Calibrating Time-Of-Flight Cameras

Error sources for TOF imagers, compensation procedures, and a novel distance calibration method using an on-chip DLL by ESPROS Photonics.

Keywords: Time-Of-Flight, TOF camera, 3D camera, TOF calibration, TOF compensation

Summary

By applying clever calibration and compensation methods, distance errors of a Time-of-Flight camera can be significantly reduced. However, to achieve this, the TOF camera needs a calibration of every pixel at several distances over the full pixel field.
Commonly this requires a space consuming setup with the camera mounted on a stage with a moving target plate. It also needs substantial time. For larger field of views, typically only the center part of the pixel field is calibrated for practical reasons.

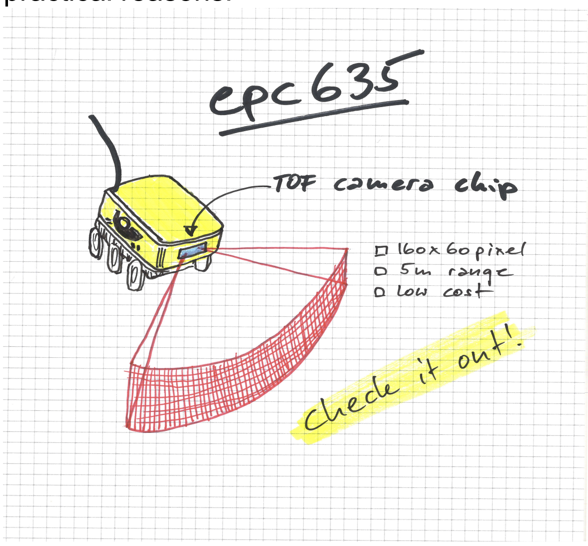

Figure 1: Use case example of a TOF camera chip in an automatic guided postal robot (AGV)

ESPROS Time-of-Flight image sensors are equipped with an on-chip DLL stage, that enables “electronic” distance variation by introducing a delay in the emitter signal chain. This allows full pixel field calibration on a small desktop setup. This paper presents the way to achieve fast and accurate camera calibration as well as the related runtime compensation algorithms.

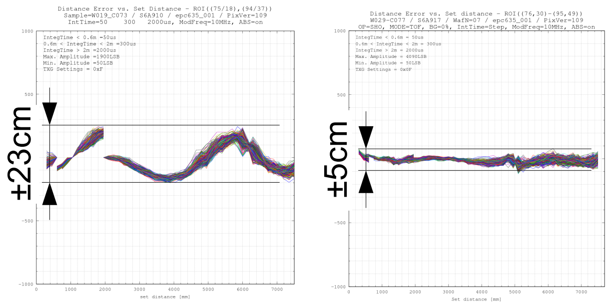

Figure 2: Distance error along the distance axis (15m)
left: no calibration – right: calibrated

Introduction

Camera calibration and compensation of standard cameras, as are found in mobile phones , is essential for obtaining the best image quality. It is therefore common practice. Several calibration parameters are stored in a memory for each individual pixel (such as dark signal offset and gain and color correction).

Time-of-Flight image sensors are subject to different error sources compared to a conventional imager, as the calculated object distance is sensitive to signal delays in the order of ten to hundred pico-seconds (equivalent to 1.5mm to 1.5cm distance change). This cannot be avoided in the design of the TOF pixel array, because wiring length differences between different parts of the pixel array exist, which causes different delays within this order of magnitude. Distance errors also occur by a few degree temperature differences, as electron mobility in silicon is highly temperature dependent. Therefore calibration and compensation are key for high performance TOF sensors.

Error sources

The main error sources which affect the accuracy of distance measurement are:

- Distance response non-uniformity DRNU of the sensor
- Temperature drift
- Ambient light
- The magnitude of the signal amplitude

Under the term DRNU, we treat all factors that lead to a different distance reading between any of the pixels in the pixel-field looking to the inside of a sphere. These factors are sensor/camera related and include:

- Flat-field error of the pixel-field
- Column A/D converter differences
- Row addressing differences
- Fix-pattern noise caused by manufacturing tolerances
- 4^{th} order harmonics distortion of the demodulation algorithm

Camera calibration

As differences in the pico-second domain are relevant, time-of-flight cameras deviate slightly from each other due to sensor chip variations described above. Furthermore, illumination driver, LED/laser diode, optical path, and other factors can differ from one camera to the next as well. Thus, individual calibration of each camera is needed.

The following is a description of a simple calibration setup, the use of the unique on-chip delay line DLL of the ESPROS TOF image sensors (such as the epc635 imager with 160x60 pixel field used here) and an adequate procedure to calibrate the camera. The procedure does not require moving targets on a linear stage as is commonly used. A small, fully passive bench-top box is entirely sufficient for the calibration. This saves enormous cost and time in camera production.

Calibration setup

A simple 30cm long calibration box is used. It allows docking of the camera (lens removed!) to the front of the box. The box contains holes for the camera illumination sources (a ring of LEDs in this example).

The purpose of the box is to shield the camera from ambient light and to provide an optical reference plane in front of the sensor. It is a simple way to create a flat field illumination for the imager which is very important for a high quality calibration. It is possible that different illumination designs may need other box geometries.

Furthermore, it is important that the amplitude of the modulated light received by the camera chip is at approx. 50% of full signal swing. In the case of an ESPROS epc635/epc660 chip, this is in the range of 1'000 to 1'500 LSB (as optimum sensitivity for our 12bit = ±2'000 LSB sensor) by using an integration time between 100 and 1'000µs. Please note that for lower amplitudes higher distance noise and thus higher uncertainty of the calibration data will be obtained.

DRNU calibration using DLL

The LED output of the ESPROS 3D TOF chips can intentionally be delayed by a DLL in order to add a phase shift between the modulation and the demodulation of the light signal. Such a delay in the modulation path is equivalent to a distance shift of the object.

The DLL is digitally controlled in steps of approx. t_{DLL} = 2.1ns by I^2C commands. Such a step is equivalent to a 31.5cm distance shift. Since the DLL contains 49 delay stages, the maximum delay is 102.9ns which represents a total maximum of a distance shift of 15.42m. By intention, this corresponds to the unambiguity distance at 10MHz modulation frequency.

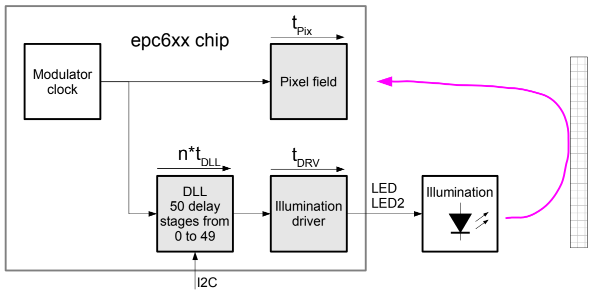

Figure 3: The DLL stages in the modulation/demodulation path

As described above, DRNU errors in general vary pixel by pixel. Additionally, they also vary as a function of the phase angle which is the distance of the object to the camera.

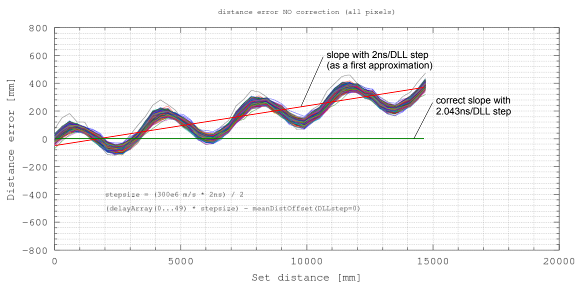

Figure 4: DRNU distance error curve

All pixels need to be compensated individually based on calibration data. ESPROS' simple way: By using the box and all DLL stages, 50 DRNU calibration images can be acquired and stored pixel-wise over the whole measurement distance range.

Runtime compensation

During runtime, full distance compensation is achieved by using DRNU correction and applying the following procedure:

Step #1
Execute common intensity compensation (offset and gain)

Step #2
Calculate the raw distance based on the values of step 1

Step #3
Calculate compensated distance by applying DRNU correction

Step #4
Compensate temperature drift

Step #5
Calculate the final absolute distance result with zero offset compensation.

Processing has to be done pixel by pixel.

A more detailed description of the individual steps can be found in ESPROS' Application Note AN10. See section Downloads on www.espros.com .

Results and conclusion

The improvement achieved with ESPROS' DME660 camera using the described algorithms are remarkable (all typical values):

	Without calibration	With calibration
Absolute distance error peak-peak (0..15m)	up to ±30cm	±5cm
Temperature drift at low TOF amplitudes (ΔT = 40K)	60cm	5cm
Drift due to strong ambient light at very low amplitude (<5% amplitude)	>100cm	10cm

Our concept for full pixel field and fast camera calibration is of high practical importance. Instead of using a giant calibration room like a barn and a huge moving target like a hangar door! a small box with the cost of a few dollars on a bench does the job. Compared to that, it has to be considered, that with conventional methods a field of view of 90 x 60° the target would need a size of 20 x 13m (260 m^2) to cover the full pixel field in a distance of 10m! With the proposed concept however, the calibration can be done in a small box within a few minutes without moving parts. Hundreds of cameras can be calibrated in parallel with a very low investment.

The presented concept can be applied with the ESPROS TOF chips: epc611, epc635 and epc660.

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