Stereo Calibration App

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Stereo Camera Calibrator Overview

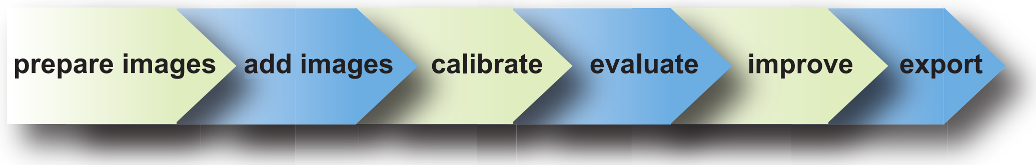
You can use the Stereo Camera Calibrator app to calibrate a stereo camera, which you can then use to recover depth from images. A stereo system consists of two cameras: camera 1 and camera 2. The app estimates the parameters of each of the two cameras. It also calculates the position and orientation of camera 2 relative to camera 1.

The app produces an object containing the stereo camera parameters. You can use this object to rectify stereo images using the `rectifyStereoImages` function, reconstruct the 3-*D* scene using the `reconstructScene` function, or compute 3-*D* locations corresponding to matching pairs of image points using the `triangulate` function.

The suite of calibration functions used by the Stereo Camera Calibrator app provide the workflow for stereo system calibration. You can use them directly in the MATLAB workspace. For a list of functions, see "Single Camera Calibration".

Note: You can use the Camera Calibrator app with cameras up to a field of view (FOV) of 95 degrees.

Stereo Camera Calibration



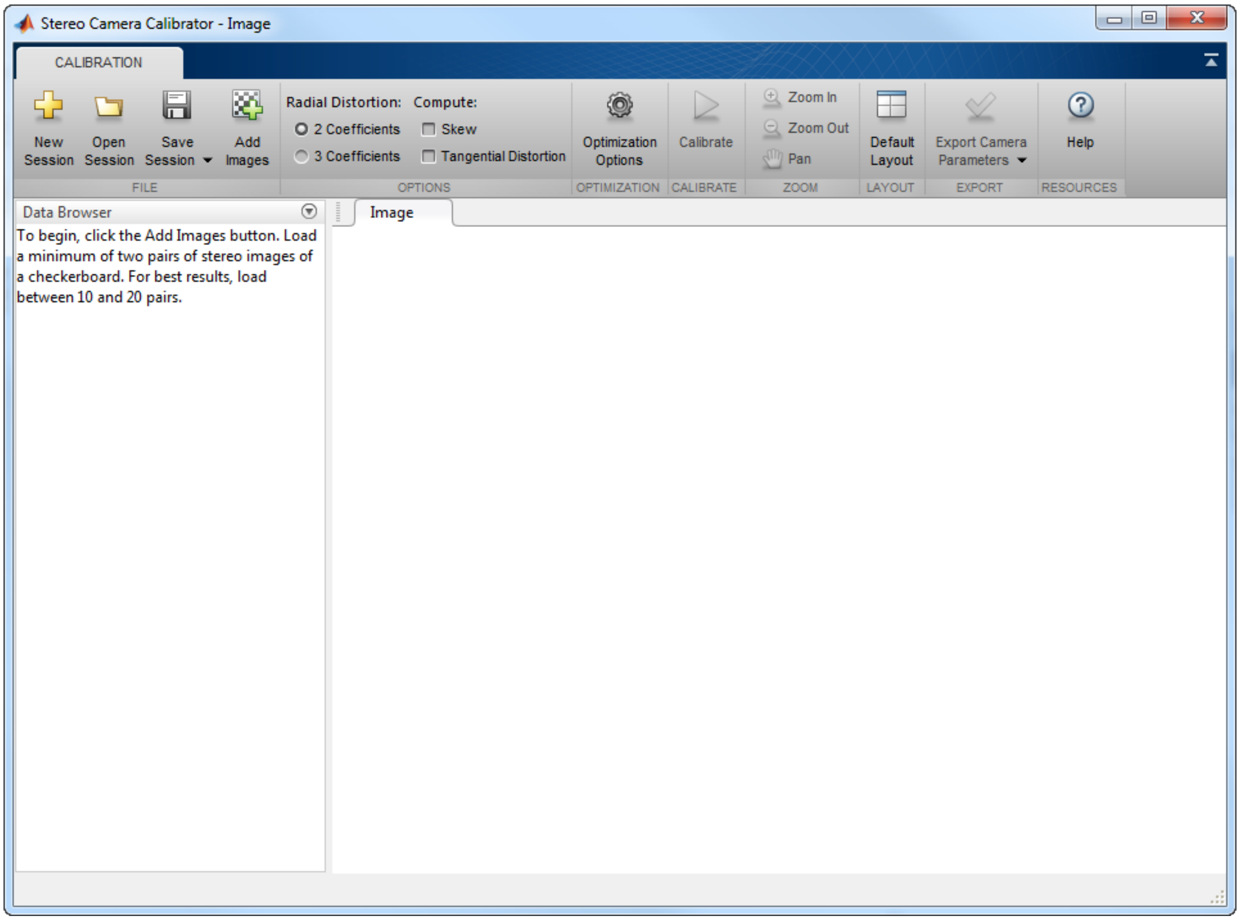
Follow this workflow to calibrate your stereo camera using the app:

1. Prepare images, camera, and calibration pattern.
2. Load image pairs.
3. Calibrate the stereo camera.
4. Evaluate calibration accuracy.
5. Adjust parameters to improve accuracy (if necessary).
6. Export the parameters object.

In some cases, the default values work well, and you do not need to make any improvements before exporting parameters. If you do need to make improvements, you can use the camera calibration functions in MATLAB. For a list of functions, see “Single Camera Calibration”.

Open the Stereo Camera Calibrator

- MATLAB Toolstrip: Open the Apps tab, under **Image Processing and Computer Vision**, click the app icon.
- MATLAB command prompt: Enter `stereoCameraCalibrator`



Image, Camera, and Pattern Preparation

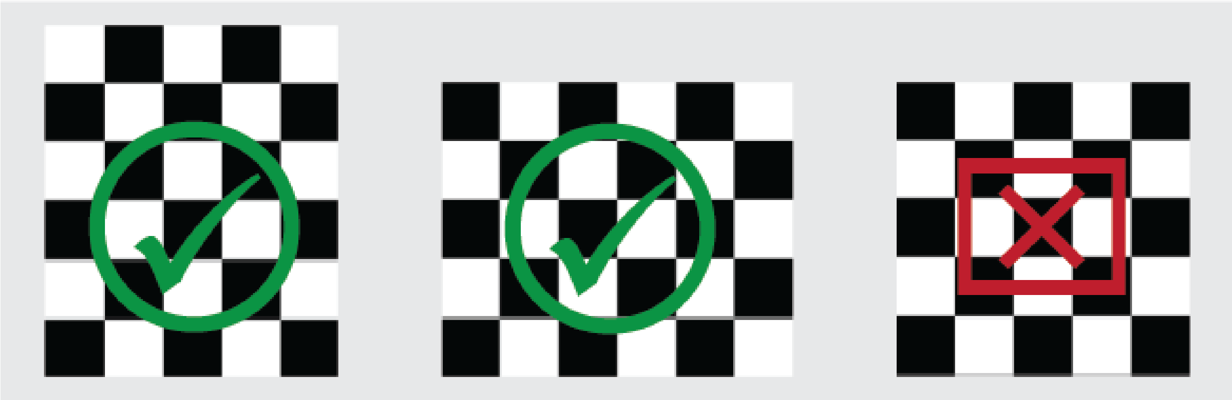
For best results, use between 10 and 20 images of the calibration pattern. The calibrator requires at least three images. Use uncompressed images or lossless compression formats such as PNG. The calibration pattern and the camera setup must satisfy a set of requirements to work with the calibrator. For greater calibration accuracy, follow these instructions for preparing the pattern, setting up the camera, and capturing the images.

Prepare the Checkerboard Pattern

The Camera Calibrator app uses a checkerboard pattern, which is a convenient calibration target. If you want to use a different pattern to extract key points, you can use the camera calibration MATLAB functions directly. See “Single Camera Calibration” for the list of functions.

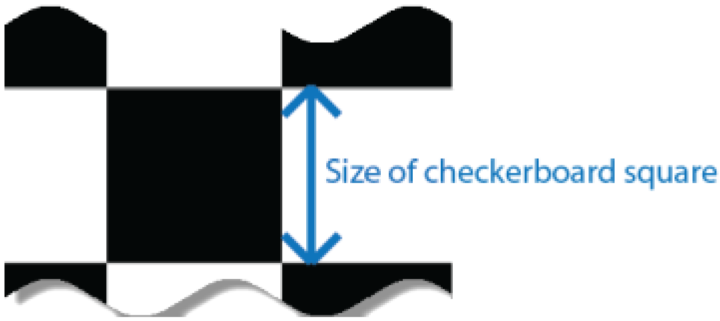
Note: The Camera Calibrator app only supports checkerboard patterns. If you are using a different type of calibration pattern, you can still calibrate your camera using the `estimateCameraParameters` function. Using a different type of pattern requires that you supply your own code to detect the pattern points in the image.

You can print (from MATLAB) and use the checkerboard pattern provided. The checkerboard pattern you use must not be square. One side must contain an even number of squares and the other side must contain an odd number of squares. Therefore, the pattern contains two black corners along one side and two white corners on the opposite side. This criteria enables the app to determine the orientation of the pattern. The calibrator assigns the longer side to be the *x*-direction.



To prepare the checkerboard pattern:

1. Attach the checkerboard printout to a flat surface. Imperfections on the surface can affect the accuracy of the calibration.
2. Measure one side of the checkerboard square. You need this measurement for calibration. The size of the squares can vary depending on printer settings.



3 To improve the detection speed, set up the pattern with as little background clutter as possible.

Camera Setup

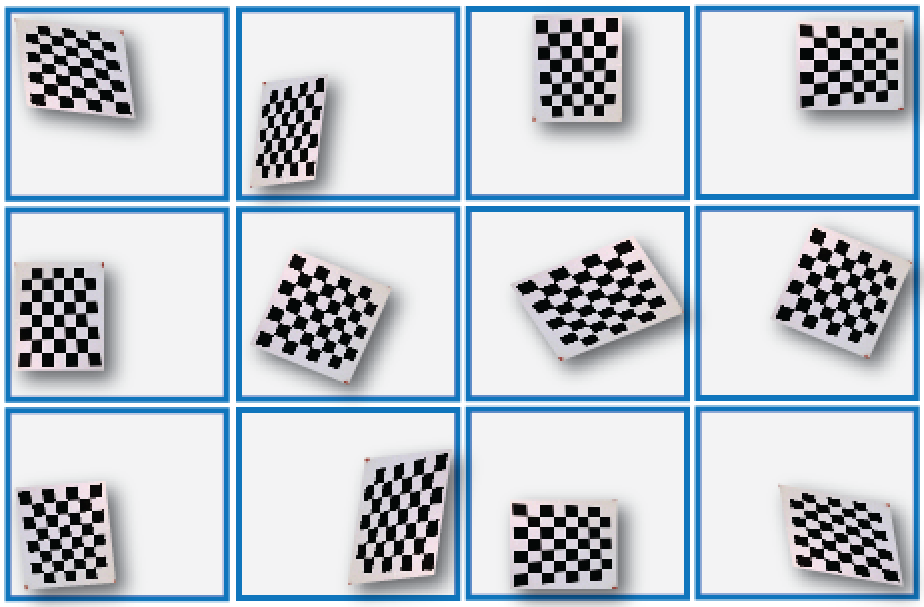
To properly calibrate your camera, follow these rules:

- Keep the pattern in focus, but do not use auto-focus.
- Do not change zoom settings between images, otherwise the focal length changes.

Capture Images

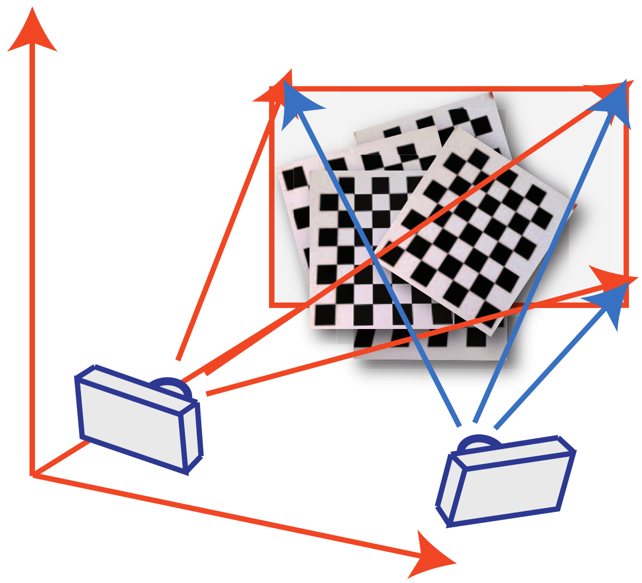
For best results, use at least 10 to 20 images of the calibration pattern. The calibrator requires at least three images. Use uncompressed images or images in lossless compression formats such as PNG. For greater calibration accuracy:

- Capture the images of the pattern at a distance roughly equal to the distance from your camera to the objects of interest. For example, if you plan to measure objects from 2 meters, keep your pattern approximately 2 meters from the camera.
- Place the checkerboard at an angle less than 45 degrees relative to the camera plane.
- Do not modify the images. For example, do not crop them.
- Do not use autofocus or change the zoom between images.
- Capture the images of a checkerboard pattern at different orientations relative to the camera.
- Capture enough different images of the pattern so that you have covered as much of the image frame as possible. Lens distortion increases radially from the center of the image and sometimes is not uniform across the image frame. To capture this lens distortion, the pattern must appear close to the edges.



Specific to stereo camera calibration:

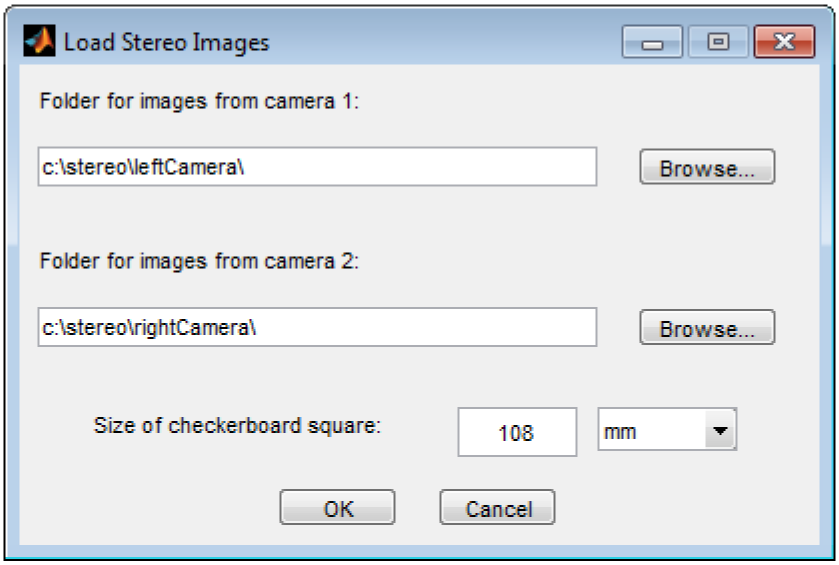
- Make sure the checkerboard pattern is fully visible in both images of each stereo pair.

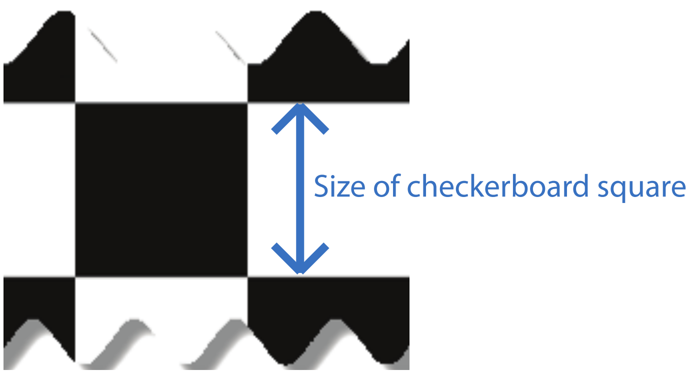


- Keep the pattern stationary for each image pair. Any motion of the pattern between taking image 1 and image 2 of the pair negatively affects the calibration.
- To create a stereo display, or anaglyph, position the two cameras approximately 55 mm apart. This distance represents the average distance between human eyes.
- For greater reconstruction accuracy at longer distances, position your cameras farther apart.

Add Image Pairs

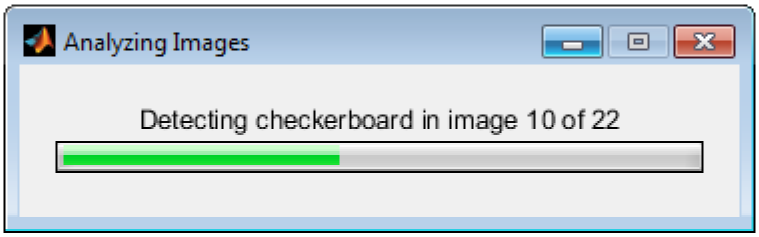
To begin calibration, click Add images to add two sets of stereo images of the checkerboard. You can add images from multiple folders by clicking Add images. Select the locations for the images corresponding to camera 1 and camera 2. Enter the length of one side of a square from the checkerboard pattern.



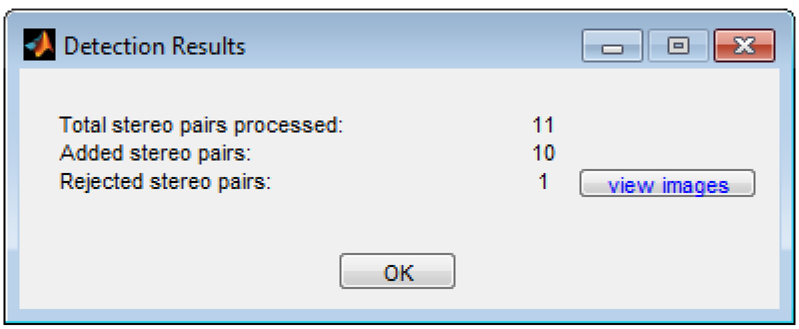


Analyze Images

The calibrator attempts to detect a checkerboard in each of the added images. An Analyzing Images progress bar window appears, indicating detection progress.



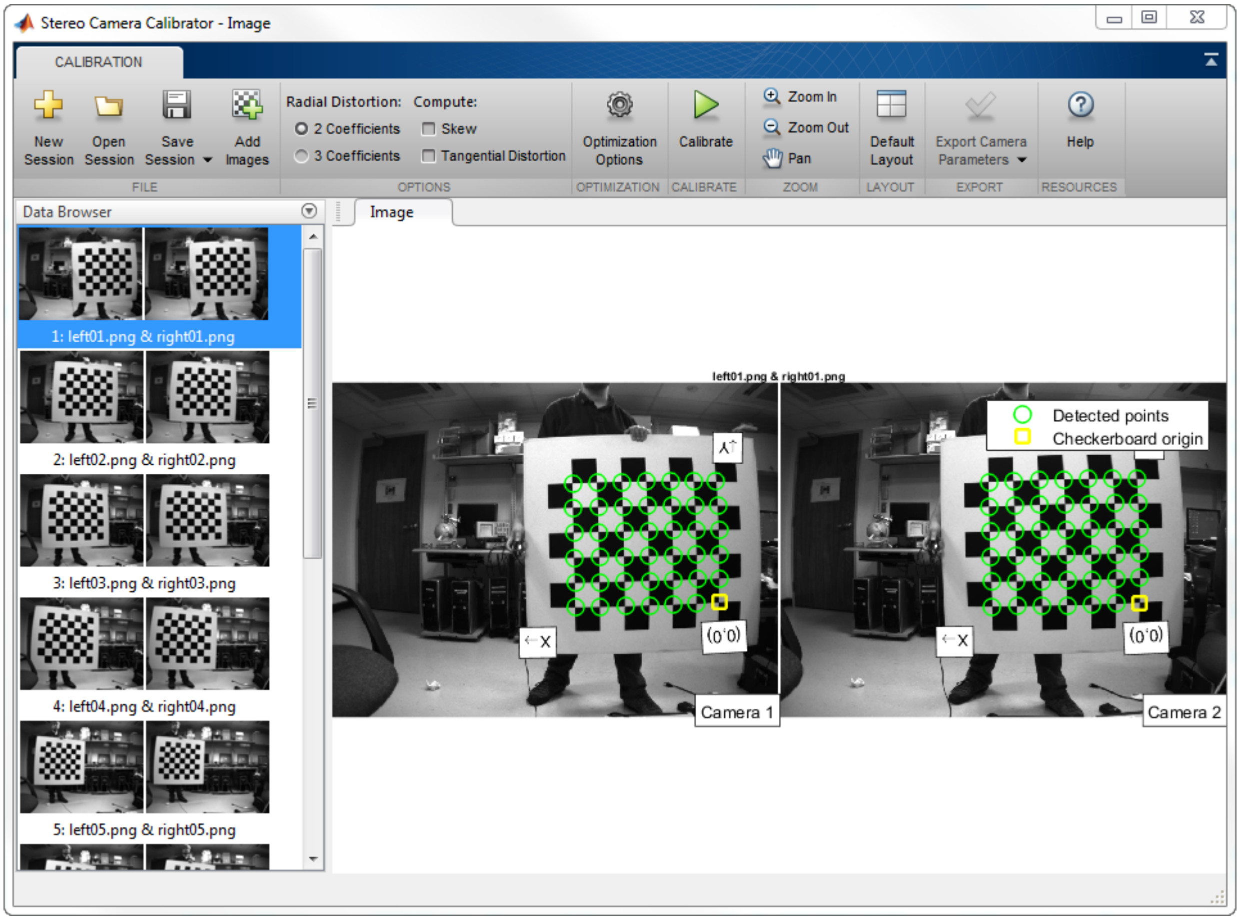
If any of the image pairs are rejected, the Detection Results window appears, which contains diagnostic information. The results indicate how many total image pairs were processed, and how many were accepted, rejected, or skipped The calibrator skips duplicate images.



To view the rejected images, click **view images**. The calibrator rejects duplicate images. It also rejects images where the entire checkerboard could not be detected. Possible reasons for no detection are a blurry image or an extreme angle of the pattern. Detection takes longer with larger images and with patterns that contain a large number of squares.

View Images and Detected Points

The Data Browser pane displays a list of image pairs with IDs. These image pairs contain a detected pattern. To view an image, select it from the **Data Browser** pane.



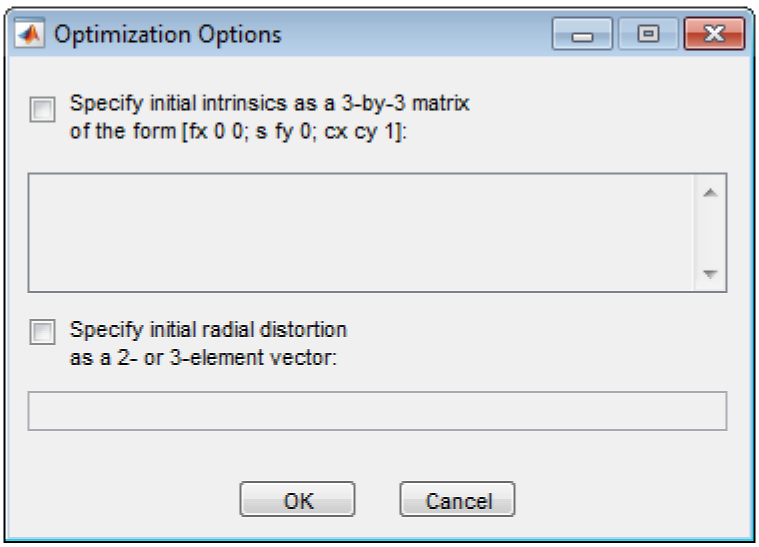
The **Image** pane displays the checkerboard image pair with green circles to indicate detected points. You can verify the corners were detected correctly using the zoom controls. The yellow square indicates the (0,0) origin. The X and Y arrows indicate the checkerboard axes orientation.

Calibrate

Once you are satisfied with the accepted image pairs, click Calibrate. The default calibration settings assume the minimum set of camera parameters. Start by running the calibration with the default settings. After evaluating the results, you can try to improve calibration accuracy by adjusting the settings and adding or removing images, and then calibrate again.

Set Initial Guesses for Camera Intrinsics and Radial Distortion

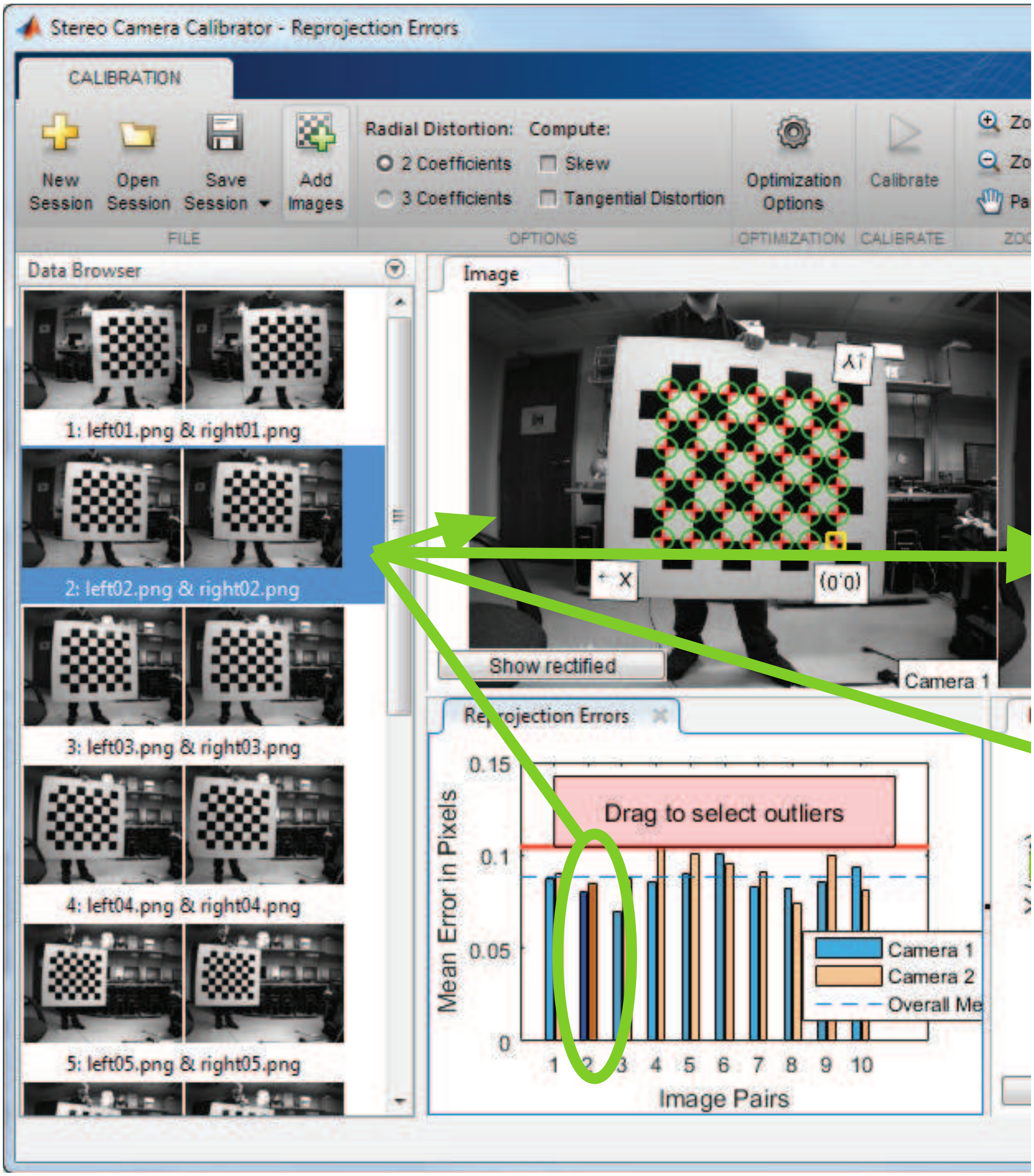
When there is severe lens distortion, the app can fail to compute the initial values for the camera intrinsics. If you have manufacturer's specifications for your camera and you know the pixel size, focal length, and/or lens characteristics, you can set the initial guesses for camera intrinsics and/or radial distortion manually. To set the initial guesses click the **Optimization Options** button.



- Select the top checkbox and then enter a 3-by-3 matrix to specify initial intrinsics. If you do not specify an initial guess, the function computes the initial intrinsic matrix using linear least squares.
- Select the bottom checkbox and then enter a 2- or 3-element vector to specify the initial radial distortion. If you do not provide a value, the function uses `0` as the initial value for all the coefficients.

Evaluate Calibration Results

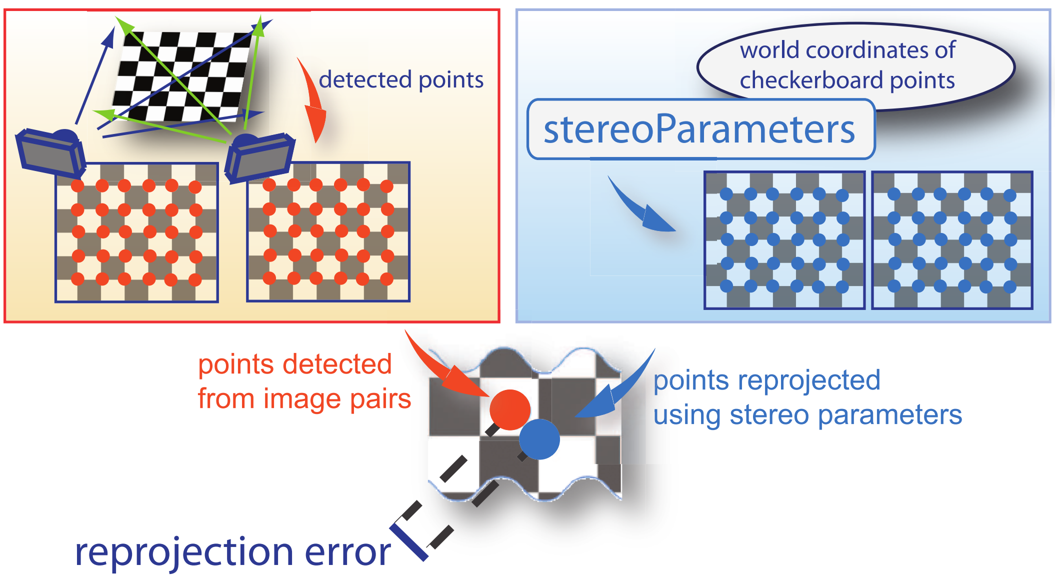
You can evaluate calibration accuracy by examining the reprojection errors and the camera extrinsics, and by viewing the undistorted image. For best calibration results, use all three methods of evaluation.



Stereo Camera Calibrator - Reprojection Errors
CALIBRATION
New Session
Open Session
Save Session
Add Images
FILE
Radial Distortion:
2 Coefficients
3 Coefficients
Compute:
Skew
Tangential Distortion
OPTIONS
Optimization Options
OPTIMIZATION
Calibrate
CALIBRATE
Data Browser
1: left01.png & right01.png
2: left02.png & right02.png
3: left03.png & right03.png
4: left04.png & right04.png
5: left05.png & right05.png
Image
Show rectified
Camera 1
Reprojection Errors
Drag to select outliers
Mean Error in Pixels
Image Pairs
Camera 1
Camera 2

Examine Reprojection Errors

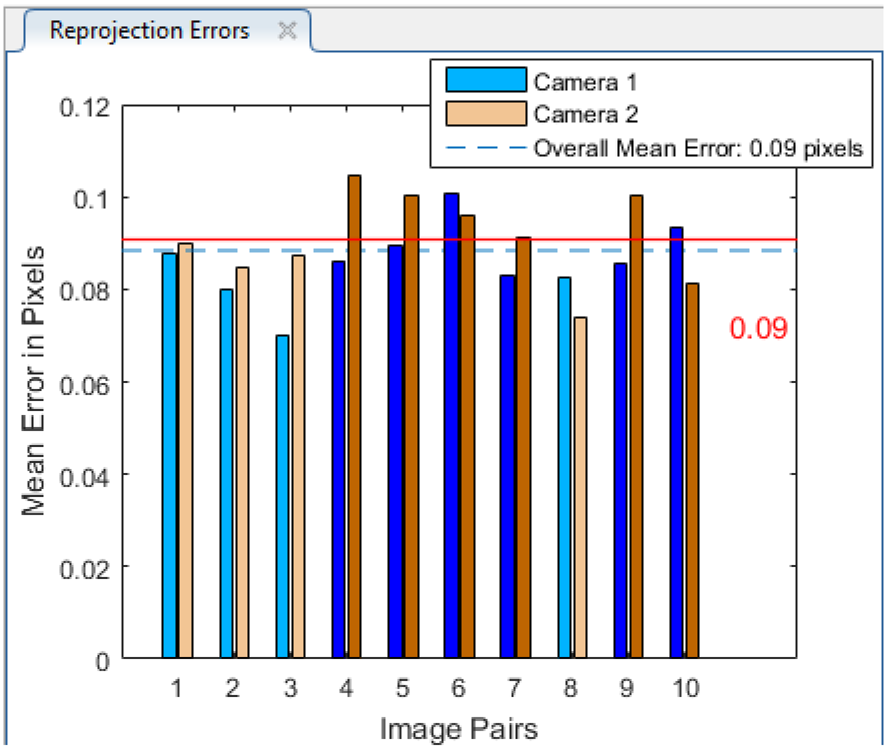
The *reprojection errors* are the distances in pixels between the detected and the reprojected points. The Stereo Camera Calibrator app calculates reprojection errors by projecting the checkerboard points from world coordinates, defined by the checkerboard, into image coordinates. The app then compares the reprojected points to the corresponding detected points. As a general rule, reprojection errors of less than one pixel are acceptable.



The Stereo Camera Calibrator app displays, in pixels, the reprojection errors as a bar graph and as a scatter plot. You can toggle between them using the button on the display. You can identify the image pairs that adversely contribute to the calibration from either one of the graphs. You can then select and remove those images from the list in the **Data Browser** pane.

Reprojection Errors Bar Graph

The bar graph displays the mean reprojection error per image, along with the overall mean error. The bar labels correspond to the image pair IDs. The highlighted pair of bars corresponds to the selected image pair.

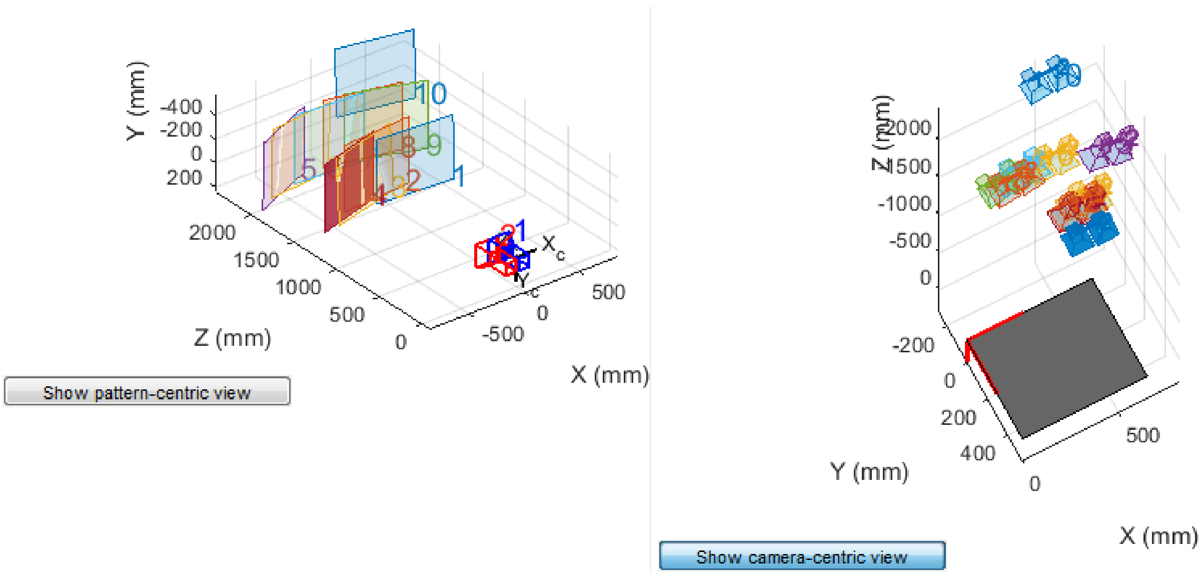


Select an image pair in one of these ways:

- Clicking the corresponding bar in the graph.
- Select the image pair from the list in the **Data Browser** pane.
- Slide the red bar to select outlier images.

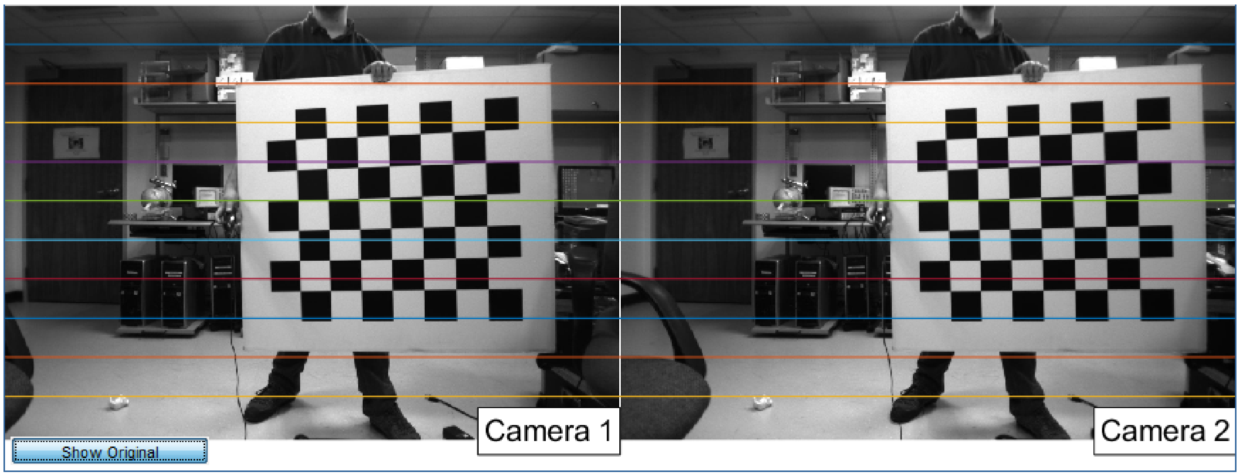
Examine Extrinsic Parameter Visualization

The 3-D extrinsic parameters plot provides a camera-centric view of the patterns and a pattern-centric view of the camera. The camera-centric view is helpful if the camera was stationary when the images were captured. The pattern-centric view is helpful if the pattern was stationary. Click the button on the display to toggle between the two visuals. Click and drag a graph to rotate it. Click a checkerboard or a camera to select it. The highlighted data in the visualizations correspond to the selected image in the list. Examine the relative positions of the pattern and the camera to see if they match what you expect. For example, a pattern that appears behind the camera indicates a calibration error.



Show Rectified Images

To view the effects of stereo rectification, in the **Image** pane, click **Show Rectified**. If the calibration was accurate, the images become undistorted and row-aligned.



It is important to check the rectified images even if the reprojection errors are low. Sometimes, if the pattern only covers a small percentage of the image, the calibration achieves low reprojection errors, but the distortion estimation is incorrect. An example of this type of incorrect estimation for single camera calibration is shown below.

Improve Calibration

To improve the calibration, you can remove high-error image pairs, add more image pairs, or modify the calibrator settings.

Add and Remove Image Pairs

Consider adding more image pairs if:

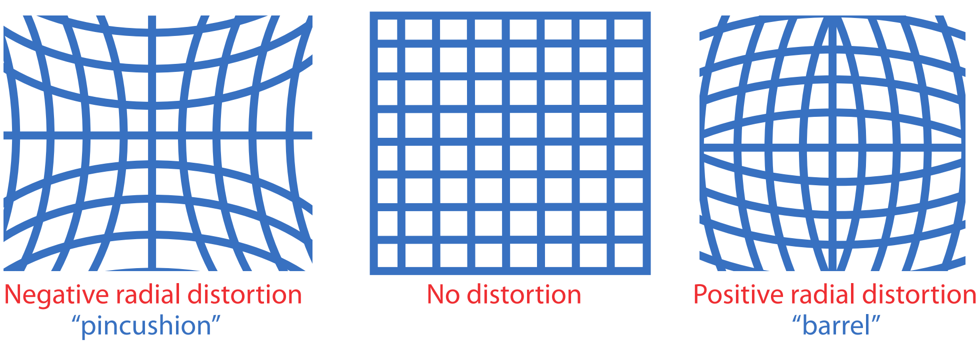
- You have less than 10 image pairs.
- The patterns do not cover enough of the image frame.
- The patterns in your image pairs do not have enough variation in orientation with respect to the camera.

YConsider removing image pairs if the images:

- Have a high mean reprojection error.
- Are blurry.
- Contain a checkerboard at an angle greater than 45 degrees relative to the camera plane.
- Contain incorrectly detected checkerboard points.

Change the Number of Radial Distortion Coefficients

You can specify 2 or 3 radial distortion coefficients by selecting the corresponding radio button from the **Options** section. *Radial distortion* occurs when light rays bend more near the edges of a lens than they do at its optical center. The smaller the lens, the greater the distortion.



The radial distortion coefficients model this type of distortion. The distorted points are denoted as ($x_{\text{distorted}}$, $y_{\text{distorted}}$):

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

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

- x, y — Undistorted pixel locations. x and y are in normalized image coordinates. Normalized image coordinates are calculated from pixel coordinates by translating to the optical center and dividing by the focal length in pixels. Thus, x and y are dimensionless.
- k_1, k_2, and k_3 — Radial distortion coefficients of the lens.
- r^2: $x^2 + y^2$

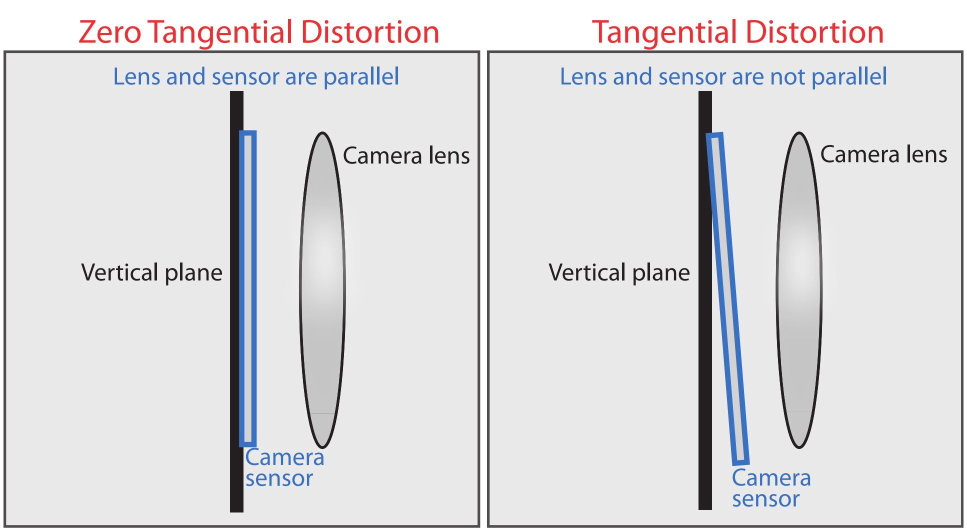
Typically, two coefficients are sufficient for calibration. For severe distortion, such as in wide-angle lenses, you can select 3 coefficients to include k_3.

Compute Skew

When you select the **Compute Skew** check box, the calibrator estimates the image axes skew. Some camera sensors contain imperfections that cause the x- and y-axis of the image to not be perpendicular. You can model this defect using a skew parameter. If you do not select the check box, the image axes are assumed to be perpendicular, which is the case for most modern cameras.

Compute Tangential Distortion

Tangential distortion occurs when the lens and the image plane are not parallel. The tangential distortion coefficients model this type of distortion.



The distorted points are denoted as ($x_{\text{distorted}}$, $y_{\text{distorted}}$):

$x_{\text{distorted}} = x + [2 * p_1 * x * y + p_2 * (r^2 + 2 * x^2)]$

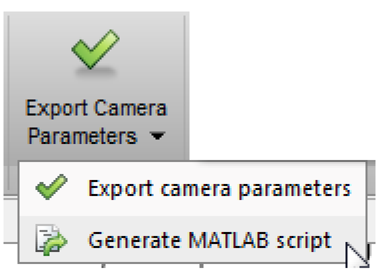
$y_{\text{distorted}} = y + [p_1 * (r^2 + 2 *y^2) + 2 * p_2 * x * y]$

- x, y — Undistorted pixel locations. x and y are in normalized image coordinates. Normalized image coordinates are calculated from pixel coordinates by translating to the optical center and dividing by the focal length in pixels. Thus, x and y are dimensionless.
- p_1 and p_2 — Tangential distortion coefficients of the lens.
- $r^2 = x^2 + y^2$

When you select the **Compute Tangential Distortion** check box, the calibrator estimates the tangential distortion coefficients. Otherwise, the calibrator sets the tangential distortion coefficients to zero.

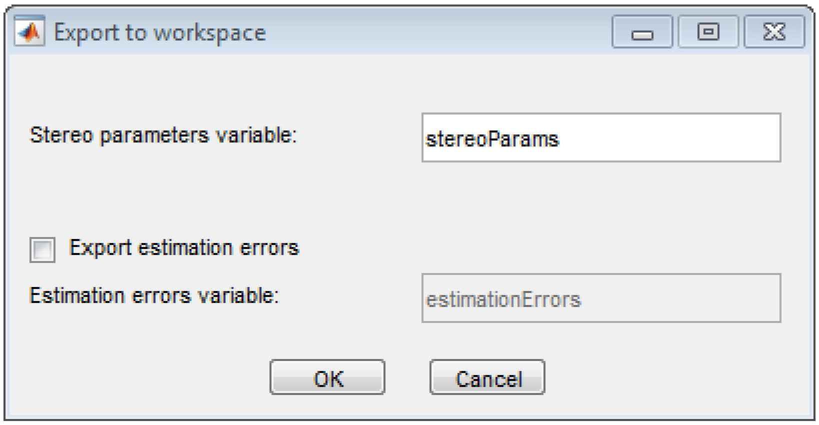
Export Camera Parameters

When you are satisfied with calibration accuracy, click **Export Camera Parameters**. You can save and export the camera parameters to an object or generate the camera parameters as a MATLAB script.



Export Camera Parameters

Click **Export Camera Parameters** to create a stereoParameters object in your workspace. The object contains the intrinsic and extrinsic parameters of the camera, and the distortion coefficients. You can use this object for various computer vision tasks, such as image undistortion, measuring planar objects, and 3-D reconstruction. You can optionally export the stereoCalibrationErrors object, which contains the standard errors of estimated stereo parameters.



Generate MATLAB Script

You can also generate a MATLAB script which allows you save and reproduce the steps from your calibration session.

References

[1] Zhang, Z. "A Flexible New Technique for Camera Calibration". *IEEE Transactions on Pattern Analysis and Machine Intelligence*.Vol. 22, No. 11, 2000, pp. 1330–1334.

[2] Heikkila, J, and O. Silven. "A Four-step Camera Calibration Procedure with Implicit Image Correction." *IEEE International Conference on Computer Vision and Pattern Recognition*. 1997.

See Also

cameraParameters | stereoParameters | Camera Calibrator | `detectCheckerboardPoints` | `estimateCameraParameters` | `generateCheckerboardPoints` | `showExtrinsics` | `showReprojectionErrors` | Stereo Camera Calibrator | `undistortImage`

Related Examples

- "Evaluating the Accuracy of Single Camera Calibration"
- "Measuring Planar Objects with a Calibrated Camera"
- "Structure From Motion from Two Views"

- “Structure From Motion From Multiple Views”
- “Depth Estimation From Stereo Video”
- “3-D Point Cloud Registration and Stitching”
- “Uncalibrated Stereo Image Rectification”
- Checkerboard pattern

More About

- “Single Camera Calibration App” on page 5-13
- “Coordinate Systems”

External Websites

- Camera Calibration with MATLAB