1. Report the calibration matrix for the camera chosen and verify (using an example) the same.

The calibration matrix, according to MATLAB's camera calibration toolbox result for the oak-d LITE camera is as follows (Please refer to appendix I for the calibration footage):

$$K = \begin{bmatrix} f_x & 0 & o_x \\ 0 & f_y & o_y \\ 0 & 0 & 1 \end{bmatrix} \tag{1}$$

```
Focal length (pixels):   [ 1434.4141 +/- 6.8278     1430.6807 +/- 6.7548  ]
Principal point (pixels):[  949.7754 +/- 1.6231      541.4124 +/- 0.8631  ]
```

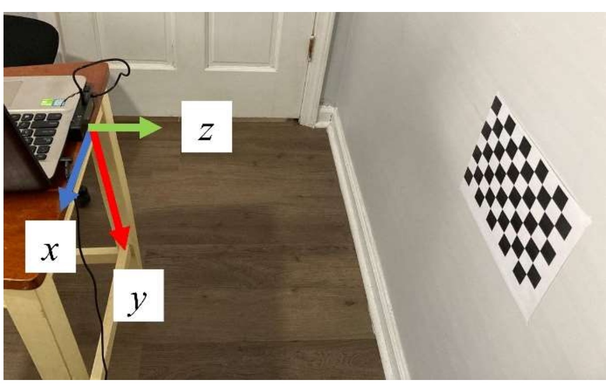
According to Eq. 1 and the results, the calibration matrix would be estimated as:

$$K = \begin{bmatrix} 1434.41 & 0 & 949.77 \\ 0 & 1430.68 & 541.41 \\ 0 & 0 & 1 \end{bmatrix}$$

To verify this calibration matrix, I perform perspective projection. I will take a picture of an object, consider some points of it, and compare resulting pixel coordinates of pre-multiplying the calibration matrix (K) with the points' coordinates with respect to camera (X_c), with the respective pixel coordinates in the image. In short, I will be testing the results of the following equation for multiple points, by comparing them to true pixel coordinates in the image.

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} \equiv \begin{bmatrix} \tilde{u} \\ \tilde{v} \\ \tilde{w} \end{bmatrix} = K \begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix} \tag{2}$$

First, in order to obtain X_c, I will define the camera coordinate system (the axes). Here's the experimentation setup:



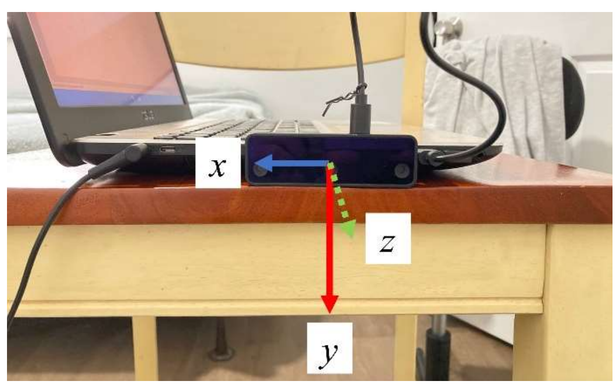


Figure 1. Experiment's setup. Camera's coordinate system (the axes)

Second, I will take an image of an object which I can easily measure coordinates of my points of choice. A checkerboard with square side length of 26mm is my choice. I will place the checkerboard in front of the camera such that the camera coordinate frame's principal point is aligned with the top left corner of its second square from the top and left. Figure 2 shows how the checkerboard is aligned with the camera coordinate system's axes. The camera is placed 68.5cm (685mm) from the object, thus, every point on the checkerboard will have $z_c = 685$.

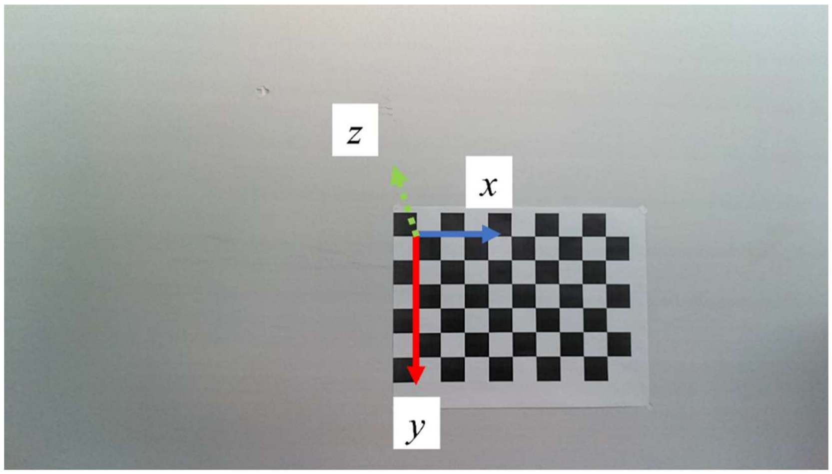


Figure 2. Alignment of the reference object to camera coordinate system axes

EXAMPLE 1: A point at (52, 52, 685) at camera coordinate frame

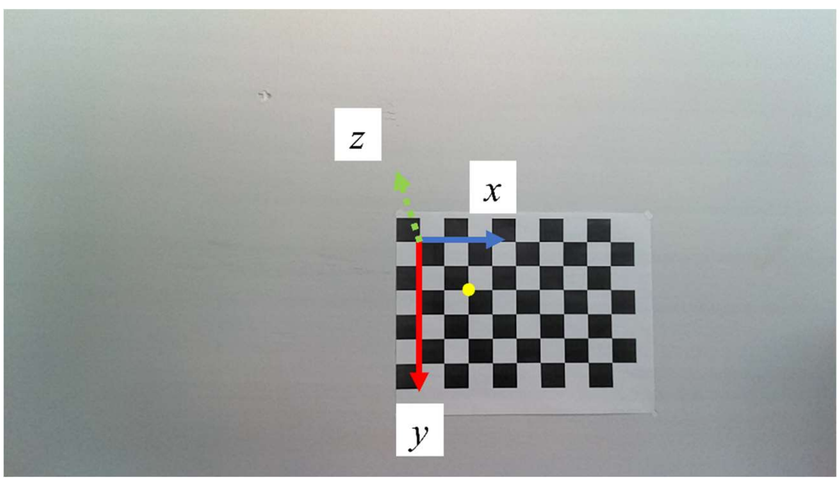


Figure 3. A reference point at (52, 52, 685) – The yellow dot

$$\begin{bmatrix} 1434.41 & 0 & 949.77 \\ 0 & 1430.68 & 541.41 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 52 \\ 52 \\ 685 \end{bmatrix} = \begin{bmatrix} 1434.41 * 52 + 0 * 52 + 949.77 * 685 \\ 0 * 52 + 1430.68 * 52 + 541.41 * 685 \\ 0 * 52 + 0 * 52 + 1 * 685 \end{bmatrix} = \begin{bmatrix} 725181.77 \\ 445261.21 \\ 685 \end{bmatrix} \equiv \begin{bmatrix} 1058.66 \\ 650.01 \\ 1 \end{bmatrix}$$

This point has true pixel coordinates of $(1071, 648)$. Comparing it with the perspective projection equation's result, and neglecting small differences due to measurement errors, the calibration matrix is verified. $(1058.66, 650.01) \cong (1071, 648)$. Figure 4 shows both the calculated point coordinates and its true pixel coordinates.

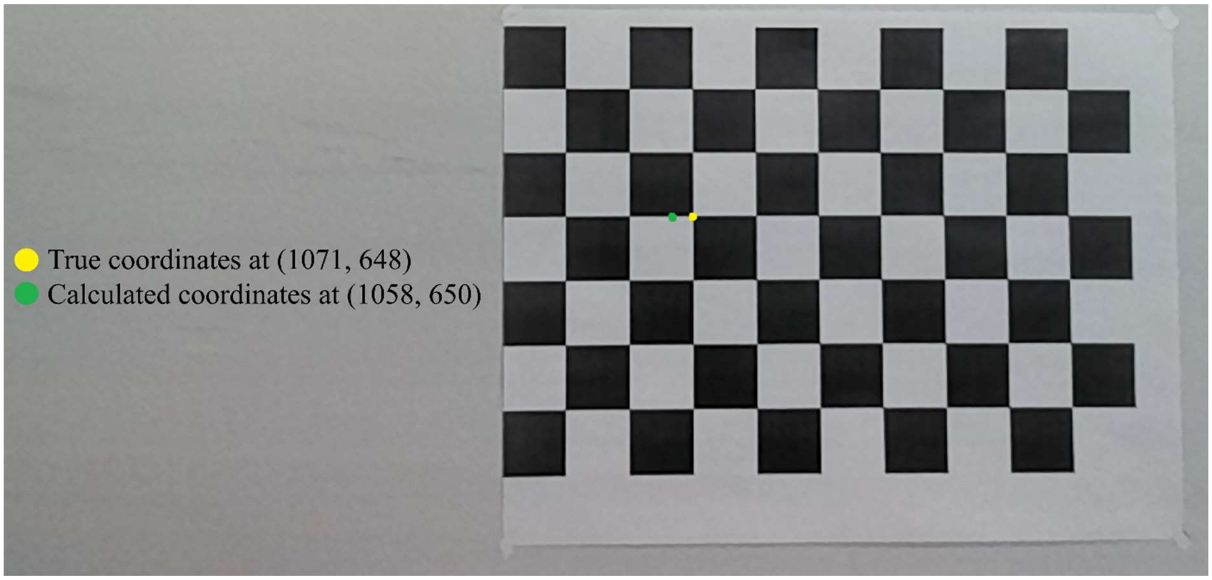


Figure 4. Comparison between true coordinates and calculated coordinates in example 1

EXAMPLE 2: A point at (-26, 78, 685) at camera coordinate frame

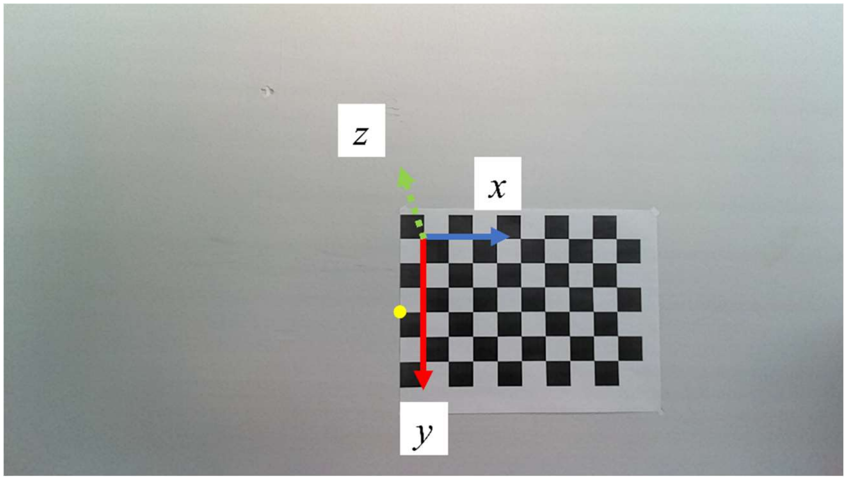


Figure 5. A reference point at (-26, 78, 685) – The yellow dot

$$\begin{bmatrix} 1434.41 & 0 & 949.77 \\ 0 & 1430.68 & 541.41 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} -26 \\ 78 \\ 685 \end{bmatrix} = \begin{bmatrix} 1434.41 * (-26) + 0 * 78 + 949.77 * 685 \\ 0 * (-26) + 1430.68 * 78 + 541.41 * 685 \\ 0 * (-26) + 0 * 78 + 1 * 685 \end{bmatrix} = \begin{bmatrix} 613297.79 \\ 482458.89 \\ 685 \end{bmatrix} \equiv \begin{bmatrix} 895.32 \\ 704.31 \\ 1 \end{bmatrix}$$

The true pixel coordinates of this reference points are (904, 705). Similar to example 1, the calibration matrix is verified. $(895.32, 704.31) \cong (904, 705)$. Figure 6 shows both the calculated point coordinates and its true pixel coordinates.

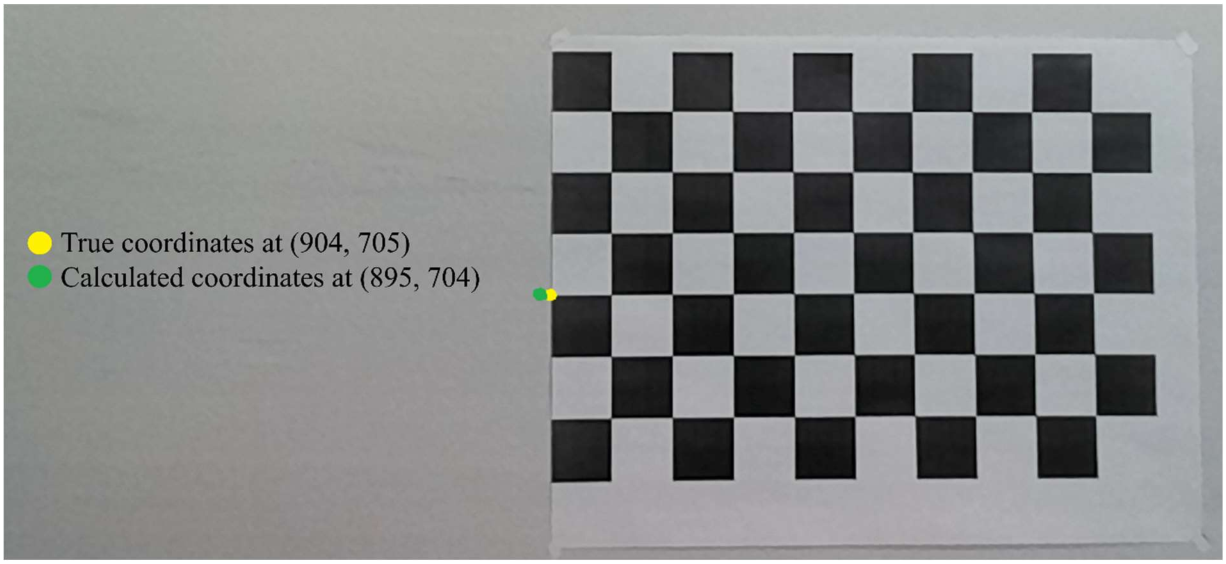
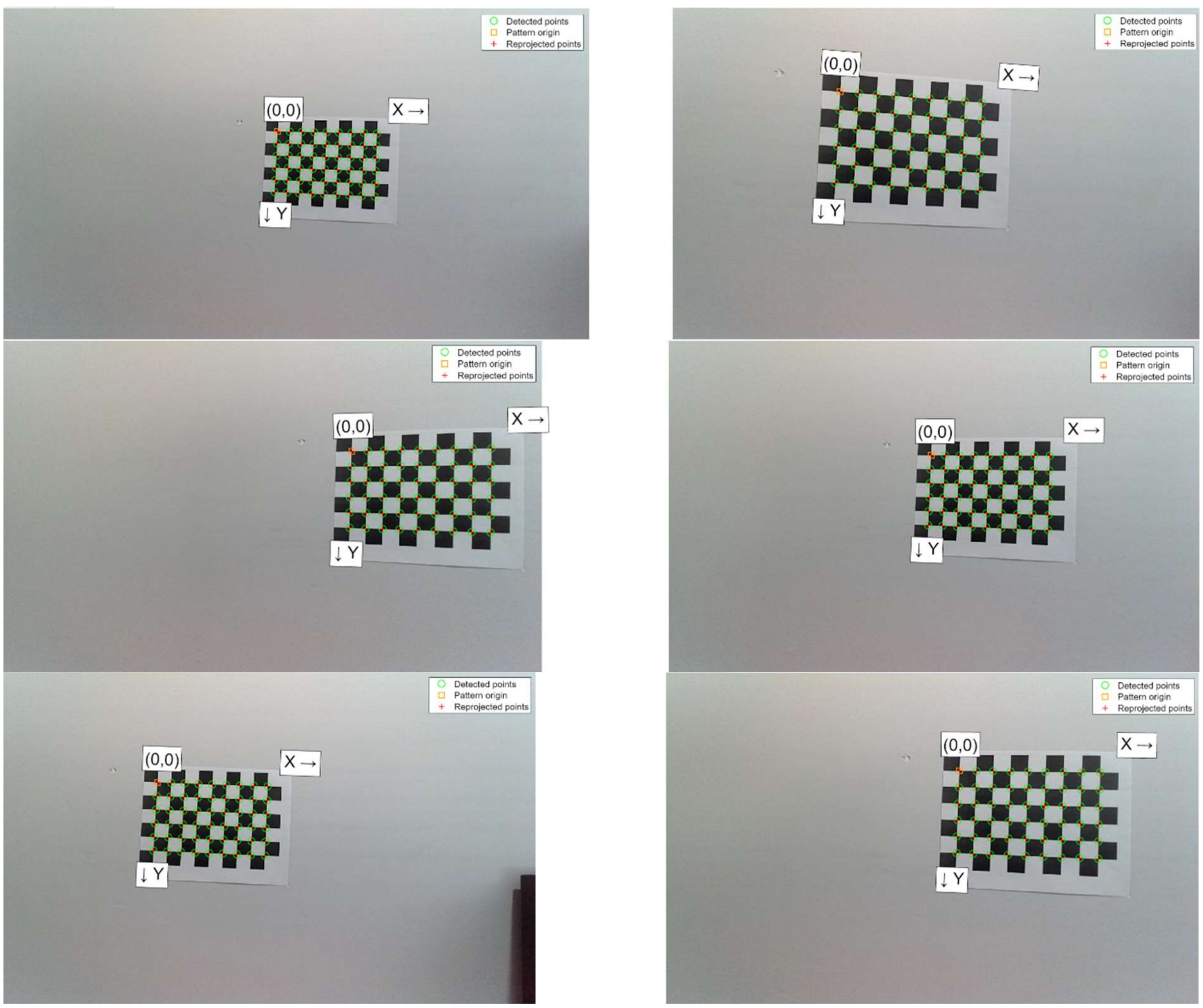
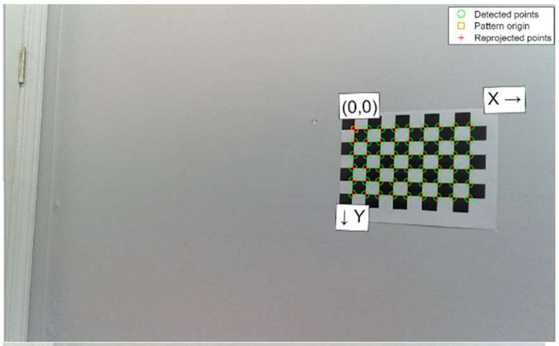
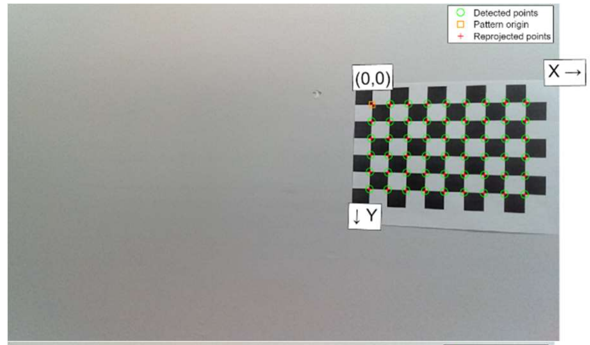


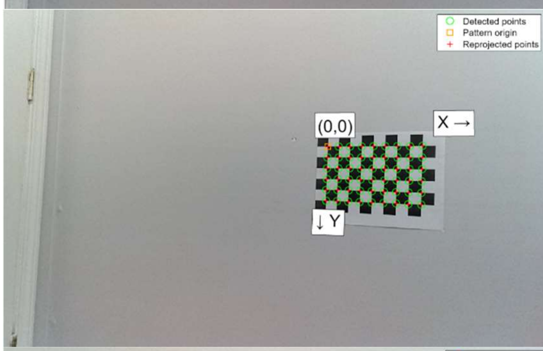
Figure 6. Comparison between true coordinates and calculated coordinates in example 2

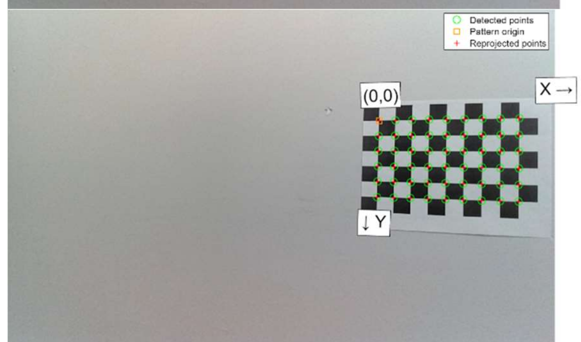
APPENDIX I: Calibration Footage

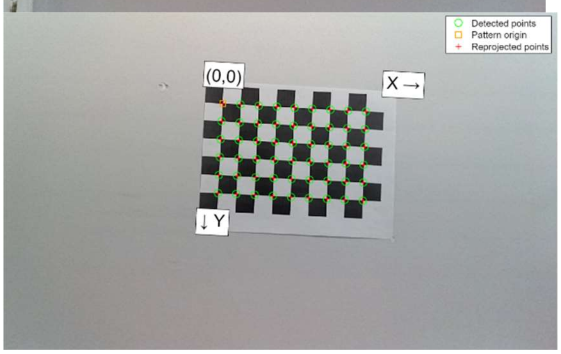


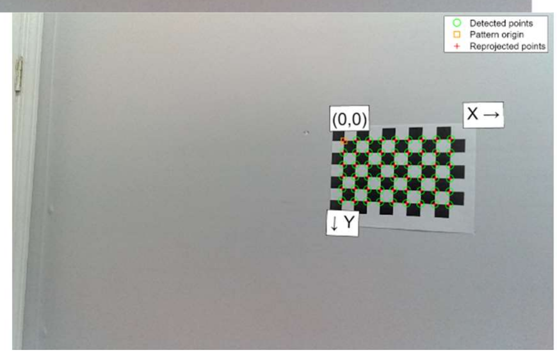

Detected points
Pattern origin
Reprojected points
(0,0)
X →
↓ Y

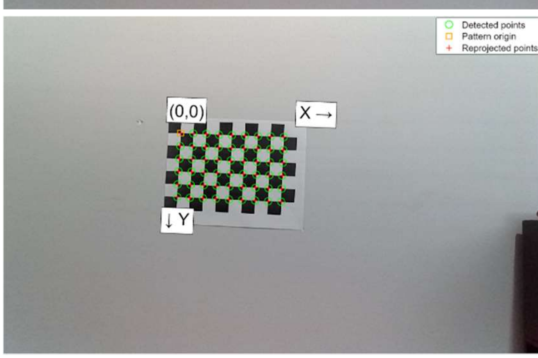

Detected points
Pattern origin
Reprojected points
(0,0)
X →
↓ Y

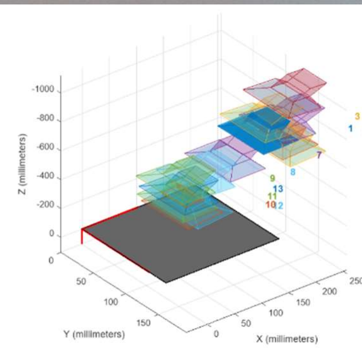

Detected points
Pattern origin
Reprojected points
(0,0)
X →
↓ Y

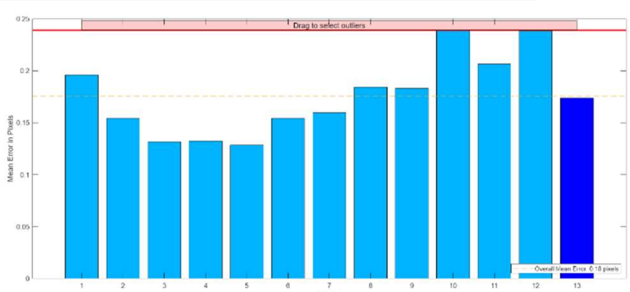

Detected points
Pattern origin
Reprojected points
(0,0)
X →
↓ Y


Detected points
Pattern origin
Reprojected points
(0,0)
X →
↓ Y


Detected points
Pattern origin
Reprojected points
(0,0)
X →
↓ Y


Detected points
Pattern origin
Reprojected points
(0,0)
X →
↓ Y


Z (millimeters)
Y (millimeters)
X (millimeters)


Drag to select outliers
Mean Error in Pixels
Images