} = \frac{\partial D[\sum d_{kl} f(x - l\Delta, y - k\Delta)]}{\partial d_{ij}} \Big|_{d_{kl} = d_{kl}^0}$$

$$M_{ij} = \frac{\partial^2 D[\sum d_{kl} f(x - l\Delta, y - k\Delta)]}{\partial d_{ij}^2} \Big|_{d_{kl} = d_{kl}^0} \quad (4)$$

Remark that the value  $M_{ij}$  is a reliability measure for the parallax value  $d_{ij}$ . Indeed, expressing the functional (1) as a Taylor expansion in terms of one sample of the parallax field, i. e.  $(d_{ij} - d_{ij}^0)$ :

$$D[d_{ij}] \approx D[d_{ij}^0] + V_{ij}(d_{ij} - d_{ij}^0) + \frac{M_{ij}}{2}(d_{ij} - d_{ij}^0)^2 \quad (5)$$

we see that if  $M_{ij}$  is large, there is a strong minimum, and hence, the estimate  $d_{ij}$  is reliable. In the other case, when  $M_{ij}$  is small, the estimate  $d_{ij}$  is unreliable; i. e. even a small amount of noise can have drastic effects. Hence, the name reliability field for the field consisting of the samples  $M_{ij}$ .

Remark that the samplewise update is very similar to one Newton-Raphson iteration to estimate each parallax value  $d_{ij}$  separately from all other samples. The field consisting of the samples  $V_{ij}$  is called the update field. If the initial solution  $d_{ij}^0$  does not lie within the convergence interval of the optimal solution the samplewise update produces unpredictable results. This is e. g. the case for parallax samples  $d_{ij}^0$  for which  $M_{ij}$  is too small. That is the reason for the function  $g$  in eq. (3). This function takes the form:

$$g(M_{ij}) = \frac{1}{1 + \left(\frac{M_{ij}}{\tau}\right)^m} \quad (6)$$

i. e. the update of the parallax samples for which the reliability  $M_{ij}$  is small, is inhibited.

In [2], it is proven that the tensor  $\mathcal{V}$  acts as a place dependent linear filter. There the tensor  $\gamma$  is calculated explicitly. This is however computationally complex. In this paper, as in [3], the effect of  $\mathcal{V}$  is approximated based on the non-linear diffusion equation.

In [4] the place dependent filtering behavior of the non-linear diffusion equation:

$$\nabla \cdot [c(x, y, t) \nabla f(x, y, t)] = \frac{\partial f(x, y, t)}{\partial t} \quad (7)$$

is studied. With  $f(x, y, 0)$  equal to the initial image, the diffused image  $f(x, y, t)$  gets smoothed

as  $t$  increases. In the case of linear diffusion, i. e. when the diffusion velocity is a constant  $c = c_{max}$ , the diffused image  $f(x, y, t)$  is the original image convoluted with a Gaussian pulse with width  $\sqrt{2c_{max}t}$ . In [4] the diffusion velocity depends on the amplitude of the gradient  $\nabla f(x, y, t)$ . In regions where the gradient is large, i. e. where an edge is expected, the local diffusion velocity is low, diffusion is inhibited, and the function  $f(x, y, t)$  does not change too much with increasing  $t$ . In regions where the gradient is low the smoothing effect remains as in the case of linear diffusion. In [4] the non-linear diffusion process was used to enhance the initial image  $f(x, y, 0)$ , i. e. to reduce the noise in the image, while preserving the edges.

We use the non-linear diffusion process here to approximate the effect of multiplying with the tensor  $\mathcal{V}$  in eq. (3). Instead of the amplitude of the gradient (see [4]), the reliability field  $M_{ij}$  determines the diffusion velocity. In places where the estimate is reliable, we inhibit the diffusion; in places where we had an unreliable estimate, we let neighboring estimates influence the unreliable estimate. So, we approximate the effect of the multiplication with the tensor  $\mathcal{V}$  in eq. (3) by a non-linear diffusion process with local diffusion velocity depending on the reliability field  $M_{ij}$ :

$$c_{ij} = \frac{c_{max}}{1 + \left(\frac{M_{ij}}{\theta}\right)^n} \quad (8)$$

The diffusion runs from  $t = 0$ , i. e. the parallax field after the samplewise update (see eq. (3)) to  $t = T$ , i. e. , the new parallax field  $d_{ij}$ . In this diffusion neighboring parallax samples influence each other, and in this way the diffusion process introduces smoothness in the parallax field.

This gives the following procedure to estimate the parallax field. Starting from the solution obtained by traditional block matching, the following two-step process is iterated. The first step consists of the samplewise update. This is followed by the second step: the non-linear diffusion with the diffusion velocity given by eq. (8) from  $t = 0$  to  $t = T$  to obtain a new smoother parallax field. This

new parallax field replaces the initial parallax field, and a new iteration can start. After some iterations (typically 100) the parallax field converges to a stable solution.

The parameter  $\tau$ , resp.  $\theta$ , is the threshold for the samplewise update, resp. for the diffusion. They are usually chosen as a fraction (typically 0.25) of the average value of the reliability samples  $M_{ij}$ . The parameters  $m$  and  $n$  determine the steepness of the thresholding functions (see resp. eq. (6) and eq. (8)). The choice of these latter parameters is not critical. They are chosen as  $m = 2$  and  $n = 1$ . The product  $c_{max}T$  determines the amount of smoothness in the resulting parallax field; the larger this product, the smoother the resulting parallax field.

## 2.2 An example

In Fig. 1 the left image of an artificial stereo pair is shown. The parallax of the background is  $-2.3$ ; the circle has a parallax of  $2.0$ ; the trapezium of  $1.0$ ; and the parallax of the rectangle ranges from  $-1.0$  on the left to  $1.0$  on the right. The right image is obtained by shifting the objects according to their parallax, and then both images are corrupted by additive white Gaussian noise with standard deviation of  $0.005$  of the maximum luminance (i. e. 255). This stereo pair is used to obtain quantitative results.

The histogram of the errors between the ground truth (the known parallax field) and the estimated parallax field is shown in Fig. 2. The block size  $\Delta$  was 4. The initial block matching exhaustively searched for parallaxes in the range  $[-3.0, 3.0]$  with a step of  $0.5$ . The parameters for the improving process were as follows;  $\tau$  and  $\theta$  were taken as  $0.25$  of the average of the reliability samples,  $c_{max}T = 1.0$ ,  $m = 2$  and  $n = 1$ . There were 100 iterations in the improving process. This figure shows that the improving process reduces the errors in the parallax field. Of course, the other advantage of the improving process is that the resulting parallax field is smoother.

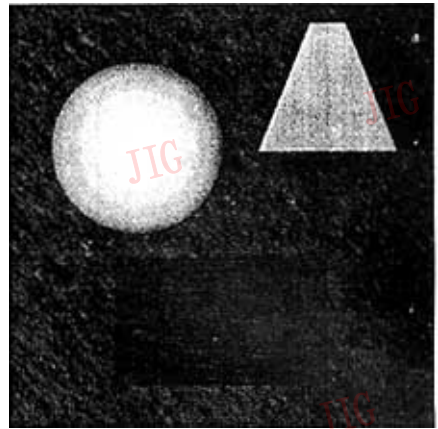


Fig. 1 Left image of the artificial stereo pair

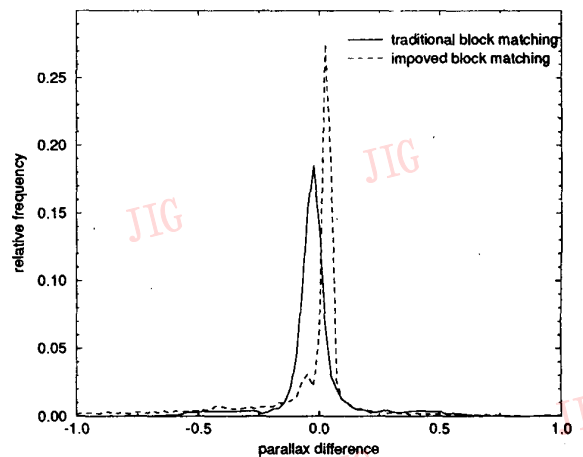


Fig. 2 Histogram of errors of the parallax field estimated with traditional block matching and improved block matching

## 3 Sensitivity of the Parallax Field

### 3.1 The corrupting process

The gain difference of the left and the right camera modifies the ideal image  $L(x_l, y_l)$ , resp.  $R(x_r, y_r)$ , to the corrupted image  $L'(x_l, y_l)$ , resp.  $R'(x_r, y_r)$ . This relation is linear as long as the corrupted value lies within the luminance interval  $[0, 255]$ . If the corrupted value is lower than  $0$ , resp. larger than  $255$ , it gets truncated to the

lower bound, resp. upper bound. This corrupting process causes a difference in average luminance and contrast in the left and the right image, and it makes the histograms of the left and the right image considerably more different than can be accounted for by noise and occlusion. It will be shown below that based on these statistical measures, the gain difference can be corrected.

Neglecting truncation the correcting process, i. e. the inverse of the corrupting process, can be modeled as:

$$\begin{aligned} L(x_l, y_l) &= (1 + \alpha)L'(x_l, y_l) + 255\beta \\ R(x_r, y_r) &= (1 - \alpha)R'(x_r, y_r) - 255\beta \end{aligned} \quad (9)$$

in which  $\alpha$  and  $\beta$  are (relatively) small. Correcting the left and the right image in such a linear way is called gain control.

### 3.2 The influence of the difference in gain

If the parameters  $\alpha$  and  $\beta$  were known, the images could be corrected before they are presented to the parallax estimation algorithm. Unfortunately these parameters are not known. Using the corrupted stereo pair, i. e.  $L'(x_l, y_l)$  and  $R'(x_r, y_r)$ , instead of the ideal stereo pair, i. e.  $L(x_l, y_l)$  and  $R(x_r, y_r)$ , perturbs the estimation of the parallax field seriously.

The perturbation of the estimated parallax field is illustrated on the artificial stereo pair (see Fig. 1) in Fig. 3 and Fig. 4. Fig. 3 shows the influence of the parameter  $\alpha$  and Fig. 4 the influence of the parameter  $\beta$ . The parameters for the traditional block matching and the improved block matching were set as for the results in Fig. 2. It is seen that the parallax field obtained by traditional block matching is influenced a great deal by a gain difference of the left and the right camera. The improving process reduces the influence of this gain difference, but even in this case the quality of the estimated parallax field using unperturbed images (see Fig. 2) is not reached.

### 3.3 Order of magnitude of the gain difference

Fig. 5 shows the left image of the real stereo pair "dodecahedron". Table 1 shows the average

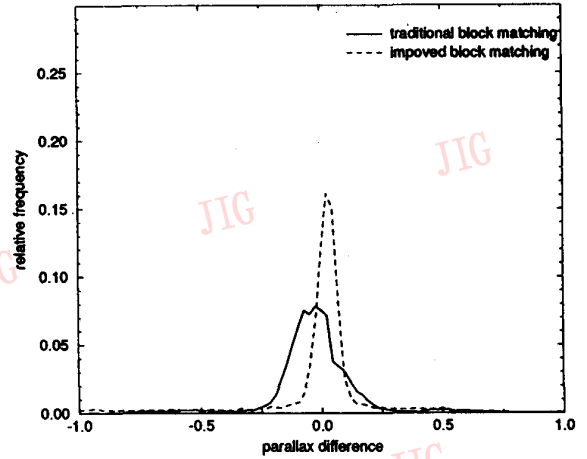


Fig. 3 Histogram of errors for a perturbation  $\alpha=0.01$

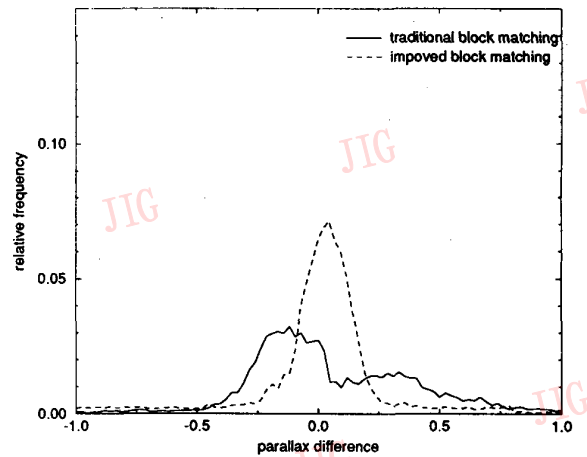


Fig. 4 Histogram of errors for a perturbation  $\beta=-0.01$

luminance and the contrast (i. e. the standard deviation of the luminance) of the left and the right image. This shows that the value of the parameters  $\alpha$  and  $\beta$  is of the order of the ones used for Fig. 3 and Fig. 4. This is a typical situation, when care is taken not to produce a too large a gain difference.

Table 1 Statistics of the stereo pair "dodecahedron"

	left	right
average luminance	$\mu_l=90.22$	$\mu_r=92.20$
contrast	$\sigma_l=36.51$	$\sigma_r=37.72$

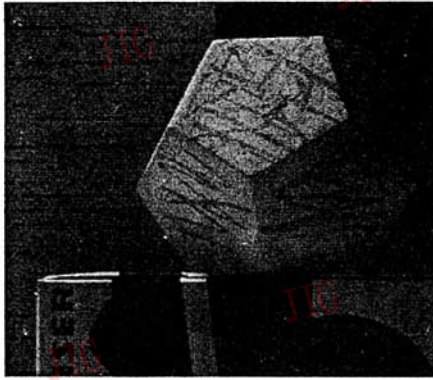


Fig. 5 Left image of the stereo pair "dodecahedron"

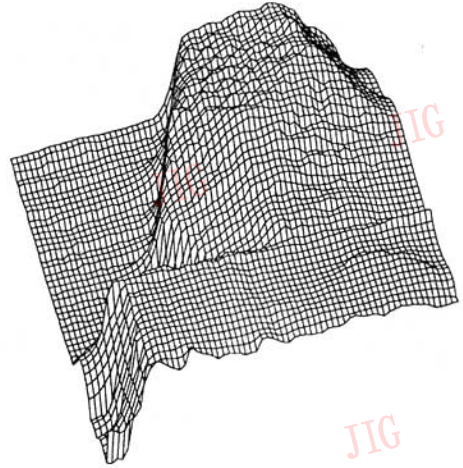


Fig. 6 Parallax field for the stereo pair "dodecahedron" without gain control

Table 2 Statistics of the stereo pair "houses"

	left	right
average luminance	$\mu_l=130.77$	$\mu_r=168.35$
contrast	$\sigma_l=47.37$	$\sigma_r=36.71$

Fig. 6 shows the result of estimating the parallax field with the improved block matching method without gain correction. The block size  $\Delta$  was 4. The initial block matching exhaustively searched for parallaxes in the range  $[-4.0, 1.0]$  with a step of 0.5. The parameters for the improving process were as follows:  $\tau$  and  $\theta$  were taken as 0.25 of the average of the reliability values,  $c_{max}T = 1.0$ ,  $m = 2$  and  $n = 1$ . There were 100 steps in the improving process. The resulting parallax field is reasonably good. Except for some border effect, the only flaw is that the planar parts of the surface of e. g. the dodecahedron, are not estimated completely flat.

Fig. 7 shows the left image of the real stereo pair "houses". It is an aerial photograph of a landscape. When recording the images, no care was taken to obtain more or less the same gain. Hence, the average luminance and the contrast of the left and the right image, shown in table 2, differ quite a lot. This is also illustrated by the cumulative histogram of both images in Fig. 10.

Presenting this corrupted stereo pair to the improved block matching algorithm (or the traditional block matching algorithm) results in a com-



Fig. 7 Left image of the stereo pair "houses"

pletely wrong parallax field. The improved block matching method, as each intensity-based method, does not work for such a severely corrupted stereo pair. The gain difference is too large. Correction of this gain difference is absolutely necessary.

#### 4 Compensating for the Gain Difference

When the gain difference is small, the effects of truncating the values,  $L'$  and  $R'$ , outside the luminance interval  $[0, 255]$  can be neglected. In that case eq. (9) are valid for every value occurring in the images  $L'(x_l, y_l)$  and  $R'(x_r, y_r)$ . There

is a linear relation between the average luminance, resp. the contrast, of the corrupted image ( $L'$  resp.  $R'$ ) and the average luminance, resp. contrast, of the ideal image ( $L$  resp.  $R$ ). The parameters  $\alpha$  and  $\beta$  can be estimated based on the requirement that after the correction of eq. (9) the average luminance and the contrast of the corrected left and right image have to be the same. This leads to the following estimates for the parameters  $\alpha$  and  $\beta$ :

$$\alpha = \frac{\sigma_r - \sigma_l}{\sigma_r + \sigma_l}$$

$$\beta = \frac{(1 - \alpha)\mu_r - (1 + \alpha)\mu_l}{2 \times 255} \quad (10)$$

When truncation has a major influence, eq. (9) break down for boundary values, i. e.  $L' = 0$  or  $L' = 255$ , resp.  $R' = 0$  or  $R' = 255$ , and eq. (10) can no longer be used.

Fig. 8 shows the result of estimating the parallax field with improved block matching with gain control on the stereo pair "dodecahedron". Based on the values of table 1, the values for gain control are  $\alpha = 0.016$  and  $\beta = -0.002$ . These are relatively small, but they do have a perturbing influence on the estimated parallax field as was shown previously. Based on the corrected images the parallax field was estimated with the improved block matching method. The parameters were set as for Fig. 6. Comparing Fig. 8 with Fig. 6, we can qualitatively see that the planar pieces of the surface are more correctly estimated when there is gain control.

Fig. 9 shows the result of estimating the parallax field with the improved block matching with gain control on the stereo pair "houses". Based on the values of table 2, the values for gain control are  $\alpha = -0.127$  and  $\beta = 0.148$ . The block size  $\Delta$  was 4. The initial block matching exhaustively searched for parallaxes in the range  $[-5.0, 15.0]$  with a step of 0.25. The parameters for the improving process were:  $\tau$  and  $\theta$  were taken as 0.25 of the average of the reliability values,  $c_{max}T = 1.0$ ,  $m = 2$  and  $n = 1$ . There were again 100 steps in the improving process. It can be seen that the houses are easily distinguished from the surroundings.

Since in this case the correcting parameters  $\alpha$

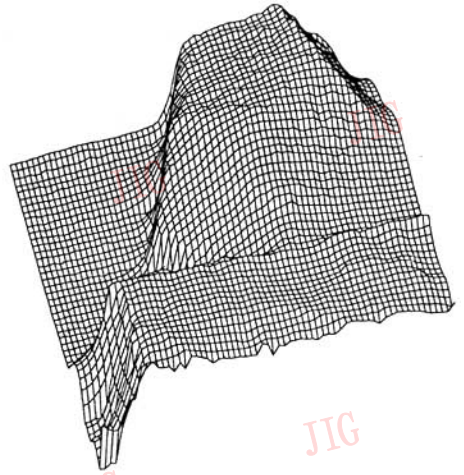


Fig. 8 Parallax field for the stereo pair "dodecahedron" with gain control

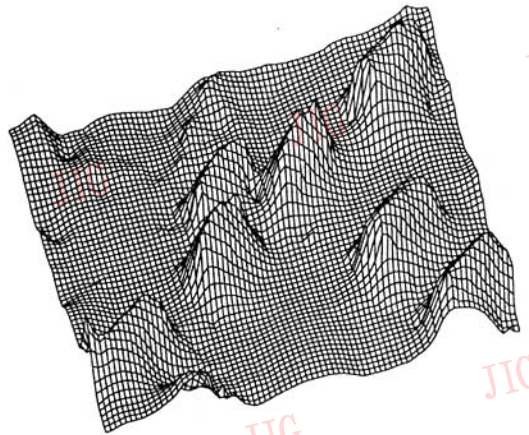


Fig. 9 Parallax field for the stereo pair "houses" with gain control

and  $\beta$  are relatively large, it has to be checked whether the effect of truncation was still negligible. Therefore, we consider the cumulative histograms of the corrected images. Since the corrupted image  $L'(x_l, y_l)$ , resp.  $R'(x_r, y_r)$  takes only values in the interval  $[0, 255]$ , its corrected counterpart takes values in  $[255\beta, 255(1 + \alpha + \beta)]$ , resp.  $[-255\beta, 255(1 - \alpha - \beta)]$ . At the boundaries of this interval the cumulative histogram possibly has a discontinuity. This makes that the cumulative histograms should only accord in the interval  $[255|\beta|, 255(1 - |\alpha + \beta|)]$ , and not out-

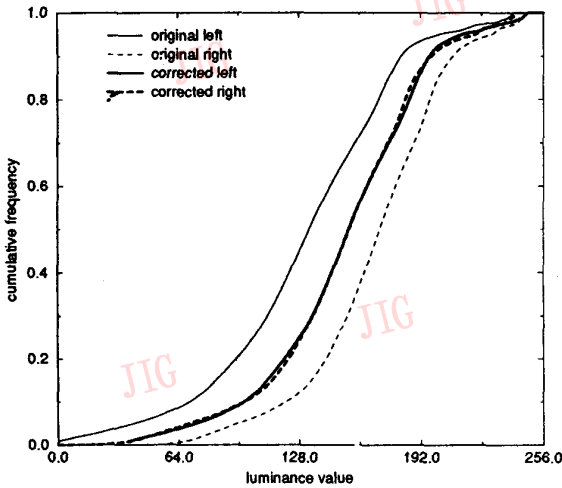


Fig. 10 Cumulative histograms of the left and right image of the stereo pair "houses" before and after gain control

side. In Fig. 10 the cumulative histogram of the left and right image of the stereo pair "houses" before and after gain control is shown. The cumulative histograms of the corrected left and right image coincide very well in the interval  $[38, 249]$ . At the boundaries of this interval there are no considerable discontinuities. We may conclude that truncation has no large effect on the gain control of this stereo pair.

This suggests a crude method to correct the images when truncation has a large influence: (manually) adjust the parameters  $\alpha$  and  $\beta$  of eq. (9) so that the cumulative histograms of the corrected images, L and R, more or less coincide in a subinterval of the luminance interval  $[0, 255]$ , centered around 127.

## 5 Conclusion

In this paper the influence of a gain difference

of the left and the right camera on the estimated parallax field was studied. An intensity-based algorithm, called improved block matching, previously shown to have better noise suppressing characteristics, was shown to be more robust against this gain difference than traditional block matching. Nevertheless, as for all intensity-based algorithms to estimate the parallax field, a sensitivity to a gain difference remained. Therefore, a method to compensate for a gain difference, called gain control, based on the statistics of the left and the right image, was developed in this paper. The increase in performance of the improved block matching method with gain control was illustrated on one artificial and two real stereo pairs.

## Acknowledgment

The original stereo pair "flat" of which the stereo pair "houses" is a window, is available via anonymous ftp from "ftp.ifp.uni-stuttgart.de" in the file "/pub/wg3/flat.tar.Z". We thank the university of Stuttgart, Germany, for the availability of this stereo pair.

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## 对视差估计中摄像机增益差的校正

**摘要** 本文讨论一种基于亮度对立体图对左右图象的视差进行估计的方法。因为最简单的基于亮度的方法,如块匹配法,在尺寸块较小时对噪声比较敏感,所以近来人们提出了一种基于非线性扩散的比传统块匹配法有更好的噪声抑制性能的改进块匹配法。本文将探讨这种新方法在由左右摄像机增益差而导致立体图对亮度和反差不同时的情况。首先我们指出改进块匹配法与传统方法相比对上述亮度和反差方面的差别更不敏感。其次我们介绍一种基于立体图对统计特性的称为增益控制的方法以改进视差估计算法的性能。

**关键词** 图象分析、立体视觉、视差场、增益控制

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张旭东,副教授,1991年3月在清华大学电子工程系研究生毕业获硕士学位,94年起攻读博士学位,主要从事专业为:多媒体通信,视频编码和数字信号处理。

## Image-Processing System Based on TMS320C80

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**Abstract** An overview of the TMS320C80 MVP parallel processor is provided in this paper, including key features and a description of the parallel processor's architecture. The TMS320C80 SDB (Software Development Board) structure is described and the individual components of the PC-base system are discussed. Lastly, a table lists the image-processing products based on TMS320C80.

**Keywords** Digital signal processor, Image processing, Parallel processing