Ultrafast Correlation Image Sensor: Concept, Design, and Applications

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Abstract— This paper proposes a new type of image sensor on which correlation detectors between incident lights and electronic signals are integrated as a 2-D array. This architecture is characterized by: 1) photo diodes for converting incident photons to currents (multiplicands), 2) one or a few external electric signals (multipliers) which are common to all pixels, 3) multipliers of the photo currents and the external signals, 4) capacitors for accumulating the products as the correlation results, and 5) CCD or MOS switching networks for scanning out the correlation results. Several design and applications of the sensor are demonstrated.

1 INTRODUCTION

In spite of its excellent spatial resolution, the most serious problem of current image sensor will be the smallness of its temporal resolution (30 frames/sec typical). One solution to this problem is given by the integration of processing element in each pixel[1, 2, 3] for performing early tasks of machine vision. But the most essential issue must be the reduction of bandwidth so that desirable information which requires less temporal resolution is demodulated from rapidly changing incident light. In this paper, we propose the correlation (sum of products) as the most efficient and widely applicable processing scheme especially in active visual sensing systems.

2 BASIC FUNCTION AND PROPERTY

Fig.1 show a block diagram of the Ultrafast Correlation Image Sensor. Let the photo current of (i, j) pixel be $f_{i,j}(t)$, and let the external signal be $g(t)$. Then the (i, j) pixel output of the proposed sensor is expressed as

$$\phi_{i,j}(t) = \int_{t-T}^{t} f_{i,j}(t)g(t)dt \equiv < f_{i,j}(t)g(t) > \qquad (1)$$

where T is the correlation interval (scanning period).

If $g(t) \equiv 1$ (external signal is constant), it is identical with conventional image sensors. But, there appears great difference if both $f_{i,j}(t)$ and $g(t)$ are rapidly changing. Fig.2 shows the frequency domain structure of the sensor. Since both $f_{i,j}(t)$ and $g(t)$ are free from scanning, we can expect the inherent device limit (e.g. GHz or more) for their bandwidth. On the contrary, the output bandwidth is greatly reduced after correlation. Therefore, the conventional scanning schemes are applicable to reading out the results.

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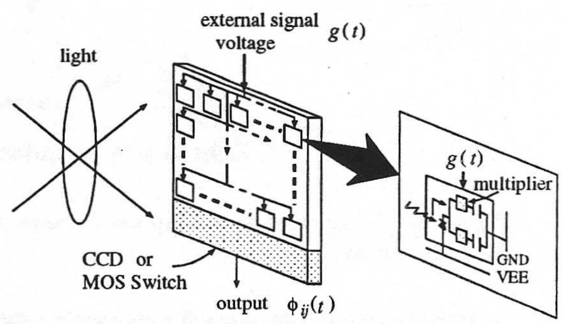


Figure 1. Architecture of the Ultrafast Correlation Image Sensor. Photo detectors, two-quadrant multipliers, and storage capacitors are integrated as a 2-D array.

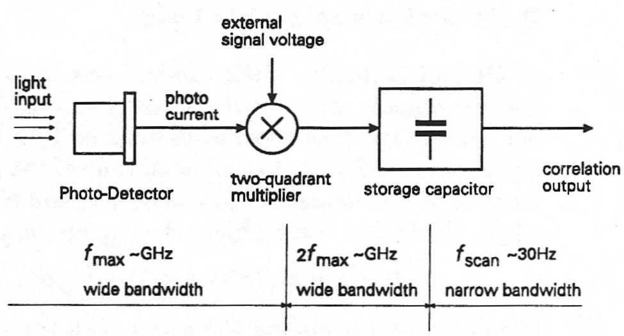


Figure 2. Bandwidth reduction in the Ultrafast Correlation Image Sensor. Input bandwidth is almost unlimited, whereas the outputs bandwidth is equal to conventional image sensors.

3 EXPECTED APPLICATIONS

The key consideration in applications of this sensor is how to give high-frequency modulation to the incident light. Two typical methods will be: 1) the use of intensity modulated illumination, and 2) movement of objects or the image sensor.

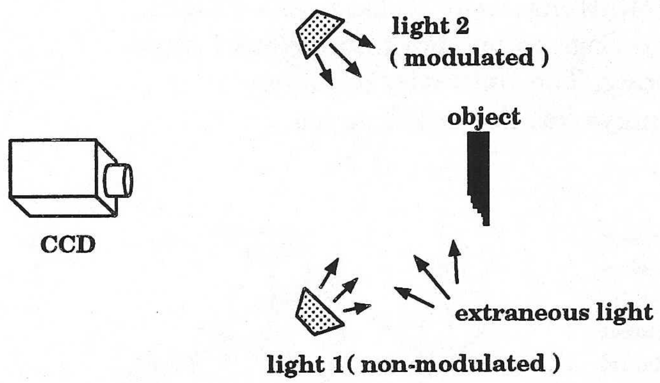
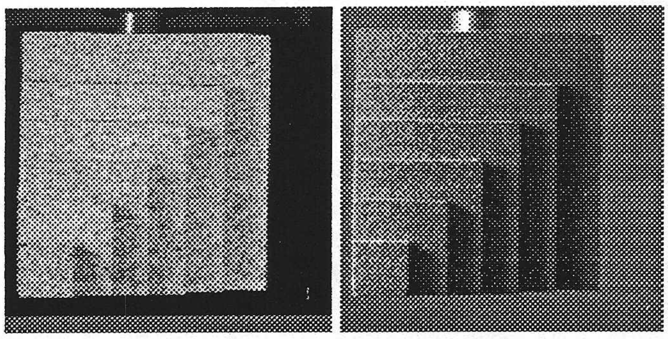


Figure 3. An experimental setup for the separation of modulated illumination.



(a) (b)

Figure 4. An experimental setup for the separation of modulated illumination. (a) usual image (sum of light 1 and light 2), (b) correlation image (light 1 only).

a) Object isolation with modulated illumination

Assume objects are in environmental (disturbing) lights, but one (a target) of them is illuminated by a modulated (ideal) source (Fig.3). Let an amplitude of the modulated source and environmental source be $g(t)$ and $l(t)$. Let the target object and other objects be $o_{i,j}$ and $n_{i,j}$. Then

$$f_{i,j}(t) = o_{i,j}(g(t) + l(t)) + n_{i,j}l(t) \qquad (2)$$

Therefore, by correlating the above with the modulating signal $g(t)$, we obtain

$$\begin{aligned} &< f_{i,j}(t)g(t) > \\ &= \; < o_{i,j}(g(t)+l(t))g(t) > + < n_{i,j}l(t)g(t) > \\ &= \; o_{i,j} < g(t)^2 > + o_{i,j} < l(t)g(t) > + n_{i,j} < l(t)g(t) > \\ &\propto \; o_{i,j} \qquad (3) \end{aligned}$$

since the correlation between $g(t)$ and $l(t)$ is zero. This means that an image output is a contribution of only the object which is illuminated by the modulated source. The other objects with environmental sources are eliminated.

Fig.4 shows an example. A 3-D object like stairs is isolated by an inclined modulated source. The image like this is applicable to the photometric stereo, etc.

b) Time-of-flight range image sensor

Fig.5 describes this application. The sensor catches an image of the object surface with a prescribed distance.

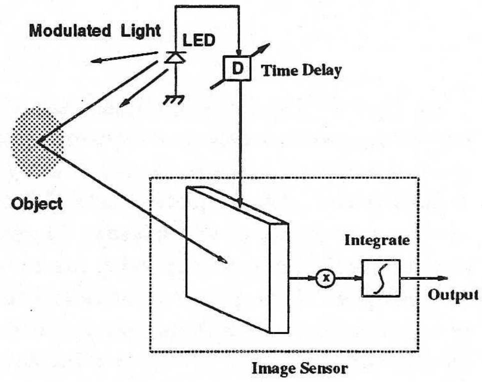


Figure 5. A possible application of the Ultrafast Correlation Image Sensor to "time-of-flight" slice range sensor.

c) Feature extraction with micro-circular sensor movements

Fig.6 describes this application. The sensor catches edges, lines, corners, etc. brightly utilizing a circular motion of the sensor and sinusoidal external signal waveforms with various frequencies.

Let a brightness distribution of an object be $o(x,y)$. Let an angular velocity and a radius of circular motion be ω and ϵ, respectively. Then

$$\begin{aligned} f_{i,j}(t) &= o(x+\epsilon\cos\omega t, y+\epsilon\sin\omega t) \\ &= o(x,y) + \epsilon o_x \cos\omega t + \epsilon o_y \sin\omega t \\ &\quad + \frac{\epsilon^2(o_{xx}-o_{yy})}{2}\cos 2\omega t + \frac{\epsilon^2 o_{xy}}{2}\sin 2\omega t + \cdots (4) \end{aligned}$$

where the suffices x, y mean differentials. Therefore, correlating with $\cos\omega t$ and $\sin\omega t$, we obtain 0 degree and 90 degree edge operators

$$< f_{i,j}(t)\cos\omega t > = \frac{\epsilon}{2}o_x, \quad < f_{i,j}(t)\sin\omega t > = \frac{\epsilon}{2}o_y, \quad (5)$$

and correlating with $\cos 2\omega t$ and $\sin 2\omega t$, we obtain 0/90 degree and 45/135 degree line operators[6]

$$< f_{i,j}(t)\cos 2\omega t > \; = \; \frac{\epsilon^2}{4}(o_{xx} - o_{yy}) \qquad (6)$$

$$< f_{i,j}(t)\sin 2\omega t > \; = \; \frac{\epsilon^2}{4}o_{xy}. \qquad (7)$$

Some examples of the above feature extraction using a conventional TV camera mounted on an XY table are shown in Fig.7.

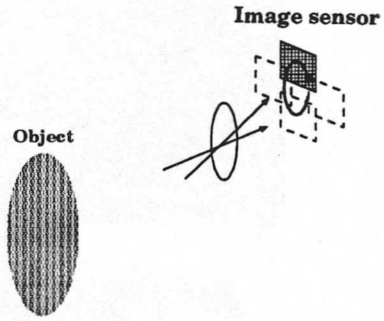


Figure 6. An experimental setup for the feature extraction with micro-circular sensor movements. Photo detectors are vibrated circularly on an image. Then, their outputs are correlated with 1sr and 2nd harmonics of the vibration.

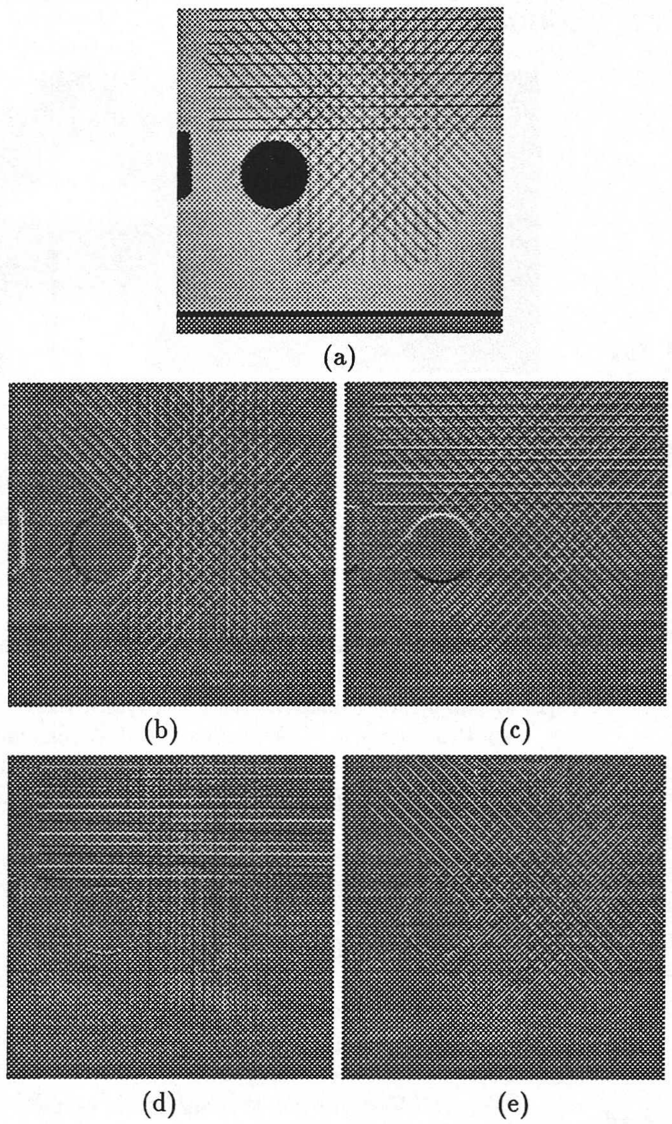


Figure 7. An application of the Ultrafast Correlation Image Sensor to edge and line detection. Vertical edges (b), horizontal edges (c), 0/90 degree lines (d), and 45/135 degree lines (e) are detected from an object (a).

4 SENSOR DESIGN AND EVALUATION

4.1 *Design of pixel circuit*

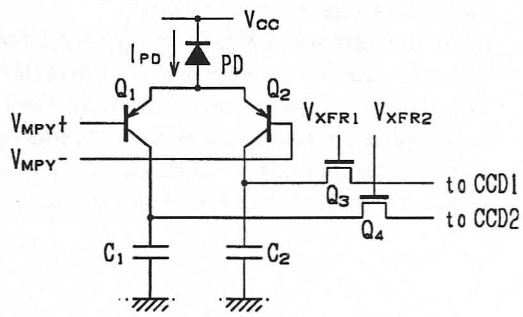


Figure 8. Realization of the Ultrafast Correlation Image Sensor utilizing transconductance multiplier/integrator (dual one-quadrant multiplier). A problem of this circuit is accumulation of DC components in both the capacitors.

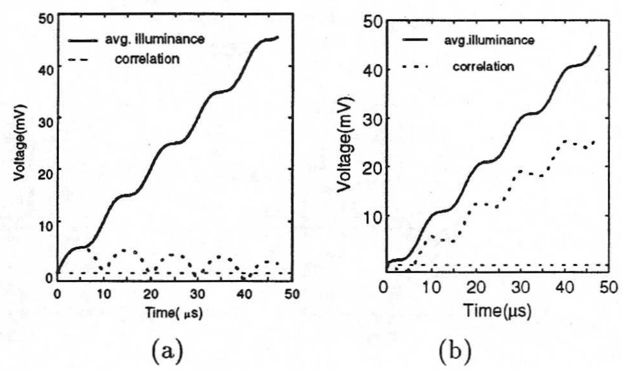


Figure 9. A simulation results using SPICE. A voltage waveform across C_1 and C_1 with correlation (a) and without correlation (b) are displayed.

a) A design with transconductance multiplier

According to Fig.8, the mutual conductance g_m against the differential input voltage $V(t) \equiv V_{MPY+}(t) - V_{MPY-}(t)$ is proportional to the photo current $I_{PD}(t)$. Therefore, by denoting the coefficient be ρ, collector currents of Q_1 and Q_2 are expressed as

$$I_{C1}(t) = g_m \frac{V(t)}{2} + \frac{I_{PD}(t)}{2} = \rho I_{PD}(t) \frac{V(t)}{2} + \frac{I_{PD}(t)}{2}$$
$$I_{C2}(t) = g_m \frac{V(t)}{2} + \frac{I_{PD}(t)}{2} = -\rho I_{PD}(t) \frac{V(t)}{2} + \frac{I_{PD}(t)}{2}.$$

Hence the charges

$$\int_{t-T}^{t} I_{C1} dt = \frac{\rho}{2} \int_{t-T}^{t} I_{PD} V dt + \frac{1}{2} \int_{t-T}^{t} I_{PD} dt \quad (8)$$
$$\int_{t-T}^{t} I_{C2} dt = -\frac{\rho}{2} \int_{t-T}^{t} I_{PD} V dt + \frac{1}{2} \int_{t-T}^{t} I_{PD} dt \quad (9)$$

accumulated on the capacitors C_1 and C_2 differentially involve a correlation component between $I_{PD}(t)$ and $V(t)$. Therefore adding and subtracting both the charges after reading out, we can obtain correlation signal and the brightness signal simultaneously.

b) A design with FET bridge multiplier

The unit circuit and its working principle are shown in Fig.10. In this design, we can obtain the largest dynamic range on correlation values because four-quadrant multiplication suppresses dc component of charges. External signal, however, is restricted to be binary.

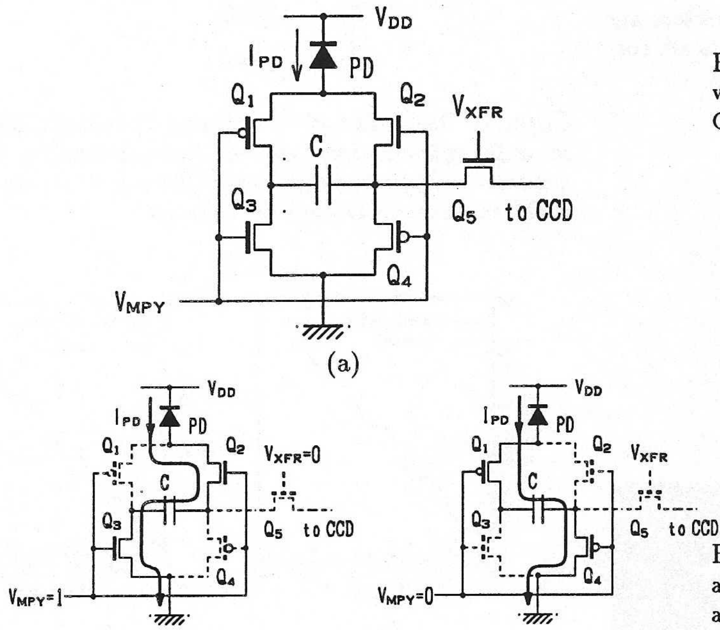


Figure 10. Quasi-binary correlator using an FET bridge circuit. In the circuit (a), two quadrant multiplication is performed by reversing connections of the storage capacitor as shown in (b).

4.2 Fabrication of 8×8 *sensor with discrete circuits*

Fig.11 shows a photograph of the 8×8 sensor and control circuits. Each transconductance cell is made of two matched transistors (Analog Devices MAT-04) and two CMOS analog switches (AD7511) for transferring the charges to column lines. Each column line is connected to charge integrators for voltage output.

4.3 On going studies

We are designing and simulating a circuit for integrated sensor of which pixel is composed of 1 PD, 2 MOS capacitors, and 4 FETs for transconductance multiplier and transfer switches. We are also applying the principle to micro vibratory and foveated vision sensor.

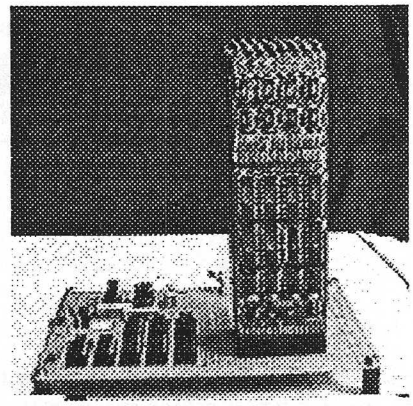
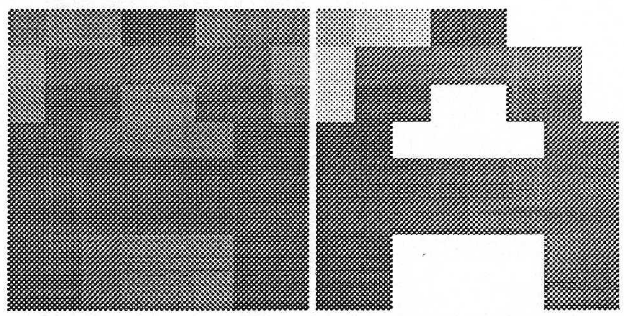


Figure 11. Photograph of an 8×8 correlation image sensor with 64 transconductance-type cells and scanning network with CMOS analog switches.



(a) (b)

Figure 12. An experimental result with 8×8 sensor. The image of an object which is illuminated by uncorrelated light (a) and correlated light (b) is clearly distinguished by the sensor.

REFERENCES

[1] M. Ishikawa: Parallel Processing Architecture for Sensory Information, Proc. Transducers'95, pp.103-106, 1995

[2] J. Eklaud, C. Svensson, and A. Astrom: Near-Sensor Image Processing, a VLSI Realization, ibid, pp.126-129, 1995

[3] M. Nishimura and J. V. der Spiegel: Orientation Sensor Using a Decoding Scheme and a Winner-Take-All Circuit, ibid, pp.163-166 (1995)

[4] S. Ando, et al.: A Feasibility Study on Time-Domain Correlation Image Sensor, Tech. Rep. IEEJ(E) SSA-96-13, pp.429-434, 1996 (in Japanese)

[5] S. Ando, et al.: Ultrafast Correlation Image Sensor: Concept, Design, and Applications, Proc. '97 IEEE CCD & AIS Workshop, Bruges (Belgium), 1997

[6] S.Ando: Texton finders based on Gaussian curvatures of correlation functions, IEEE Int. Conf. on Systems, Man, and Cybernetics, Beijing/Shenyang (China), pp.25-28, 1988.

[7] S.Ando: Micro Order Emphasis: a Probability Cohesion Approach to Image Noise Reduction and Enhancement, IEEE Int. Conf. on Systems, Man, and Cybernetics, Chicago, pp.1235-1240, 1992.