Accurate Measurements with OPT3101

TEXAS INSTRUMENTS

OPT3101 is a Time-of-flight (ToF) based optical proximity and range sensor AFE which can be used to build systems for wide variety of applications like long range proximity, wide field of view proximity detection, collision avoidance is autonomous robots just to name a few. This versatile AFE is compatible with a wide variety of photo-diodes and emitters, and can be configured to fit different applications based on performance and power requirements. Performance of the system comprises of several aspects like data rate, noise performance, power, size and distance error. Based on the application one or more of the performance parameters take priority over the others. Distance error or absolute accuracy is one such critical parameter for some applications. For more information and to view the definition of this, refer to the *Introduction to Time-of-Flight Long Range Proximity and Distance Sensor System Design* user's guide (Section 4.7, Figure 9 [Distance Error]). Like other optical time of flight systems, OPT3101 systems require factory calibration for compensating various system level artifacts. This is a critical process to achieve accurate measurements. Realistically, there are several phenomenon that affects the accuracy, impact of which is analyzed in this document. With this tech note, we assume that you are familiar with the OPT3101 device and have read the *Introduction to Time-of-Flight Long Range Proximity and Distance Sensor System Design* user's guide prior to reading this tech note.

OPT3101 is a continuos time indirect time of flight AFE which measures target distance by measuring the phase delay between light pulses emitted and received, fundamentals of which can be found in Section 1 and Section 2 of system design guide. OPT3101 measures 16 bit phase output in digital codes or counts which is translated to distance in the host processor. There are two constants involved in this translation listed below

1. Frequency of modulation ➡ This translates the measured phase in codes to delay measured in nano seconds
2. Speed of light in medium ➡ This translates the delay in nano seconds to distance traveled

Speed of light in air is considered a constant and is barely affected by temperature and humidity, which leaves us with frequency of modulation to consider. OPT3101 uses internal oscillator, **frequency of which changes by around 4% over a temperature range of 100°C**. This directly translates to distance error when uncompensated. Using OPT3101 **continuos frequency calibration mode**, as explained in Section 4.1 of calibration guide, compensates for this error. Error due to this phenomenon may be diminished to around 1mm or lower when compensated appropriately. With 16 bit phase output, **quantization error of around 0.2mm** never limits system performance; most often other error sources dominate as explained below.

Residue from Electrical and Optical crosstalk is a prominent source of error, especially at lower signal amplitudes. Although crosstalk correction and crosstalk temperature correction coefficients are applied, it is possible that fractions of uncorrected residue crosstalk remain in the system. This residue crosstalk is what typically limits the range of the system for a given accuracy specification. Technical details for this phenomenon can be found in Section 8.1 of the *Introduction to Time-of-Flight Long Range Proximity and Distance Sensor System Design* document. From the formula for distance error, a strong dependency towards signal amplitude can be observed.

$$distanceError = \pm \frac{\tan^{-1}\left(\frac{residueCrosstalkAmplitude}{signalAmplitude}\right)}{2\pi} \times 15000 \quad in \quad mm \tag{1}$$

For example, assume a residue crosstalk amplitude of 10 codes; with a lower signal amplitude, such as 1000 codes, the error is around ±24 mm, while the distance error with full signal amplitude (2^{15}) is around ±0.7 mm, Therefore, it is crucial to keep the system crosstalk to a minimum, thus enabling crosstalk correction to be more accurate in turn minimizing residue crosstalk. For more information, refer to the *Introduction to Time-of-Flight Long Range Proximity and Distance Sensor System Design*

Temperature change causes delay changes in the system, which in turn causes change in the measured phase. This phenomenon is dominated by the emitter delay changes with temperature. Compensation for this is done by phase temperature correction digital block using phase temperature coefficients programmed to the device. Typically these coefficients are common for a hardware design and same coefficients are programmed to all units during factory calibration. OPT3101 offers two methods for such compensation using

- Internal Temperature sensor
- External Temperature sensor IC

The internal temperature sensor has a resolution of 1ºC , whereas with an external temperature sensor IC like TMP102,a resolution of up to 0.0625ºC can be achieved. Using internal temperature sensor provides a quick response low resolution (1ºC) compensation vs using external which provides a relatively slow response high resolution (0.0625ºC) compensation. Since emitters are connected to OPT3101 device pins, internal temperature sensor senses the emitter temperature way faster as compared to external temperature sensor IC. By placing external temperature sensor very close to the emitter along with good thermal coupling would improve external temperature sensor response times. Typical temperature coefficient for this phenomenon are around 6 mm per ºC depending on the type of the emitter and operating current, which means that with the usage of internal temperature sensor the absolute accuracy gets limited around 6mm.Using high resolution external temperature sensor fractions of mm of accuracy is achievable. Based on the application requirements, one or a combination of the two compensation schemes could be used to achieve desired accuracy.

Ambient current emerging from the photo-diode is handled by the ambient cancellation block of OPT3101. Although OPT3101 rejects ambient current from photo-diodes, the photo-diodes have a phenomenon where the amount of **ambient light falling on the photo diode, affects the phase delay of the modulated current.** This can be observed at system level as a phase offset error dependent of the ambient light. OPT3101 has a digital correction block to compensate for this phenomenon. For more information about this, refer to the *OPT3101 Distance Sensor System Calibration* user's guide. Typically the phase offset error is non-linear with ambient light, which can be compensated with four segment piece wise linear (PWL) correction. The residue non-linear fraction from the PWL correction could cause distance error with ambient light changes. This is highly dependent on the photo-diode model and the coefficients determined, typically adds a few mm to the distance error.

Square wave non-linearity is a phenomenon that occurs because the light source modulation waveform is not purely sinusoidal. This causes a period of error in the distance measurement, based on the amount of harmonic content in the modulated light. A typical error is about ±20 mm with a periodicity of 3.75 m which is $1/4^{th}$ of the unambiguous range. OPT3101 has a digital correction block for compensation, where coefficients can be programmed based on measurements in a lab environment as part of system level calibration. Since the digital correction is high resolution, with appropriate coefficients, the error could be reduced to 1 mm or lower.

The field of view of the system affects the accuracy profoundly, this is explained in section 7.1 of system design document. Wider field of view systems inherently have higher errors due to the following factors

- The measurement compromises of light rays from the actual target of interest and the background, which causes error unless the target occupies the wide field of view system entirely.
- Even if target covers the entire field of view, since a large portion of the target contributes to the measurement, the apparent distance measured by various rays at different angles sum up to cause higher error.
- Spacing between the emitter and the receiver creates triangulation distance errors. These are more sensitive within the field of view systems.
- Multiple reflectivity points with in target would cause light rays to disproportionately add up causing distance errors.

Some of these physical effects are fundamental to any optical system which cannot be corrected, however it is possible to measure and compensate some of these effects as part of additional calibration on the host application processor.

To summarize, since OPT3101 systems can be tailored for different configurations, the accuracy depends on several factors. The most important factor is the system level calibration's thoroughness. A more narrow field of view system can achieve absolute accuracies of a few millimeters when the signal levels are good and few centimeters when the signal levels are low. To get the accuracy measurement to be less than 1 millimeter, additional calibration and compensation of the host application processor may be required. At close distances, as a result of physical properties of optical systems, especially where the separation of the emitter and receiver are comparable to the distances measured, the errors may be a few mm due to triangulation artifacts. In such cases, additional triangulation compensations could be performed on the host application processor to improve accuracy. In wider field of view systems, definition of accuracy fails to make sense since the target area measured enlarges rapidly with increase in distance bringing more objects in to the field of view. In such cases it makes sense to include the application algorithm in to account and look at the overall reliability of the system functionality rather tan the OPT3101 system measurement accuracy.

1 Related Documentation

- Texas Instruments, *OPT3101 ToF-Based Long-Range Proximity and Distance Sensor AFE* data sheet
- Texas Instruments, *Introduction to Time-of-Flight Long Range Proximity and Distance Sensor System Design* user's guide
- Texas Instruments, OPT3101 System Estimator tool
- Texas Instruments, *Application of OPT3101 in Precise Distance Measurement and Ranging Applications* application report