Distance image sensors (Front-illuminated type)
S11961-01CR, S11962-01CR, S11963-01CR, S12973-01CT

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Distance image sensors are image sensors that measure the distance to the target object using the TOF (time-of-flight) method. Used in combination with a pulse modulated light source, these sensors output phase difference information on the timing that the light is emitted and received. The sensor signals are arithmetically processed by an external signal processing circuit or a PC to obtain distance data.

1. Features

- High-speed charge transfer
- Wide dynamic range and low noise by non-destructive readout (S11961/S11963-01CR, S12973-01CT)
- Built-in column gain amplifier (S11963-01CR)
  Gain: × 1, × 2, × 4
- Fewer detection errors even under fluctuating background light (charge drain function)
- Real-time distance measurement

[Table 1-1] Product lineup

<table>
<thead>
<tr>
<th>Type</th>
<th>Linear</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type no.</td>
<td>S11961-01CR</td>
<td>S12973-01CT</td>
</tr>
<tr>
<td>Pixel height</td>
<td>50 µm</td>
<td>40 µm</td>
</tr>
<tr>
<td>Pixel pitch</td>
<td>20 µm</td>
<td>22 µm</td>
</tr>
<tr>
<td>Number of pixels</td>
<td>256</td>
<td>64</td>
</tr>
<tr>
<td>Video data rate</td>
<td>5 MHz</td>
<td>10 MHz</td>
</tr>
</tbody>
</table>

2. Structure

Distance image sensors consist of a photosensitive area, shift register, output buffer amplifier, bias generator, timing generator, and so on. The block diagram is shown in Figure 2-1. Distance image sensors are different from typical CMOS image sensors in the following manner.

- Pixel structure that allows high-speed charge transfer
- Outputs two phase signals representing distance information from two output terminals

Like a typical CMOS image sensor, the output signal from the photosensitive area is processed by the sample-and-hold circuit or column gain amplifier circuit, scanned sequentially by the shift register, and read out as voltage output.
[Figure 2-1] Block diagram
(a) S11961-01CR, S12973-01CT

* S11961-01CR: 272 pixels, number of effective pixels 256
  S12973-01CT: 80 pixels, number of effective pixels 64

(b) S11962-01CR

* S11962-01CR: 272 pixels, number of effective pixels 256
  S12973-01CT: 80 pixels, number of effective pixels 64
3. Operating principle

3-1. Phase difference (indirect) TOF (time-of-flight)

The timing chart of the photosensitive area of the distance image sensor is shown in Figure 3-1. Output voltages Vout1 and Vout2 obtained by applying charge-to-voltage conversion on accumulated charges Q1 and Q2 based on their integration capacitances Cfd1 and Cfd2 are expressed by equations (3-1) and (3-2).

\[
V_{out1} = \frac{Q_1}{C_{fd1}} = N \times I_{ph} \times \frac{(T_0 - T_d)}{C_{fd1}} \quad (3-1)
\]
\[
V_{out2} = \frac{Q_2}{C_{fd2}} = N \times I_{ph} \times \frac{T_d}{C_{fd2}} \quad (3-2)
\]

Cfd1, Cfd2: integration capacitance of each output
N: charge transfer clock count
Iph: photocurrent
T0: pulse width
Td: delay time

Delay time Td when Cfd1=Cfd2 in equations (3-1) and (3-2) is expressed by equation (3-3).

\[
Td = \frac{V_{out2}}{V_{out1} + V_{out2}} \times T_0 \quad (3-3)
\]

Using the values (Vout1, Vout2) output according to the distance, distance (L) is expressed by equation (3-4).

\[
L = \frac{1}{2} \times c \times Td = \frac{1}{2} \times c \times \frac{V_{out2}}{V_{out1} + V_{out2}} \times T_0 \quad \cdots (3-4)
\]

c: speed of light (3 \times 10^8 \text{ m/s})
The structure and surface potential of the photosensitive area of the distance image sensor are shown in Figure 3-2. Typical CMOS image sensors can be driven with a single power supply, but the transfer time needed for the charge to move from the photosensitive area to the integration area is in the microsecond order. On the other hand, high-speed charge transfer (nanosecond order) is possible on CCD image sensors, but they require multiple voltage inputs including high voltage.

To achieve the high-speed charge transfer (several tens of nanoseconds) needed to acquire distance information, we have developed a pixel structure that enables high-speed charge transfer like the CCDs in the CMOS process. This has allowed distance image sensors to achieve the high-speed charge transfer needed for distance measurement.

The number of electrons generated in each pulse emission is several e-. Therefore, the operation shown in Figure 3-2 is repeated several thousand to several tens of thousands of times, and then the accumulated charge is read out. The number of repetitions varies depending on the incident light level and the required accuracy of distance measurement.
[Figure 3-2] Structure and surface potential of photosensitive area

(a) VTX1: on, VTX2: off (in the case of Figure 3-1①)

(b) VTX1: off, VTX2: on (in the case of Figure 3-1②)
[Table 3-1] Distance measurement range and VTX1, VTX2, and light-emission pulse widths

<table>
<thead>
<tr>
<th>Distance measurement range</th>
<th>VTX1, VTX2, light-emission pulse widths</th>
</tr>
</thead>
<tbody>
<tr>
<td>max. (m)</td>
<td>(ns)</td>
</tr>
<tr>
<td>4.5</td>
<td>30</td>
</tr>
<tr>
<td>6</td>
<td>40</td>
</tr>
<tr>
<td>9</td>
<td>60</td>
</tr>
</tbody>
</table>

Note: Light travels approximately 30 cm in 1 ns.

3-2. Charge drain function

A distance image sensor has charge transfer gates (VTX1, VTX2), which transfer the charges that are generated at the photosensitive area, and a charge drain gate (VTX3), which discharges unneeded charges. When VTX1 and VTX2 are off and VTX3 is on, the charge drain function is turned on without the accumulation of signal charges. This makes it possible to drain unneeded charges caused by ambient light during the non-emission period. The charge drain function enables the following:

① Detection of high-speed pulses
   Signal charges from pulse laser diodes and other high-speed pulse light sources can be integrated efficiently.

② Shutter operation

[Figure 3-3] Structure of photosensitive area
3-3. Non-destructive readout

Non-destructive readout is a method of outputting voltages at different integration times without resetting the integration capacitors Cfd1 and Cfd2 in the pixel (without destroying integration charge). Distance accuracy is improved with the adjustment of integration time (e.g., shortening the integration time when the incident signal is strong in order to avoid saturation; lengthening the integration time when the incident signal is weak). Using non-destructive readout, a large signal suitable for distance measurement can be selected from the signals read out with different integration times, and a wide dynamic range can be realized. Figure 3-5 shows a schematic diagram of non-destructive readout (relationship between output voltage and integration time). Set the threshold voltage Va lower than the saturation voltage. The output voltage immediately before exceeding Va is the optimum value for achieving high measurement accuracy. By taking the difference between any two points with different integration times, it is possible to cancel the noise generated when Cfd1 and Cfd2 are reset. One disadvantage of non-destructive readout is that the readout is performed several times in each frame, so the frame rate decreases as the number of readouts increases.

[Figure 3-5] Non-destructive readout

---

If the incident signal or ambient light is weak
If the incident signal or ambient light is strong
3-4. Subtracting signals caused by ambient light

The charge drain function allows draining of unneeded charges accumulated during the light emission period. However, unneeded charges caused by ambient light and the like are also accumulated during the non-emission period (VTX1 and VTX2 are on). The way to eliminate these unneeded charges is to calculate the difference between the following two signals read out within a single frame and extract only the AC signal component. One of the signals is that obtained under the combination of light pulse (AC light) and ambient light (DC light), and the other is that obtained only under ambient light. This enables more accurate distance measurements.

[Figure 3-6] Function for subtracting signals caused by ambient light

\[
L = \frac{1}{2} \times c \times T_o \times \left( \frac{V_{out2} - V_{out2(DC)}}{V_{out1} - V_{out1(DC)}} + \frac{V_{out2} - V_{out2(DC)}}{} \right)
\]

where:
- \(L\): distance to the target object
- \(c\): speed of light
- \(T_o\): pulse width
- \(V_{out1}, V_{out2}\): output generated from signal light
- \(V_{out1(DC)}, V_{out2(DC)}\): output generated from ambient light

3-5. Timing chart

Figure 3-7 shows the timing chart for the S11963-01CR when a signal is read out twice in a frame. The first time, the signal immediately after a pixel reset is read out, and the second time, the signal after signal integration is read out. Pulse emission and signal integration are repeated in the period within the frame in Figure 3-7 (the number of repetitions must be set according to the required distance accuracy). If you want to perform non-destructive readout, repeat pulse emission, signal integration, and signal readout.
3-6. Calculating the frame rate

Frame rate = 1/(Time per frame)
= 1/(Integration time + Readout time) \cdots (3-5)

Integration time:
It is necessary to be changed by the required distance accuracy and usage environment factors such as fluctuating background light.

It is possible to read out only the signal level without reading out the reset level signal. However, noise will increase because the pixel reset noise cannot be removed. Sensitivity variations in the photosensitive area will also increase because the fixed pattern noise in each pixel cannot be removed either.

When operating in non-destructive readout mode:
Time per frame = Integration time + (Readout time \times Non-destructive readout count) \cdots (3-6)

[Linear image sensor]

Readout time = \frac{1}{\text{Clock pulse frequency}} \times \text{Number of horizontal pixels}
= \text{Time per clock (Readout time per pixel)} \times \text{Number of horizontal pixels} \cdots (3-7)

Calculation example of readout time (clock pulse frequency=5 MHz, number of horizontal pixels=272)
Readout time = \( \frac{1}{5 \times 10^6 \text{ [Hz]}} \times 272 \)
= 200 [ns] × 272
= 0.0544 [ms] \( \cdots (3-8) \)

[Area image sensor]

\[
\text{Readout time} = \frac{1}{\text{Clock pulse frequency}} \times \text{Horizontal timing clock}^* \times \text{Number of vertical pixels}
\]
= Time per clock (Readout time per pixel) × Horizontal timing clocks × Number of vertical pixels
\( \cdots (3-9) \)

Calculation example of readout time
(clock pulse frequency = 10 MHz, horizontal timing clocks* = 208, number of vertical pixels = 128)

Readout time = \( \frac{1}{10 \times 10^6 \text{ [Hz]}} \times 208 \times 128 \)
= 100 [ns] × 208 × 128
= 2.662 [ms]

\* Horizontal timing clock 208 = charge transfer 40 + total number of horizontal pixels 168

4. How to use

4-1. Configuration example

A configuration example of a distance measurement system using the distance image sensor is shown in Figure 4-1. The system consists of the distance image sensor, light source and its driver circuit, light emitting/receiving optical system, timing generator, and arithmetic circuit for calculating distance. The distance accuracy depends greatly on the light source emission level and the light emitting/receiving optical system.

[Figure 4-1] Configuration example of distance measurement system
4-2. Light source selection

When the distance image sensor is used to measure distance, a light source (LED or pulse laser diode) suitable for the pulse width of the distance image sensor’s charge transfer clock must be selected. For example, to measure up to 4.5 m, the pulse width of the charge transfer clock and the light emission pulse width must be set to 30 ns. Thus, the response speed of the light source needs to be around 10 ns or less for rise and fall times. Since the light source must be irradiated in a line in the case of the S11961-01CR and S12973-01CT distance linear image sensors and over an area in the case of the S11962-01CR and S11963-01CR distance area image sensors, large output power is required. For this, multiple light sources are sometimes used. When multiple light sources are used, a driver circuit for driving the multiple light sources at high speeds and high output is also required.

5. Distance measurement examples

5-1. Distance measurement (S11961-01CR, S12973-01CT)

For your reference, the following is an example of distance measurement using the S11961-01CR or S12973-01CT and an evaluation light source under the following conditions.

[Conditions]
- S11961-01CR or S12973-01CT distance image sensor (measured at the center pixel)
- Non-destructive readout
- Integration time=30 ms
- Charge transfer clock width VTX1, 2=30 ns
- Light receiving lens: F=1.2, light receiving angle=37.5° × 27.7°
- Light source (LED): output=10 W, duty ratio=0.3%, light emission pulse width=30 ns, λ=870 nm
- Light projection angle=10° × 10°
- Ambient light: room light level
- Ta=25 °C

[Figure 5-1] Distance measurement characteristics (S11961-01CR, S12973-01CT, typical example)
5-2. Short distance measurement (S11961-01CR, S12973-01CT)

Figures 5-3 and 5-4 show a measurement example for short distance (up to 100 cm).

[Conditions]
- Distance image sensor: S11961-01CR or S12973-01CT (measured at the center pixel)
- Integration time=20 ms
- Charge transfer clock width VTX1, 2=30 ns, VTX3=3300 ns
- Light receiving lens: F=1.2, light receiving angle=37.5° × 27.7°
- Light source (LED): output=10 W, duty ratio=0.9%, light emission pulse width=30 ns, λ=870 nm
- Light projection angle=10° × 10°
- Ambient light: room light level
- Ta=25 °C
- When measuring short distance (5 to 20 cm): change the sensor and light source positions
5-3. Improving the distance accuracy by averaging the measurement data

One method to improve the distance accuracy is averaging the measurement data. There are two averaging methods. One is averaging over time, and the other is averaging over multiple pixels. Figure 5-5 shows an example of averaging over multiple pixels.
5-4. Measuring the distance to a cylinder

The following are measurement examples when a metal cylinder (about ø10 cm) and a white cylinder (diffuser) are used for target objects. In the case of a metal cylinder with regular reflection, fairly accurate measurement is possible when the cylinder is in front of the light source but not when it is off aligned.
[Figure 5-7] Example of metal cylinder

(a) Metal cylinder

(b) White cylinder
[Figure 5-9] Measured distance vs. light incident pixel no.

(a) Metal cylinder

(b) White cylinder
5–5. Distance measurement (S11961-01CR, S12973-01CT) using pulse laser diode

The following is an example of distance measurement taken under the following conditions.

**[Conditions]**
- S11961-01CR or S12973-01CT distance linear image sensor
- Light source: pulse laser diode (for evaluation within Hamamatsu)
  - Peak power=50 W, \( \lambda = 870 \) nm, pulse width=50 ns, duty ratio=0.1%, FOV=\( 40^\circ \times 2^\circ \) (horizontal \times \text{vertical})
- Target object: standard diffuser panel, white (reflectance: 90%), black (reflectance: 10%)
- Light receiving lens: SPACECOM L8CSWI (f=8 mm, F=1.2, 1/3 inch CS mount)
- Ambient light: under fluorescent lamp
- The data of a pixel with the highest return light level is extracted.

**[Figure 5-10] Distance measurement example [white object (reflectance: 90%)]**

**[Figure 5-11] Distance measurement example [black object (reflectance: 10%)]**
5–6. Distance measurement (S11963–01CR)

The following is an example of distance measurement taken under the following conditions.

[Conditions]
- S11963-01CR distance image sensor (measured at the center pixel)
- Integration time=2 ms
- Charge transfer clock width VTX1, 2=40 ns, VTX3=920 ns
- Light receiving lens F=1.2, light receiving angle=37.5° × 27.7°
- Light source (LED 8 × 8): 10 W, \( \lambda =870 \text{ nm} \)
- Light projection angle=17.2° × 17.2°
- Ambient light: room light level
- \( T_a=25 \degree \text{C} \)

[Figure 5-12] Measured distance, distance accuracy vs. actual distance
[white object (reflectance: 90%), S11963-01CR, typical example]

[Figure 5-13] Measured distance, distance accuracy vs. actual distance
[gray object (reflectance: 18%), S11963-01CR, typical example]
5-7. Short distance measurement (S11963-01CR)

Figures 5-14 and 5-15 show a measurement example for short distance (up to 100 cm).

[Conditions]
- S11963-01CR distance image sensor (measured at the center pixel)
- Integration time=10 ms
- Charge transfer clock width VTX1, 2=20 ns, VTX3=460 ns
- Light receiving lens F=2.0, f=4 mm, light receiving angle=±35°
- Light source (LED × 8): 5.6 W, \( \lambda =850 \, \text{nm} \)
- Light projection angle=±45°
- Ambient light: room light level
- Ta=25 °C

[Figure 5-14] Measured distance, distance accuracy vs. actual distance
[white object (reflectance: 90%), evaluation kit for S11963-01CR, typical example]

[Figure 5-15] Measured distance, distance accuracy vs. actual distance
[gray object (reflectance: 18%), evaluation kit for S11963-01CR, typical example]
6. Calibration

After the distance image sensor and the light source are combined, distance calibration is necessary. The reasons why calibration is necessary are shown below.

[Reasons why calibration is necessary]
• Delay in the light emission timing
• Delay in the wiring between the sensor and light source
• Shape of the light emission pulse of light source
• Peripheral circuits

The following shows an example of the calibration method.

Distance L is given by equation (6-1).

\[ L = \alpha \frac{V_{out2}}{V_{out1} + V_{out2}} \times \frac{cT_0}{2} - Dofs \quad \text{...(6-1)} \]

\( \alpha \): slope  
\( c \): speed of light  
\( T_0 \): light emission pulse width  
\( Dofs \): Distance offset

You need to set the light emission timing delay (Light_pulse_delay), distance offset (Dofs), and slope (\( \alpha \)).

Setting the light emission timing delay and distance offset
The calculated distance is shifted by changing the light emission timing delay and distance offset so that the calculated distance matches the actual distance.

Setting the slope \( \alpha \)
Select two points in the linear range of distance, and calculate \( \alpha \) to match the ideal line [Figure 6-1].

[Figure 6-1] Calculated distance vs. actual distance
Approximate distance measurement becomes possible by performing the calibration mentioned earlier. If we want to further improve the distance measurement characteristics and bring the calculated distance closer to the actual distance, we set the sensitivity ratio \( SR \).

In equation (6-2), \( SR \) is added to the distance calculation equation (6-1).

\[
L = \alpha \frac{V_{out2}}{(V_{out1} \times SR) + V_{out2}} \times \frac{C_0}{2} - D_{ofs} \quad ...(6-2)
\]

6-1. Calculating the sensitivity ratio \( SR \)

[Figure 6-2] Calculating the sensitivity ratio

(1) Synchronize the incident light pulse with VTX1 and measure \( V_{out1} \) (timing ①).

(2) Synchronize the incident light pulse with VTX2 and measure \( V_{out2} \) (timing ②).

(3) Calculate \( SR \) from \( V_{out1} \) and \( V_{out2} \) measured in (1) and (2)  

\[
SR = \frac{V_{out2}}{V_{out1}} \quad ...(6-3)
\]

Perform these measurements in the dark state. We also recommend the light level to about half the saturation exposure.

6-2. Linear range and nonlinear range

The distance image sensor has a linear range and nonlinear range in distance measurement. The nonlinear range depends on the pulse waveform of the light source. This phenomenon is described below.

Signal charges shown in Figure 6-3 are accumulated due to the delay in the light pulse incident timing. The linear range (range in which distance calculation is possible) is between timing ① and ③.
Actually, since the linear range of Vout1 and Vout2 is narrower because of the rise time and fall time of the light pulse, the linear range of distance measurement is also narrower.

[Figure 6-4] Output vs. light output delay time (2)
7. Calculating the incident light level

If you want to construct a camera module using a distance image sensor, you need to set the parameters according to the operating conditions to maximize the performance of the sensor. For example, when outdoors under strong sunlight, various measures need to be taken such as reducing the integration time or suppressing the incident sunlight using a band-pass filter to avoid pixel saturation. How much to reduce the integration time or which band-pass filter is most suited in reducing the sunlight to the appropriate level varies depending on the operating conditions. To make things easier, we created a model of the camera module configuration and derived an equation that simply calculates the incident light level (signal light, ambient light) per pixel. Please use this when designing camera modules.

Camera module parameters
The following are main parameters of a camera module that uses a distance image sensor. In addition, Figure 7-1 shows the schematic. We assume that the light from the light source is shaped into a rectangle by the angle of view ($\theta_H, \theta_V$) determined by the lens and directed on the sensor.

(1) Target object
- Distance to the target object $L$ [m]
- Reflectance of the target object $R$ [%]

(2) Light projection section
- Light source output $P$ [W/sr]
- Light projection efficiency $EP$ [%]
- Duty ratio “duty”
- Integration time $T_{acc}$ [s]
- Light emitter’s angle at half maximum $\theta_{source}$ [°]
- Light projection angle (horizontal, vertical) $\theta_H$, $\theta_V$ [°]

(3) Ambient light
- Sunlight intensity $P_{amb}$ [W/m²]
- Band-pass filter’s transmission wavelength range (short-wavelength side, long-wavelength side) $\lambda_{short}$, $\lambda_{long}$ [nm]

(4) Photosensitive area
- Light receiving lens efficiency $ER$ [%]
- Band-pass filter’s signal light transmittance $EF$ [%]
- Light receiving lens F value
- Light receiving lens focal distance $f$ [m]

(5) Distance image sensor
- Pixel size (horizontal, vertical) $H_{pix}$, $V_{pix}$ [m] (area $S_{pix}$)
- Fill factor $FF$ [%]
- Photosensitivity $S_{sens}$ [A/W]
- Pixel capacitance $C_{fd}$ [F]
- Maximum voltage amplitude $V_{max}$ [V]
- Random noise $RN$ [V]
- Dark output $V_0$ [V/s]
Calculation method

First, we calculate the light spot level $P_{\text{spot}} \ [W/m^2]$ on the target object [equation (7-1)].

$$P_{\text{spot}} = P \times \frac{A}{L^2} \times E_p \times \frac{1}{S_{\text{spot}}} \quad \text{(7-1)}$$

$P$: Light source output [W/sr]

$A$: Area of a spherical surface obtained by cutting a sphere with radius $L$ at an angle of $\theta_{\text{source}}$

$\frac{A}{L^2}$: solid angle of the projected light [sr]

$E_p$: light projection efficiency [%]

$S_{\text{spot}}$: area of the light spot projected on the target object [m$^2$]
Sspot is given by equation (7-2).

\[ S_{\text{spot}} = 2L \tan \theta_H \times 2L \tan \theta_V \ldots (7-2) \]

A is given by equation (7-3).

\[ A = 2\pi \left(1 - \cos(\theta_{\text{source}})\right) \times L^2 \ldots (7-3) \]

Next, we calculate angle of the reflected light from a small area of the target object that enters the light receiving lens. If the diameter of the light receiving lens is D [m], the angle \( \theta_R \) formed between a given point on the target object and the edge of the light receiving lens is given by equation (7-4).

\[ \theta_R = \tan^{-1}\left(\frac{D}{2L}\right) \ldots (7-4) \]

If we use \( \theta_R \), solid angle \( \Omega t \) [unit: sr] is given by equation (7-5).

\[ \Omega t = 4\pi \sin^2 \frac{\theta_R}{2} \ldots (7-5) \]

\( \theta_R \) varies depending on the position on the target object, but here it is approximated to a fixed value. Of the reflected light diffused in all directions from the target object, we assume the portion corresponding to \( \Omega t \) to enter the lens.

The region on the target object that the distance image sensor can receive the reflected light of corresponds to the projection plane of the pixels displayed on the object through the light receiving lens. The relationship between pixel area \( S_{\text{pix}} \) and the pixel projection area \( S'_{\text{pix}} \) on the target object is given by equation (7-6).

\[ S'_{\text{pix}} = \left(\frac{L}{f}\right)^2 S_{\text{pix}} \ldots (7-6) \]

We determine the level of signal light and ambient light that hit and reflect off the target object and enter a single pixel through the lens. To simplify the calculation, we assume the target object to be a perfect diffuser. If the incident light level is I [W], the reflected light level is \( I/\pi \) [W/sr] for a point light source and I [W/sr] for an extremely wide surface light source such as sunlight. The signal light level \( P_{\text{pix}} \) [W] entering a single pixel is given by equation (7-7).

\[ P_{\text{pix}} = P_{\text{spot}} \times R \times \frac{1}{\pi} \times \Omega t \times S'_{\text{pix}} \times E_R \times E_F(\text{sig}) \times FF \ldots (7-7) \]

The ambient light level \( P_{\text{pix}}(\text{amb}) \) [W] entering a single pixel is given by equation (7-8).

\[ P_{\text{pix}}(\text{amb}) = P_{\text{amp}} \times R \times 1 \times \Omega t \times S'_{\text{pix}} \times E_R \times E_F(\text{amb}) \times FF \ldots (7-8) \]

\( E_R(\text{sig}) \): band-pass filter transmittance for signal light
\( E_R(\text{amb}) \): band-pass filter transmittance for ambient light
Output voltage $V_{pix}$ [V] generated from the signal light is given by equation (7-9).

$$V_{pix} = P_{pix} \times T_{acc} \times \text{duty} \times \left(\frac{S_{sens}}{C_{fd}}\right) \ldots (7-9)$$

- $T_{acc}$: integration time [s]
- duty: duty ratio
- $S_{sens}$: photosensitivity [A/W]
- $C_{fd}$: pixel capacitance [F]

Output voltage $V_{pix(amb)}$ [V] generated from the ambient light is given by equation (7-10).

$$V_{pix(amb)} = P_{pix(amb)} \times T_{acc} \times \text{duty} \times \left(\frac{S_{sens}}{C_{fd}}\right) \ldots (7-10)$$

**Distance accuracy**

Using the levels of signal light and ambient light entering a single pixel determined above, we calculate the distance accuracy of the camera module. Photocurrent $I_{pix}$ [A] per pixel generated by the signal light is given by equation (7-11).

$$I_{pix} = P_{pix} \times S_{sens} \ldots (7-11)$$

The number of electrons $Q_{pix}$ [e$^{-}$] per pixel generated by the signal light is given by equation (7-12).

$$Q_{pix} = I_{pix} \times T_{acc} \times \text{duty}/e \ldots (7-12)$$

$$= P_{pix} \times S_{sens} \times T_{acc} \times \text{duty}/e$$

- $e$: quantum of electricity=$1.602 \times 10^{-19}$ [C]

The number of electrons $Q_{pix(amb)}$ [e$^{-}$] per pixel generated by the ambient light is given by equation (7-13).

$$Q_{pix(amb)} = P_{pix(amb)} \times S_{sens} \times T_{acc} \times \text{duty}/e \ldots (7-13)$$

Next, noise components are described. The amplitudes of light shot noise $N_{L}$, random noise $N_{R}$, dark current shot noise $N_{D}$ are given by the following equations [unit: e$^{-}$].

$$N_{L} = \sqrt{Q_{pix} + Q_{pix(amb)}} \ldots (7-14)$$

$$N_{R} = R_{N} \times C_{fd}/e \ldots (7-15)$$

$R_{N}$: random noise [μV]
\[ \text{ND} = \sqrt{V_0 \times T_{acc} \times Cfd/e} \cdots (7-16) \]

\[ V_0: \text{dark output [V]} \]

Total noise \( N \) [e] is given by equation (7-17).

\[ N = \sqrt{N_L^2 + N_R^2 + N_D^2} \cdots (7-17) \]

The S/N is the ratio of the number of signal electrons \( Q_{pix} \) to \( N \).

Distance accuracy \( \sigma \) [m] is given by equation (7-18).

\[ \sigma = \frac{N}{Q_{pix}} \times \frac{cT_0}{2} \cdots (7-18) \]

\( c: \text{speed of light} \)

\( T_0: \text{light emission pulse width} \)

Increasing the incident signal level helps to improve the distance accuracy. As the temperature rises, dark current shot noise increases and distance accuracy worsens, so it is necessary to consider the heat dissipation design of the distance image sensor.

**Calculation example**

Table 7-1 shows an example of camera module parameters. Using these values, we calculate the output voltages generated from the signal light and ambient light.

\[ A = 2\pi \left(1 - \cos 14^\circ\right) \times 1^2 = 0.18664 \text{ [m}^2\text{]} \]

\[ S_{spot} = 2 \tan 45^\circ \times 2 \tan 2.5^\circ = 0.17464 \text{[m}^2\text{]} \]

\[ \theta_R = \tan^{-1}\left(\frac{f}{2FL}\right) = \tan^{-1}\left(\frac{2.8 \times 10^{-3}}{2 \times 1.2}\right) = 0.066845[^\circ] \]

\[ \Omega t = 4\pi \sin^2 \left(\frac{0.06684545^\circ}{2}\right) = 4.276 \times 10^{-6} \text{[sr]} \]

\[ S'_{pix} = \left(\frac{1}{2.8 \times 10^{-2}}\right)^2 \left(20[\mu \text{m}] \times 50[\mu \text{m}]\right) = 1.2755 \times 10^{-4} \text{[m}^2\text{]} \]

\[ P_{spot} = 100 \times \frac{0.18664}{1^2} \times 0.6 \times \frac{1}{0.17464} = 64.1 \text{[W} / \text{m}^2\text{]} \]

\[ P_{pix} = 64.1 \times 0.1 \times \frac{1}{\pi} \times 4.276 \times 10^{-6} \times 1.2755 \times 10^{-4} \times 0.6 \times 0.88 \times 0.3 = 176.3 \text{[pW]} \]

\[ P_{pix(amb)} = 1000 \times 0.1 \times 1 \times 4.276 \times 10^{-6} \times 1.2755 \times 10^{-4} \times 0.6 \times 0.06 \times 0.3 = 590.4 \text{[pW]} \]

\[ V_{pix} = 176.3 \times 10^{-12} \times 15 \times 10^{-3} \times 0.001 \times 0.3 \left(\frac{1}{40 \times 10^{-15}}\right) = 19.8 \text{[mV]} \]

\[ V_{pix(amb)} = 590.4 \times 10^{-12} \times 15 \times 10^{-3} \times 0.001 \times 0.3 \left(\frac{1}{40 \times 10^{-15}}\right) = 66.4 \text{[mV]} \]
The voltages generated from the signal light and ambient light are 1.24% and 4.15% of the saturation voltage of a single pixel, respectively. In terms of the number of electrons, they are given by the following equations.

\[
Q_{\text{pix}} = 176.3 \times 10^{-12} \times 0.3 \times 15 \times 10^{-3} \times 0.001/(1.602 \times 10^{-19}) = 4952.2 [\text{e}^-]
\]

\[
Q_{\text{pix(amb)}} = 590.4 \times 10^{-12} \times 0.3 \times 15 \times 10^{-3} \times 0.001/(1.602 \times 10^{-19}) = 16584.3 [\text{e}^-]
\]

Noise components and total noise are given by the following equations.

\[
N_{L} = \sqrt{4952.2 + 16584.3} = 146.8 [\text{e}^-]
\]

\[
N_{R} = 500 \times 10^{-6} \times 40 \times 10^{-15}/(1.602 \times 10^{-19}) = 124.8 [\text{e}^-]
\]

\[
N_{D} = \sqrt{1 \times 15 \times 10^{-3} \times 40 \times 10^{-15}/(1.602 \times 10^{-19})} = 61.2 [\text{e}^-]
\]

\[
N = \sqrt{146.8^2 + 124.8^2 + 61.2^2} = 202.2 [\text{e}^-]
\]

The distance accuracy is given by the following equation.

\[
\sigma = \frac{202.2}{4952.2} \times 3 \times 10^8 \times 30 \times 10^{-9} \times \frac{2}{2} = 0.184 [\text{m}]
\]

Figure 7-3 shows the actual measurement of the distance accuracy when a light source is driven with Hamamatsu's evaluation kit and the distance is measured and the calculated distance accuracy determined by entering the evaluation kit parameters in the above equations. The calculated values tend to show poorer results.

<table>
<thead>
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<th>[Table 7-1] Example of camera module parameters</th>
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[Figure 7-3] Calculated and measured distance accuracy
(typical example, calculated value: light projection efficiency=light receiving efficiency=100%)

Measurement conditions
- Indoors (200 lx)
- Ambient light cut filter: none
- Distance image sensor: S11963-01CR
  Integration time=30 ms
- Hamamatsu evaluation kit
- Light receiving lens: image format=1/3"
  Field of view (horizontal × vertical)=37.5° × 27.7°
- Light source: LED array module
  Emission wavelength=870 nm
  Emission intensity=10 W
  Light projection angle (horizontal × vertical)=±12.2°
  Light emission pulse width=30 ns
  Duty ratio=0.1%
- Target object: White board (reflectance=90%)
8. Characteristics

8-1. Light incident angle characteristics

The photosensitivity varies depending on the light incident angle. When we measured using the S11963-01CR distance area image sensor, the photosensitivity was about one-half at incident angle of ±50°.

[Measurement method]
The LED light source is directed so that only mostly collimated light is allowed to enter the distance image sensor through the aperture. The sensor-equipped circuit board placed on a rotary stage is installed so that its photosensitive area is aligned along the rotary axis of the rotary stage. The rotary stage is turned, and the incident angle characteristics of sensitivity are measured.

[Measurement conditions]
Light pulse width=30 ns
VTX1=VTX2=30 ns
VTX3=19940

[Figure 8-1] Measurement method of the light incident angle characteristics of sensitivity
8-2. Distance accuracy vs. incident signal level

Increasing the incident signal level is effective in improving the distance accuracy [Figure 8-3].

[Figure 8-3] Distance accuracy vs. number of incident signal electrons (S11961-01CR, S12973-01CT, typical example)
Distance accuracy ∝ \sqrt{(N_{\text{R}}^2 + N_{\text{sh}}^2 + N_{\text{D}}^2) / S \times (C \times T_0 / 2)} \cdots (8-1)

- \(S\): number of incident photons
- \(N_{\text{R}}\): readout circuit noise
- \(N_{\text{sh}}\): light shot noise
- \(N_{\text{D}}\): dark current shot noise
- \(c\): speed of light
- \(T_0\): light emission pulse width

8–3. Temperature characteristics of distance accuracy

If the incident signal level is high, the distance accuracy does not change much even when the temperature increases. If the incident signal level is low, the distance accuracy degrades when the temperature increases. This is because dark current shot noise increases as the temperature increases.

[Figure 8-4] Distance accuracy vs. chip temperature (S11961-01CR, S12973-01CT, typical example)

9. Evaluation kit

Figure 9-1 shows a configuration example using the evaluation kit for the distance image sensor. This evaluation kit can generate sensor drive timing with an FPGA and sensor bias voltage with a DAC-IC, perform A/D conversion on the sensor output signal, and transfer data to a PC via Ethernet. This evaluation kit can be driven with only a 5 V power supply.

Hamamatsu provides evaluation kits (with LED array and light receiving lens) for the S12973-01CT, S11961-01CR, and S11963-01CR.
[Figure 9-1] Configuration example of distance measurement using the evaluation kit

[Figure 9-2] Example of evaluation kit for linear image sensor

[Figure 9-3] Example of evaluation kit for area image sensor
[Figure 9-4] Example of evaluation kit (with case)