Intel® RealSense™ Depth Module D400 Series Custom Calibration

Revision 2.1

January 2023

Contents

Tables

List of Figures

Revision History

Revision Number	Description	Revision Date
1.0	Initial Release	01/2018
1.1	Update with Calibration API 2.5.2.0 release	01/2018
1.2	Update with Calibration API 2.6.4.0 release	06/2018
1.3	Update calibration frame image format details	08/2018
1.4	Updated with Calibration API 2.6.7.0 release	10/2018
1.5	Updated with Calibration API 2.6.8.0 release	12/2018
1.6	Updated with Calibration API 2.8.0.0 release	03/2019
1.7	Updated with Calibration API 2.11.1.0 release	04/2021
1.8	Supports Intel® RealSense™ Camera D455	10/2021
1.9	Supports Intel® RealSense™ Camera D405	04/2022
2.0	Updated with Calibration API 2.12.0.0 release Enahancement for calibrating custom 3rd party RGB	06/2022
2.1	Updated with Calibration API 2.13.1.0 release	01/2023

1 Introduction

1.1 Purpose and Scope of This Document

Intel® RealSense™ D400 devices should be well calibrated to operate efficiently and accurately. The Intel supplied calibration tools including Intel® RealSense™ Dynamic Calibrator and OEM Calibration Tool for Intel® RealSense™ Technology are designed to calibrate the devices using Intel proprietary algorithms. Some customers or developers may choose to use their own calibration algorithms and update the device with their custom calibration data.

This document contains technical information to assist those developing custom calibration solutions for Intel® RealSense™ D400 series modules. The primary goal is to guide the user to create a calibration application, using the D400 corresponding APIs and tools. It includes a description how to configure the device under calibration, define the calibration parameters, and how to read/write these parameters from/into the device. In addition, a simple sample application based on OpenCV algorithm is provided as an example.

It is not in the scope of this document to discuss details of calibration algorithm or accuracy. Developing custom calibration requires knowledge in computer vision as well as good understanding of the RealSense device operating details. It is a complex topic and intended only for those with expert level knowledge.

1.2 Organization

This document is organized into four main parts: overview, setup, calibrating a device with custom calibration sample app, and developing custom solution:

- **Overview** – brief overview of the Calibration API and parameters.
- **Setup** – hardware and software setup for running the Custom Calibration Sample App to calibrate a device and developing custom calibration solutions.
- **Calibrating Device with Custom Calibration Sample App** – describes the necessary hardware and software setup required running the Custom Calibration Sample App and details steps to calibrate device.
- **Developing Custom Calibration Solution –** uses the sample application as an example to describe details of steps implementing a custom calibration solution for Intel® RealSense™ D400 series modules.

This document also provides additional information on calibration frame image formats and calibrating devices with non-Intel 3rd Party RGB Sensor.

- **Appendix: Unrectified Left/Right Image Formats for Calibration** – describes unrectified image format for the left and right sensors.
- **Appendix: Calibrating Device with 3rd Party RGB Sensor** – address calibration issues on Intel® RealSense™ D400 series modules with non-Intel 3rd Party RGB sensors.

2 Overview

2.1 Calibration API and Calibration Data Read/Write/Restore

Intel provides a software interface in Calibration API to enable user uploading those calibration parameters to Intel® RealSense™ D400 devices and read the parameter back from device:

- WriteCustomCalibrationParameters – write parameters to device
- ReadCalibrationParameters – read parameters from device

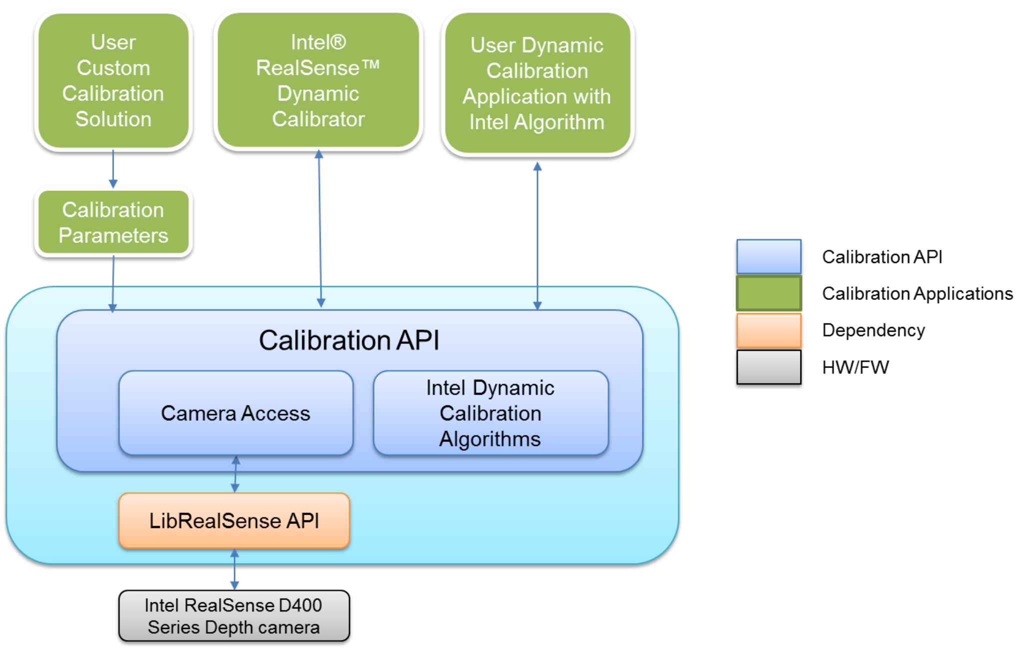


Figure 2-1 Software Stack with Dynamic Calibration API and Calibration Apps

An example tool CustomRW is also included in Calibration API to read calibration parameters from XML file and write them to the device.

A user custom calibration app can choose one of the two approaches to update the results to the device:

- To link to the WriteCustomCalibrationParameters and ReadCalibrationParameters and write directly to the device through the APIs.
- To write the results into a parameter XML file and then use CustomRW to read/write the parameters to the device.

In case user needs to restore the calibration data on the device, ResetDeviceCalibration in Calibration API can be called to programmatically restore the device calibration to gold settings.

- ResetDeviceCalibration – restore device calibration to gold settings

The CustomRW example tool also supports restore through command line option.

2.2 Calibration Parameters

Calibration parameters includes INTRINSICS and EXTRINSICS. Assume left camera is the reference camera and is located at world origin. RGB parameters only apply to modules with RGB, e.g., D415, D435, and D455.

Intrinsic includes

- Focal length - specified as [fx; fy] in pixels for left, right, and RGB cameras
- Principal point - specified as [px; py] in pixels for left, right, and RGB cameras
- Distortion - specified as Brown's distortion model [k1; k2; p1; p2; k3] for left, right, and RGB cameras

Extrinsic includes

- RotationLeftRight - rotation from right camera coordinate system to left camera coordinate system, specified as a 3x3 rotation matrix
- TranslationLeftRight - translation from right camera coordinate system to left camera coordinate system, specified as a 3x1 vector in millimeters
- RotationLeftRGB - rotation from RGB camera coordinate system to left camera coordinate system, specified as a 3x3 rotation matrix
- TranslationLeftRGB - translation from RGB camera coordinate system to left camera coordinate system, specified as a 3x1 vector in millimeters

The calibration data read/write API allows user to upload both INTRINSICS and EXTRINSICS. The user custom algorithm is free to optimize all these parameters. The sample in this document optimizes both intrinsic and extrinsic parameters.

The following table shows how the various calibration tools would impact calibration parameters for Intel® RealSense™ D400 series depth cameras.

	Factory Calibration	OEM Calibration	User Custom Calibration	Dynamic Calibration
Intrinsic	x	x	x	
Extrinsic	x	x	x	x

2.3 Frame Formats Used in Custom Calibration

The Intel® RealSense™ D400 series modules supply unrectified calibration frame formats for use in custom calibration. The device hardware provides unrectified left/right images in Y12I format and RGB sensor images in YUY2 format (on modules with RGB sensor). If user application streams through Intel LibRealSense, the left/right images are transformed into Y16 format.

The Custom Calibration Sample App example uses Intel LibRealSense for streaming from the device and the following image formats for calibration.

Table 2-1. Frame Formats Used in Custom Calibration*

Format	SKU	Used	Comment
Y16 (16-bit)	D400	Left and Right Sensors: 1920x1080 @ 15 FPS	Intel® RealSense™ Camera D400, D410, D415
	D410		
	D420	Left and Right Sensors: 1280x800 @ 15 FPS	Intel® RealSense™ Camera D430 D420, D435, D435i, D435f, D455, D457
	D430		
	D455		
	D457		
	D405	Left and Right Sensors: 1288x808 @ 15 FPS	Intel® RealSense™ Camera D405
YUY2	D415	RGB Sensor: 1920x1080 @ 15 FPS	Intel® RealSense™ Camera D415, D435, D435i, D435f
	D435		
	D455	RGB Sensor: 1280x800 @ 15 FPS	Intel® RealSense™ Camera D455, D457
	D457		
	D405	RGB Sensor: 1280x720 @ 15 FPS	Intel® RealSense™ Camera D405

*Frame stream formats supported by librealsense

For details on Y12I and Y16 formats, please refer to *Appendix: Unrectified Left/Right Image Formats for Calibration*.

2.4 Frame Sync

The left/right calibration frame itself is always synced between the left and right images, whether it's in the original Y12I format or later Y16 format through librealsense. However, if the camera supports RGB, the left/right and RGB frames are not synced.

To avoid possible motion blur, calibrate the device with images captured at static positions. In this sample, a tripod is used to keep the camera device at fixed positions while capturing the images for calibration. This is same if you want to develop your own custom calibration app.

2.5 Accuracy

The main purpose of this document is to demonstrate the process to calibrate Intel® RealSense™ D400 series cameras with user custom algorithms. Calibration algorithm accuracy is not the focus. For simplicity, default OpenCV calibration alogirthm is used in the sample app.

A few factors could impact accuracy of the sample calibration app:

1) The app defaults to an 8x7 checkerboard calibration target with a 60x60mm checker size (described in section ***3.1.2 Target***). If user prints the target on regular 8.5"x11" printer paper, the target checker size will be smaller, and the appropriate target setting should be modified in CalibrationManager.h
   // change to 30.0f if target printed on regular letter size 8.5" x 11" printer paper
   const float CHESSBOARD_SQUARE_SIZE = 60.0f;
2) The calibration will not be accurate if the checkerboard doesn't sufficiently cover the camera FOV (field of view) or the poses are not diverse enough between captures.
3) The calibration will also not be accurate if the camera or board is handheld (or not completely still) as there is no frame sync in calibration mode.

3 Setup

This section describes the required hardware and software setup for running the Custom Calibration Sample Application to calibrate a device and developing a Custom Calibration Application.

3.1 Hardware

The required hardware includes a calibration target, D400 series device to be calibrated, USB cable, and a Windows 10 computer. To avoid motion blur, images are captured at static device positions with a tripod during calibration.

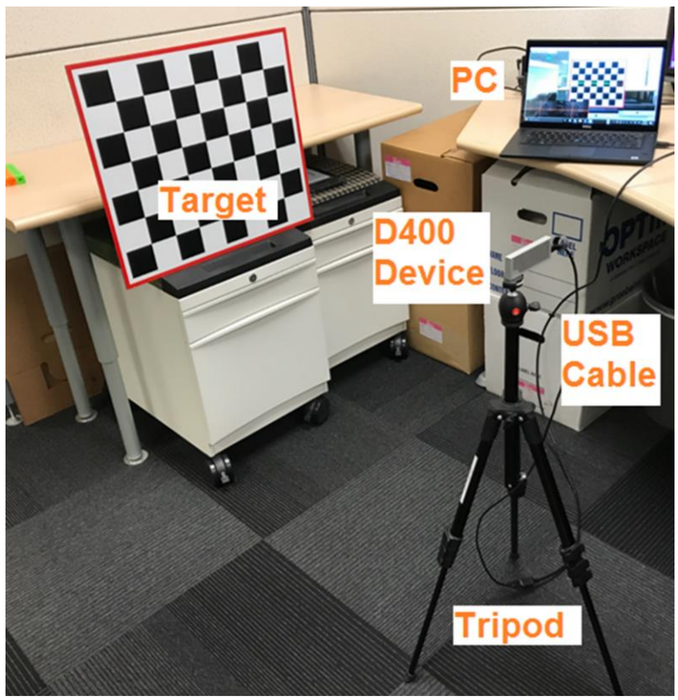


Figure 3-1 Hardware Setup

3.1.1 Device

Intel® RealSense™ D415 device as shown below is used to show case the custom calibration process. All D400 series devices can use the same process.

Figure 3-2 D415 Device

3.1.2 Target

The target used in this custom calibration example is an 8x7 checkerboard with a 60x60mm checker size.

The calibration target image 540x480_60mm.pdf is included in the software package described in sections ***3.2.1 Custom Calibration Sample Application*** *and* ***3.2.2 Intel® RealSense™ Calibration Tool and API****.* It's located under the **CustomCalibration** directory.

For better accuracy, users must ensure that when printing the target, the target is not scaled.

If no suitable printer or printing service is available, the target can be scaled down by 50% and printed on 8.5" x 11" US letter size paper or similar on regular laser printer. However, the checker size configuration is the sample app code should be changed from 60.0 mm to 30.0 mm (CHESSBOARD_SQUARE_SIZE in CalibrationManager.h).

The specific target used in this application is for demonstration purpose only. A developer may choose to use a different target for their own calibration algorithm but will need to modify the sample application accordingly and recompile.

Figure 3-3 8x7 60x60 mm Checker Calibration Target

3.1.3 Tripod

Any medium sized tripod should be sufficient. In this example setup, we used a Manfrotto Compact Light Aluminum Tripod with ball head. The ball head makes adjustment to device orientation easier.

Figure 3-4 Tripod

3.1.4 USB

A long USB type C cable to connect the device to the host computer where the custom calibration sample application will run.

3.1.5 PC

A Windows 10 computer.

3.2 Software

Install the following to the windows computer.

3.2.1 Custom Calibration Sample Application

The CustomCalibration sample sand its source code is included in Intel® RealSense™ Calibration API package which is available for download at the Intel® RealSense™ download center (the download link is shown in Table 3-1).

3.2.2 Intel® RealSense™ Calibration Tool and API

The calibration example uses support functions provided by the Intel® RealSense™ Calibration API to store updated calibration parameters into the non-volatile flash storage on the Intel® RealSense™ D400 series modules.

Required functions were first introduced in version 2.6.5.0 of the Dynamic Calibration API, so install the latest version and ensure that it is version 2.6.5.0 or later.

Table 3-1 lists where to download the Intel® RealSense™ Calibration API software and associated documentation.

Table 3-1. Intel® RealSense™ Calibration API Resources

Resource	URL
Intel® RealSense™ Product Family D400 Series Dynamic Calibration Software Download	https://downloadcenter.intel.com/download/27415/?v=t
Intel® RealSense™ Product Family D400 Series Dynamic Calibration User Guide	https://downloadcenter.intel.com/download/27415/?v=t
Intel® RealSense™ Product Family D400 Series Dynamic Calibration Programmer Guide	https://downloadcenter.intel.com/download/27415/?v=t

Download **Calibration Tool and Calibration API** installer and follow instruction to install. The latest version 2.13.1.0. After installation, the directory structure should look like below:

```
CalibrationToolAPI
      |
      |-------- 2.13.1.0
      |            |-------- bin
      |            |            |-------- Intel.Realsense.CustomRW.exe
      |
      |            |-------- api
      |            |            |-------- DynamicCalibrationAPI.Zip
      |            |
      |            |-------- attributions.txt
      |            |-------- license.txt
      |            |-------- target
```

Intel.Realsense.CustomRW.exe under bin directory is the calibration data read/write tool. We will be using it to update the calibration parameters to the device after running the Custom Calibration Sample App and obtained optimized parameters for the device.

DynamicCalibrationAPI.Zip under the api directory contains the calibration api and examples, including the Custom Calibration Sample App. Unzip it into any user folder into a directory structure as following:

```
DynamicCalibrationAPI
    |
    |-------- 2.13.1.0
    |            |-------- Include
    |            |-------- lib
    |            |-------- attributions.txt
    |            |-------- license.txt
    |            |-------- examples
    |            |              |-------- CustomCalibration
    |            |              |            |-------- 540x480_60mm.pdf
```

CustomCalibration under examples directory is the Custom Calibration Sample App source code and project solution files to compile it. We will go over it later in this document.

540x480_60mm.pdf is the 8x7 checkerboard calibration target used in the CustomCalibration example as described in section *3.1.2 Target*.

3.2.3 Intel® RealSense™ SDK

The custom calibration application package contains a pre-compiled LibRealSense library to conveniently open and access Intel® RealSense™ D400 series modules, so Intel® RealSense™ SDK is not required but it will be convenient to operate the camera, examine images and debugging. ***Table 3-2*** contains pointers to the SDK homepage, GitHub* repository where you can download the latest release, and the SDK documentation.

Table 3-2. Intel® RealSense™ SDK Resources

Resource	URL
Intel® RealSense™ SDK Home Page	https://software.intel.com/en-us/realsense/sdk
LibRealSense GitHub*	https://github.com/IntelRealSense/librealsense
SDK Documentation	https://github.com/IntelRealSense/librealsense/tree/master/doc

3.2.4 OpenCV 3.3.1

The calibration example presented in this document uses several OpenCV 3.3.1 libraries for computations, so OpenCV 3.3.1 must be installed. ***Table 3-3*** lists URLs for downloading OpenCV 3.3.1, and ***Table 3-4*** lists the specific OpenCV libraries that are required by the example code.

Table 3-3. OpenCV 3.3.1 Resources

Resource	URL
OpenCV GitHub* Repository	https://github.com/opencv/opencv
OpenCV 3.3.1 Download	https://github.com/opencv/opencv/releases/tag/3.3.1

Table 3-4. OpenCV 3.3.1 Libraries Required for the Example

OpenCV 3.3.1 Library
ittnotify.lib
opencv_calib3d331.lib
opencv_core331.lib
opencv_features2d331.lib
opencv_flann331.lib
opencv_imgproc331.lib
zlib.lib

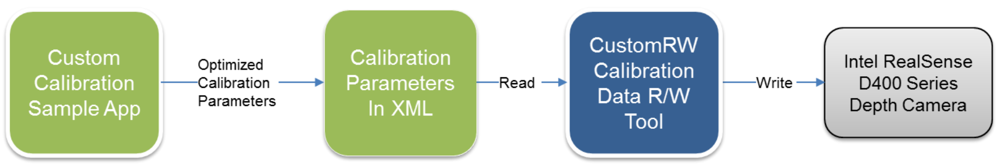
3.2.5 Glut Library

The FreeGLUT package is an open source alternative to the OpenGL Utility Toolkit for displaying graphical output to the operator of the custom calibration application. You can download and install the FreeGLUT package at http://freeglut.sourceforge.net/.

4 Calibrating Device with Custom Calibration Sample Application

4.1 Process Overview

The general process to calibrate a device with the Custom Calibration Sample App involves running the app capturing images of the target from various viewpoints, the app optimizes the calibration parameters based on the captured images and writes the results to an XML file. The user then run CustomRW calibration data R/W tool to read the parameters from the XML file and write them to the device.



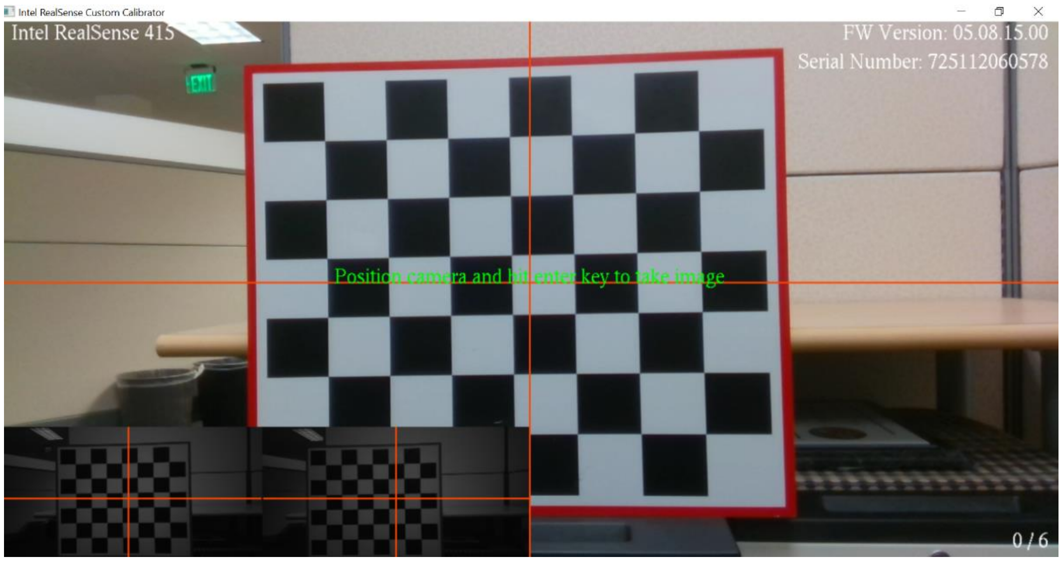
4.2 Connect Device to Computer

Connect the device through the USC cable to the PC where Custom Calibration Sample App locates.

4.3 Running Custom Calibration Sample Application

4.3.1 Starting Application

Use Windows explorer to browse to CustomCalibration\bin directory and find the CustomCalibrationTest.exe and double click it to start running.



The app runs with a simple UI. The main window displays the image from RGB imager, the lower left corner displays the left and right images. In case the device does not have RGB, only the left and right images display on the lower left corner.

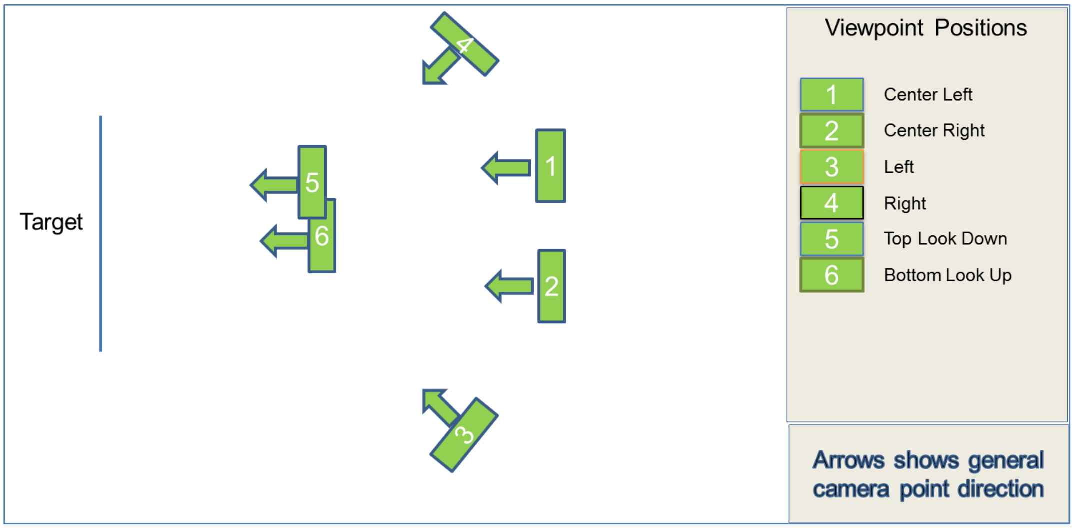
A few text messages are overlay on top of the images:

- On the top left corner, it displays the device model name, for example, Intel RealSense 415.
- On the top right corner, it displays the FW version and serial number of the device.
- On the bottom right corner, it displays a progress counter in the form of x/6 where x is the number of images captured and accepted out of the total 6 images required.
- In the middle of the Window is a green help message to instruct the user to position the camera and press the enter key to capture image.
- In the top middle portion of the Window is an area where error message will display in red when the image is not accepted or other error conditions.

4.3.2 Capturing Images from 6 Viewpoints

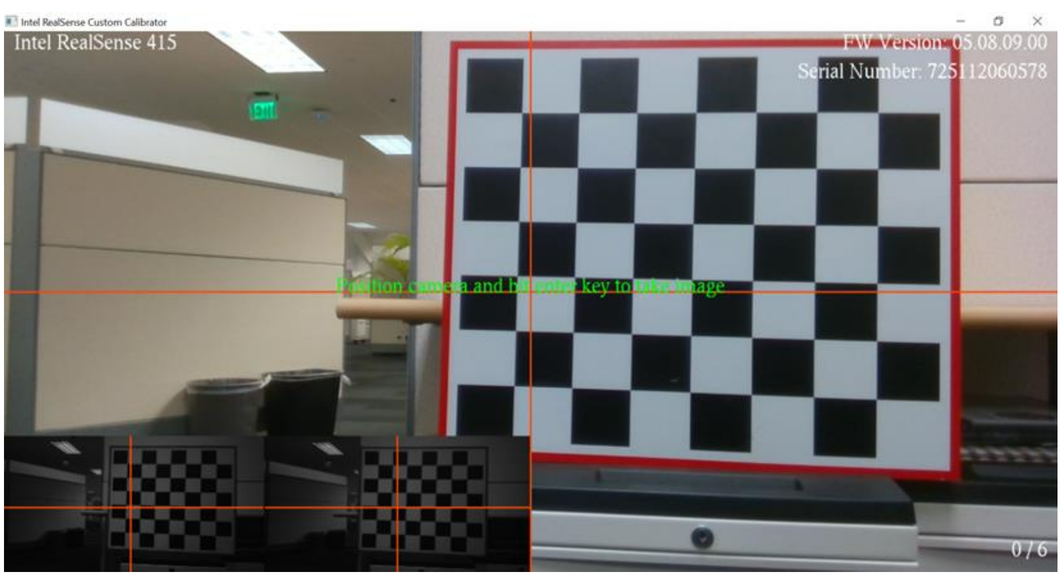
The calibration algorithm in the Custom Calibration Sample Application requires 6 images of the target from different viewpoints. This is the minimum number of images for simplicity. The application UI will guide the user to go through the image capturing process.

- **Viewpoints** - the choice of the viewpoint is critical to the accuracy of the calibration results. A general rule is that the target in these 6 images combined should cover as much as possible of the entire field of view and from different angles and distances from the target.

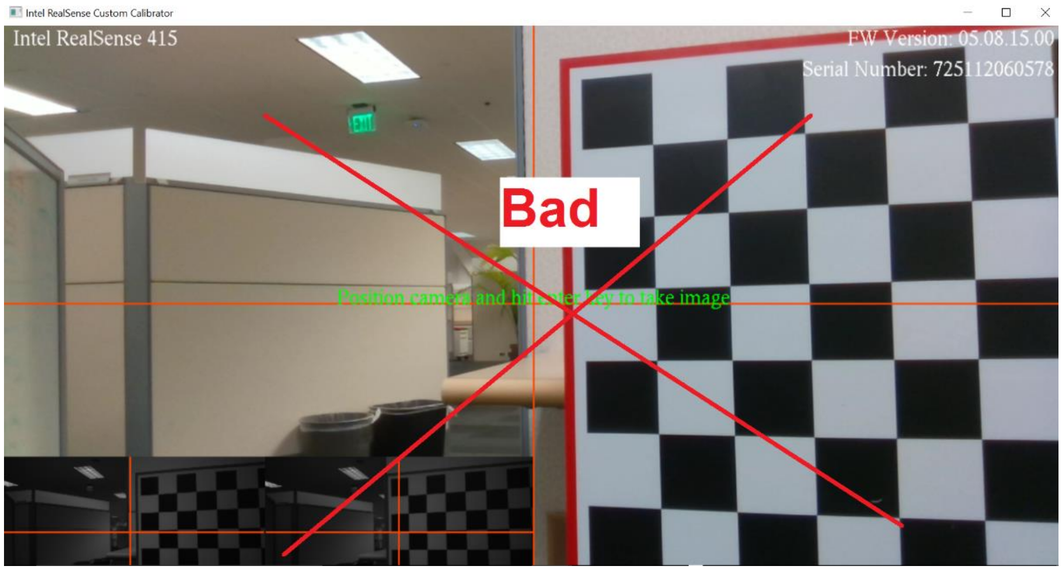


- **Cover whole target** - images from any of the viewpoints should cover the entire target in all imagers (Left, Right and RGB).

Good example – cover the entire target in all three imagers:



Bad example - cover only portion of the target in any of the three imagers:



Now, let’s capture the images.

4.3.2.1 Viewpoint #1 – Center Right

Adjust the tripod and position the device on the center right facing directly to the target.

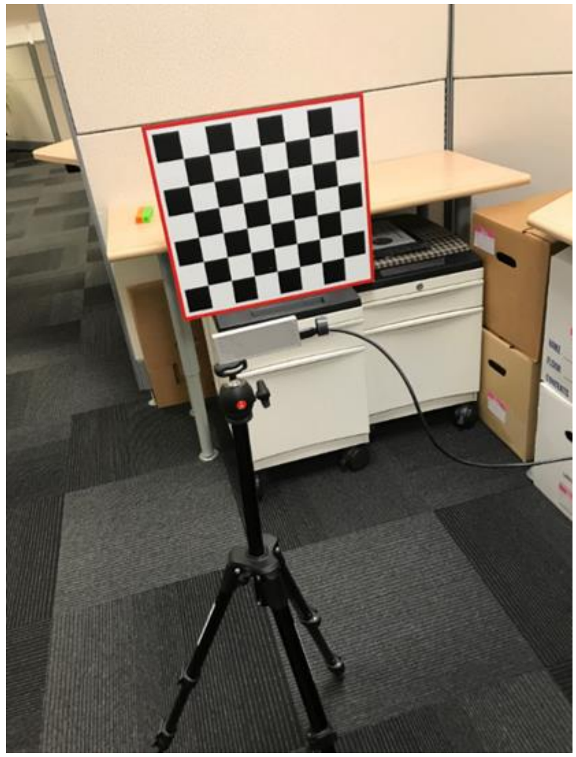


Figure 4-1 Center Right Position

The viewpoint should look like below with the target cover much of the right side the FOV.

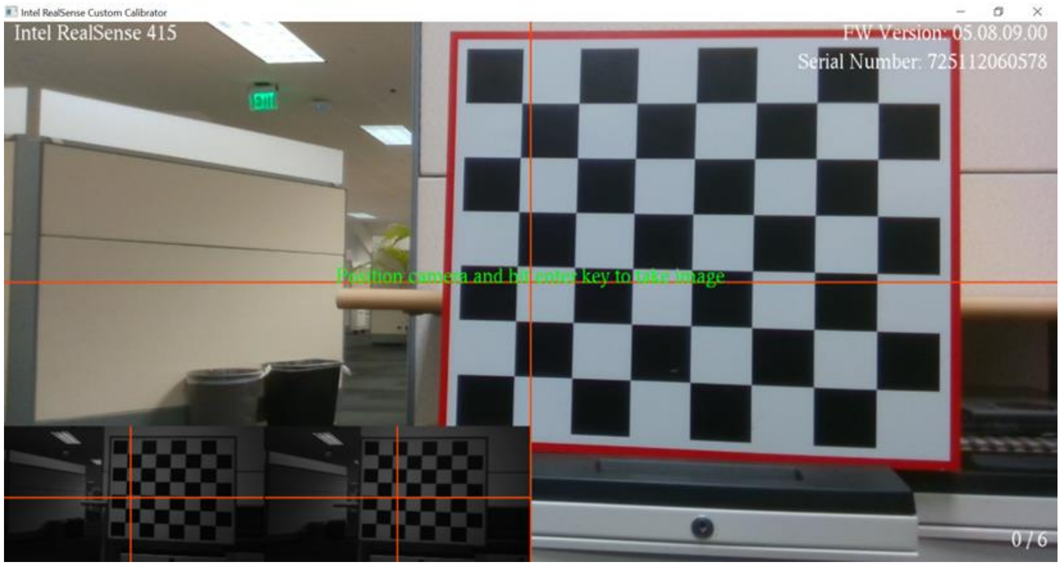


Figure 4-2 Viewpoint #1

Press Enter key to capture the image. If successful, the frame counter on the lower right corner will increase to 1/6 meaning 1 out of 6 images are captured. If it failed, a red error message will appear on screen and user is directed to retake a viewpoint.

4.3.2.2 Viewpoint #2 - Center Left

Move the device to the center left directly facing the target so the target covers much of the left portion of the FOV.

Figure 4-3 Center Right

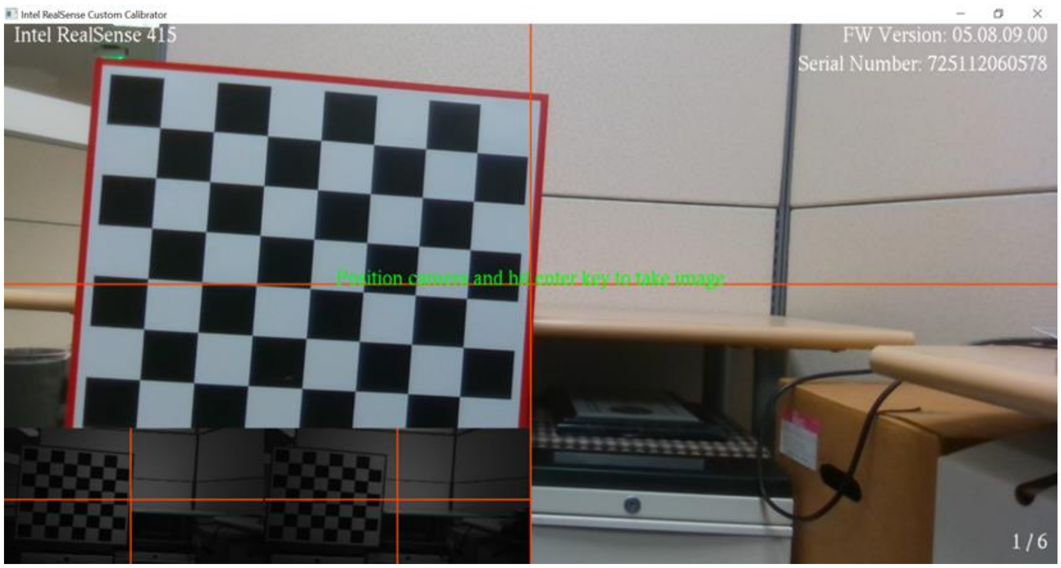


Figure 4-4 Viewpoint #2

Press Enter key to capture the image. If successful, the frame counter on the lower right corner will increase to 2/6 meaning 2 out of 6 images are captured. If it failed, a red error message will appear on screen and user is directed to retake a viewpoint.

4.3.2.3 Viewpoint #3 - Left

Move the device to the left of the camera facing the device at an angle. Use the viewpoint below for reference.

Figure 4-5 Left

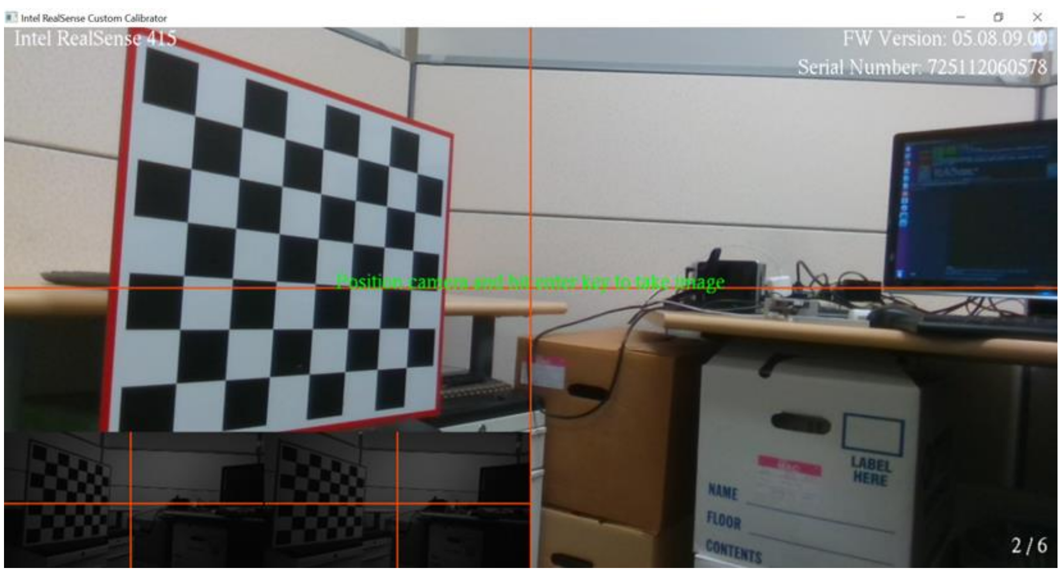


Figure 4-6 Viewpoint #3

Press Enter key to capture the image. If successful, the frame counter on the lower right corner will increase to 3/6 meaning 3 out of 6 images are captured. If it failed, a red error message will appear on screen and user is directed to retake a viewpoint.

4.3.2.4 Viewpoint #4 – Right

Move the device to the right facing the target at an angle. Use the viewpoint below for reference.

Figure 4-7 Right

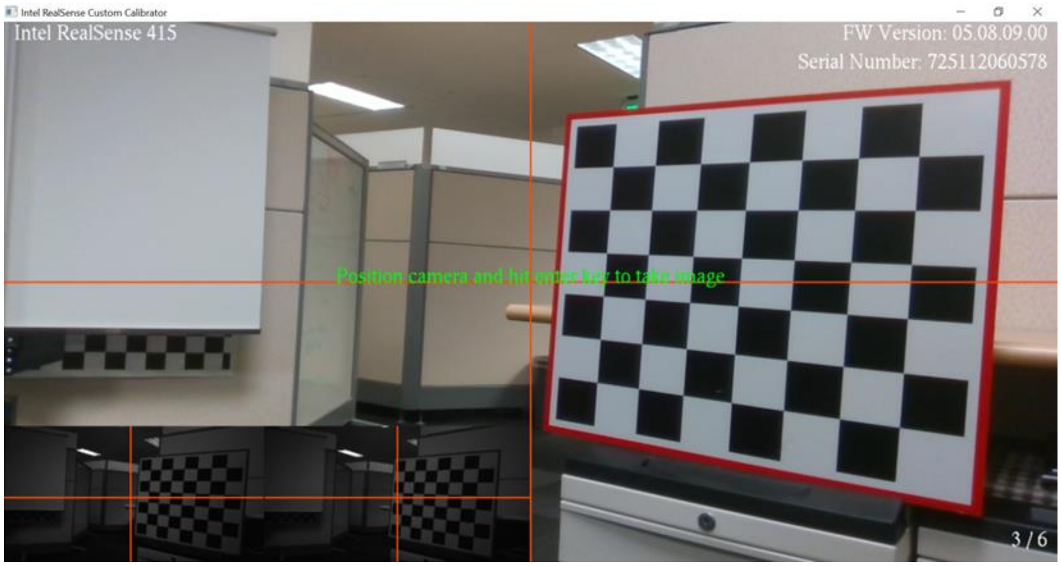


Figure 4-8 Viewpoint #4

Press Enter key to capture the image. If successful, the frame counter on the lower right corner will increase to 4/6 meaning 4 out of 6 images are captured. If it failed, a red error message will appear on screen and user is directed to retake a viewpoint.

4.3.2.5 Viewpoint #5 – Top Looking Down

Adjust the tripod so the device high enough to look down the target at an angle. Use the viewpoint below for reference.

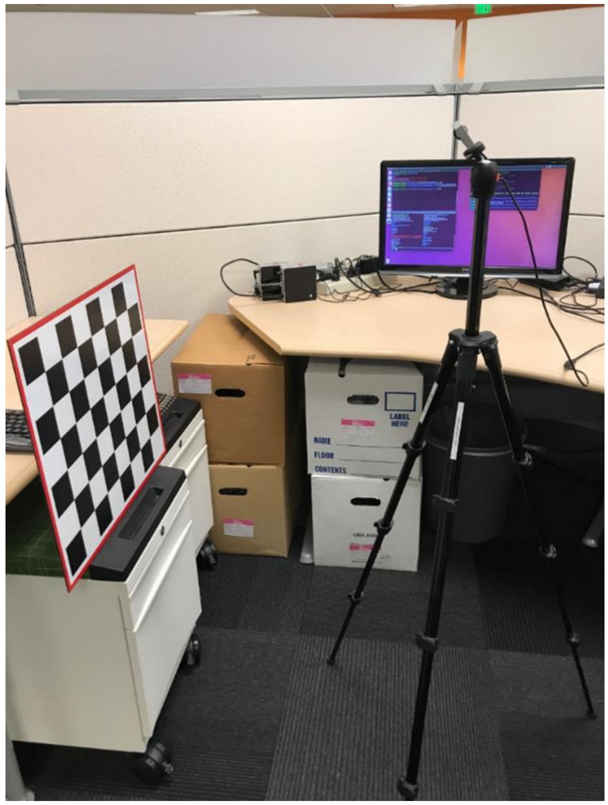


Figure 4-9 Top Looking Down

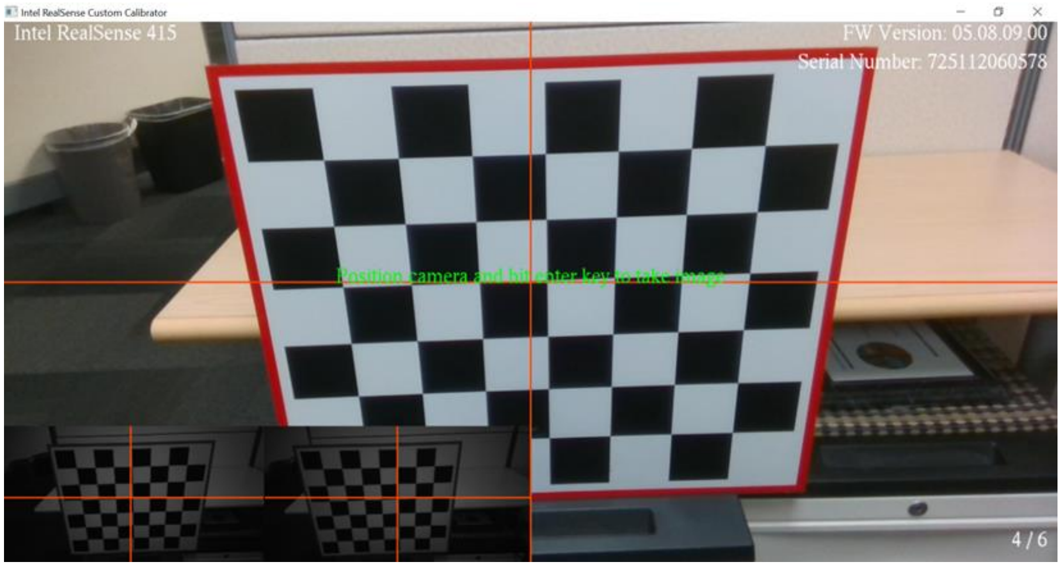


Figure 4-10 Viewpoint #5

Press Enter key to capture the image. If successful, the frame counter on the lower right corner will increase to 5/6 meaning 5 out of 6 images are captured. If it failed, a red error message will appear on screen and user is directed to retake a viewpoint.

4.3.2.6 Viewpoint #6 – Bottom Looking Up

Folding the tripod so that the device will be in a very low position looking up to the target. Use the viewpoint below for reference.

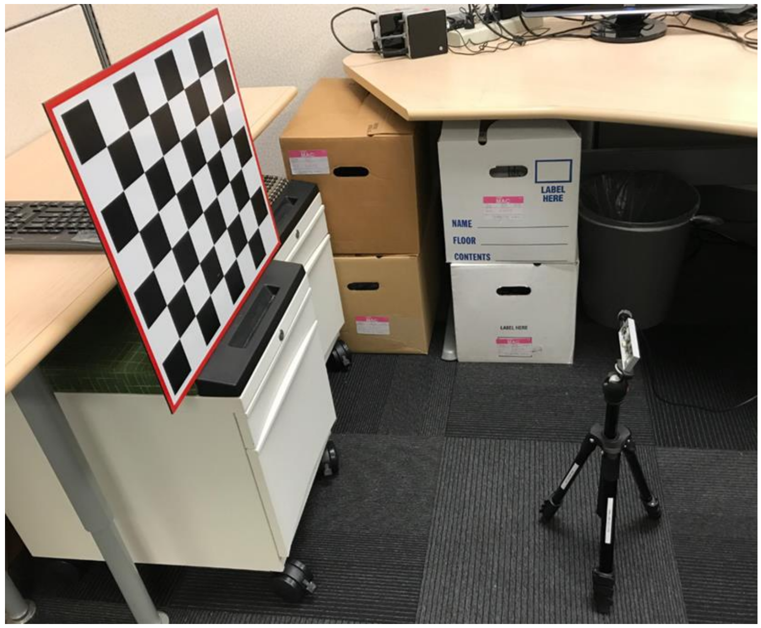


Figure 4-11 Bottom Looking Up

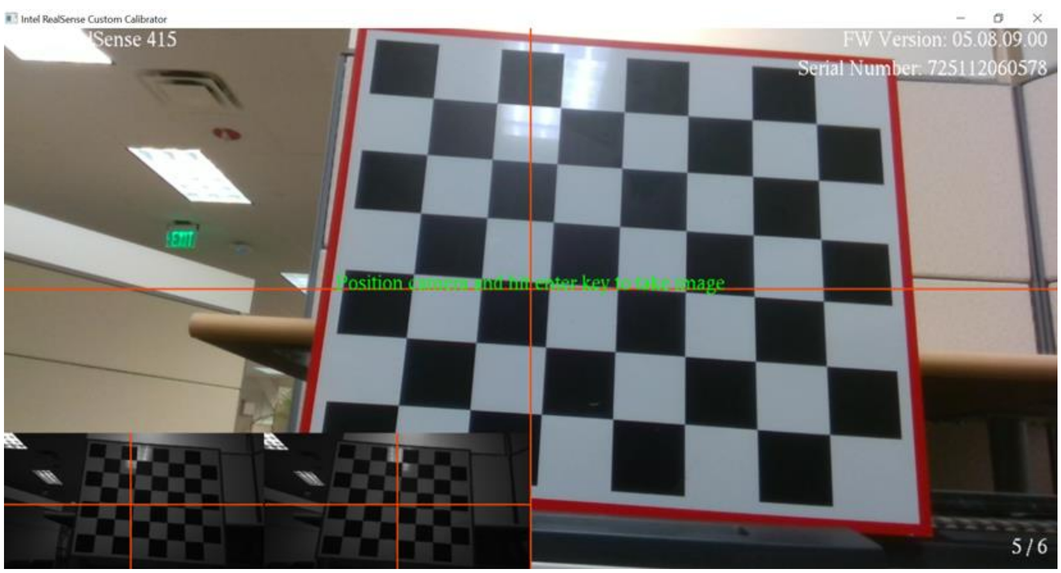


Figure 4-12 Viewpoint #6

Press Enter key to capture the image. If successful, the frame counter on the lower right corner will increase to 6/6 meaning 6 out of 6 images are captured. If it failed, a red error message will appear on screen and user is directed to retake a viewpoint.

4.4 Calibration Result

Once all 6 images captured, calibration will run and should finish very quickly. The results usually located under the CustomCalibrationSample\CustomResult folder with device serial number as the folder name. For example, CustomCalibrationSample \CustomResult\725112060578\DC1

6 RGB images:

colorImage001.png
colorImage002.png
colorImage003.png
colorImage004.png
colorImage005.png
colorImage006.png

6 left images:

leftImage001.png
leftImage002.png
leftImage003.png
leftImage004.png
leftImage005.png
leftImage006.png

Right RGB Images

rightImage001.png
rightImage002.png
rightImage003.png
rightImage004.png
rightImage005.png
rightImage006.png

Optimized calibration parameters in XML:

CalibrationParameters.xml

For example:


```xml
<?xml version="1.0"?>
<Config>
  <param name = "ResolutionLeftRight">
    <value>1920</value>
    <value>1080</value>
  </param>
  <param name = "FocalLengthLeft">
    <value>1378.69</value>
    <value>1379.13</value>
  </param>
  <param name = "PrincipalPointLeft">
    <value>965.562</value>
    <value>542.603</value>
  </param>
  <param name = "DistortionLeft">
```

```
  <value>0.09689</value>
  <value>-0.0235634</value>
  <value>-5.05513e-05</value>
  <value>0.000105855</value>
  <value>-0.640377</value>
</param>
<param name = "FocalLengthRight">
  <value>1389.55</value>
  <value>1390.1</value>
</param>
<param name = "PrincipalPointRight">
  <value>957.402</value>
  <value>553.108</value>
</param>
<param name = "DistortionRight">
  <value>0.123289</value>
  <value>-0.290911</value>
  <value>0.000149083</value>
  <value>0.000723527</value>
  <value>0.0992178</value>
</param>
<param name = "RotationLeftRight">
  <value>0.999983</value>
  <value>0.00150008</value>
  <value>-0.00558928</value>
  <value>-0.00150249</value>
  <value>0.999999</value>
  <value>-0.000428313</value>
  <value>0.00558863</value>
  <value>0.000436704</value>
  <value>0.999984</value>
</param>
<param name = "TranslationLeftRight">
  <value>-55.3888</value>
  <value>0.0448052</value>
  <value>1.52189</value>
</param>
<param name = "HasRGB">
  <value>1</value>
</param>
<param name = "ResolutionRGB">
  <value>1920</value>
  <value>1080</value>
</param>
<param name = "FocalLengthRGB">
  <value>1376.09</value>
  <value>1376.4</value>
</param>
<param name = "PrincipalPointRGB">
  <value>947.958</value>
  <value>531.068</value>
</param>
<param name = "DistortionRGB">
```

```
        <value>0.109862</value>
        <value>-0.122685</value>
        <value>-0.000453445</value>
        <value>-8.61456e-05</value>
        <value>-0.396171</value>
    </param>
    <param name = "RotationLeftRGB">
        <value>0.999994</value>
        <value>0.00346622</value>
        <value>0.000876088</value>
        <value>-0.00346642</value>
        <value>0.999994</value>
        <value>0.000222113</value>
        <value>-0.000875313</value>
        <value>-0.000225148</value>
        <value>1</value>
    </param>
    <param name = "TranslationLeftRGB">
        <value>14.6987</value>
        <value>-0.0644999</value>
        <value>0.448085</value>
    </param>
</Config>
```


4.5 Updating Results to Device

We will use Intel.Realsense.CustomRW to read the CalibrationParameters.xml and write the parameters to the device. Checking the depth quality before and after updating the calibration data on the device.

4.5.1 Depth Quality Check before Updating Calibration

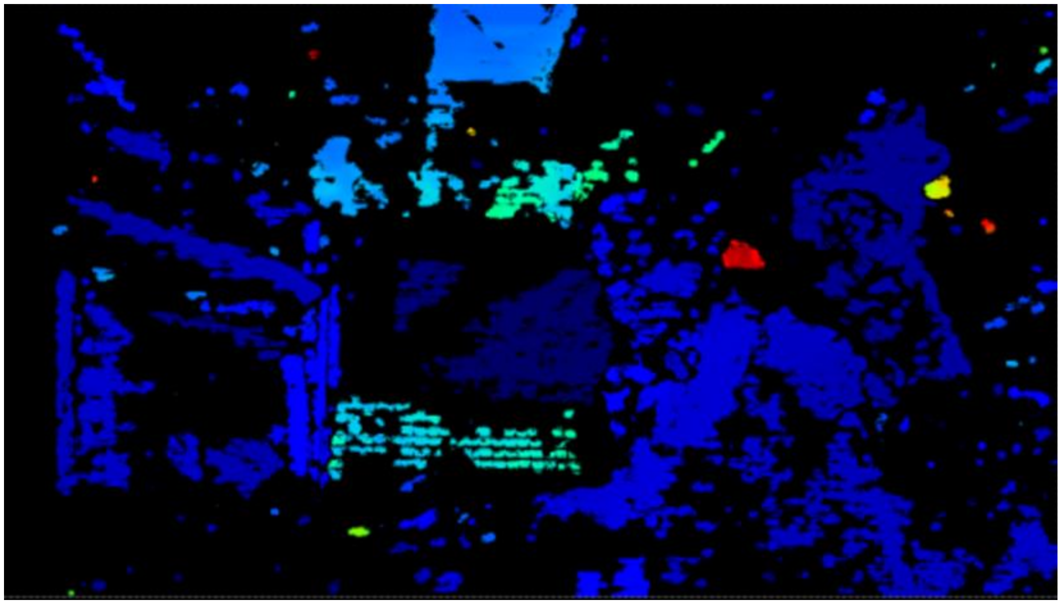


Figure 4-13 Depth Quality before Updating Calibration

4.5.2 Writing Optimized Calibration to Device

Run Intel.Realsense.CustomRW.exe tool to write the calibration result in XML to the device. The tool is usually located under C:\Program Files\Intel\CalibrationToolAPI\2.13.1.0\bin.

Dump the current parameters on the device into before.txt:

Intel.Realsense.CustomRW.exe –r > before.txt

Writing the parameters in the XML result file into device:

Intel.Realsense.CustomRW.exe –w -f CalibrationParameters.xml

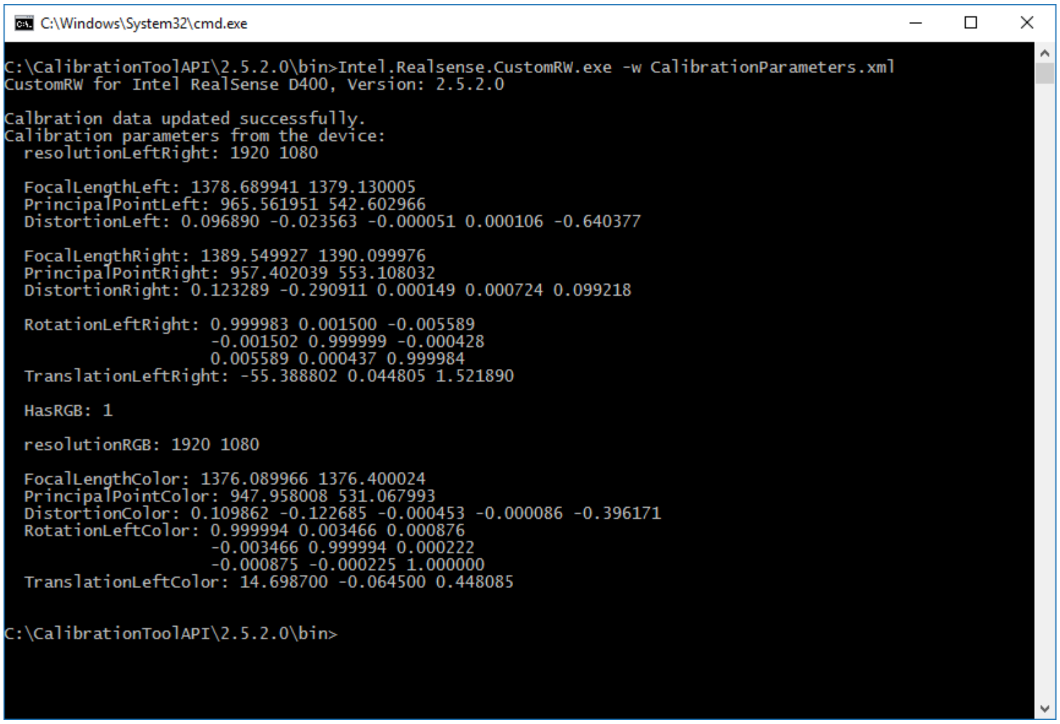


Figure 4-14 Updating Calibration Parameters to Device

Dump the parameters from device into after.txt:

Intel.Realsense.CustomRW –r > after.txt

Compare the parameters changed:

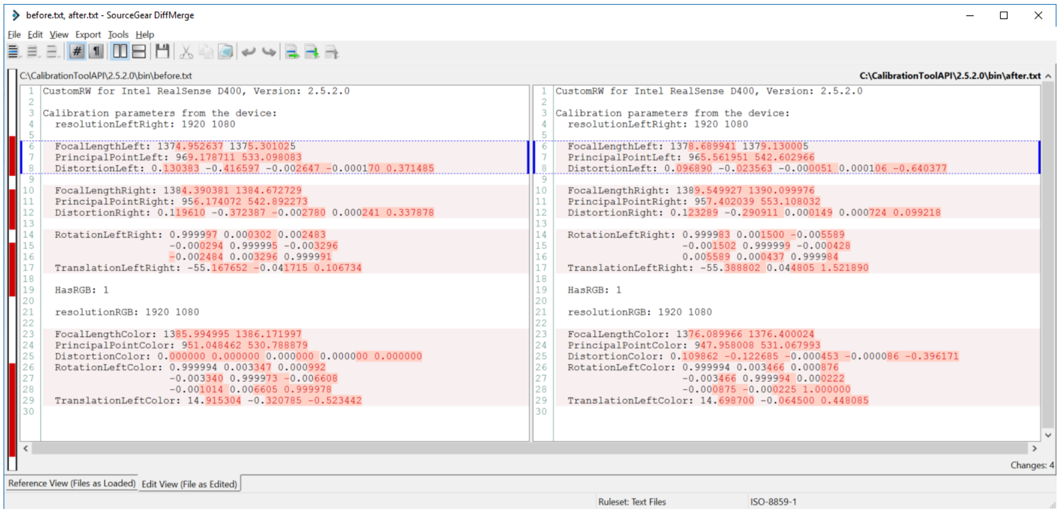
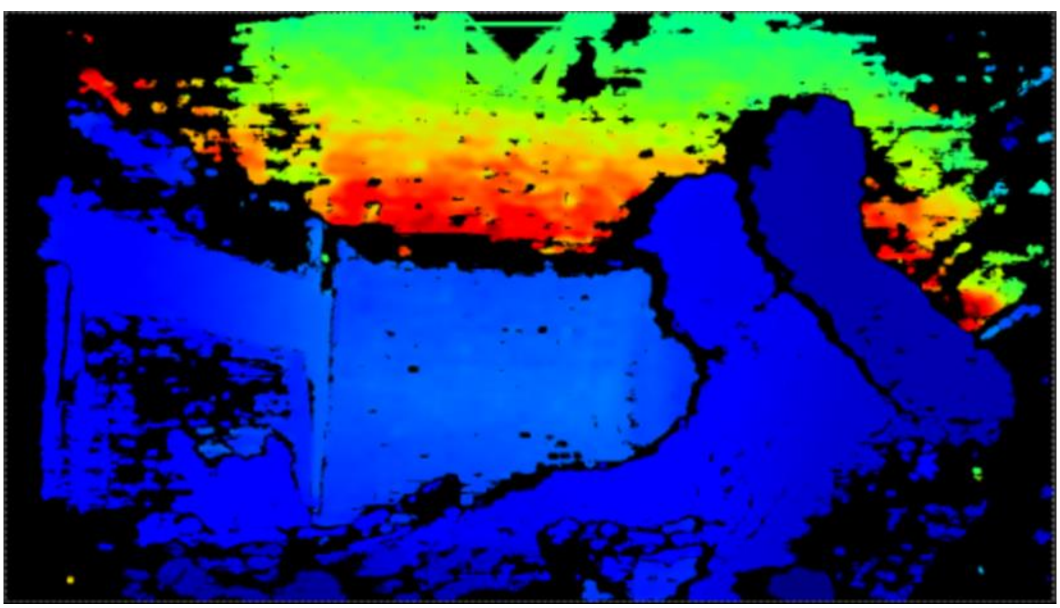


Figure 4-15 Calibration Parameter Change

4.5.3 Depth Quality Check after Updating Calibration



5 Developing Custom Calibration Application

This section demonstrates how to develop custom calibration application through key aspects of the sample app we used in *Calibrating Device with Custom Calibration Sample Application.* The sample app uses OpenCV algorithm as example.

The general process is to configure the Intel® RealSense™ device for calibration, capture images from the camera module, perform the desired calibration computations with OpenCV, and to write the new calibration parameters back to the cameras using routines from the Intel® RealSense™ calibration library.

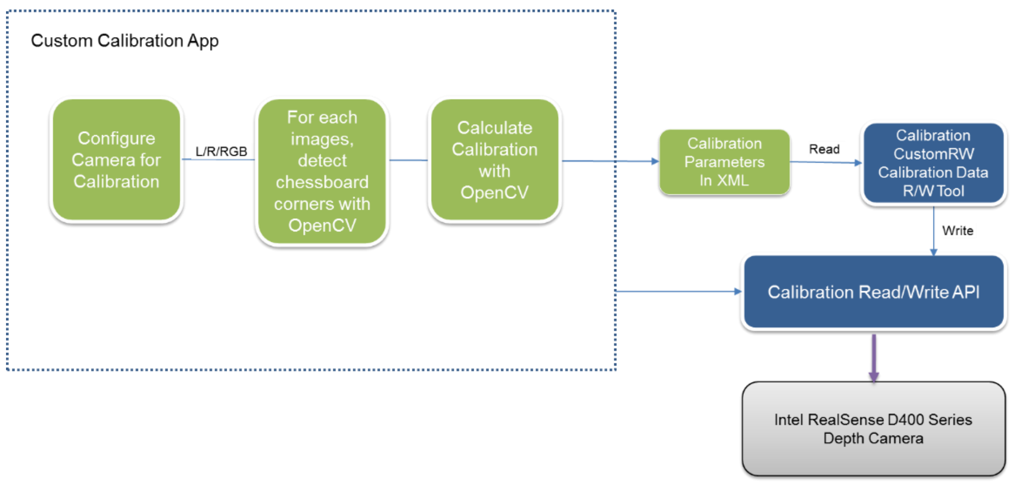


Figure 5-1 General Process for custom Calibration

5.1 Sample Application Source Code and Compile

The source code for Custom Calibration Sample Application is included in the Calibration API package as example. The packages are described in section 3.2.2 "Intel® RealSense™ Calibration Tool and API".

The following directory structure is related to the sample app:

```
CalibrationToolAPI
    |
    |-------- 2.13.1.0
    |          |----------- bin
    |          |             |------- DSDynamicCalibrationAPI.dll
```

```
|          |          |------- freeglut.dll
|          |          |------- realsense2.dll
|          |
|          |-------- Include
|          |          |------- DSDynamicCalibration.h
|          |          |------- DSOSUtils.h
|          |          |------- DSShared.h
|          |
|          |------------- lib
|          |          |------- DSDynamicCalibrationAPI.lib
|          |
|          |-------- librealsense
|          |          |------- include
|          |          |------- lib
|          |
|          |-------- examples
|          |          |------- CustomCalibration
|          |          |            |-------- 540x480_60mm.pdf
|          |          |            |-------- CalibrationManager.cpp
|          |          |            |-------- CalibrationManager.h
|          |          |            |-------- CustomCalibration.cpp
|          |          |            |-------- CustomCalibration.h
|          |          |            |-------- CustomCalibrationWrapper.cpp
|          |          |            |-------- CustomCalibrationWrapper.h
|          |          |            |-------- Rs400Dev.cpp
|          |          |            |-------- Rs400Dev.h
|          |          |            |-------- FileOp.h
|          |          |            |-------- Main.cpp
|          |          |            |-------- CustomCalibrationTest.vcxproj
|          |          |            |-------- CustomCalibrationTest.sln
|          |
|          |          |------- Common
|          |          |            |-------- CalibParamXmlWrite.h
|          |
|          |          |------- ThirdParty
|          |          |            |-------- glut
```

The sample app depends on a few third party libraries, including GLUT, LibRealSense, and OpenCV 3.3.1. GLUT is included under examples\ThirdParty\glut. LibRealSense is included under librealsense.

- **bin** contains the runtime libraries for Calibration API, GLUT, and LibRealSense.
- **Include** contains header files for Calibration API.
- **lib** contains Calibration API library.
- **librealsense** contains the header files and libraries for LibRealSense
- **examples** contains all Calibration API examples and related files. The CustomCalibration sample app source is under CustomCalibration folder.

OpenCV 3.3.1 is not included. To compile the CustomCalibration sample app, user will need to download sources from https://github.com/opencv/opencv/releases/tag/3.3.1, compile, and set it up so that the OpenCV header files and libraries is under CalibrationToolAPI\2.13.1.0 as below. OpenCV setup is discussed in section 3.2.4 "OpenCV 3.3.1" earlier in this document.

```
CalibrationToolAPI
    |
    |---- 2.13.1.0
    |        |------- OpenCV
    |        |          |------- OpenCV331
    |        |          |          |-------- include
    |        |          |          |          |--------opencv
    |        |          |          |          |          |-------- cv.h
    |        |          |          |          |          |-------- cv.hpp
    |        |          |          |          |          |-------- cvaux.h
    |        |          |          |          |          |-------- ... ...
    |        |          |          |          |
    |        |          |          |          |--------opencv2
    |        |          |          |          |          |-------- bioinspired
    |        |          |          |          |          |-------- calib3d
    |        |          |          |          |          |-------- core
    |        |          |          |          |          |-------- ... ...
    |        |          |          |
    |        |          |          |-------- x64
    |        |          |          |          |------- vc14
    |        |          |          |          |          |-------staticlib
    |        |          |          |          |          |          |-------- ittnotify.lib
    |        |          |          |          |          |          |-------- ittnotifyd.lib
    |        |          |          |          |          |          |-------- opencv_calib3d331.lib
    |        |          |          |          |          |          |-------- opencv_calib3d331d.lib
    |        |          |          |          |          |          |-------- opencv_core331.lib
    |        |          |          |          |          |          |-------- opencv_core331d.lib
    |        |          |          |          |          |          |-------- opencv_features2d331.lib
    |        |          |          |          |          |          |-------- opencv_features2d331d.lib
    |        |          |          |          |          |          |-------- opencv_flann331.lib
    |        |          |          |          |          |          |-------- opencv_flann331d.lib
    |        |          |          |          |          |          |-------- opencv_imgproc331.lib
    |        |          |          |          |          |          |-------- opencv_imgproc331d.lib
    |        |          |          |          |          |          |-------- zlib.lib
    |        |          |          |          |          |          |-------- zlibd.lib
```

To build the project, open the **CustomCalibrationTest.sln** under examples\CustomCalibration with **Visual Studio 2015 Update 3** and build "Release" "x64".

5.2 Calibration Mode Camera Configuration

For calibration, the camera device needs to be configured to capture calibration images for both depth and RGB camera using LibRealSense. Basic device operations are defined in Rs400Dev.h and Rs400Dev.cpp. The Configurations for the device is defined in CalibrationManager.h and CalibrationManager.cpp.

5.2.1 Emitter

The emitter should be turned off during calibration to avoid interference.

Sample code in Rs400Device:

```
m_rsDevice->EnableEmitter(0.0f);
```

5.2.2 Auto Exposure

Auto exposure should be turn on and the AE setpoint be adjusted according to lighting condition. In indoor room lighting, a setpoint value around 500 – 800 should be sufficient. In outdoor, 1200 or higher.

```
m_rsDevice->EnableAutoExposure(1.0f);
if (m_cameraInfo.isWide)
        m_rsDevice->SetAeControl(800);
else
        m_rsDevice->SetAeControl(500);
```

5.2.3 Streaming Resolution and Format

Calibration frame resolutions and formats are described in *Table 2-1 Frame Formats Used in Custom Calibration, for example, in this sample, or D415 device, the resolution is 1920x1080 with frame rate of 15 fps. The L/R format is Y16 and the RGB format is YUY2.*

```
m_rsDevice->SetMediaMode(m_width, m_height, m_fps, m_rgbWidth, m_rgbHeight, m_cameraInfo.isRGB);

m_rsDevice->StartCapture([&](const void *leftImage, const void *rightImage,
        const void *colorImage, const uint64_t timeStamp)
```

5.2.4 Image Captures

The sample app captures 6 images. More images from different positions may improve accurate. The number of images is defined in CalibrationManager.h:

```
const int NUM_SHOTS = 6;
```

5.2.5 Demosaic Left/Right Images for ASR / PSR SKUs

For ASR/PSR SKUs, left and right images need to be **demosaiced**.

5.3 Detecting the Chessboard in an Image with OpenCV

For each of the captured images, find the chessboard corners with OpenCV findChessboardCorners.

```
#include <opencv2/opencv.hpp>
#include <opencv2/core/core.hpp>
#include <opencv2/calib3d.hpp>
#include <vector>

using namespace std;
using namespace cv;

bool DetectChessboard(const Mat& image, const Size& chessboardSize, vector<Point2f>&
corners)
{
        // Find chessboard corners
        if (!findChessboardCorners(image, chessboardSize, corners,
CALIB_CB_ADAPTIVE_THRESH | CALIB_CB_NORMALIZE_IMAGE | CALIB_CB_FILTER_QUADS))
                return false;

        // Refine them
        cornerSubPix(image, corners, Size(11, 11), Size(-1, -1),
TermCriteria(CV_TERMCRIT_EPS | CV_TERMCRIT_ITER, 30, 0.1));
        return true;
}
```

5.4 Calculating Depth Camera Calibration with OpenCV

```
#include <opencv2/opencv.hpp>
#include <opencv2/core/core.hpp>
#include <opencv2/calib3d.hpp>
#include <vector>

using namespace std;
using namespace cv;

static void CreateCorners3D(const Size& chessboardSize, float checkerSize, size_t
numImages, vector<vector<Point3f> >& corners3D)
{
        corners3D.resize(numImages);
        corners3D[0].resize(chessboardSize.width * chessboardSize.height);

        for (int i = 0; i < chessboardSize.height; i++)
                for (int j = 0; j < chessboardSize.width; j++)
```

```
                        corners3D[0][i * chessboardSize.width + j] = Point3f(j *
checkerSize, i * checkerSize, 0.0f);

        for (size_t i = 1; i < numImages; i++)
                        corners3D[i] = corners3D[0];
}

double CalibrateDepthCamera(const vector<vector<Point2f> >& cornersLeft, const
vector<vector<Point2f> >& cornersRight, const Size& chessboardSize, float checkerSize,
const Size& imageSizeLR, Mat& Kl, Mat& Dl, Mat& Kr, Mat& Dr, Mat& Rlr, Mat& Tlr)
{
        CV_Assert(cornersLeft.size() != 0 && cornersLeft.size() == cornersRight.size());
        CV_Assert(checkerSize > 0.0f);

        // Create 3D prototype of the corners
        vector<vector<Point3f> > corners3D;
        CreateCorners3D(chessboardSize, checkerSize, cornersLeft.size(), corners3D);

        // Calibrate each camera individualy
        calibrateCamera(corners3D, cornersLeft, imageSizeLR, Kl, Dl, noArray(),
noArray(), CV_CALIB_FIX_ASPECT_RATIO, TermCriteria(TermCriteria::COUNT +
TermCriteria::EPS, 60, DBL_EPSILON));
        calibrateCamera(corners3D, cornersRight, imageSizeLR, Kr, Dr, noArray(),
noArray(), CV_CALIB_FIX_ASPECT_RATIO, TermCriteria(TermCriteria::COUNT +
TermCriteria::EPS, 60, DBL_EPSILON));

        // Calibrate the extrinsics between them
        return stereoCalibrate(corners3D, cornersLeft, cornersRight, Kl, Dl, Kr, Dr,
Size(-1, -1), Rlr, Tlr, noArray(), noArray(), CV_CALIB_FIX_INTRINSIC |
CV_CALIB_USE_INTRINSIC_GUESS, TermCriteria(TermCriteria::COUNT + TermCriteria::EPS, 300,
DBL_EPSILON));
}
```

5.5 Calculating RGB Camera Calibration with OpenCV

Note: Assumes good depth camera calibration

```
double CalibrateRGBCamera(const vector<vector<Point2f> >& cornersLeft, const
vector<vector<Point2f> >& cornersRGB, const Size& chessboardSize, float checkerSize,
const Size& imageSizeRGB, const Mat& Kl, const Mat& Dl, Mat& Kc, Mat& Dc, Mat& Rlc, Mat&
Tlc)
{
        CV_Assert(cornersLeft.size() != 0 && cornersLeft.size() == cornersRGB.size());
        CV_Assert(checkerSize > 0.0f);

        // Create 3D prototype of the corners
        vector<vector<Point3f> > corners3D;
        CreateCorners3D(chessboardSize, checkerSize, cornersLeft.size(), corners3D);

        // Calibrate RGB camera
        calibrateCamera(corners3D, cornersRGB, imageSizeRGB, Kc, Dc, noArray(),
noArray(), CV_CALIB_FIX_ASPECT_RATIO, TermCriteria(TermCriteria::COUNT +
TermCriteria::EPS, 60, DBL_EPSILON));

        // Calibrate the extrinsics between them
        return stereoCalibrate(corners3D, cornersLeft, cornersRGB, Kl, Dl, Kc, Dc, Size(-
1, -1), Rlc, Tlc, noArray(), noArray(), CV_CALIB_FIX_INTRINSIC |
CV_CALIB_USE_INTRINSIC_GUESS, TermCriteria(TermCriteria::COUNT + TermCriteria::EPS, 300,
DBL_EPSILON));
```

```
}
```

5.6 Calculating RGB Camera Calibration Extrinsics with OpenCV

Note: Assumes good depth camera calibration and intrinsics for the RGB camera.

The **`CustomCalibration.h`** header file in the sample code contained the following unimplemented prototype:

```
double RecalibrateRGBCamera(const std::vector<std::vector<cv::Point2f> >& cornersLeft,
const std::vector<std::vector<cv::Point2f> >& cornersRGB, const cv::Size& chessboardSize,
float checkerSize, const cv::Mat& Kl, const cv::Mat& Dl, const cv::Mat& Kc, const
cv::Mat& Dc, cv::Mat& Rlc, cv::Mat& Tlc);
```

5.7 Writing Calibration Parameters

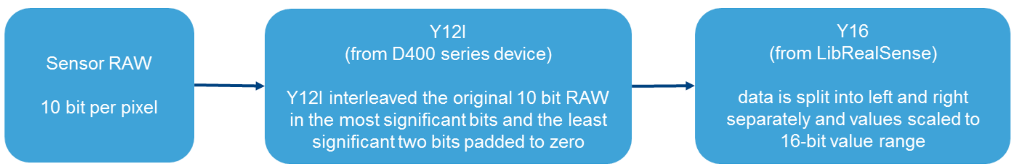
A user custom calibration app can choose one of the two approaches to update the results to the device:

- To link to the WriteCustomCalibrationParameters and ReadCalibrationParameters and write directly to the device through the APIs.
- To write the results into a parameter XML file and then use CustomRW to read/write the parameters to the device.

Custom Calibration Sample Application write the results into a parameter XML file and use CustomRW to update the calibration parameters to the device.

6 Appendix: Unrectified Left/Right Image Formats for Calibration

D400 series devices stream unrectified frames from left and right imagers in advanced mode. These streams are usually used in calibrating the devices. Y12I is the native format from the hardware. If users access the streams through LibRealsense, these unrectified frames are exposed in Y16 format.



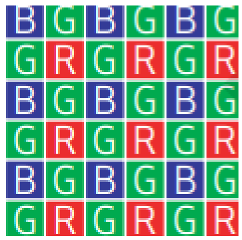
6.1 Unrectified Calibration Format

Both Y12I and Y16 are unrectified. In Y12I, the left and right frames are interleaved in the same file in 3 bytes every two pixels format. In Y16, the left and right frames are separated buffers and each in two bytes per pixel format.

Table 6-1. Left/Right Unrectified Calibration Image Formats

Device	Sensor	Unrectified Frame Resolution	From Device HW	From LibRealsense	Note
D400, D410, D415	Bayer pattern	1920x1080	Y12I	Y16	Data is in BG/GR Bayer pattern. User will need to demosaic the image before using in calibration.
D420, D430, D435, D435i, D435f, D455, D457	Monochrome	1280x800	Y12I	Y16	Data is monochrom. No need to demosaic.

On devices with regular lens, for example, D400/D410/D415, the left and right imager sensors are colored and data is in BG/GR bayer pattern. User will need to demosaic the data before using them in their calibration algorithms.



On devices with wide angle lens, for example, D420, D430, D435, D435i, D435f, D455, and D457, the left and right imager sensors are monochrome. Demosaic is not needed.

6.2 Y12I Format

The device outputs the unrectified frames in Y12I format with left and right images interleaved in the same frame. This mode interlaces 12 bits of data from the left imager and 12 bits of data from the right imager as described below:

Table 6-2 Y12I Format

<table>
<tr><td>7</td><td>6</td><td>5</td><td>4</td><td>3</td><td>2</td><td>1</td><td>0</td><td>7</td><td>6</td><td>5</td><td>4</td><td>3</td><td>2</td><td>1</td><td>0</td><td>7</td><td>6</td><td>5</td><td>4</td><td>3</td><td>2</td><td>1</td><td>0</td><td>7</td><td>6</td><td>5</td><td>4</td><td>3</td><td>2</td><td>1</td><td>0</td></tr>
<tr><td colspan="8">RY0 [0..7]</td><td colspan="4">LY0 [0..3]</td><td colspan="4">RY0 [8..11]</td><td colspan="8">LY0 [4..11]</td><td colspan="8">RY1 [0..7]</td></tr>
<tr><td colspan="4">LY1 [0..3]</td><td colspan="4">RY1 [0..3]</td><td colspan="8">LY1 [4..11]</td><td colspan="8">RY2 [0..7]</td><td colspan="4">LY2[0..3]</td><td colspan="4">RY2 [8..11]</td></tr>
<tr><td colspan="8">LY2 [4..11]</td><td colspan="8">RY3 [0..7]</td><td colspan="4">LY3 [0..3]</td><td colspan="4">RY3 [8..11]</td><td colspan="8">LY3 [4..11]</td></tr>
</table>

Y12I data is 12-bit per pixel.

6.3 Y16 Format

Librealsense outputs the unrectified calibration frames in Y16 format. Each pixel is represented by 16-bits of intensity or bayer pattern data from the left or right imagers. The data is scaled to the full 16-bit value range. The organization of the pixels in the image buffer is from left to right and top down, i.e, the first 16 bits of the image buffer corresponds to the first pixel of the first line of the image and the second 16 bits represent the second pixel, etc.

Table 6-3 Y16 Format

<table>
<tr><td>15</td><td>14</td><td>13</td><td>12</td><td>11</td><td>10</td><td>9</td><td>8</td><td>7</td><td>6</td><td>5</td><td>4</td><td>3</td><td>2</td><td>1</td><td>0</td><td>15</td><td>14</td><td>13</td><td>12</td><td>11</td><td>10</td><td>9</td><td>8</td><td>7</td><td>6</td><td>5</td><td>4</td><td>3</td><td>2</td><td>1</td><td>0</td></tr>
<tr><td colspan="16">Y0 [0..15]</td><td colspan="16">Y1 [0..15]</td></tr>
</table>

Y16 data is 16-bit per pixel and is scaled to the full 16-bit 0 – 65535 range.

7 Appendix: Calibrating Device with 3rd Party RGB Sensor

Intel provided calibration tools, like OEM Calibration, as well as the sample calibration tool in this document, only supports calibrating RGB sensor comes with the Intel® RealSense™ D400 series cameras. In some cases, customer products have non-Intel 3rd party RGB sensor and would like to calibrate it along with the Intel depth sensor.

Intel firmware and LibRealsense do not support the non-Intel 3rd party RGB sensor, however, user still can calibrate it so the images from 3rd RGB sensor can be aligned with the depth images from Intel® RealSense™ D400 series modules.

7.1 Calibration with Rectified Left Sensor

The Intel® RealSense™ D400 series devices use the left sensor as reference. Rectified left IR image is aligned with the depth. The left and right IR Y8 format are rectified.

If depth on the device is not calibrated, calibrate it first, either with Intel OEM Calibration tool or with user custom algo as illurstrated in this document. Then, calibrate the non-Intel 3rd party RGB sensor with the rectified Y8 left images.

The disadvantage of this approach is that it requires capturing images in two separate calibration passes: first unrectified Y16 left and right images to calibrate the depth sensor, then rectified Y8 left images and unrectified RGB images to calibrate the RGB sensor.

7.2 Calibration with Unrectified Left/Right Images

In cases where user would like to capture a single set of images to calibrate the depth and non-Intel 3rd party RGB sensor, they can utilize similar approach as illustrated in the sample calibration app in this document, i.e., calibrate with the unrectified Y16 left and right images and the unrectified images from the 3rd party RGB sensor.

Assume the calibration result is as follows in a test.xml file:


```
<?xml version="1.0"?>
<Config>
  <param name = "ResolutionLeftRight">
    <value>1920</value>
    <value>1080</value>
  </param>
  <param name = "FocalLengthLeft">
    <value>1374.09</value>
    <value>1373.27</value>
  </param>
  <param name = "PrincipalPointLeft">
    <value>965.852</value>
    <value>545.399</value>
  </param>
  <param name = "DistortionLeft">
    <value>0.147338</value>
```

<value>-0.501116</value>
<value>-0.00132364</value>
<value>0.000331959</value>
<value>0.464562</value>
</param>
<param name = "FocalLengthRight">
<value>1369.71</value>
<value>1368.89</value>
</param>
<param name = "PrincipalPointRight">
<value>974.997</value>
<value>548.52</value>
</param>
<param name = "DistortionRight">
<value>0.152532</value>
<value>-0.512907</value>
<value>-0.000651227</value>
<value>-0.00223614</value>
<value>0.482976</value>
</param>
<param name = "RotationLeftRight">
<value>0.999988</value>
<value>-0.0038831</value>
<value>0.00313714</value>
<value>0.00389059</value>
<value>0.99999</value>
<value>-0.00238443</value>
<value>-0.00312785</value>
<value>0.00239661</value>
<value>0.999992</value>
</param>
<param name = "TranslationLeftRight">
<value>-54.9355</value>
<value>-0.184512</value>
<value>0.362117</value>
</param>
<param name = "HasRGB">
<value>1</value>
</param>
<param name = "ResolutionRGB">
<value>1920</value>
<value>1080</value>
</param>
<param name = "FocalLengthRGB">
<value>1386.99</value>
<value>1386.58</value>
</param>
<param name = "PrincipalPointRGB">
<value>949.827</value>
<value>544.798</value>
</param>
<param name = "DistortionRGB">
<value>0</value>
<value>0</value>
<value>0</value>
<value>0</value>
<value>0</value>
</param>
<param name = "RotationLeftRGB">
<value>0.999995</value>

```
    <value>-0.000964127</value>
    <value>0.00308445</value>
    <value>0.000979274</value>
    <value>0.999987</value>
    <value>-0.00491298</value>
    <value>-0.00307968</value>
    <value>0.00491597</value>
    <value>0.999983</value>
  </param>
  <param name = "TranslationLeftRGB">
    <value>14.7957</value>
    <value>0.124071</value>
    <value>-0.505658</value>
  </param>
</Config>
```

The calibration results can be updated to the Intel® RealSense™ D400 series module, D410, for example, with the Intel.RealSense.CustomRW tool. Since the modules does not come with an Intel RGB sensor, by default, the tool does not write the RGB calibration data. The -rgb option instructs the tool to write the 3rd party RGB calibration data even though the module does not have Intel RGB sensor.

```
Intel.RealSense.CustomRW.exe -w -rgb -f test.xml
```

Once the calibration result is updated, the depth calibration data will be used automatically by the hardware to rectify the left and right images and generate depth stream. However, the calibration data from the 3rd party RGB will not be used automatically.

During rectification, rotation is applied to both left and right images and there is a transformation between the unrectified and rectified left images. The RGB calibration obtained here is against the unrectified left images, so in order to align the RGB image with depth, the RGB extrinsic needs adjustment to compensate the transformation between the unrectified Y16 and rectified Y8 images.

The option -ex is provided in Intel.RealSense.CustomRW to extract the additional transformation information:

```
Intel.RealSense.CustomRW.exe -r -rgb -ex

World to left rotation matrix (inverse rotation of the left camera in rectified coordinate system):
 0.999994  0.000536  0.003463
 -0.000540  0.999999  0.001191
 -0.003462  -0.001192  0.999993

World to right rotation matrix (inverse rotation of the right camera in rectified coordinate system):
 0.999973  -0.003351  0.006595
 0.003359  0.999994  -0.001180
 -0.006591  0.001203  0.999978

RGB camera intrinsics:
width: 1920
height: 1080
principal point ppx: 949.827026
principal point ppy: 544.797974
focal length fx: 1386.989990
focal length fy: 1386.579956
```

distortion coefficients: 0.0000000000 0.0000000000 0.0000000000 0.0000000000 0.0000000000
distortion model: BROWN CONRADY

RGB extrinsics in rectified coordinate system:
Rotation Matrix:
0.9999787211 -0.0004317180 0.0065463032
0.0004560712 0.9999925494 -0.0037190265
-0.0065446557 0.0037219268 0.9999715090

Translation Vector:
14.7987508774 0.1158004776 -0.4092478752

The above extra information including world to left rotation matrix, world to right rotation matrix, and RGB extrinsics in rectified coordinate system can be used in user app to align the 3rd party RGB images to depth.