Technical Brief: Introduction to Camera Calibration

This technical brief introduces the traditional and state-of-the-art PixelTraq approaches to camera calibration. Reading this should help you understand why you might use camera calibration and how the PixelTraq based calibrations could improve your process. This document assumes a basic understanding of vision systems, camera models, and 3D geometry. If you need some more background on camera models, please see the Introduction to Camera Models Technical Brief document.

Motivation

Most measurements made using real cameras can be improved by employing a camera model. Even for a very high quality lens, specification sheet focal lengths may not provide the necessary tolerances to model the true value, and the assembled lens and sensor may not be well aligned positionally or angularly. For this reason, camera calibration is an essential step in getting the highest quality measurements possible.

Traditional Camera Calibration Method

The traditional approach to camera calibration is largely based on the procedure proposed by Zhang [1]. All of the common open source and commercially available tools follow this procedure. The MATLAB Computer Vision Toolbox and OpenCV are two common examples of this. The basic procedure is to fix either a camera or chart in space and capture many images with varying poses of the chart relative to the camera.

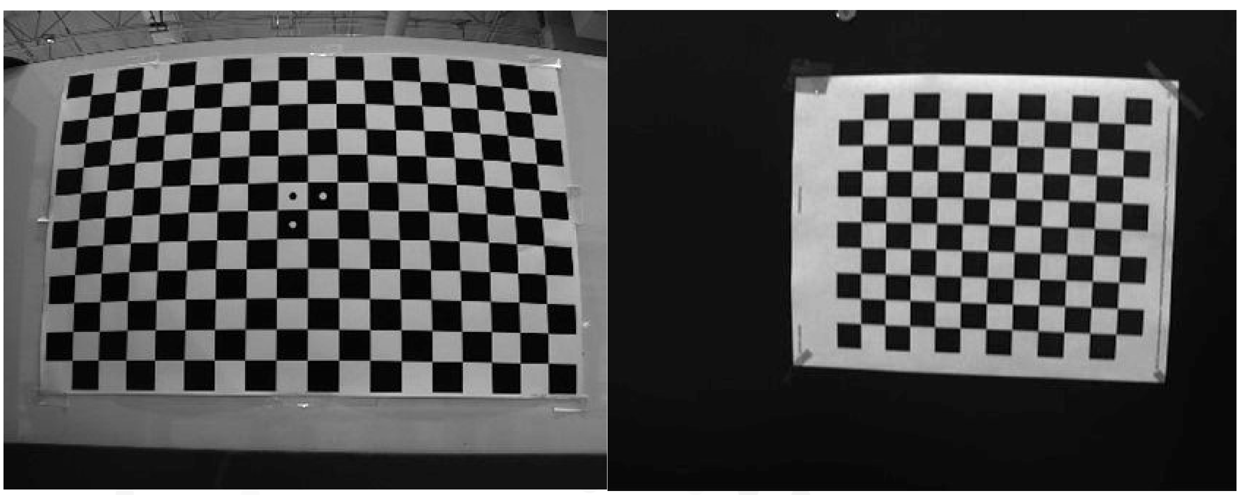


Figure 1: Typical Images for OpenCV style chart calibration used often for "self" calibration

If the relative poses of the chart and camera are diverse enough and there are sufficient points on the chart, the problem will be well conditioned, and the camera model parameters can be computed via a non-linear least squares optimization problem. This procedure relies on optimization of the errors in image space between the observed points in the image and the projected points. The optimization is often initialized with a closed form solution combined with a linear-least squares and refined using the Levenberg–Marquardt non-linear least squares algorithm. This process seeks to minimize the following functional:

$$\sum_{i=1}^{n}\sum_{j=1}^{m}\left\|r_{ij} - f\left(i_1, i_2, \dots, i_q, R_i, t_i, p_j\right)\right\|^2$$

Here r_{ij} are the image points in the ith image and the jth fiducial, f is the projection function of the camera model that maps from object space to image space, $i_1, i_2, \dots, i_q$ are the q intrinsic parameters of the selected model, R_i and t_i are the extrinsic parameters of the camera with respect to the chart for each pose and p_j are the individual points on the chart. The intrinsic parameters $i_1, i_2, \dots, i_q$ are typically taken to be used as the output camera model parameter and the R_i and t_i parameters discarded.

The traditional camera calibration process outlined above makes a few critical assumptions that impact accuracy of the calibration:

1. The chart is assumed to be perfectly flat.
2. The author encourages using a printed chart which may not be well characterized and may have poorly resolved features depending on the printing process.
3. Little attention is paid to the structure of the relative poses of the chart and how those may affect calibration accuracy over the entire camera FOV.

Despite these issues, for many applications, this method is sufficient for the computing the parameters of a camera model. Results can be improved by using a very high quality chart, increasing the number of viewpoints and by varying the relative poses between the camera and chart to fill the field of view appropriately. Additionally, targeting specific working distances for performing the calibration can improve results around the region of interest.

Due to the nature of this optimization problem, this model solution requires the computation of at least $6n + q$ parameters where n is the number of poses used in the calibration and q is the number of intrinsic parameters. Although the majority of the parameters computed are the extrinsic ones, these are often thrown away after optimization due to the fact that they relate the camera pose to the chart at a particular instance in time during calibration and provide no insight into its pose in space relative to fixed features that may be of interest in the future. The extrinsic calibration of the camera to a datum or other reference frame is often left to secondary calibrations such as a hand-eye calibration.

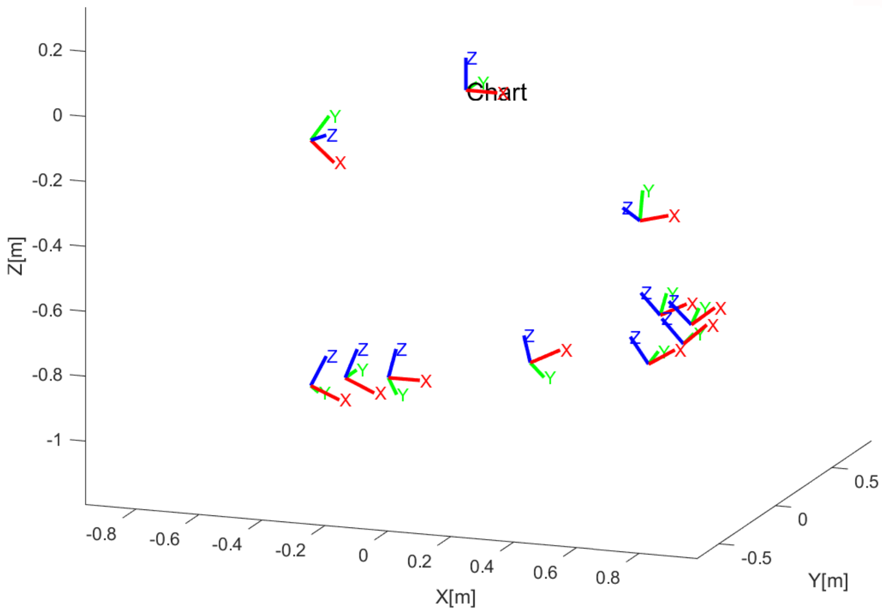


Figure 2: Common arrangement of poses that must be estimated by the multi-pose chart based calibration proposed by Zhang

In summary, the major drawbacks of the traditional calibration process proposed by Zhang and used by nearly all of the common calibration tools are:

1. Imperfections in the chart are not considered which introduces point inaccuracy into the process.
2. Relative poses of the chart are not well controlled and do not necessarily target filling the FOV and obtaining data at the working distances of interest.
3. The majority of parameters in the model are thrown away extrinsic parameters which degrade model accuracy and do not correlate to an external usable datum.
4. The process is left to the user to perform a calibration on their own leading to hours of frustrating debugging and time being taken away from their actual research or project or worse, naïve acceptance of parameters generated by a black box process. Implementing this type of calibration setup can be costly to a business in terms of employee hours spent troubleshooting.

An unfortunate trend in the computer vision community is that most users are encouraged to simply perform these calibrations on their own and use the results attained without necessarily refining them or verifying their validity. As with any measurement, attaining accurate and precise results requires a well calibrated set of tools, controlled environments, and good methodology. Achieving this can be quite expensive for the typical user, so it is common to omit some or all of the elements required to obtain high quality results. Just as many other measurement tools require calibration services, there is a need for comparable high quality calibration services for computer vision cameras.

The PixelTraq calibration process was devised to address the drawbacks of traditional camera calibration and produce high quality camera calibrations with a flexible and automated workflow.

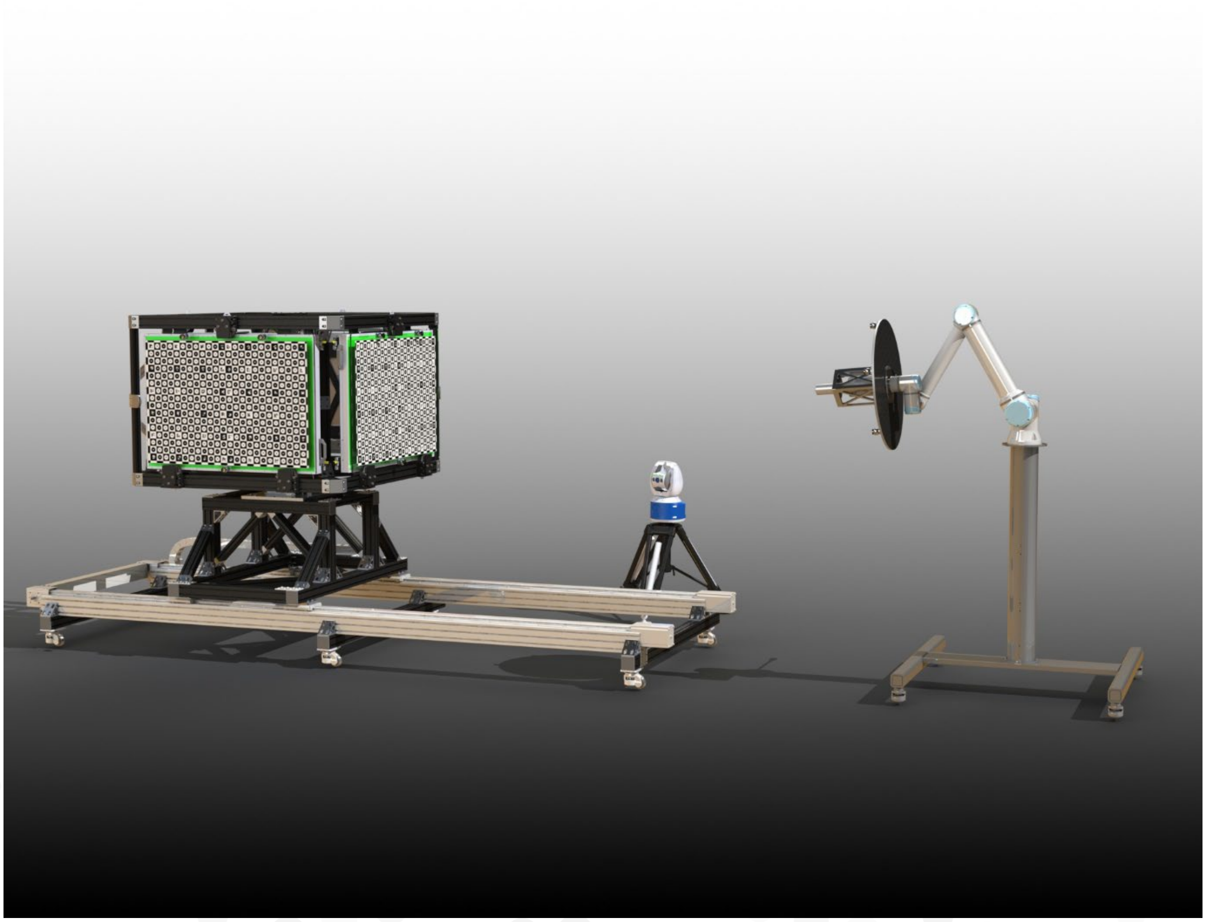
PixelTraq Camera Calibration Method

The PixelTraq Camera Calibration method is a patented process that works differently than the traditional camera calibration technique. Individual views of panels are combined into a composite "Superchart" 3D structure that is placed relative to a physical datum. Instead of calibrating a separate set of extrinsic parameters for each pose, it is as if the camera took a single image of the Superchart. The resulting calibration requires the computation of $6 + q$ parameters only and is among the most precise and robust calibrations available.

PixelTraq System

The PixelTraq system uses state of the art components to achieve the highest accuracy calibration. The system is comprised of:

- A robot arm with an extended low-CTE carbon fiber platform with 3D measurement fiducials
- A four-sided chart turret with backlit chrome-on-glass precision artwork charts
- Specially coded artwork inspired by the CALTag paper to allow partially occluded panels to be recognized by image processing for exact point correspondences in every image [2]
- A linear rail system with range >3m
- A precision 3D measurement system, typically a laser tracker



PixelTraq Process

The PixelTraq processing can be broken down into three steps, pre-processing, data collection, and calibration.

Preprocessing

The preprocessing step is where the Superchart geometry is defined. Instead of arbitrarily placing panels of the chart in space, the Superchart is designed to place panels in locations that fill the FOV and give data at the appropriate working distances. Many Superchart geometries are available to suit various FOV and working distance requirements and most are customized for the application resulting in the ideal FOV coverage for your particular camera. To ensure coverage is sufficient, the Superchart is projected into a simulated camera image plane before running the data collection.

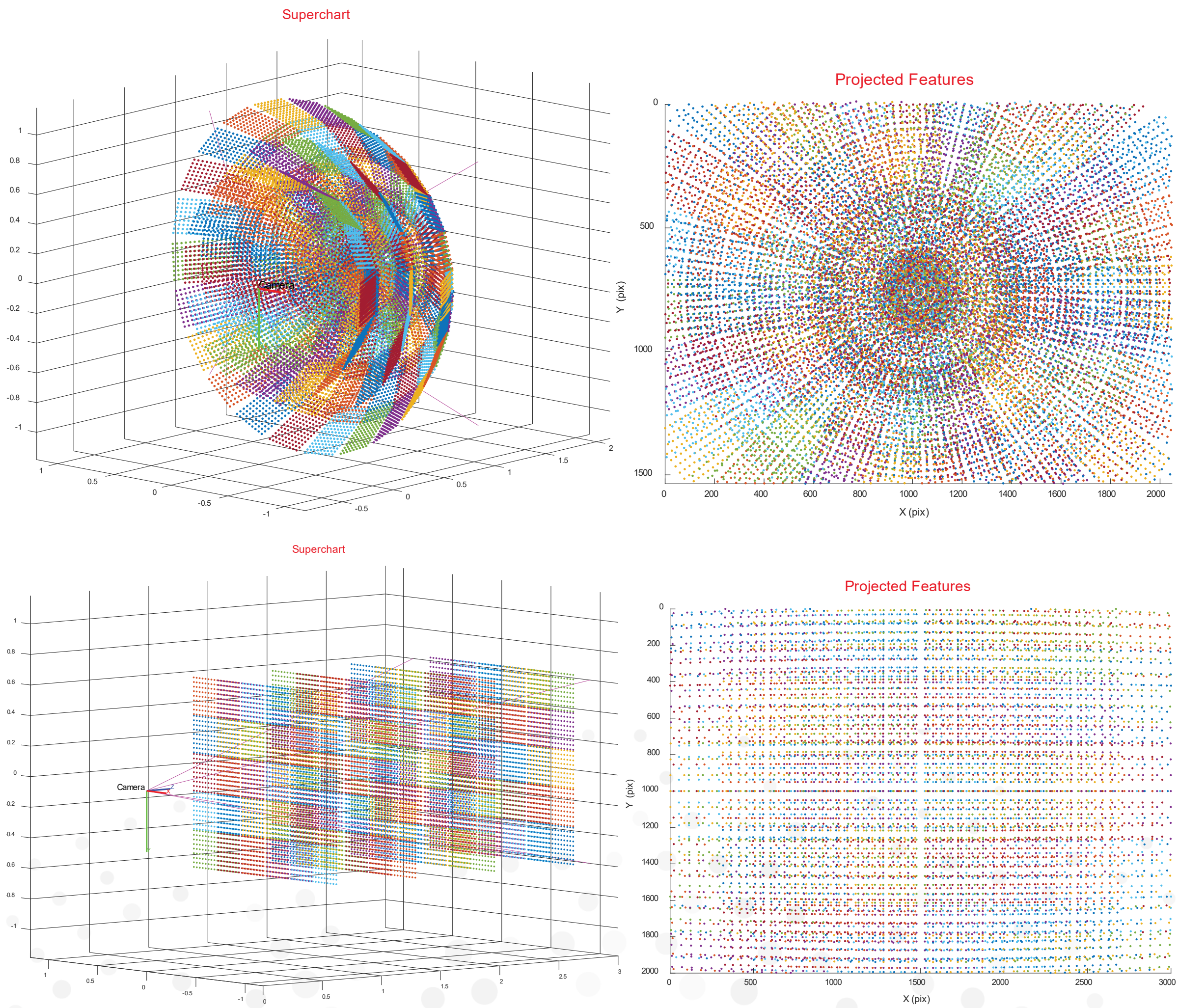


Figure 3: Examples of Superchart in Preprocessor (left) and Expected Features in Image (right)

Next, the Superchart geometry is realized by our robot motion planner that determines collision free paths between the poses needed to create the Superchart in real life. This motion plan also predicts where our tracking fiducials will appear for our 3D measurement system to make the calibration run efficiently. The motion plans are exported for execution on the real system.

Data Collection

The next step of the PixelTraq process is data collection. This process combines multiple precision measurements to construct the Superchart structure. The composition of these datasets is a major advantage of the PixelTraq process. Before the data collection is conducted, the chart is characterized in 3D on an optical CMM. This provides knowledge of the 3D coordinates of every chart feature (no 2D planar assumption) to high accuracy of around two microns as well as the locations of the 3D measurement fiducials relative to the same reference frame. Next, the camera mount is inspected with respect to the reference datum of interest on a tactile CMM. The camera side 3D measurement fiducials are also measured in this setup. Finally, the data collection sequencer executes the collection process by commanding the preplanned robot moves, collecting images, and measuring the 3D measurement fiducials at each pose.

Calibration

The calibration step combines the data acquired in the previous step to assemble the Superchart. The Kabsch algorithm is used to fit the chart and camera mount data sets to the 3D measurement data set and place the individual chart panel features in the camera datum frame [3].

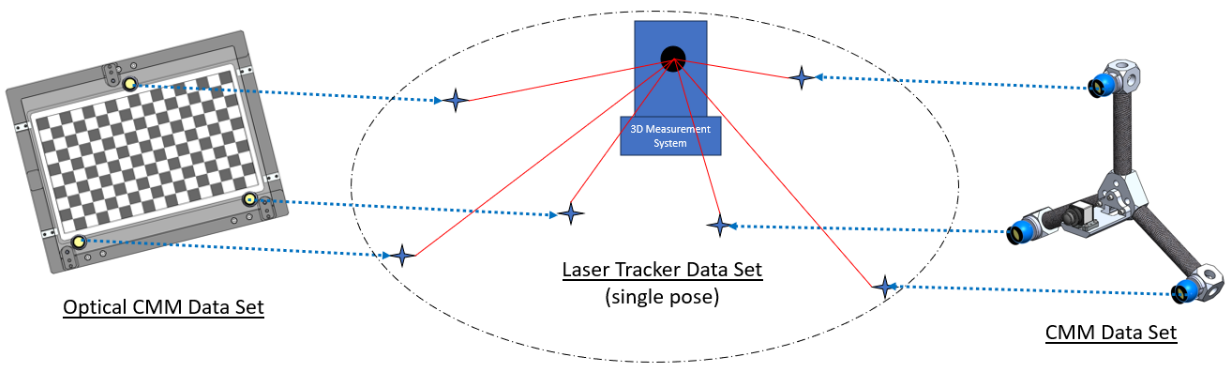


Figure 4: Precision geometric data assembly process

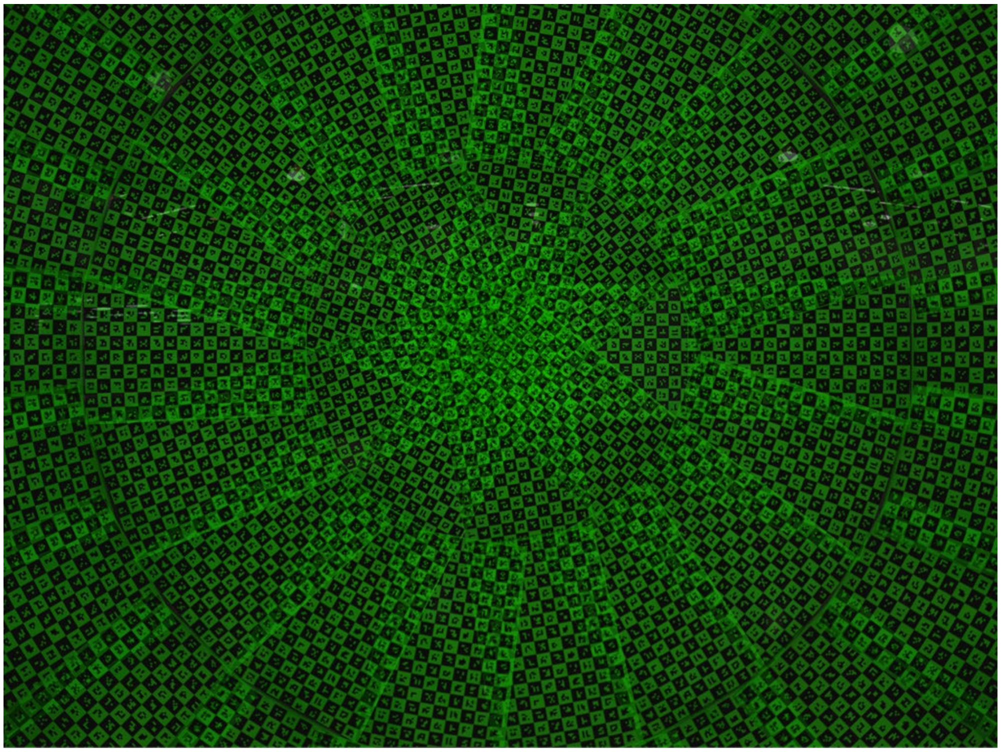


Figure 5: Example of the type of image coverage attainable with the PixelTraq process

The image set is processed and image features are extracted to subpixel accuracy. These are paired with the Superchart points to form the calibration data set.

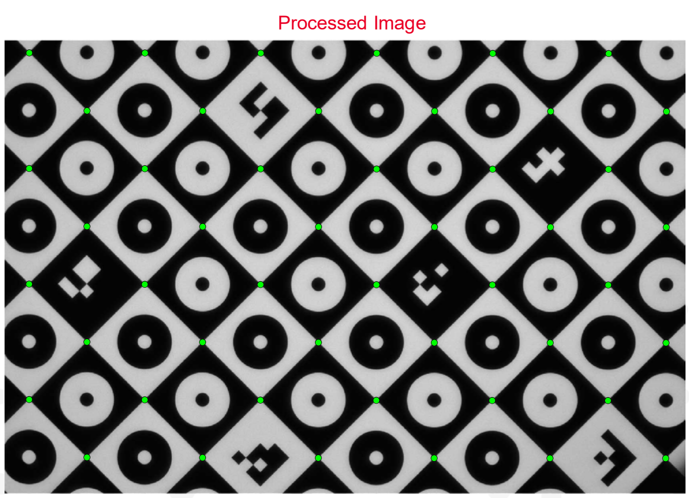


Figure 6: Example image features determined to subpixel accuracy

Finally, the calibration problem is set up. A standard calibration minimizes the following objective function[1]:

$$\sum_{i=1}^{n} \left\| r_i - f\left(i_1, i_2, \ldots, i_q, R, t, p_i\right) \right\|^2$$

1 PixelTraq also supports robust M-estimator loss functions, object space optimization, and multi-camera optimization for specialized applications

Where r_i are the image points and f is the projection function of the camera model that maps from object space to image space, $i_1, i_2, \ldots, i_q$ are the q intrinsic parameters of the selected model, R and t are the extrinsic parameters of the camera with respect to the datum frame and p_i are the Superchart points corresponding to the image point r_i. Although this only differs from Zhang's equation by a few subscripts, this makes a significant difference in the end results.

A non-linear optimization technique is used to minimize the objective function, and the outputs are the optimal intrinsic parameters $i_1, i_2, \ldots, i_q$, extrinsic parameters R and t, and their estimated parameters errors.

The plots below show just a few of many possible visualizations of 3D errors from the resulting calibration. Angular, image reprojection error, and object space error are all measurable using the PixelTraq process.

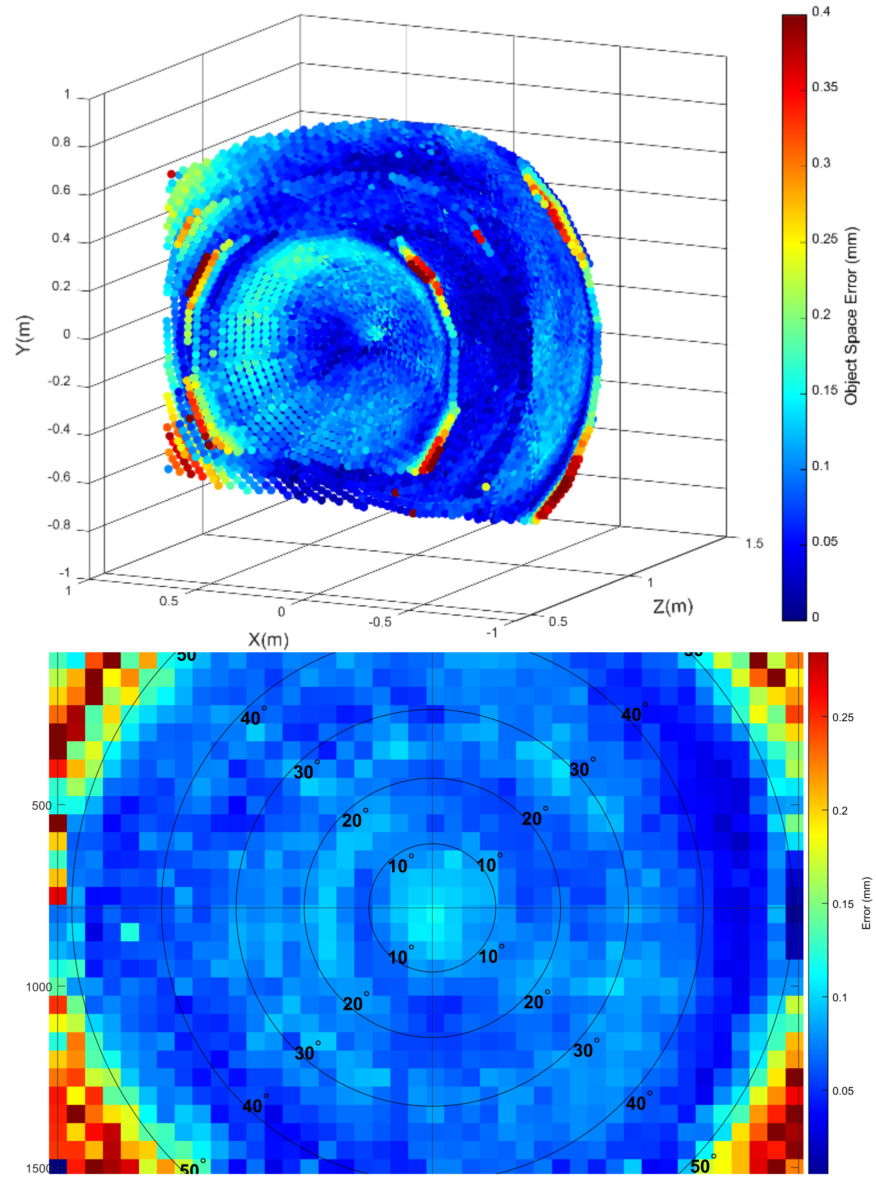


Figure 7: 3D Visualization of calibration errors projected back into object space (top), 3D error with FOV overlay (bottom)

Reporting

The integrated PixelTraq pipeline makes reporting and sharing the generated calibrations a seamless and efficient process while giving a deeper look into the quality of the overall calibration. The report is accompanied by a JSON format parameter file containing the model parameters and calibration tracking information.

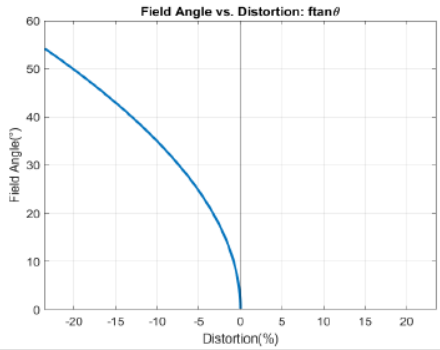
quartus ENGINEERING

CALIBRATION CERTIFICATE

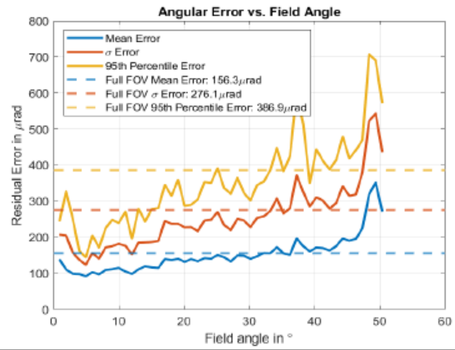
Digital Calibration Certificate:

Camera Information			Calibration Summary
Part Information	Part Number	23204-33856	**Intrinsic Parameters**
	Serial Number	001	EFLx EFLy: [1193.7 1193.7] pixels PPx PPy: [1046.4 787.1] pixels Radial Distortion Coeff: [0.0636 0.0398 0.0379 0.0080]
Calibration Information	Calibration IDN	173684434872336	
	Date Recorded	14-Jan-2025 08:45:48	
Camera	Manufacturer	Allied Vision	
	Model Number	1800 U-319m	
	Part Number	23-204	
	Serial Number	06H9P	
	Sensor Size	2064 x 1544	
Lens	Part Number	33-856	
	Serial Number	N/A	**Extrinsic Parameters**
Intrinsic Summary	Reprojection Error [pix]	0.2104	Rx Ry Rz: [-1.5828 0.0018 -1.5710] rad Euler XYZ Intrinsic x y z: [-0.01439 -0.01448 -0.03413] m
	Model Type	KannalaModel	

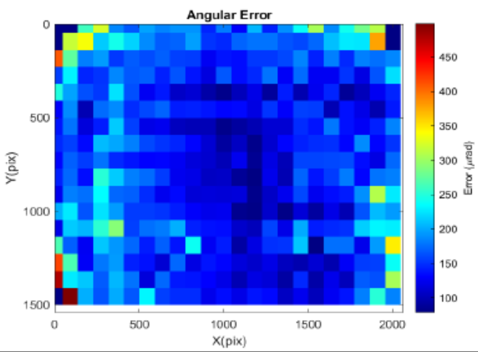
Percent Distortion Deviation



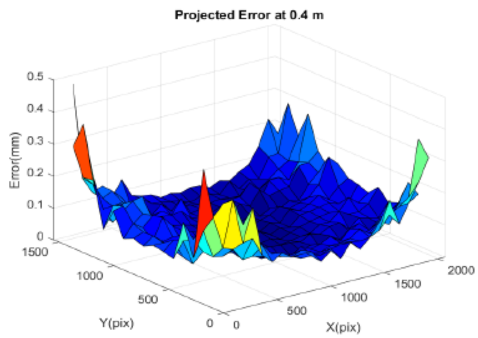
Angular Error



Angular Error



Surface Error 3D



For more information on how to deploy this calibration, visit: www.quartus.com\pixeltraq or scan

References

[1] Z. Zhang, "A flexible new technique for camera calibration," *IEEE Transactions on Pattern Analysis and Machine Intelligence,* vol. vol. 22, no. no. 11, pp. pp. 1330-1334, Nov 2000.

[2] B. Atcheson, F. Heide and W. Heidrich, "CALTag: High Precision Fiducial Markers for Camera," *Vision, Modeling, and Visualization,* 2010.

[3] W. Kabsch, "A solution for the best rotation to relate two sets of vectors," *Acta Crystallographica Section A: Foundations and Advances,* vol. A32, pp. 922-923, 1976.

Glossary

camera calibration – the process of determining the optimal camera models of a mathematical camera model given a set of measurement data

CMM – coordinate measurement machine. A device for measuring coordinates of mechanical features, typically to very high accuracy.

Datum – A reference feature, often defined by physical mechanical features for registration or defining relative measurements.

Functional – a mathematical function of a function, typically in an optimization problem

Superchart – a composite 3D calibration object constructed from combinations of multiple precision measurements and realized by relative motion of a camera relative to a chart