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Paper

Pixel Parameter Optimization for Jaggy Reduction in Line Representation using Pseudorandom Pixel Placement

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Abstract The conventional image systems have been developed in order to enhance the quality of the image representation. Jaggy appearing at the edge of a slant line are, however, easily perceived by human eyes, which often severely defect the 'perceived' image quality, because of the spatial perceive characteristics of our eye system. Although the size of the jaggy can be reduced by reducing the pixel size, it is hard to completely eliminate the perceived jaggy by using the conventional lattice pixel placement, since our eye system is sensitive enough to perceive such jaggy.

In this paper, we describe the basic concept of the pseudorandom pixel placement to reduce the jaggy effect, and discuss the relation of jaggy reduction effect and the pixel structure characteristics, in terms of the fill factor and the number of pixel types.

Key words: Pseudorandom pixel placement, Perceive, Line representation, Jaggy, Spatial frequency, Pixel parameter

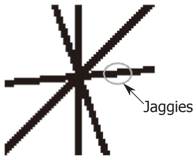

Fig. 1 Example of jaggy at the edge of a slant line

1. Introduction

The conventional image systems have been developed in order to enhance the quality of the image representation. One of the most simple but clear ways to enhance the image quality is to increase the image resolution, or the number of pixels. If the number of the pixels increases, the image information quantity and the power consumption in image systems will become higher. Jaggy appears at the edge of the slant line will be perceived, because a human eyes are sensitive enough to perceive such jaggy[1], as shown in Fig.1. Although the size of jaggy can be smaller by reducing pixel size, it is hard to completely eliminate jaggy by using the conventional lattice pixel placement, since our eye system is sensitive enough to perceive such jaggy[6].

The authors have been proposing the method of reducing the jaggy by arranging the "effective area," which contributes to compose the image, such as photo detector or light emitting area, at pseudorandom positions, while keeping the lattice arrangement of pixel boundaries[2]. It is indicated that the pseudorandom pixel placement has the jaggy reduction effect compared with the conventional lattice pixel placement when pixel size is the same[3]. Reduction of the number of pixels required realizes the power consumption and computational power smaller, and to enhance the higher image processing speed in practical applications. The jaggy reduction effect of the pseudorandom pixel placement can be considered as the high effective spatial frequency of the pixel placement[4]. The larger ratio of the effective area to the pixel area gives the lower jaggy reduction effect, while the smaller effective area will decrease the image quality.

In this paper, we describe the basic concept of the pseudorandom pixel placement for jaggy reduction, and discuss the relation beterrn jaggy reduction effect and the pixel structure characteristics, in terms of fill factor and the number of pixel types.

2. Expression of Line With Pseudorandom Pixel Placement

2.1 Principle of pseudorandom pixel placement

The concept and the example of pseudorandom pixel placement for jaggy reduction are shown in Fig.2, where the white boxes and black boxes represent the pixel boundary and the area that practically compose an im-

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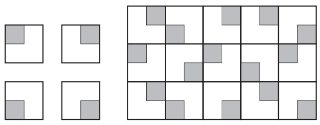


(a) (b)

Fig. 2 Pixel structure and pixel placement. (a)four types of pixels, (b)generated pseudorandom pixel placement.

(a) (b)

Fig. 3 Examples of slant line representation with different pixel placement. (a)using lattice placement, (b)using pseudorandom placement.

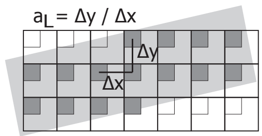
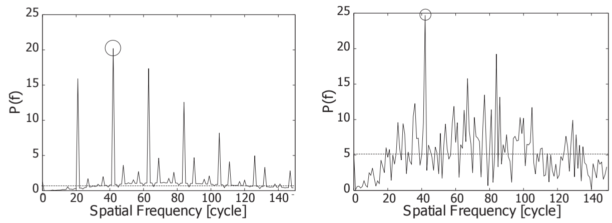


Fig. 4 Definition of local slope, a_L, at the edge of a slant line.

age, respectively. We call this area which practically compose an image 'effective area' in this paper, such as the photo receptor or light emitting area, Since the effective area occupies a part of pixel, we can generate pseudorandom arrangement of the effective areas by placing various types of pixels whose effective area positions are different, as shown in Fig.2(b). We can obtain almost completely 'random' effective area placement by arranging the randomly selected several types of pixels with different effective area positions[2] by using random numbers . The spatial positions of the effective areas by pseudorandom pixel placement have the small random scatter at the edge, and the jaggy steps are 'dissolved' into the pairs of the pixels. Although we highly sensitive to perceiving the jaggy or the isolated step[5], we are not as sensitive as to the continuous random step generated by pseudorandom arrangement. Thus, the 'dissolved' jaggy are not clearly perceived. The small random scatter at the edge by pseudorandom pixel placement is not easily perceived by human eyes, as shown in Fig.3.

The merit of the pseudorandom pixel placement is to obtain the same image quality or image measurement accuracy with the smaller number of pixels compared with the lattice placement. It also contributes to reducing the power consumption and computational power, and enhancing image processing speed.



(a) (b)

Fig. 5 Examples of the spatial spectrum of the a_L for the slant line with the angle of 10[deg] for cases of (a)lattice placement, and (b)pseudorandom placement. (Dotted line: average power except peak, circle indicates: peak factor)

2. 2 Definition of jaggy appearance measure in a slant line representation

The index how we clearly perceive the jaggy depends not only on the spatial resolution, but also on how we perceive the image. For example, we usually evaluate the characteristics of our eye system in term of the spatial resolutions; how small the gap we can perceive. However, it is known that we clearly perceive the small step at the edge of the line, so called the Vernier Acuity of the eye[6]; we can perceive the step with approximately 1/20 in size compared with the random dots. This fact indicates that we cannot discuss the jaggy appearance / reduction effect in term of the simple spatial resolution. There exist no conventional index for evaluating how we clearly perceive the jaggy. Thus, we have to define one index how we clearly perceive the jaggy.

The measure of how we clearly perceive the jaggy at the edge of a slant line is relational to the cycle of jaggy, or the spatial frequency of the jaggy. Here, we assume that we watch the presented image composed of the pixels whose pitch is 0.3 [mm] at the distance of 60 [cm]. Here, we define the local slope at the edge of a slant line, a_L as shown in Fig.4. The value of a_L greater than 0 means the step at the edge of a line and the cyclic occurrence of the step form jaggy.

At first, we calculated a_L along with the horizontal axis at each pixel to obtain its spatial spectrum. Then, we calculated the product of the spatial spectrum and the spatial characteristics of the human eye's perceiving sensitivity[4], $P(f)$ to obtain the 'perceived' spatial spectrum of jaggy. Jaggy are considered as the standing factor in the spatial spectrum within the range where we clearly perceive. Note that multiple factors or flat ('white') spatial spectrum within the range where we clearly perceive jaggy will NOT form clear jaggy.

The existence of the distinguished factor in the spatial spectrum within the range we clearly perceive jaggy

(a) (b) (c)

Fig. 6 Examples of the represented slant lines and the value of Top/Other of (a)23.4, (b)6.6, and (c)2.7.

is corresponding to the perceived jaggy, as shown in Fig.5 in both cases of the lattice and the pseudorandom pixel placement . Here, we define the measure to evaluate how clearly we can perceive jaggy, 'Top/Other', as the ratio of the strongest factor in the spatial spectrum to the average of the other factors in the calculated spectrum as follows.

$$\text{Top/Other} = \frac{P_{\max}}{\overline{P}} \tag{1}$$

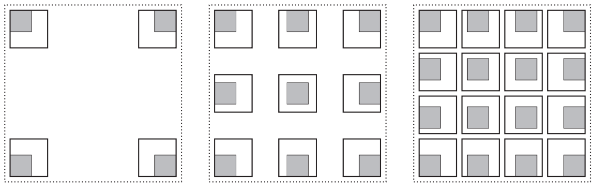
Here, $P_{\max}$ and $\overline{P}$ are the power of the peak factor and the average power of the factors except the peak factor in $P(f)$, respectively. In the examples in Fig.5(a) and (b), the values of Top/Other are 16.01 and 4.81, respectively.

We should perform the subjective experiments[7] in order to make an evaluation of how we actually perceive the jaggy. Although the qualitative evaluation of the relation between the value of Top/Other and the subjective results of jaggy perceive should be discussed in our future works, it has been revealed that if the value of Top/Other is smaller, we can perceive less jaggy on a slant line, as shown in Fig.6.

3. Evaluation of Jaggy Reduction Effect

In order to perform the evaluation of the pseudorandom placement's characteristics in a simulation, we employed the method of 'virtual pixel' to deal with the pseudorandom pixel placement. Here we define one 'virtual pixel' composed of actual 72×72 pixels. In a virtual pixel, the part of the area is defined as the effective area. For example, the effective area composed of 36×36 pixels represents a 'virtual' pixel with the fill factor of 25%. The size and the location of the effective area can be changed by the pixel parameters representing the characteristics of the effective area. The pixel parameters are, for example, the fill factor, the displacement of the effective area within a virtual pixel, the appearance probability of selection in the pseudorandom pixel placement generation.

In the simulation below, we used 300×300 virtual pixels plane, where the types of virtual pixels are randomly selected to form the virtual pixel plane. Next, we generated the slant line with various slopes on the virtual pixel plane, where the binary value of each virtual pixel is determined whether its effective area is included in the slant line or not, as shown in Fig.4. We calculated the value of Top/Other for this generated simulation image to evaluate how clearly we can perceive the jaggy.



(a) (b) (c)

Fig. 7 Pixel types. (a)4 types, (b)9 types, and (c)16 types.

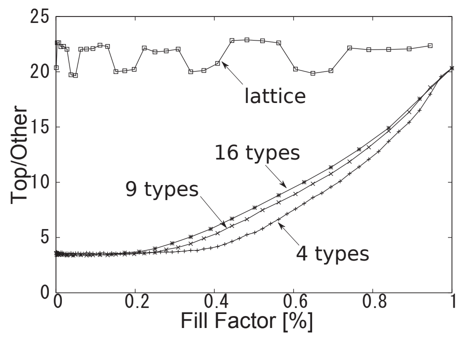


Fig. 8 Top/Other for pseudorandom placements with 4, 9, 16 pixel types, and lattice placement.

3. 1 Type of effective area placement

The characteristics of the virtual pixels can affect the jaggy reduction characteristics. Here, we assumed the three types of the virtual pixel pairs for pseudorandom placement generation, as shown in Fig.7(a), Fig.7(b) and Fig.7(c), that has four, nine, and sixteen different types of effective area locations in the virtual pixels, respectively. The number of pixel types affects spatial characteristics of the effective area positions generated by randomly selected virtual pixels, thus, the jaggy appearance / reduction effect.

We calculated Top/Other for pseudorandom pixel placement with four, nine, and sixteen types of pixels, as well as the conventional lattice placement, as shown in Fig.7, in the various case of the line representation with the slope of 1 [deg] to 45 [deg] with 1 [deg] steps, and various value of fill factor. Fig.8 shows the average of Top/Other with various fill factors of the virtual pixel for all lines with 10 trials in pseudorandom generation, with pixel types of four, nine, and sixteen, respectively, including the case of the lattice placement. This result shows that the pseudorandom pixel placement gives the smaller Top/Other, or the less strongly perceived jaggy than the conventional lattice placement. This result

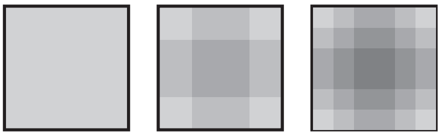


Fig. 9 Occupation probability of effective area (dark area corresponds to the higher occupation probability of the effective area). (a)4 types, (b)9 types, and (c)16 types.

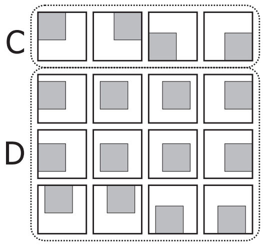


Fig. 10 Two groups of pixel types in 16 pixel types.

also shows that in case of four pixel types, Top/Other becomes smallest with the fill factor of larger than 25%.

3. 2 Effect of appearance probability of specific pixel placement

As shown in Fig.8, in case of sixteen pixel types, the value of Top/Other becomes larger than that of other cases. This phenomenon can be caused due to non-uniform occupation of the effective area in a virtual pixel. Fig.9 shows the probability, or how often the effective area occupies in a virtual pixel area for the constant selection probability at the process of pseudorandom pixel placement generation. When the number of pixel types increases, the occupation probability at the center of a virtual pixel area becomes higher, as shown in Fig.8, that reduces the effect of scattering the effective area positions.

The sixteen types of pixels are categorized into two groups of C and D, as shown in Fig.10. Pixels in groups C have the effective area at the corners of a virtual pixel, which will reduce the effective area occupation probability at the center of a virtual pixel. The higher selection probability for group C is expected to obtain the reduced effective area occupation probability at the center of a virtual pixel, and thus, the lower Top/Other.

We have already demonstrated that Top/Other of sixteen pixel type becomes smaller than that of four pixels type, with giving the specific selection probability for group C pixels for the case of the fill factor of 25%[5]. Here, we discuss the relation between the pixel selection probability and the fill factor in terms of the jaggy reduction effect. We carried out the simulation of Top/Other for the case of sixteen pixel types, with

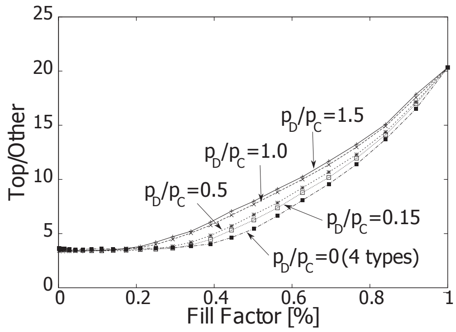


Fig. 11 Top/Other for various p_C/p_D

different appearance probability for the groups of C and D, p_C and p_D, respectively. Note that p_D of 0 corresponds to the case of four pixel types.

Fig.11 shows the calculated Top/Other for various value of p_D/p_C, as a function of the fill factor. In case of the larger fill factor than 25%, it was shown that the smaller p_D/p_C gives smaller Top/Other, or higher jaggy reduction effect. This result indicates that the pseudorandom pixel placement with four pixel type gives the highest jaggy reduction effect for the larger fill factor of 25%.

4. Conclusion

In this paper, we proposed the pseudorandom pixel placement for reducing the jaggy effect, and discussed the measure of how clearly the jaggy are perceived. We also discussed the optimum pixel parameters for jaggy reduction. In case of the pseudorandom pixel placement with four pixel types, the highest jaggy reduction effect results.

It is also indicated that the lower fill factor gives the higher jaggy reduction effect, however, the lower fill factor also decreases the image quality. The total performance in image quality of an image sensor should be discussed in wide viewpoints, such as photo sensitivity, resolution, the number of pixels (or the total amount of image information quantity), and so on, as well as jaggy reduction effect discussed in this paper, that will be discussed in our future works.

We also discussed the relation between jaggy reduction effect and the pixel structure characteristics in terms of the fill factor and the number of pixel types.

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