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INTELLIGENT OPTO SENSOR

Number 33

DESIGNER'S NOTEBOOK

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Signal, Noise, Offset and TAOS Proximity Sensors

by Kerry Glover

August 2011

Overview

TAOS proximity sensors operate by flashing an invisible IR light towards a surface and measuring the amount of reflected energy from that surface. While this process is relatively straight forward, the level of signal from the IR detector is very small and noise becomes a factor which must be managed. In order to understand the details, the signal path and the noise path will be analyzed. This document covers the basic concepts. DN34 applies these concepts to the TSL2771 specifically targeting shorter distance proximity such as found in cell phones. DN35 applies these concepts to the TCS3771 specifically targeting longer distance proximity such as user presence in front of a computer or printer. DN13B Optical Window Design discusses the impact of the aperture on the system.

Factors Impacting Proximity Detection

As the light travels from the IR LED, through the glass, bounces from the target and is received by the sensor, several outside factors must be taken into account.

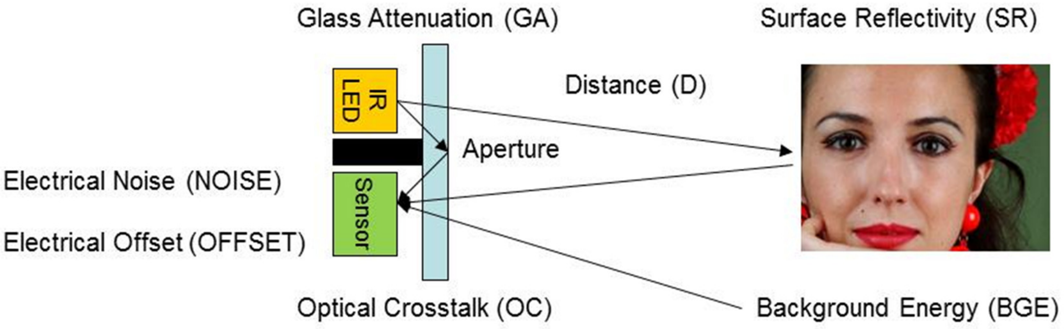

Figure 1. Factors Impacting Proximity Detection

The transmitted signal is first attenuated by the aperture or glass that is placed over the IR LED (Glass Attenuation, GA). Next, the signal is attenuated with distance as it spreads over a large area before it reaches the target. Next, the target only reflects a portion of the energy back to the sensor (Surface Reflectivity, SR). The return path suffers from distance and glass attenuation as well.

During this process, two major factors impact the received signal. First, the Background Energy (BGE) is the ambient light in the room, or sunlight if the system is outdoors. Bright sunlight or flashing lights can limit the proximity sensor's performance. Target movement can impact performance and must be taken into account in the final system algorithm. Second, electrical noise (NOISE) and electrical offset (OFFSET) in the sensor must be understood. Remember, the system is flashing a small IR LED light and collecting the very small amount of energy reflected back from a surface. High gains are required to amplify this signal, which introduces a noise component that must be taken into account.

Optics can also improve the system performance. Please refer to DN36: Proximity Detection and Optical Lenses for details on how to improve performance using a lens.

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TAOS Architecture

There are two ways to change the amount of IR energy presented to and reflected from the target object which are both under software control in the TAOS device. The first is by the amount of current driving the IR LED, the second is to increase the number of pulses emitted by the IR LED.

The TAOS device has a unique method of sensing the reflected signal and then cancelling the background signal at a high enough frequency so as not to be impacted by typical usage models such as hand waving, moving through shadows or moving from a dark room to a lighted room. On the first half of each proximity pulse (PPULSE) cycle, the device sums the reflected IR energy and background energy. On the second half of the cycle it subtracts the background energy with the LED off. This is done at a ~60kHz rate.

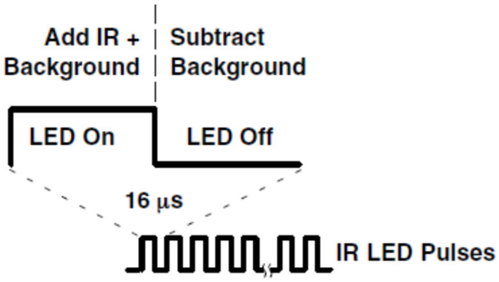

Figure 2. TAOS Background Subtraction

Signal Power

The device output signal power is related to the IR pulse energy emitted from the LED and reflected back to the sensor. The IR LED power can be controlled by the drive current (PDRIVE) and by the number of PPULSE cycles.

Output Signal ~ PDRIVE * PPULSE

The signal typically travels through glass or a light pipe. The effect of the glass can be modeled as the glass attenuation (GA) which is the opposite of glass transmissivity (GT). For example, if the glass transmits 5% of the light, GA = 1/(1-0.05) = 1/0.95 = 20.

Transmitted Signal ~ PDRIVE * PPULSE / GA

The glass has an impact in both transmit and the receive direction. After this, the signal drops off inversely as the square of the distance from a reflective surface; assuming that the target is adequately large. The signal is then reflected from the surface and back to the detector. The percentage of the signal reflected back is surface reflectivity (SR). The angle of reflection also impacts the amount of energy. In addition, background energy (BGE) also gets added to the signal.

Received Signal ~ PDRIVE * PPULSE * GT * SR * cos(x) / (D * D * GA* GA) + BGE / GA

If we assume a perpendicular approach, the cos(x) become unity. If we assume clear glass, the GA becomes unity. The formula then simplifies to:

Received Signal ~ PDRIVE * PPULSE * SR / (D * D) + BGE

Crosstalk is a function of the enclosure and will be related by a constant, the Crosstalk Coupling (CC), which is independent of the distance to the object.

Crosstalk (CT) ~ PDRIVE * PPULSE * CC

Received Signal ~ PDRIVE * PPULSE *[CC+ SR / (D * D)] + BGE

Background Energy Subtraction

The device amplifies the signal received by the internal photo diode. This signal is processed during two halves of each proximity pulse (PPULSE) cycle. The first half of the cycle integrates the received signal with the IR LED on, and the second half subtracts the received signal with the IR LED off. The added background energy must also be taken into account during this single processing.

Processed Signal(LED On) ~ Gain * PDRIVE * PPULSE *(CC+ SR / (D * D) + Gain * PPULSE * BGE1
Processed Signal(LED Off) ~ Gain * PPULSE * BGE2
Processed Signal ~ Gain * PDRIVE * PPULSE *[CC+ SR / (D * D)] + Gain * PPULSE * (BGE1-BGE2)

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The background energy accumulated during the integration cycle is subtracted from the energy accumulated while the IR LED is off. While this is very accurate, there is still a small amount of error. This error is proportional to BGE1 – BGE2 and results in an Electrical Offset (OFFSET). This error is dependent upon many systems factors. While very small with a large number of pulses, this creates some offset that must be understood.

PDATA ~ Gain * PDRIVE * PPULSE *[CC+ SR / (D * D)] + Gain * PPULSE * (OFFSET)

While not intuitive, the Electrical Offset (OFFSET) is strongly dependent upon the electrical noise on the power supply. Critical guidelines are outlined in DN32 Layout Recommendations and must be followed to minimize OFFSET. Most critical is using an RC filter (22ohm/1uF) on the VDD lines and a large 22uF capacitor on the LEDA line.

Noise Analysis

The majority of the electronic noise is created in the amplification of the IR sensor diode signal. This noise dominates all other types of noise and will be the focus of the analysis. Most of this noise is Gaussian but a small portion is non-Gaussian limiting the extent that a signal can be recovered by averaging. The analysis will focus on Gaussian noise since its impact can be manipulated.

Gaussian noise does not add linearly but rather as the square root of the sum of the squares. This results in the noise being related as follows:

Gaussian Noise ~ Gain * NOISE * sqrt (PPULSE)
Signal+Noise ~ Gain *{PPULSE * [(PDRIVE *(CC+ SR / (D * D)] + NOISE * sqrt (PPULSE)}

For a fixed distance, we can replace the distance and surface reflection with a fixed Attenuation Factor (AF). The Signal+Noise reduces to the following:

Signal+Noise ~ Gain * PDRIVE * PPULSE * (CC + AF) + Gain * NOISE * sqrt(PPULSE)
SNR ~ Gain * PDRIVE * PPULSE * (CC + AF) / Gain * NOISE * sqrt(PPULSE)

Since both PPULSE and Gain appear in the numerator and denominator, the Signal to Noise Ratio (SNR) equation reduces to the following:

SNR ~ PDRIVE * sqrt (PPULSE) * (CC + AF) / NOISE

From this analysis, the SNR is directly related to the IR LED intensity and the square root of the number of pulses. So, the first choice to increase the SNR is to increase the LED intensity, and second the number of pulses. Also from the SNR equation, the gain cancels. Typically the gain should be set to the minimum value to ensure maximum dynamic range.

Gaussian Noise

The TAOS sensor Analog Digital Converter (ADC) digitizes the data at a resolution that includes noise. This ADC produces results that have several Least Significant Bits (LSB) of noise. Using signal processing techniques, we can extract more signal from the noise as needed by a particular application. Before this can be done, the behavior of the noise must be understood.

Gaussian noise is well understood. The noise can be analyzed to prove that it is Gaussian by looking at a histogram of a large amount of data. From this data, the standard deviation can be extracted. Using the standard deviation, we can determine the number of bits of noise in the data. The noise can also be reduced by averaging a number of samples.

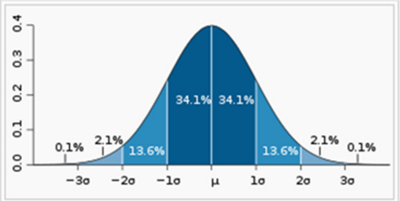

Figure 3. Gaussian Distribution

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Effective Resolution and Accuracy

To get to the Effective Resolution (ER), the noise must first be quantified. Please refer to separated appendix to this document for details on of specific TAOS products. The noise is a function of the number of pulses and is normalized to 1 pulse. Since the ADC used in the TAOS product have a minimum resolution of 10 bits (at 2.7ms integration time), the total range for the TAOS ADC of 10 bits will be used in this analysis.

Effective Resolution (ER) = $10 - \log_2$ (Standard Deviation)

Targeting a system where each bit represents +/-1 standard deviation giving a 68% probability of a correct result gives:

$R68 = 10 - \log_2 (2 * \text{Standard Deviation}) = ER - 1$

PPULSE and Averaging

Recall from earlier:

Gaussian Noise ~ Gain * NOISE * sqrt (PPULSE)

If we include the number of pulses in the formula above we get:

$R68 = 10 - \log_2 [2 * \text{Standard Deviation} * \text{sqrt(PPULSE)}]$

$R68 = 10 - \log_2 (2 * \text{Standard Deviation}) - \log_2 [\text{sqrt(PPULSE)}]$

Since the TAOS proximity sensor works at a very fast rate, we can typically take several samples and average them to increase the accuracy of the data. Averaging has a similar but opposite effect:

$R68 = 10 - \log_2 [2 * \text{Standard Deviation} / \text{sqrt(Samples Averaged)}]$

$R68 = 10 - \log_2 (2 * \text{Standard Deviation}) + \log_2 [\text{sqrt(Samples Averaged)}]$

The final formula is:

$R68 = 10 - \log_2 (2 * \text{Standard Deviation}) + \log_2 [\text{sqrt(Samples Averaged)}] - \log_2 [\text{sqrt(PPULSE)}]$

If a 99% confidence level is required, then:

$R99 = R68 - 1.5$

Crosstalk and Offset

Recall:

$\text{PDATA} \sim \text{Gain} * \{\text{PDRIVE} * \text{PPULSE} * [\text{CC} + \text{SR} / (D * D)] + \text{PPULSE} * \text{OFFSET}\}$

Assuming the Gain = 1, SR = 1, PDRIVE = 100mA:

$\text{PDATA/PPULSE} \sim 1 / (D * D) + \text{CC} + \text{OFFSET}$

This shows that offset and crosstalk are similar as long as the diode drive does not change.

Measuring Distance

While absolute distance cannot be measured from any target, distance measurements can be made from a specific target such as the Kodak Gray Card which is typically used by the industry as a standard reflective surface.

Recall:

$\text{PDATA/PPULSE} \sim 1 / (D * D) + \text{CC} + \text{OFFSET}$

Assuming the OFFSET = 0, Crosstalk = 0:

$\text{PDATA} \sim \text{PPULSE} / (D * D)$

$\text{Distance} \sim \text{sqrt}(\text{PPULSE} / \text{PDATA})$

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Distance Accuracy and the Resolution

Figure 4 shows examples of transfer functions using 4 bit and 6 bit resolution at the same pulse count.

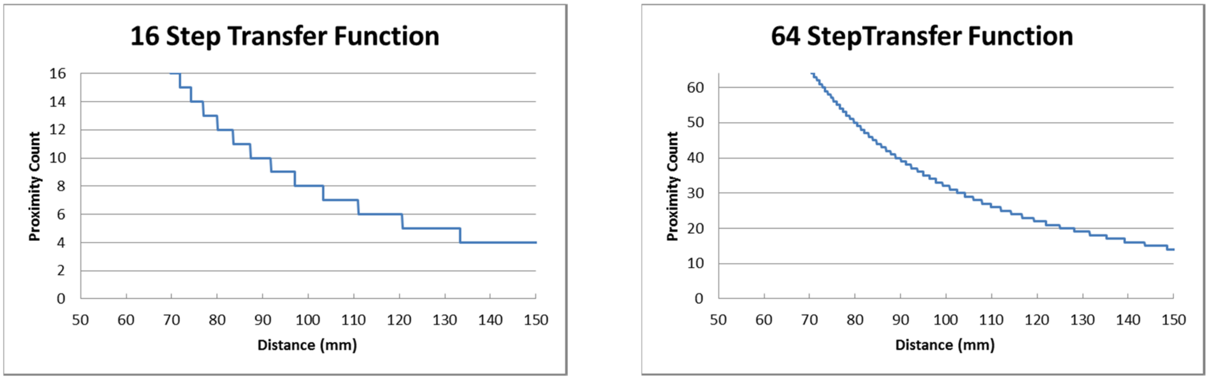

Figure 4 – Noisy and Noise Free Transfer Functions

Mathematically, this is:

Mid-Range Step Size = (DistanceMidScale+0.5 – (DistanceMidScale-0.5)) / DistanceMidScale

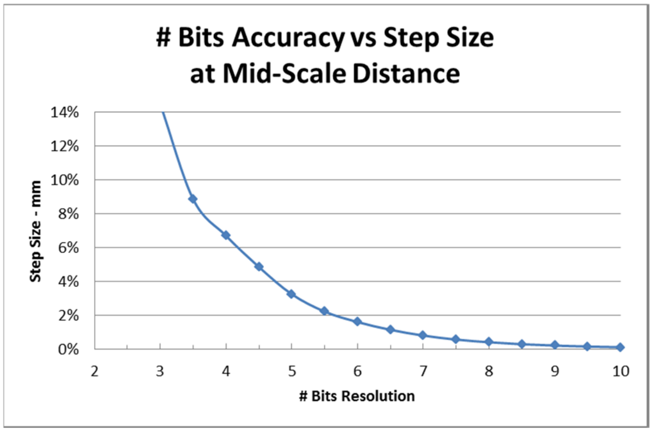

Figure 5 – # Bits Resolution vs. Step Size at Mid-Scale

1/3 scale target is about 1/2 of the mid-range, and 3/4 scale target is about 2x of mid-range.

Distance and Noise

If we add noise back into the equation above and assume there is no crosstalk, we will get:

PDATA ~ PPULSE / (D * D) + NOISE * sqrt(PPULSE)

Solving for D gives:

D ~ sqrt {PPULSE/[PDATA – NOISE * sqrt(PPULSE)]}

Figure 5 shows an example of how the noise impacts the accuracy of the distance measurement.

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Offset and Crosstalk

Offset appears as an up or down shift to the transfer curve. This is dependent upon the system noise and the VDD voltage. Crosstalk is caused by the glass or other components that reflect the IR LED light back into the sensor. Crosstalk also appears in a similar way as an offset to the signal, but this will always be in a positive direction as shown in Figure 6.

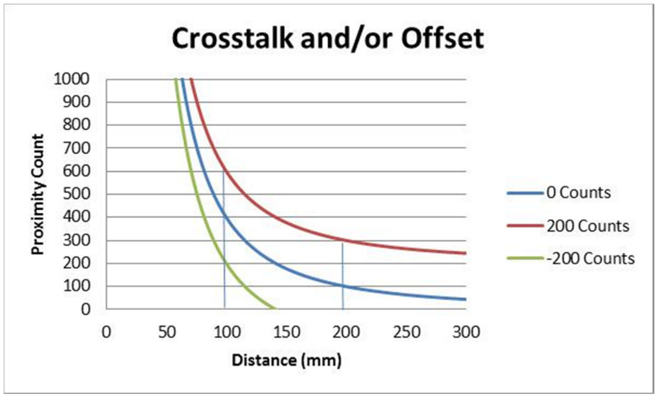

Figure 6. Transfer Function with Crosstalk

Estimating Offset

If offset is positive and more than one standard deviation above zero, offset is simply measured with no reflective surface present. However, if the offset is close to zero or negative, this is not the case. In this case, measuring the response at two different distance could be used to determine the offset.

Recall from DN33:

PDATA/PPULSE ~ 1 / (D * D) + OFFSET

Distance ~ sqrt [1 / (PDATA/ PPULSE - OFFSET)]

Applying a Distance Correlation Factor (DCF), yields:

Distance = DCF * sqrt [1 / (PDATA/ PPULSE - OFFSET)]

From this equation, Offset and DCF is calculated using two points on a curve and writing 2 equation. Using 100mm at 600 counts and 200mm at 300 counts with both at 8 pulses, we can calculate the DCF and OFFSET as follows:

DCF = Distance * sqrt(PDATA/PPULSE– OFFSET)
DCF = 100 * sqrt(600 – OFFSET), where PDATA/PPULSE = 600 counts (@ 8 pulses)
DCF = 200 * sqrt(300 – OFFSET)
Equating both sides:
100 * 100 * (600 – OFFSET) = 200 * 200 * (300 – OFFSET)
600 – OFFSET = 4 * (300 – OFFSET)
600 – OFFSET = 1200 – 4 * OFFSET
3 * OFFSET = 600
OFFSET = 200
Plugging OFFSET back into the original equation:
DCF = 100 * sqrt(600 – 200) = 100 * sqrt(400) = 100 * 20 = 2000

Conclusions

This design note give an outline of the factors impacting proximity detection and provide some basic formula for dealing with signal to noise, crosstalk and long distance proximity detection. For application to specific product, please refer to other TAOS publications which apply these concepts to specific devices.

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Table 1 : Acronyms

Acronym	Description	Acronym	Description
ADC	Analog Digital Converter	IR	Infrared
AF	Attenuation Factor	LED	Light Emitting Diode
BGE	Background Energy	PDRIVE	Drive Current
CC	Crosstalk Coupling	PPULSE	Proximity Pulse
D	Distance	PDATA	Proximity Counts
DCF	Distance Correlation Factor	OC	Optical Crosstalk
DN	Designer's Notebook	OFFSET	Electrical Offset
ER	Effective Resolution	NOISE	Electrical Noise
GA	Glass Attenuation	SNR	Signal to Noise Ratio
GT	Glass Transmissivity	SR	Surface Reflectivity

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