Test points of the ToF module calibration software

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Abstract

During the two-box calibration process there are multiple test points available to check for valid device performance. This document provides an overview of the most meaningful tests performed during calibration.

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1. Introduction

The two-box calibration process relies on measurement data in well-aligned mechanical setups. Besides creating calibration data and having limits on the calibration parameters the measurement data can also be used to apply test limits to ensure performance. For testing or validating the actual accuracy, an additional validation step should be considered (see “Cal-6-1-PR-ToF_Calibration_Validation.pdf” for a validation concept proposal).

2. Test Point Overview

2.1. Lens calibration: projection error

In the lens calibration setup, the camera records images of multiple markers in known positions. The camera’s lens system projects the markers into the image plane. The lens calibration software matches a lens model that describes this projection. For this, the lens model parameters are adjusted using a numerical fit function. The remaining deviations between the projected marker positions in the image plane and the positions predicted by the best fitting lens model parameters is a quality measure of the lens model fit quality. The squared mean error of all marker positions is evaluated as “projection error” by the calibration software.

2.2. Lens calibration: focal length (fx/fy)

The lens calibration yields a lens model that describes the overall optical system. The focal lengths (fx/fy in the lens model) are calculated and can be sanity checked. The values are given in units of pixel. For example: With a ToF pixel size of 17.5 µm, a lens with a nominal focal length of 3.6 mm should have a focal length in the lens model of fx = 3.6 mm / 17.5 µm/px = 206 px. The exact value also depends on the focusing position of the lens. Too far deviations are an indicator for a failed calibration or a bad/defocused lens.

2.3. Lens calibration: optical axis (cx/cy)

The lens calibration yields a lens model with a center of symmetry in the image plane. This denotes the position of the optical axis of the lens in respect to the pixel matrix of the ToF sensor. The cx and cy values describe this position horizontally and vertically and should vary only slightly more than the manufacturing tolerances of the mechanical lens placement. Too far deviations are an indicator of a bad calibration or mechanical deficiencies of the ToF module.

2.4. Lens calibration: rotation vector (rvec = [rvec_x, rvec_y, rvec_z])

The rotation vector is a fit result of the lens calibration. The direction of the vector defines an axis of rotation. The amount of the rotation is given by the length of the vector (in rad).

See for example “Axis–angle representation” on Wikipedia:

https://en.wikipedia.org/wiki/Axis%E2%80%93angle_representation

A small rotation can be tolerated due to mechanical manufacturing and mounting tolerances. Typical limits are for example 0.05 rad = 3 degrees. Larger rotations are an indicator for significant quality deviations and should be investigated.

2.5. Defect pixel

Defect pixels are tolerated according to the IRS sensor specification. The calibration software applies limits regarding the defect pixel count “defect_pixel_count“ as well as the maximum defect pixel cluster size “defect_cluster_size”.

2.6. Valid pixels

Only pixels that are not subject to sensor defects (defect pixels) can be used for ToF measurements. Additionally, the pixel has to receive sufficient modulated light emitted from the ToF module’s light source. In many ToF systems the pixels in the image corners do not receive enough light due to multiple reasons: e.g. lens vignetting or VCSEL beam profile limitations. Also a too high lens distortion may lead to very inaccurate lens calibrations in the image corners. These pixels cannot be used for certain ToF applications. The calibration software therefore differentiates between defect pixels and valid pixels. The limit for the valid pixels is applied as “valid_pixel_count”.

2.7. Dark current

The ToF pixels of the IRS image sensor can be placed in a grayscale mode, then operating similar to a traditional 2D image sensor. In this mode it is possible to measure the dark current of all pixels. There are limits for the dark current for every individual pixel as well as a limit for the averaged dark current of all pixels.

2.8. FPN / reset values

The FPN (fixed pattern noise) value describes the inhomogeneity of the reset values of the ToF pixels. The reset values are the pixels’ starting values of the exposure period. Since ToF pixel raw measurement values can be positive and negative, this value should be in the center of the ADC according to the IRS specification (2048 DN for a 12 bit ADC).

2.9. Amplitude

A measurement with a ToF pixel yields a phase shift value, which contains the time-of-flight or distance information, and an amplitude value, which is the signal strength. For a good ToF performance the amplitudes (signal strength) should be high so that the measurement noise (or phase noise) is low. Therefore, the amplitude of every pixel as well as a mean amplitude of all pixels can be used as test criteria. However, if the amplitude during the calibration is too low, the exposure time should be increased. A low amplitude therefore only means, that there is not enough amplitude for processing the calibration data. Also a too high amplitude by itself only states that the data is not suitable for calibration as it may be saturated (in contrast, a normalized performance indicator is given by the “efficiency” parameter, see section 2.17). There is a separate limit for the average amplitude value of all valid pixels (Amplitude_mean) to ensure data quality and for the maximum amplitude (Amplitude_max) to avoid saturation during calibration.

2.10.Phase noise

There may be other sources for high phase noise besides low amplitude values, e.g. an unstable power supply, unstable MIPI readout or an unstable light source. Therefore there is a separate test limit for the phase noise during calibration. The noise is given by the standard deviation of multiple phase measurements (typically 20 frames).

2.11.FPPN

The FPPN image is calculated by the calibration software. It describes phase offsets of the individual pixels. Since all pixels of a ToF camera should have a reasonably similar phase offset, a too high deviation is an indicator for a bad calibration or a sensor defect. The deviation is evaluated as the standard deviation of all FPPN values.

2.12.Amplitude Wiggling Offset and DME

The DME (dynamic mixing efficiency) basically describes the ToF mixing performance. It should only rely on the signal shapes (optical and electrical) and typically is highly frequency dependent. Low DME values may indicate pixel defects, sensor defects or irregular signals of the active light source. Since similar modules should have similar performance, the DME value can be used to monitor device performance.

There are two calculations of a DME value during calibration process: the offset value of the amplitude wiggling, which is a measurement of a few pixels with different phase shift values, and the measurement at a planar surface for all pixels, but only with a limited phase shift range. These two measurements are complementary and therefor both have test limits.

The DME is defined as the ratio of amplitude after demodulation of electrical and optical signals and intensity measurement, which is a grayscale measurement (static modulation gate voltages for the time-of-flight pixels) with the same optical output energy. This ratio is equal to the ratio of AC contrast and DC contrast when assuming 50 percent duty cycle and perfectly rectangular optical signals.

The AC contrast is basically the signal-to-noise ratio of a time-of-flight measurement system and therefore a major quality metric. It describes how well the time-of-flight pixel is able to perform charge separation at a given modulation frequency. The DC contrast describes the same quantity, ratio of separated charge and total charge, at zero modulation frequency.

On system level, contrast cannot be measured directly, since it requires a measurement of the separated charges (D channel) and the sum of all accumulated charges (A channel plus B channel of the time-of-flight pixel). On system level, only the D channel is available.

The AC contrast strongly relies on the optical signal shapes. The DC contrast only relies on the pixel itself. The DC contrast is also specified and tested on chip-level already (see Infineon’s data sheet for example). This means we can use the ratio (DME) to measure the AC contrast indirectly. Limits for the DME value can therefore be derived from requirements for the AC contrast, the signal-to-noise ratio of the time-of-flight system, which should be provided by a ToF system specification: Limits_DME = Limits_AC / DC_Contrast.

Please note that typically the DME of a multi-frequency calibration is evaluated by measuring the grayscale intensity only at a specific modulation frequency of the optical signal. The DME limit for a second modulation frequency must be rescaled by the ratio of optical output power between those modulation frequencies.

Additionally, please note that due different duty cycles than 50 percent in some camera systems, the amplitude and DME calculation may over-estimate the AC contrast in the calibration software’s current implementation. This affects the upper test limit of the above calculation. A revised DME calculation algorithm may need to be considered.

2.13.Amplitude Wiggling Amplitude and Phase Wiggling Amplitude

The main cause of phase and amplitude wiggling are the non-perfect electrical and optical modulation signal shapes. Since similar devices with similar performance should have similar electrical and optical signals. Outliers are an indicator for deviating module performances. These test values have no direct meaning of module performance, but outliers should be examined thoroughly before adjusting the limits.

2.14.Temperature compensation

For VCSEL-based ToF cameras the temperature drift is typically between 0.5 and 1.5 mm per degrees Celsius. These values may deviate due to different temperature sensor placements or illumination driver circuits. Outliers of the temperature compensation values are an indicator for a bad calibration or defective modules.

2.15.Illumination temperature

To apply a temperature compensation a ToF module requires a working temperature sensor. For fully functional modules the temperature readout value during calibration should be reasonable (e.g. between 18 and 35 degrees for a “cold” calibration without long warm-up times).

2.16.Noise parameters

The noise model for a ToF camera can be used to calculate the measurement noise based on amplitude values. Noise parameters are used for this calculation. Since noise parameters should not change significantly for different ToF modules with the same architecture, they are not calibrated per-device. To verify the validity of the noise parameters, the calibration software compares the calculated phase noise with the measured phase noise using multiple frames (e.g. 20 frames). The ratio of both values is evaluated as “PhaseNoiseRatio” and should be close to 1 (typically within 15 percent).

2.17.Efficiency

The efficiency values can be used as a performance indicator. Amplitude values as ToF signal strength values depend on the actual exposure time, the target distance and the target reflectivity. The efficiency describes an amplitude value normalized to those parameters and therefore can be used as to compare module performance. There are test limits for the average performance of all pixels (“Efficiency_mean”) as well as the homogeneity of the performance, evaluated by calculating the standard deviation of all pixels (“Efficiency_std”).

2.18.Beam Profile

For a VCSEL-based ToF camera the VCSEL diffusor should form a beam profile to ensure a homogeneous data quality for all pixels (similar efficiency values). But the diffusor is also essential to ensure eye-safety. If it is broken or malfunctioning eye-safety cannot be guaranteed. Since the test scene during calibration is a planar homogenous surface, the VCSEL beam profile may be sanity checked for sufficient smoothness. **But please note**: The beam profile test in the calibration software does **<u>not</u>** guarantee eye-safety! This test is merely a complementary sanity check. The underlying algorithm may be changed and adopted to new VCSEL diffusor specifications.

Document History

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Revision	Origin of Change	Submission Date	Description of Change
0	SBe	2016-10-06	New Application Note
1	SBe	2017-02-11	Added notes on rotation vector Renamed document from "Calibration Limits" to "Calibration Software Test Points"
2	SBe	2017-02-24	Extended DME section

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