CMOS Image Sensor with Pseudorandom Pixel Placement for Image Measurement using Hough Transform

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Abstract The pixels in the conventional image sensors are placed at lattice positions, and this causes the jaggies at the edge of the slant line we perceive, which is hard to resolve by pixel size reduction.

The authors have been proposing the method of reducing the jaggies effect by arranging the photo diode at pseudorandom positions, with keeping the lattice arrangement of pixel boundaries that are compatible with the conventional image sensor architecture. In this paper, the authors discuss the design of CMOS image sensor with pseudorandom pixel placement, as well as the evaluation on image measurement accuracy of line parameters using Hough transform.

Key words: CMOS image sensor, jaggy, displacement, Hough transform

Fig. 1 Example of jaggies at the edge of the slant line.

1. Introduction

The image sensors have been developed for enhancing the quality of the image representation, with the trend of pixel size reduction in conjunction with the other technologies. The pixels in the conventional image sensors are placed at lattice positions, and this causes the jaggies at the edge of the slant line as shown in Fig.1. The jaggies also affect the image measurement accuracy, such as the area and the line angle, since the pixel representation will be dependent on the direction of the target object.

The authors have been proposing the method of reducing the jaggies by arranging the effective area (photo diode) at pseudorandom positions, with keeping the lattice arrangement of pixel boundaries that are compatible with the conventional image sensor architecture. The authors have indicated that the area measurement error can be reduced by using the pseudorandom pixel placement compared with the conventional lattice pixel placement with the same pixel size.

In this paper, the authors discuss the design of CMOS image sensor with pseudorandom pixel placement, as well as the evaluation on image measurement accuracy of line parameters using Hough transform.

2. Pseudorandom pixel placement

The concept and the example of pseudorandom pixel placement for jaggies reduction are shown in Fig.2. The white box and black box represent the pixel boundary and the photo diode (PD) area, respectively. Here we call the PD area as the active area, which effectively contributes to the image acquisition. Since the PD occupies a part of pixel area, we can generate several pixels with different active area positions. The four types of pixels are shown in Fig.2(a). We obtain the conventional pixel placement by placing one of these pixels at lattice positions, as shown in Fig.2(b). By placing randomly-chosen one of the four pixels at lattice position, we obtain the randomly-placed active areas, as shown in Fig.2(c), which we call pseudorandom pixel placement. Note that since the circuit configuration
and physical electric terminals of the four type pixels are identical, we can design the image sensor with pseudorandom pixel placement by placing the pixels as the conventional image sensor design with the additional random choice procedure. It is also notable that the variety of the pixels can be more than four, for example, nine or sixteen. However, the variety of four types shows the good performance in terms of the spatial spectrum, jaggy elimination effect, and the circuit design$^6$.

The pseudorandom pixel placement has the jaggy elimination effect as shown in Fig.3. There are periodic steps at the edge of the slant line in Fig.3(a), which we perceive the jaggies. Since the spatial frequency of the jaggy exists in the range we strongly perceive and we have higher sensitivity for the steps in jaggies, it is hard to eliminate the jaggy by pixel size reduction. Note that the jaggy frequency depends on the angle of the line.

In the line representation with the pseudorandom pixel placement in Fig.3(b), there are small random steps at the edge of the line, and the appearance of these random steps is independent on the angle of the line. Since the spatial frequency of these random steps is higher than that of the jaggies, we don’t strongly perceive these random steps, and these random steps can be easily eliminated by the pixel size reduction. Note that the displacement of the active area requires the reduction of the active area size, resulting in the decreased fill factor and the decreased photo sensitivity. The jaggy elimination effect by the pseudorandom pixel placement has the possibility of enhancing the image quality overcoming the photo sensitivity reduction$^7$.

There are conventional algorithms of anti-aliasing operation using multi-value (gray scale) pixels for jaggy elimination. The jaggy elimination effect of anti-aliasing depends on the angle of the line, which we strongly perceive in case of moving image where the line angle changes. The pseudorandom pixel placement has the advantage of jaggy elimination effect, since the appearance of pixel-size small steps scarcely depends on line angle$^7$.

There are the design parameters in the pixels used in the pseudorandom pixel placement as shown in Fig.4. The ratio of the active area to the pixel area, $f$, or the fill factor, is corresponding to the photo sensitivity. The displacement ratio of the active area in the pixel area, $d$, defines the spatial characteristics of the pseudorandom pixel placement. The smaller $d$ will reduce the jaggy elimination effect by the pseudorandom pixel placement, while the larger $d$ will result in the strong step appearance at the edge of the line. Note that $d = 0$ corresponds to the lattice placement, while $d = 1$ corresponds to the case the active area’s edge fits the pixel boundary. It is also notable that $d$ of approximately 0.6 will result in the best jaggy elimination effect$^5$.

3. Design of CMOS image sensor with pseudorandom pixel placement

We’ve previously designed a 128×128 pixel CMOS image sensor with pseudorandom pixel placement, and have reported its preliminary operation$^8$. Based on this result, We have designed the CMOS image sensor with pseudorandom pixel placement with 500×1000 pixels. It is possible to design four types of pixels with the different positions of the photo diodes, with keeping the identical physical electric terminals$^3$. However, it is difficult to keep the large photo diode area under the physical design restriction to realize these pixels. For example, the pixel under this design strategy has the fill factor of 25%$^3$. We started the image sensor design using the conventional CMOS image sensor. We employed a pixel with LOFIC capacitor for dynamic range enhancement$^{10,11}$ using CMOS 0.18μm, five metal layers image sensor process. The pixel size is 7.8μm×7.8μm with the photo diode of 6.26μm×5.06μm, where the fill factor is 51.8%.

Here, we designed the photo shield as shown in Fig.5(a) to implement the four types of pixels for the pseudorandom pixel placement. The boundary box size is equal to the size of the photo diode aperture of the
Fig. 5 Partial photo shield (a), four types of photo shields (b), the top metal layout of the original pixel (c), and the four types of pixels with different photo diode positions (d).

Figure 5(b) shows the four types of the photo shield generated by rotating the photo shield. We can obtain the four types of pixels with the different “effective” photo diode positions by overlapping them to the original pixel (Fig. 5(c)) as shown in Fig. 5(d). The fill factor is 35.7%, and the displacement radio \( d \) is 0.384.

Figure 6 shows the whole layout of the designed CMOS image sensor using the pixels in Fig. 5(c). The chip size is 5mm\( \times \)5mm, and the number of pixels is 128\( \times \)128. The upper half 128\( \times \)64 pixels are designed without photo shields (lattice plain), while the lower half 128\( \times \)64 pixels are designed with randomly chosen photo shield (pseudorandom plain), as shown in Fig. 7.

Fig. 6 Layout of the designed CMOS image sensor with pseudorandom pixel placement.

4. Simulation for Hough Transform Measurement

4.1 Simulation condition

The Hough transform is one of the methods to measure the parameters of shapes in an image. Here we assume that a line in an image is represented as follows

\[
\rho = x \sin \theta + y \cos \theta
\]  

(1)

Here, \( \rho \) and \( \theta \) are the distance to the line from \((0,0)\), and the angle of the line, respectively, as shown in Fig. 8.

We can operate the Hough transform for this line to obtain the Hough histogram, \( H(\rho, \theta) \) as the following steps:

- Find all the points representing the line, or included the line, \( P_n \).
- For all \( P_n \), add a post for the Hough histogram, \( H(\rho, \theta) \), for all the \( \theta \). Note that \( \rho \) for this line can be calculated from Eq.1, where \((x,y)\) are the coordinates of \( P_n \).
- The peak in \( H(\rho, \theta) \) gives the most adequate line parameters for the given line in an image.

We can extend the Hough transform for a line with applying the pseudorandom placement of active area. Here, we assume that the points representing the line, \( P_n \), are decided by the following conditions as shown in Fig. 9.

- Assume that the parameters of the active area are
the displacement ratio, $d$, and the fill factor, $a$, as defined in section 2.

- Calculate the ratio of the line included in the active area, $r$, for all the pixels.
- If $r$ is greater than the threshold, $r_{TH}$, we treat this pixel as included in the line.

We can carry out the Hough transform to measure the line parameters by using this algorithm, for not only lattice placement of pixels, but the pseudorandom placement pixels. Although this Hough transform algorithm handles the binary image, we can extend the algorithm to multi-value (gray scale) image. For example, we can use the histogram of Hough transform as the sum of the value which is proportional to the pixel value included in line. However, since we can apply this multi-value algorithm to Hough transform independently on pseudorandom pixel placement, we discuss on the characteristics of Hough transform on pixel placement parameters using the binary image algorithm.

We can consider that the pseudorandom pixel placement has an equivalent higher resolution compared with the lattice placement for its random displacement of the active area in the pixel region. Because of this fact, we can expect that the pseudorandom pixel placement can detect the thinner, and closer lines using Hough transform compared with the lattice placement.

In order to evaluate this effect, we carried out the following two types of simulations using the following two conditions, where $r_{TH}$ is determined to obtain the appropriate binary flags for Hough transform.

**Sim.1** Placing ten lines in a image, with the same $\theta$ and the random $\rho$, and finding them using Hough transform. Line width is set to $\times 0.2$ of pixel pitch. Line slope is set to 0, 15, 30, and 45[deg]. $r_{TH}$ is set to 0.15. The number of pixels is 200×200.

**Sim.2** Placing two lines at distance of $\rho$ of $\times 0.1$ of pixel pitch, where $\rho$ is randomly generated. Line width is set to $\times 0.1$ of pixel pitch. $\theta$ is set to 45[deg], and $r_{TH}$ is set to 0.15. The number of pixels is 100×100.

After Hough transform, we counted the number of peaks in the Hough histogram whose parameters ($\rho$, $\theta$) represent the given lines, and we calculated $R$ as the ratio of lines found to the total number of given lines.

### 4.2 Simulation results

We carried out 50 and 1000 trials for Sim.1 and Sim.2, respectively. The active area displacement, $d$, is set to 0.0, 0.384 (parameter for the designed CMOS image sensor in section 3), 0.6 (parameter for general optimal parameter[5]) , and 1. The fill factor, $f$ is set to 0.357 as in designed CMOS image sensor in section 3. Figure 10 and 11 show the $R$ for Sim.1 and Sim.2, respectively.

From the simulation result for Sim.1, it is found that the pseudorandom pixel placement has an ability to find the thin lines compared to the lattice placement. Note that $\theta=0$[deg] and 45[deg] are the special cases for the lattice placement, where the lattice placement has possible cases of ‘missing’ thin lines for its pixel placement characteristics. The pseudorandom pixel placement has the higher active area coverage than the lattice placement, which result in higher $R$. $R$ is measured to be higher for the higher active area displacement, $d$.

From the simulation result for Sim.2, it is found that the pseudorandom pixel placement has an ability to distinguish the lines at the distance of less than pixel pitch. $R$ is also measured to be higher for the higher active area displacement, $d$.

### 5. Conclusion

In this paper, we described the idea of the pseudorandom pixel placement, and applying it to the image measurement using Hough transform. We also described the design of CMOS image sensor with pseudorandom pixel
placement by adding the L-shaped photo shield to the conventional CMOS image sensor.

We also carried out the simulations to evaluate the line measurement accuracy using Hough transform in the cases of thinner line than the pixel pitch. The simulation results indicate that the pseudorandom pixel placement has an ability to measure the lines whose width and distance are smaller than the pixel pitch.

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References


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