High speed 2D motion detection image sensor with velocity filtering function

Toshiyuki Sugita , Kenichi Nakayama , Takashi Yoshida , Takayuki Hamamoto
Tokyo University of Science
1-3 Kagurazaka, Shinjuku-ku, Tokyo 162-8601, Japan
{sugita, nakayama, hamamoto}@isl.ee.kagu.tus.ac.jp

Kazuya Kodama
National Institute of Informatics
2-1-2, Hitotsubashi, Chiyoda-ku, Tokyo 101-8430, Japan
kazuya@nii.ac.jp

1. Introduction

We propose a method of objects tracking implemented on a smart image sensor. The proposed method uses not a normal block-based approach but a pixel-based approach using frame difference between neighbor pixels. In general, the methods of block-based matching are used for objects tracking systems [1]–[4]. However, the methods need large quantity of calculation to control the block size adaptively. Therefore, the block-based matching cannot be performed on a smart image sensor at a high frame rate.

In this paper, we describe new smart image sensor on which the proposed method is implemented. Because the sensor uses strong inter-frame correlation by high speed imaging, the 2D moving vector (direction and speed) can be detected into a limited area. Therefore the processing can be done by small column-parallel circuits on the sensor. Further, the sensor can detect various speeds by changing the processing interval of the detection.

2. Algorithm of on-sensor 2D motion detection

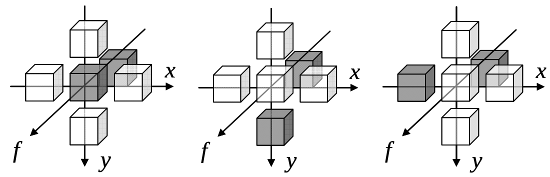
2.1 Detection of moving direction

In general, the moving pixel can be detected by comparing the frame difference of same position with a threshold as shown in Fig. 1(a). The difference between frames f and f-1, $d_{x,y}$, is given by Eq.(1).

$$d_{x,y} = \left| l_{f:x,y} - l_{(f-1):x,y} \right| \quad \ldots(1)$$

where $l_{f:x,y}$ and $l_{(f-1):x,y}$ represent pixel values at (x,y) of frames f and f-1 respectively. Motion of each pixel can be detected with $d_{x,y}$, but the velocity can't be directly detected only with $d_{x,y}$.

For detection of the direction and speed, frames f and f-1 are compared by shifting the position of



(a) (b) (c)

Fig.1 Detection of optical flow by frame difference; (a) without shift, (b) shift to the down, (c) shift to the left.

reference to one of the neighbor pixels as shown in Figs. 1(b) and (c). The evaluation values for directions of top, bottom, right, and left are calculated by using Eqs. (2a)–(2d) as well as Eq. (1).

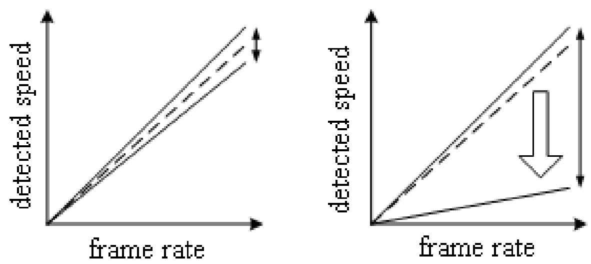
$$m_{up} = \left| l_{f:x,y-1} - l_{(f-1):x,y} \right| \quad \ldots(2a)$$

$$m_{down} = \left| l_{f:x,y+1} - l_{(f-1):x,y} \right| \quad \ldots(2b)$$

$$m_{right} = \left| l_{f:x+1,y} - l_{(f-1):x,y} \right| \quad \ldots(2c)$$

$$m_{left} = \left| l_{f:x-1,y} - l_{(f-1):x,y} \right| \quad \ldots(2d)$$

By controlling the frame rate of an image sensor, the movement quantity between two frames is adjusted to equal to or less than 1 pixel. If an object moves to a certain direction, the evaluation value of the correct direction is smaller than the other values. The optical flow for each pixel is detected by using these four values with shifting and the value without shifting. In actual, the correct moving direction is determined for vertical and horizontal directions separately.



(a) (b)

Fig.2 Relationship between detected speed and frame rate; (a) normal imaging, (b) extension of detected speed.

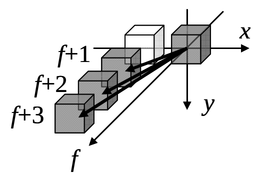
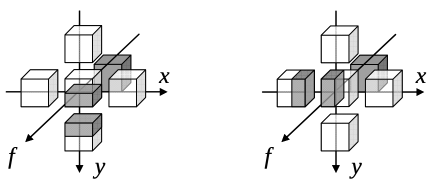


Fig.3 Interval of detecting optical flow.



(a) (b)

Fig.4 Detection of optical flow by using the pixel values of decimal accuracy; (a) 1/2 shift to the down, (b) 1/2 shift to the left.

This method is applied to the pixels in not plain part but edge part. Therefore, the edge detection is processed before the comparison.

2.2 Detection of moving velocity

2D moving direction is simply detected by the above mentioned method based on frame difference. In the method, there is a correlation between a frame rate of sensor and a speed of object. Because the moving distance between two frames is limited into about 1 pixel, there is a most suitable frame rate to detect the speed of the motion. In this method, the detectable speed range can be controlled on the sensor and moved to lower speed by two methods as shown in Fig.2. One is changing the reference timing for the frame difference from next frame to later frames and the other is changing the reference pixel position from neighbor pixel to interpolated pixels.

2.2.1 Control of the reference timing

By changing the frame rate, the detectable range of speed can be controlled. In place of controlling the frame rate, motion detection is processed repeatedly during *k* frames in the sensor. The moving speed can be calculated from the interval between the basis frame and the detected reference frame. As shown in Fig. 3, when the motion is detected at frame *f+3*, the detected speed is one third of the maximum speed.

2.2.2 Control of the reference pixel position

The method of detecting an optical flow compares the values of frame difference with or without shifting the reference pixel. In the method, if the moving distance for the frame interval is near 1 pixel, the speed can be calculated from the frame rate. However, the accuracy of the detection is degraded for the object that is moving at a different speed. Therefore, the pixel values of a decimal position are estimated and used to detect the speed as shown in Fig. 4. We adopt 1/2 pixel accuracy for the detection by consideration of the calculation amount. Therefore moving direction is detected by using four values shown in Eqs. (3a)–(3d).

$$m_{up1/2} = \left| \frac{(l_{f;x,y-1} + l_{f;x,y})}{2} - l_{f-1;x,y} \right| \quad \ldots(3a)$$

$$m_{down1/2} = \left| \frac{(l_{f;x,y+1} + l_{f;x,y})}{2} - l_{f-1;x,y} \right| \quad \ldots(3b)$$

$$m_{right1/2} = \left| \frac{(l_{f;x-1,y} + l_{f;x,y})}{2} - l_{f-1;x,y} \right| \quad \ldots(3c)$$

$$m_{left1/2} = \left| \frac{(l_{f;x+1,y} + l_{f;x,y})}{2} - l_{f-1;x,y} \right| \quad \ldots(3d)$$

3. Further processing of motion detection in depth axis

By using the detected 2D motion velocity, the moving direction in the depth axis can be estimated using an outside FPGA. In a depth axis, the shorter distance between an object and a sensor is, the larger the object's size is. In this method, the moving direction is detected by using the change of the object size.

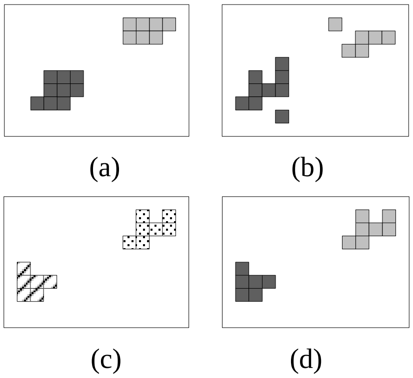


Fig.5 Correspondence of motion regions; (a) detected position in frame *f*, (b) predicted position in frame *f*+*k*, (c) detected position in frame *f*+*k*, (d) result of correspondence.

In order to detect the size change, this method uses the results of the detected moving velocity in the X-Y plane to correspond objects in current frame *f*+*k* with the objects in the previous frame *f*. As shown in Fig 5(a), motion regions are first extracted by grouping the pixels of which the motions are detected in the X-Y plane at frame *f*. The positions at frame *f*+*k* for the pixels in the motion regions are predicted by using the results of moving velocity in X-Y plane as shown in Fig. 5(b). Using the predicted positions, the motion regions extracted at frame *f*+*k*, as shown in Fig. 5(c), can be corresponded with the motion regions at frame *f* (Fig. 5(a)). The results of correspondence are represented by the same colors of the motion regions shown in Figs. 5(a) and 5(d). Then the number of pixels at frame *f* is compared with the number at frame *f*+*k* in each corresponding region. If the number increases or decreases, it is decided that the object is moving forward or backward respectively.

4. Evaluation of the proposed method

We evaluated the proposed method by simulation using some moving images captured at 1000fps by a high speed camera. Fig.6 shows the results of 2D moving direction and speed. In Figs. 6(c) and (d), the darker pixels than a brightness of the background represent moving to right, and the brighter pixels represent moving to left. In addition, the larger the color difference between the detected pixel and background is, the higher the speed is. In these images, two objects were moving to different directions each other as drawing a character “8”. As shown in Figs. 6 (c) and (d), the moving direction and speed for the pixels of the objects were detected reasonably. Fig. 7 shows an example frame of the sequence and the detected moving direction in the depth axis. In this image, an object was moving straight from left backward to right forward. In Fig.7(b), the darker pixels represent moving to backward, and the brighter pixels represent moving to forward. The moving direction of the object was detected correctly.

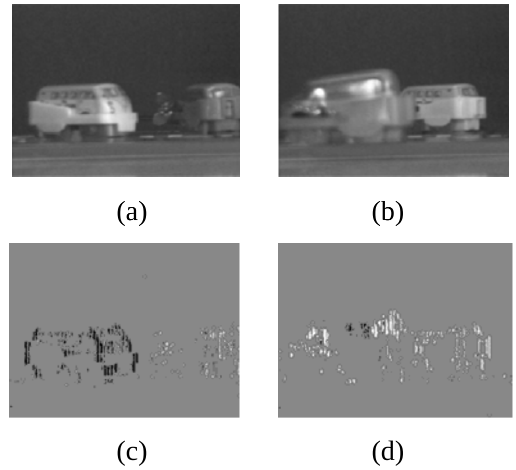


Fig.6 Simulation of the motion detection in the X-Y plane; (a)original image (left object moved to the right, right moved to the left), (b)original image(both objects moved to the left), (c)result of (a), (d)result of (b).

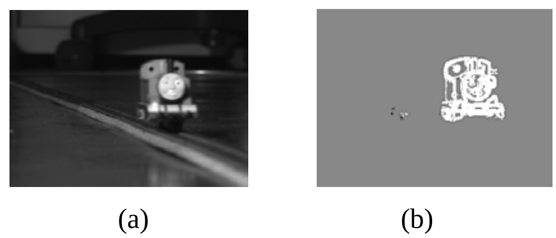


Fig.7 Simulation of the motion detection in depth axis; (a)original image, (b)result of (a).

5. Design and fabrication of new image sensor

We have designed new image sensor on which the 2D motion detection function is implemented. The prototype chip was fabricated using a 2-poly 4-metal 0.35um CMOS process. This chip consists of eight parts as shown in Fig.8. They are APS array, temporary memories for 3 lines, detecting edge pixels, detecting motion, memory array for the positions of the edge pixels, memory array for the pixel values of first basis frame, and counter. Table 1 shows the outline of the prototype chip and Fig.9 shows the photograph of the chip.

The following is the flow of processing on this prototype chip. First, the luminance values of pixels are readout from the APS array and are stored in the memories for 3 lines temporarily. If the current frame is the first frame (basis frame) of the motion detection, the luminance values are also stored in the memory array for the image of basis frame in the same way. Using the luminance values of the central pixel and 4 neighbor pixels located on the left, right, top, and bottom stored in the temporary memories for 3 lines, the edge intensity is calculated in the edge detecting part. By comparing the edge intensity with a threshold inputted from the outside, edge pixels are detected. The result of edge detection is written in the other memory array.

If the current frame is the second or later frame (reference frame), the luminance value of edge pixels of the basis frame and the central and four neighbor pixels of the current frame are used for the motion detection. The direction of motion is determined by comparing the frame difference values. If the motion isn't detected on the frame, the sensor continues with this processing in the next frame.

In this sensor, the number of the pixels for each direction can be obtained by using the counter circuit and calculated for not only whole image but also arbitrary area controlled from the outside. The sensor outputs not only the results of detected motion direction for each pixel but also the number of pixels for each direction.

6. Conclusion

In this paper, we propose 2D motion detection image sensor. In this sensor, moving direction is detected by using the frame difference with shifting the referential pixels under a high speed imaging. Moving speed is also detected by changing a frame rate or a processing interval of the motion detection. Additionally, we explain the method of the moving direction in depth axis by using a change of the object's size.

The image sensor is now under evaluation.

Table 1 Outline of the prototype chip.

process	2poly, 4metal, CMOS 0.35 μm
power[V]	3.3
chip size[mm^2]	1.98 × 4.48
pixel number[pixels]	64 × 64
pixel size[μm^2]	16 × 16
fill factor[%]	52.8
Num. of trans. (transducer)[Tr./pixel]	3
Num. of trans. (digital memory) [Tr./pixel, 2bit]	8
Num. of trans. (analog memory) [Tr./pixel]	4

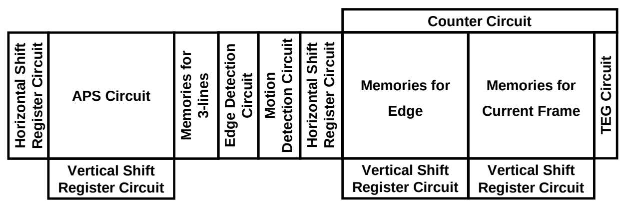


Fig.8 Layout of the prototype chip.

Fig.9 Photograph of the prototype chip.

References

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