Binocular range-sensor LSI with improved distance detection precision by coordinated pixel placement

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Abstract: We developed a binocular three-dimensional range-sensor LSI with improved distance detection precision. The range-sensor LSI is fabricated by a 0.35 μm CMOS 1-poly 3-metal process, and the chip size is $4.10 \times 3.90 \text{mm}^2$. In stereovision, the detectable distance resolution is limited by the lateral number of pixels of the image sensors. However, improvement by increasing the number of pixels requires a large increase in the chip size. Therefore, we designed a method of improving the distance detection precision by slight slide coordination of pixel placement without increasing the lateral number of pixels. By an evaluation using the developed LSI, we confirmed that the distance detection precision of the range-sensor LSI was improved fourfold in comparison with that with normal pixel placement.

Keywords: CMOS, range sensor LSI, stereo vision, image sensor

Classification: Integrated circuits

References

1 Introduction

In recent years, the three-dimensional range sensor has found various applications including those in collision avoidance systems of automobiles and interface devices of game equipment. These systems are classified into active and passive types. In the active system used in automobiles, the distance to an obstacle is measured using a laser [1] and millimeter-wave irradiation [2]. These systems have problems such as interference, a narrow field of vision and high equipment cost. Active systems using a sensor LSI include the time-of-flight (TOF) method [3] or pattern irradiation method [4]. In the TOF method, an obstacle is irradiated with near-infrared light and the distance is determined from the time taken for the reflected light to return. In the pattern irradiation method, spatially structured patterned light is projected and the distance is detected using a characteristic point displayed on an obstacle. Therefore, these methods have the problem that the detectable distance is limited by the attenuation of the reflected light and interference with natural light. On the other hand, passive systems use a stereocamera [5, 6] or binocular-sensor LSI [7, 8] to calculate the distance on the basis of stereovision. The stereocamera has synchronization problems and a high cost because it requires two cameras and a high-speed processing device. Also, the conventional binocular-sensor LSI has problems with the correlative calculation function. Because the computational complexity necessary for stereovision is huge, in binocular-sensor LSIs, the operation is carried out by partial time sharing or off chip. Therefore, the chip size must be increased to realize a high-speed frame rate, or an external high-speed processing device must be used.

We previously developed binocular range-sensor LSIs that solve the above problems [9, 10, 11]. We realized a small low-cost obstacle recognition system by integrating two image sensors and all the processing circuits on a single chip. High-speed processing was also achieved by fully parallel data processing. However, these range sensors measure distances up to only 127 gradations, and the detection precision decreases with increasing distance. Therefore, these sensors have the problem that the detection error increases when an obstacle is farther away. A simple method of solving this problem is to increase the lateral number of pixels of the image sensors. However, by this method, the problem that the chip size increases in proportion to the square of the lateral number of pixels arises.

To solve the above problem, we developed a range-sensor LSI with improved distance detection precision simply by coordinated pixel placement. The method is effective without affecting the chip size or pixel size. The pixel placement is shifted slightly at each row of the image sensor. As a result, the visual angle of each row of the image sensor is gradually changed, and the detection precision of the range-sensor LSI is improved.
2 Chip-level configuration

Fig. 1(a) shows a micrograph of the binocular range-sensor LSI that we developed. The developed LSI chip was produced by a 0.35 µm CMOS 1-poly 3-metal process and has a die size of $4.10 \times 3.90 \text{mm}^2$. Fig. 1(b) shows the configuration of the binocular range-sensor LSI. The binocular range sensor LSI is composed of two image sensors, two sets of 128 analog voltage-to-pulse width conversion (APWC) circuits, difference (DIF) circuits, invalid correlation canceling (ICC) circuits, two sets of 256 difference signal width modulation (DSWM) circuits, a matrix of 128 by 127 correlation circuits, and an output circuit.

![Micrograph of the binocular range-sensor LSI](image1)

![Configuration of the binocular range-sensor LSI](image2)

Fig. 1. (a) Micrograph of the binocular range-sensor LSI. (b) Configuration of the binocular range-sensor LSI.

The left and right image sensors both have a pixel array of 128 columns and 24 rows. A set of left and right images is irradiated into the left and right image sensors through a binocular lens (optical module [12]).

The APWC circuit can control the logic threshold value through the bias voltage [9, 11]. If the bias voltage is changed with time, the output signal inverts when the logic threshold exceeds the input voltage. As a result, the APWC circuit changes the photosensor output voltage to a corresponding pulse width.

The DIF circuit compares the output of two adjacent APWC circuits [9, 11]. The DIF circuit output is determined by the difference between the two pulses. As a
result, the DIF circuit output is related to the brightness and the spatial variation in brightness.

The DSWM circuit can remove the small noiselike signal and modulate the input signal pulse width [9]. The ICC circuit removes the correlation response in places where there is no brightness difference [9, 11]. As a result, the correlation response becomes clear.

The correlation circuit calculates the correlation between the left and right pulses and detects any targets [9, 11]. There is a $128 \times 127$ correlation circuit matrix on the LSI chip. The correlation circuit matrix is shown in Fig. 2. This circuit matrix simultaneously matches and measures the degree of coincidence among all the outputs from one row of the left and right image sensors. In this matrix, the part (upper and lower domains) that does not affect correlative detection is removed. This correlation process is completed in 2 µs. As a result of the correlation, the positional information of the object is output as the address “x” and “y”. Therefore, we can uniquely detect the 3D position of the target from these addresses and the row number of the image sensor.

![Fig. 2. Configuration of the correlation circuit matrix.](image)

3 Improvement of distance detection precision

An example of distance detection using stereovision is shown in Fig. 3. The convergence angle is 0 degrees. When an object is detected at pixel “i” in the left image sensor and at pixel “j” in the right image sensor, the address (x, y) of the corresponding correlation circuit is output. At that time, the distance detected by pixels “i” and “j” is $D_{ij}$. It is expressed by the following equation [12].

$$D_{ij} = \frac{B \times f \times N}{w \times (i - j)}$$  \hspace{1cm} (1)

$B$: base length, $f$: focal length of combined lens, $N$: number of lateral pixels, $w$: width of image area (as shown in Fig. 3)

The interval of detectable distance “$\Delta D_{ij}$” widens in inverse proportion to the size of the detection parallax:
\[ \Delta D_{i,j} = \frac{B \times f \times N}{w \times ((i-j)^2 + (i-j))} \]  
\( i-j: 1 \) to \( N-1 \),

where, “i-j” is the parallax detected with the left and right image sensors. “i-j” is the difference between the pixel positions detected on the left and right. As is shown in this equation, the binocular-vision range sensor has the problem that the distance detection precision decreases rapidly as the parallax becomes smaller.

Fig. 3. Example of distance detection by stereovision.

Fig. 4 shows the configuration of the left and right image sensors. In these image sensors, the pixel placement is shifted by one-eighth of the pixel width in each row of the image sensor. The pixel shift is repeated every four rows. The directions of the shift are opposite in the left and right image sensors. As a result, the visual angle gradually changes over four rows of the image sensor and the distance detection precision increases.

Fig. 5 shows examples of distance detection when the pixel placement shifts. When the pixel placement of the left and right image sensors is shifted by “s”, the distance “\( D_{i,j,s} \)” detected by “i” and “j” is expressed by equation (3). The interval of detectable distance “\( \Delta D_{i,j,s} \)” is expressed by equation (4). Here, “s” is 0, 1/8, 2/8, or 3/8.
Equation (4) is rewritten as equation (5) using \( n = 8s \). Here, \( n \) is an index that expresses the sliding size of the pixel and is 0, 1, 2, or 3 \((n = 8s)\).

\[
\Delta D_{i,j,s} = D_{i,j,s} - D_{i,j,s+1/8} = \frac{B \times f \times N}{4w \times (i-j-2s)(i-j-2s+1/4)}
\]  

(4)

Equation (5) shows that the lateral number of pixels increases fourfold. As a result, the distance detection precision improves fourfold with each change of “n”.

\[
\Delta D_{i,j,n} = \frac{B \times f \times 4N}{w \times [(4 \times (i-j) - n)^2 + (4 \times (i-j) - n)]}
\]  

(5)

The correlative value detected in each correlation circuit is determined by the similarity between the brightness and the change in the value of each pixel \((i,j)\) on the image sensor [9]. If the correlative values exceed the threshold set beforehand, it is
determined that an object exists at the position. The correlative value of each correlation circuit \((i,j)\) is compared by an accumulated comparator, and the correlation result \(C(i,j)\) is given as “1” when the values exceed the threshold, and otherwise it is given as “0”. These correlative results are detected at every row of the image sensor and indicated as correlative result \(C_k(i,j)\) for row “\(k\)” of the image sensor.

The developed range-sensor LSI employs a method of improving the distance detection precision fourfold using the correlative result of four rows. The shifted placement of the pixels in every row enables parallax detection at a resolution of one-quarter of the pixel width. It is necessary to estimate the distance using four correlative results in four rows of the neighborhood to realize a fourfold better resolution. The correlative values at places where the parallax is small become similar. Then the threshold value is set such that the correlative result of at least four rows in that neighborhood becomes “1”. For the four correlative results used in the distance estimation, it is necessary for the change in the parallax to be continuous. In consideration of the continuity of parallax, the placement of the correlative point must be as shown in Fig. 6. In Fig. 6, the vertical axis shows row “\(k\)” of the image sensor, and the horizontal axis shows distance. The index “\(n\)” and the new indices “\(m\)” and “\(l\)” are also shown, and they take values from 0 to 3. In the figure, the black circles indicate the points of an existing correlative circuit, and the white circles indicate the points that do not exist. The new index “\(m\)” indicates sliding from an existing correlative circuit. Therefore, \(m=0\) at the point with a black circle. Here, the relationship between “\(k\)” and “\(n\)” is “\(n=k \mod 4\)”, and the relationship between “\(l\)”, “\(m\)”, and “\(n\)” is “\(l=(n+m) \mod 4\)”. The “\(\mod\)” operator is the modulus operation, which gives the remainder after division.

![Fig. 6. Placement of the correlative point.](image-url)
In Fig. 7, a method of estimating the distance using four correlative results in four rows of the neighborhood is shown. In the figure, the domains of the correlative results used for the distance estimation for each point indicated by the small square are shown. The estimated correlative result $C^+_k(i,j,m)$ can be expressed by the following Boolean expression (7) using the four correlative results of the index “m”:

$$C^+_k(i,j,m) = \{ C_{k-2}(i_{2-L}, j_{2-L}, 0) + C_{k-2}(i_{2-R}, j_{2-R}, 0) \}$$
$$\cdot \{ C_{k-1}(i_{-L}, j_{-L}, 0) + C_{k-1}(i_{-R}, j_{-R}, 0) \}$$
$$\cdot C_{k}(i,j,0) \cdot \{ C_{k+1}(i_{+L}, j_{+L}, 0) + C_{k+1}(i_{+R}, j_{+R}, 0) \}$$

In equation (7), “$i$” and “$j$” in each term are given by the conditional expressions below, which depend on “$l$” in order to maintain the continuity of the parallax.

In the case of “$l=0$ or 1”: $i_{2-L}=i+1$, $j_{2-L}=j$, $i_{2-R}=i$, $j_{2-R}=j-1$
Otherwise: $i_{2-L}=i$, $j_{2-L}=j$

In the case of “$l=2$”: $i_{L}=i+1$, $j_{L}=j$, $i_{R}=i$, $j_{R}=j-1$
Otherwise: $i_{L}=i-R$, $j_{L}=j$

In the case of “$l=3$”: $i_{+L}=i$, $j_{+L}=j+1$, $i_{+R}=i-1$, $j_{+R}=j$
Otherwise: $i_{+L}=i+1$, $j_{+L}=j$.

When $C^+_k(i,j,m)$ becomes “1”, the distance to the object can be calculated using equation (8) with “$l$” substituted for the index “$n$”:

$$D_{i,j} = \frac{B \times f \times N}{w \times (i - j - l/4)}$$

$$n=k \mod 4, \ l=(n+m) \mod 4$$

However, the correct distance is calculated with equation (7) only when the position of the object does not change in four rows. Therefore, we introduce equation (9) for the case when the position of the object changes in four rows or the size of the object is smaller than four rows.
\[ C^*_k(i, j, 0) = \begin{cases} C^*_k(i-L_L, j-L_L, 3) + C^*_k(i-R_R, j-R_R, 3) \\ C^*_k(i, j, 0) \cdot \left[ C^*_k(i+L_L, j+L_L, 1) + C^*_k(i+R_R, j+R_R, 1) \right] \\ + \left[ C^*_k(i_2+L_L, j_2+L_L, 2) + C^*_k(i_2+R_R, j_2+R_R, 2) \right] \end{cases} \] (9)

Here, when \( l=2 \) or \( 3 \), \( i_2+L_L=i, j_2+L_L=j+1 \) and \( i_2+R_R=i-1, j_2+R_R=j \), and, otherwise, \( i_2+L_L=i_2+R_R=i \) and \( j_2+L_L=j_2+R_R=j \). In equation (9), a correlative result that was not utilized in the estimation using equation (7) is detected and \( C^*_k(i,j,0) \) is newly given. In this case, the distance detection precision may decrease. However, even in the worst case, the distance detection precision is equal to that before the shift of the pixel.

4 Measurement result

Fig. 8 shows the experimental setup for distance detection using the developed range-sensor LSI. Targets A and B are positioned 138 cm and 170 cm away from the range sensor, respectively.

Fig. 8. Experimental setup for distance detection.

Fig. 9(a) shows the detection result of the initial normal pixel placement. Targets A and B appear to be at the same distance and no difference in the distance can be detected. Fig. 9(b) shows the detection result obtained using the four correlation results. In this result, the difference in the distance between targets A and B can be detected. Other detection results are shown in Fig. 9 for when the position of target B was changed to (c) 158 cm and (d) 147 cm. In the case of the experiment adopting the detective method using the single row, a different of up to 40 cm is rounded and is detected as the same distance. On the other hand, in the detection experiment using four rows, differences of 9 cm, 11 cm, and 12 cm for each respective distance can be detected. The improvement of such distance detection precision is as effective as increasing the lateral number of pixels fourfold. From the results of evaluations using the developed LSI, we confirmed that the distance detection precision of the range-sensor LSI was improved fourfold in comparison with that of normal pixel placement. In this evaluation, the
developed LSI used a 3.3 V supply voltage and had a power consumption of 140 mW at a clock frequency of 10 MHz.

5 Conclusions

We developed a binocular three-dimensional range-sensor LSI whose distance detection precision was improved by simply coordinating the pixel placement. The pixel placement was shifted by one-eighth of the pixel width in each row of the image sensor. The pixel shift was repeated every four rows. As a result, the visual angle changed gradually over four rows. By the Boolean operation using the correlative result for these four rows, the distance detection precision of the range-sensor LSI was improved fourfold. This method has the advantage that the

![Fig. 9.](image)

(a) Detection result using single row (A: 138 cm, B: 170 cm).
(b) Detection result using four rows (A: 138 cm, B: 170 cm).
(c) Detection result using four rows (A: 138 cm, B: 158 cm).
(d) Detection result using four rows (A: 138 cm, B: 147 cm).
distance detection precision can be improved without changing the pixel or chip size.

The range-sensor LSI was fabricated by a 0.35 µm CMOS 1-poly 3-metal process, and it has a chip size of $4.10 \times 3.90 \text{mm}^2$. By an evaluation using the developed LSI, we confirmed that the distance detection precision of the range-sensor LSI was improved fourfold in comparison with that of normal pixel placement. The LSI used a 3.3 V supply voltage and had a power consumption of 140 mW at a clock frequency of 10 MHz.