ANALOG DEVICES

ToF Camera Calibration Overview ADSD3100

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Revision History

11/2019 – **Rev. A: Initial version**

1. Overview

This document describes the different calibration routines required for the engineering implementation of the ADSD3100 ToF camera module. The minimum subset of calibration stations required for initial sampling to customers are described at a high level, along with estimates on station size and equipment required for each calibration. The additional calibration stations that will be required for a full production calibration pipeline are also listed at the end of the document.

Figure 1. ADSD3100 engineering module calibration flow

2. General Requirements

The ADSD3100 module is connected via flex cable and FFC connector to a “Frame Grabber” which acts as the mechanical mount for the module as well as the host to setup the module, initiate frame captures, process frames before sending to a PC, and write calibration data to the non-volatile memory on the module. The frame grabber is powered via wall wart and has a USB connection to a PC.

The calibration stations can have dedicated frame grabbers in which case only the module is moved between stations, or the frame grabber and module can be moved together between stations. Each station can either have a dedicated PC or a centralized networked PC can be used to communicate with all stations.

A software calibration pipeline will be developed to run all of the calibration stations. This will consist of a UI (user interface) to initiate a specific calibration. The results of each calibration station will be stored in a log file on the PC, along with the module ID of the module under test.

3. Initial Calibration Stations

The minimum set of calibration stations for initial module verification and sampling are described in the following sections.

3.1 Incoming Quality Check (IQC)

The module should be checked to ensure it is electrically functional before going through the calibration pipeline. The frame grabber has measurement circuitry to perform basic electrical tests on power supply voltages, clock/PLL frequencies, and to verify MIPI streaming from the image sensor. Therefore, there shouldn't be any requirement for additional equipment and this IQC test can be performed before calibration or at the first calibration station.

3.2 Lens Focus Adjustment

The imaging lens is manually rotated in the lens barrel until the desired focus level is achieved. The focus test is performed with a dedicated focus chart and software that measures the modulation transfer function (MTF) at different points on the focus chart. Passive IR illumination is used to illuminate the chart and the camera captures a 2D IR image to be used for the focus adjustment.

The calibration station size and focus chart size will depend on the FOV and desired focus distance of the camera. For the initial module design, the station size is approx. 1.5m x 1.5m x 1m (to cover multiple different FOV designs) and focus chart size is approx. 0.85m x 0.6m.

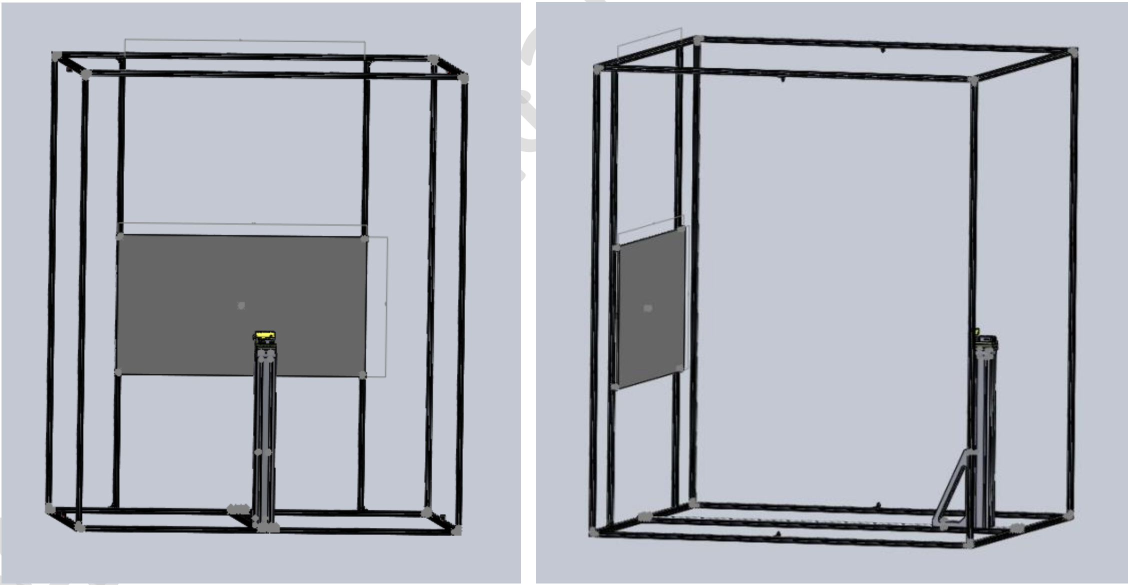

Figure 2. Lens focus adjustment station CAD

For a production setup, the focus adjustment will be automated with servo-motor assistance. The lens will also be glued in place for production modules.

3.3 Gain and Offset Calibration

The gain and offset of amplifiers and ADCs internal to the sensor are calibrated to ensure the largest measurement range can be achieved across the full image sensor without hitting saturation.

The gain and offset calibration doesn't require a dedicated calibration station or any dedicated hardware (other than the frame grabber that controls and processes frames from the camera). For this reason, the gain and offset calibration is typically performed at one of the initial calibration stations (e.g. after incoming quality check or at lens focus). The performance post-calibration can be validated with the lightbox at the Blemish station (if implemented).

3.4 Geometric Calibration

Geometric calibration estimates the distortion parameters of the lens and image sensor. These parameters are then used to correct for lens distortion and to calculate the real world XYZ coordinates of the 3D image.

The calibration assumes a pinhole camera model. The following calibration parameters are calculated:

- **Camera Intrinsic Parameters**
  The imager intrinsic parameters include the focal length, optical center (or principal point), and the skew coefficient. The corresponding camera matrix containing the intrinsic parameters is defined as:

$$\begin{bmatrix} f_x & 0 & 0 \\ s & f_y & 0 \\ c_x & c_y & 1 \end{bmatrix}$$

  (c_x, c_y) = optical center in pixels
  (f_x, f_y) = focal length in pixels
  s = pixel skew coefficient (typically close to 0 in most modern image sensors)

- **Camera Extrinsic Parameters**
  Camera extrinsics consist of a rotation, R, and a translation, t. The real-world points are transformed to the camera coordinates using the extrinsic parameters. Since the geometric calibration setup uses a fixed camera and fixed target location, the extrinsics shouldn't change much between devices.

- **Distortion parameters**
  Radial distortion occurs because light rays bend more near the edges of a lens than at the center of the lens. The radial distortion coefficients model this type of distortion. The distorted points are denoted as $x_{distorted}$ and $y_{distorted}$, where

$$x_{distorted} = x(1 + (k_1 \times r^2) + (k_2 \times r^4) + (k_3 \times r^6))$$
$$y_{distorted} = y(1 + (k_1 \times r^2) + (k_2 \times r^4) + (k_3 \times r^6))$$

  x, y – Undistorted pixel locations
  k1, k2, k3 – radial distortion coefficients of the lens
  r_2: $x_2 + y_2$
  Tangential distortion occurs when the lens and image plane are not parallel. The tangential distortion coefficients model this type of distortion.

$$x_{distorted} = x(1 + (k_1 \times r^2) + (k_2 \times r^4) + (k_3 \times r^6))$$
$$y_{distorted} = y(1 + (k_1 \times r^2) + (k_2 \times r^4) + (k_3 \times r^6))$$

  p_1, p_2 – tangential distortion coefficients of the lens

The pinhole camera parameters f_x, f_y, c_x, c_y, s and the lens distortion parameters k_1, k_2, k_3, k_4, k_5 are estimated by capturing images of a calibration target (e.g. checkerboard pattern) with different orientations/planes relative to the camera. The most popular algorithm of this kind is Zhang's algorithm which has been implemented in many open source computer vision libraries.

The size of the calibration station and calibration target is similar to the lens focus station (e.g. 1.5m x 1.5m x 1.5m). The station structure can be reused during the prototype and low volume calibration phase by changing the calibration target. The location of the camera mount may also need to be adjusted to ensure the calibration target fills the FOV of the camera optimally.

The geometric calibration procedure also relies on passive NIR illumination and 2D IR images are processed by the algorithm. The geometric calibration should be performed after lens focus.

3.5 Optical Power Calibration

The optical power level is measured and calibrated at each operating frequency. This ensures consistent performance and eye safety across all modules and modulation frequencies.

The calibration is performed by measuring the optical power level with an integrating sphere and optical power meter. Instrumentation control is required for timing synchronization of the meter with the camera illumination. The correction factors for the LD driver DAC at each modulation frequency are stored in NVM on the module. These are then applied in real time for each modulation frequency during camera operation.

The optical power calibration must be performed before P0 calibration as it may alter the phase measurements.

The optical power calibration enclosure is approximately 0.5m x 0.5m x 0.5m. The power meter and instrumentation control will be external to the enclosure.

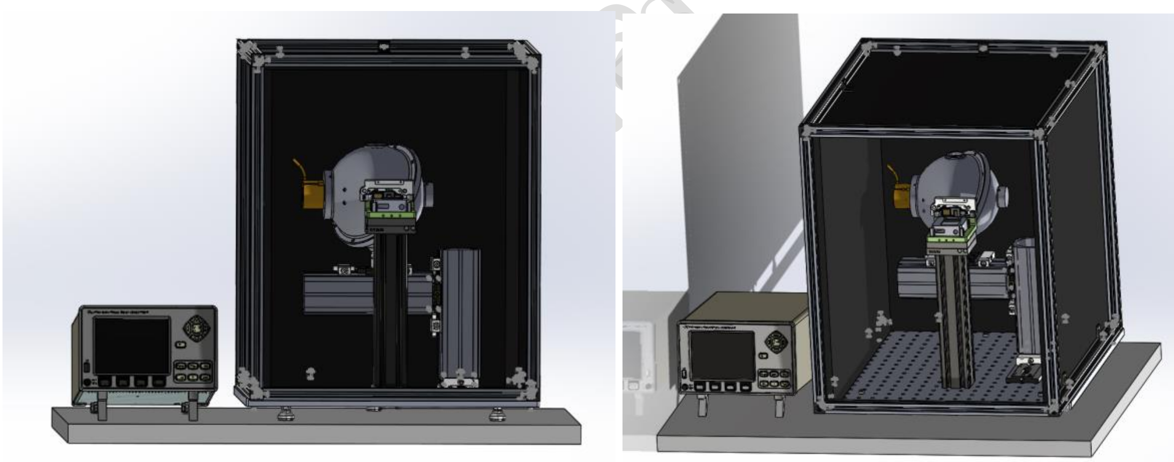

Figure 3. Optical power calibration station CAD

3.6 Phase Offset (“P0”) Calibration

The P0 parameter is a frequency dependent phase delay that includes various delays both internal and external to the sensor itself. This phase delay must be calibrated for each pixel in order for the depth engine to provide an accurate depth measurement.

The P0 phase delay is measured by placing a target at a known fixed distance from the camera. The time of flight is then calculated for each pixel at each operating frequency. Every effort is made to minimize stray light and reflections within the enclosure so that most of the signal measured by each pixel is the direct path from illumination to sensor via the test target.

The P0 calibration station enclosure is approximately 0.5m x 0.5m x 0.5m.

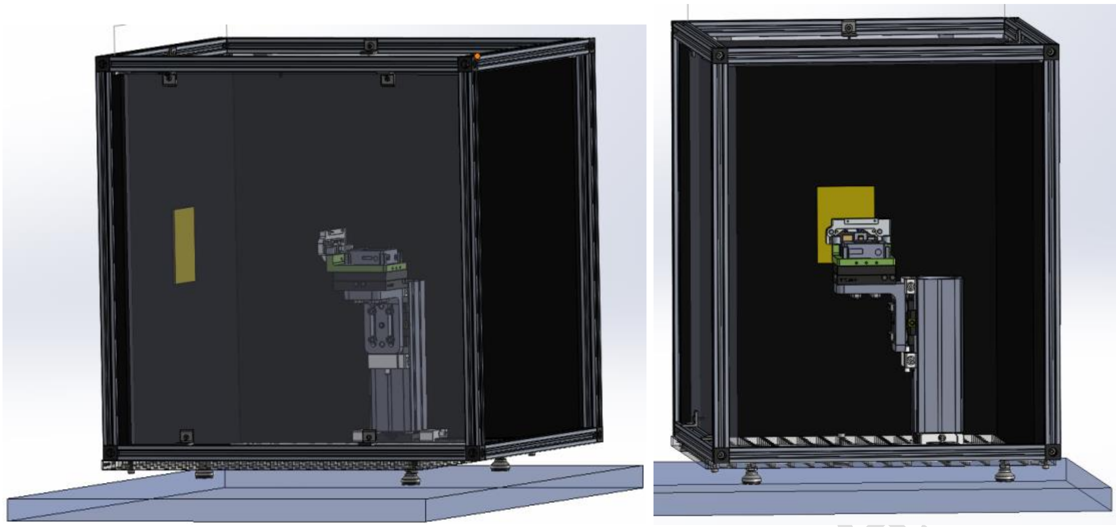

Figure 4. P0 calibration station CAD

4. Future Calibration Stations

The following calibration stations will be required for production testing of modules but are not required for initial sampling of engineering modules. More details will be added on these stations in future document revisions.

Calibration Station	Description
Blemish Test	Check for hot spots, dark pixels, and uniformity using an IR Lightbox
Beam Profile Check	Using fixed target (e.g. wall) with known reflectivity, check light profile variations and ensure no hot spots. Measure reflectivity from received intensity + range.
Final Check (optional)	Depth verification using a multi-target scene