Camera Calibration

The Caltech Camera Calibration MATLAB toolbox was used for camera calibration using a grid of 30mmx30mm squares taped down to a flat surface. Using a cell-phone camera, pictures were taken of this grid at varying angles.

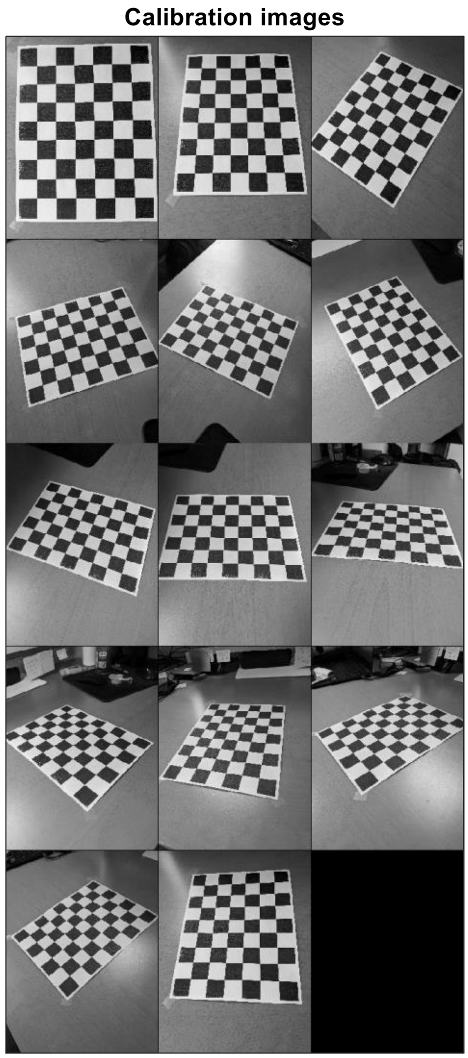

Figure 1: Calibration Images

The resultant reprojection pixel error can be seen in the plot below. Modern cell phone cameras are already well-calibrated, so there are already minimal reprojection error centered at the origin. Compared to the examples provided, these pixel errors appear large, but that is due to the larger images and more pixels in modern cameras.

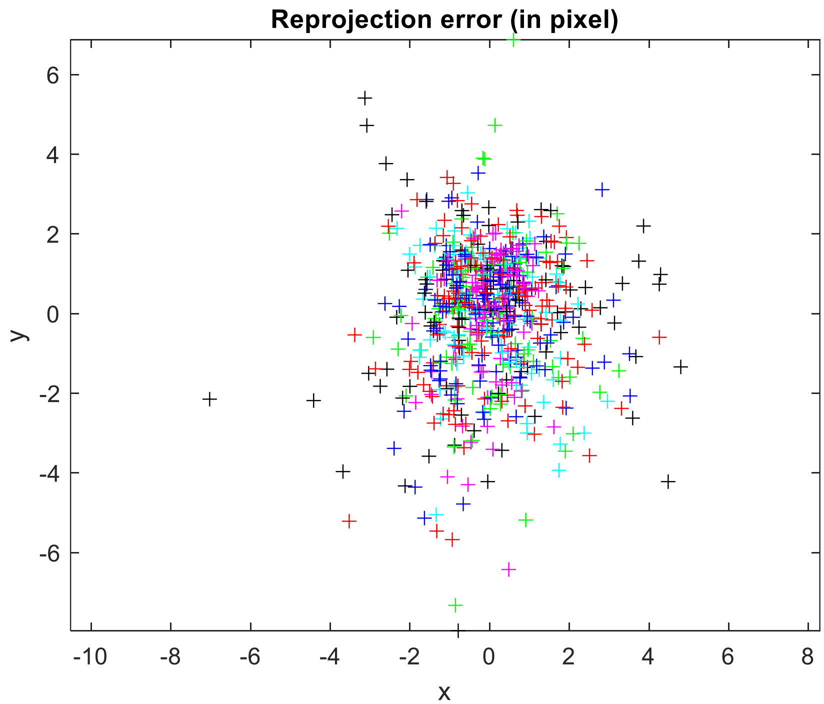

Figure 2: Reprojection Error from Camera Calibration

The outputted calibration parameters were saved in a "Calib_results.mat" file that will be reused for future image calibration.

```
Calibration parameters after initialization:

Focal Length:          fc = [ 3300.77755   3300.77755 ]
Principal point:       cc = [ 1511.50000   2015.50000 ]
Skew:             alpha_c = [ 0.00000 ]   => angle of pixel = 90.00000 degrees
Distortion:            kc = [ 0.00000    0.00000    0.00000    0.00000    0.00000 ]

Main calibration optimization procedure - Number of images: 14
Gradient descent iterations: 1...2...3...4...5...6...7...8...9...10...11...12...13...14...15...16...17...18...19...20...done
Estimation of uncertainties...done
```

```
Calibration results after optimization (with uncertainties):

Focal Length:          fc = [ 3281.84786   3287.12842 ] +/- [ 33.97110   32.24001 ]
Principal point:       cc = [ 1486.37124   2000.94491 ] +/- [ 14.63533   28.21233 ]
Skew:             alpha_c = [ 0.00000 ] +/- [ 0.00000  ]   => angle of pixel axes = 90.00000 +/- 0.00000 degrees
Distortion:            kc = [ 0.10193   -0.33109   -0.00228   0.00094  0.00000 ] +/- [ 0.01628   0.06673   0.00179   0.00181  0.00000 ]
Pixel error:          err = [ 1.30682   1.71608 ]

Note: The numerical errors are approximately three times the standard deviations (for reference).


Number(s) of image(s) to show ([] = all images) =
Pixel error:      err = [1.30682   1.71608] (all active images)
```

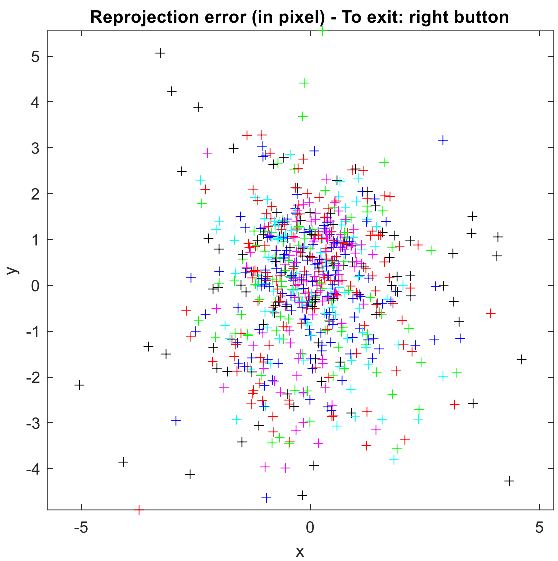

Figure 3: Recalibrated Reprojection Error from Camera Calibration

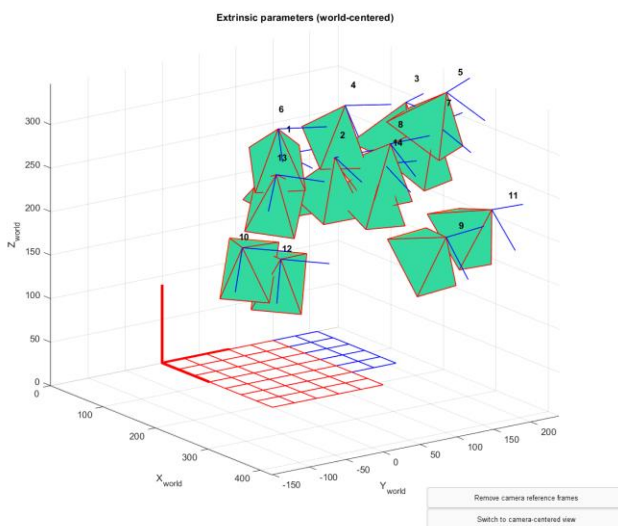

Figure 4: Display of estimated angles of camera

```
Calibration results after optimization (with uncertainties):

Focal Length:          fc = [ 3263.95909   3269.40421 ] +/- [ 30.69452   29.12832 ]
Principal point:       cc = [ 1485.72759   2012.72183 ] +/- [ 13.07483   25.52335 ]
Skew:             alpha_c = [ 0.00000 ] +/- [ 0.00000  ]   => angle of pixel axes = 90.00000 +/- 0.00000 degrees
Distortion:            kc = [ 0.09825   -0.31841   -0.00236   0.00107   0.00000 ] +/- [ 0.01445   0.05823   0.00161   0.00162  0.00000 ]
Pixel error:          err = [ 1.22106   1.51678 ]
```

Using these calibrated parameters, the calibrated image set looks like below. The calibration impacts can be seen as small columns of white (empty) pixels at the sides of the images.

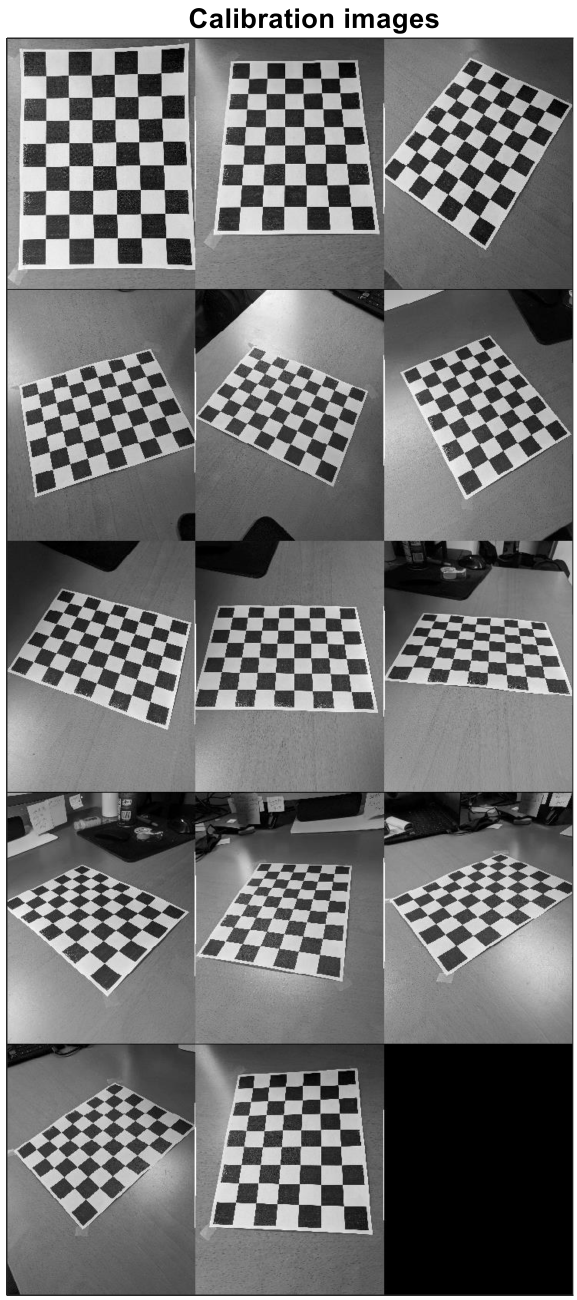

Figure 5: Calibrated Image Set

Data Collection

Five images were taken of the street art on the Latino Students Center building on Forsyth street with an approximate overlap of 50%. These images were calibrated using the generated "Calib_Results.mat" file from the previous section.

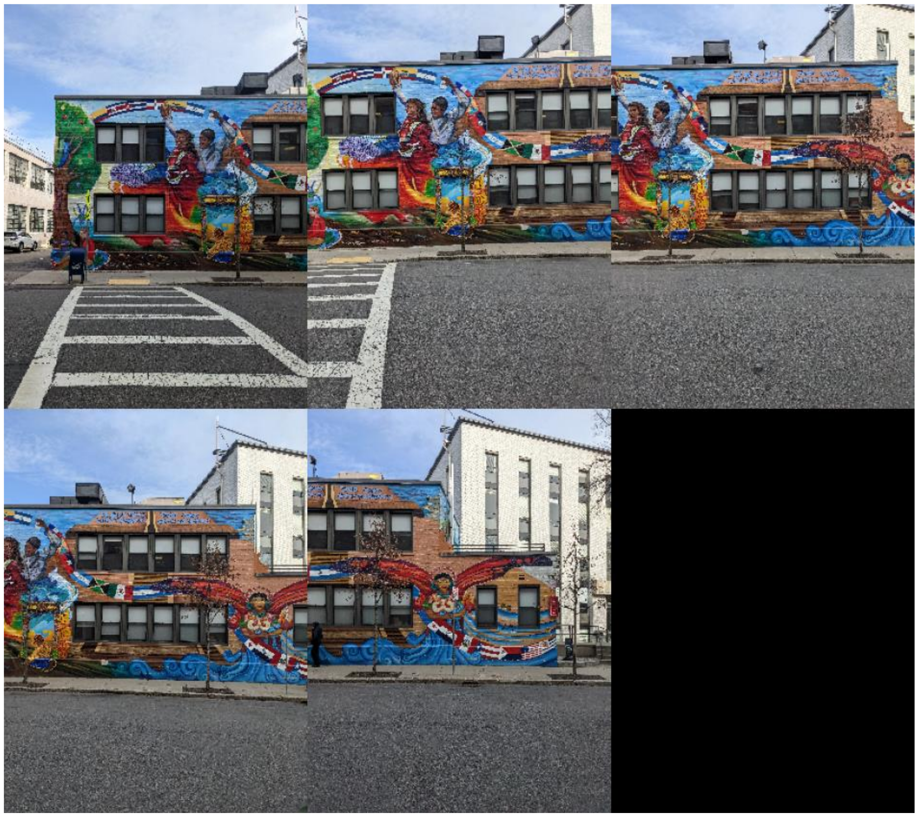

Figure 6: Images of Mural used for photomosaic

Harris Corner Detection

The *harris.m* function is used to find corners in an image. The corner distribution can be seen in the example image below. The adjustable parameters are the number of interest points, the magnitude of smallest response threshold, the size of gaussian smoothing mask, the standard deviation of the gaussian mask, and the tile size for regional processing. The default parameters provided a reasonable resulting stitched image, using a regional tiling of 2x2 and with 1,000 points of interest. After some tweaking with different features, the best results were found with an increased regional tiling of 4x4 and with 5,000 points of interest. The increased tiling allows for greater coverage and spacing of interest points while the total number of interest points is a tradeoff between effectiveness and computational cost. There were diminishing returns beyond 5,000 points of interest.

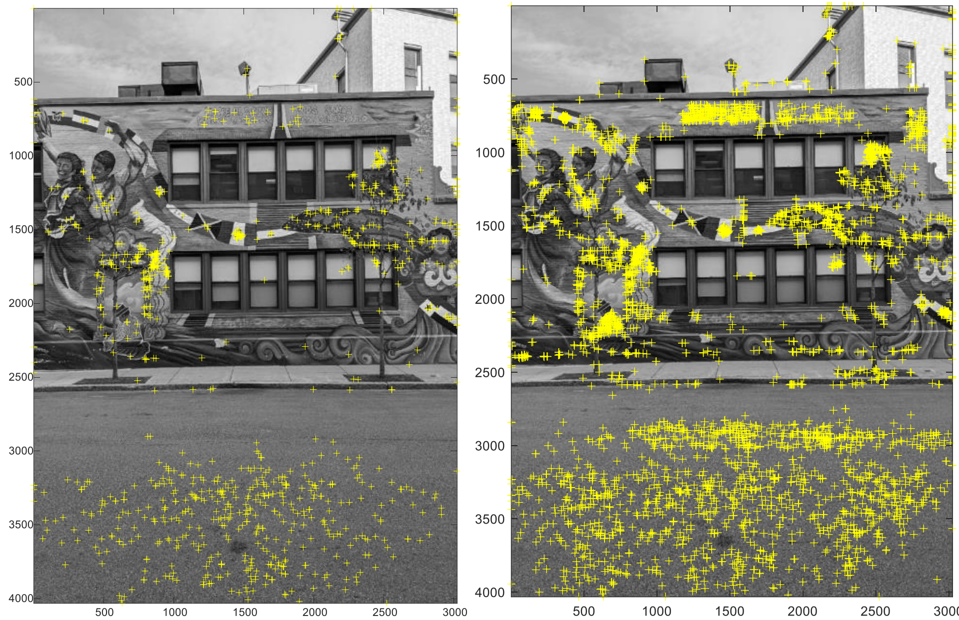

Figure 7: Example of Harris points of interest with 1000 points and tile size of [2 2] (left) and with 4000 points and tile size of [4 4] (right)

Final Mosaic

Using the Matlab example code, a panoramic mosaic of the entire building was stitched together using the Harris detector. The panorama effectively stitched together the building and sidewalk but was unable to create a realistic representation of the crosswalk or distant buildings. There are distortions and discontinuities at both close and far. This is due to parallax error. Put simply, as the camera moves horizontally, the pixels closer to the camera appear to be moving faster than those in the distance. This causes a lower percentage of overlap with close objects and a greater percentage of overlap with far objects. When most of the features are in the middle-ground, it is expected to see an ineffective stitching unless the photos can be distorted and curved to compensate.

Figure 8: Final Panorama

Blank Wall

Using the same image-stitching procedure, images of a brick wall were stitched together at a similar overlap percentage. One might expect this to fail because there are no clear patterns to discover, but this is not what was found. It did not fail because, even on a seemingly featureless wall, there are patterns that can be extracted on a pixel-level that are beyond the perception and pattern recognition capabilities of the humans.

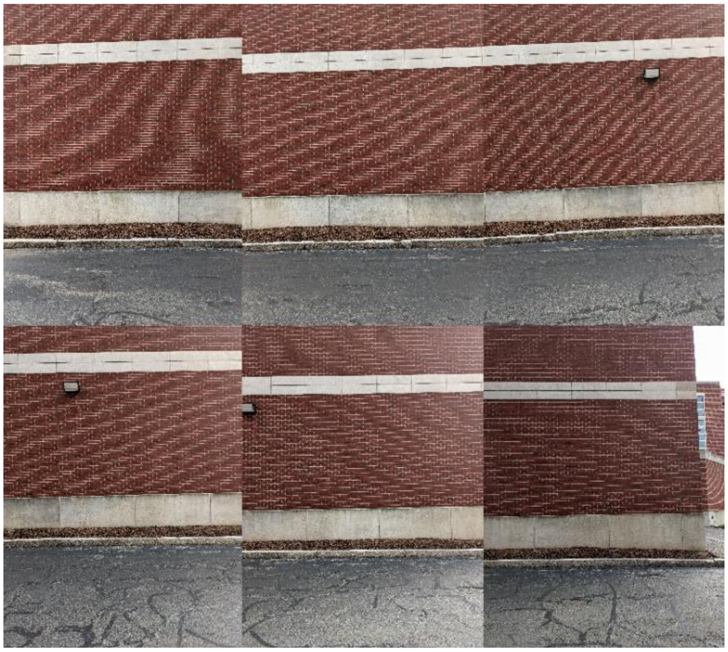

Figure 9: Images of a plain brick wall

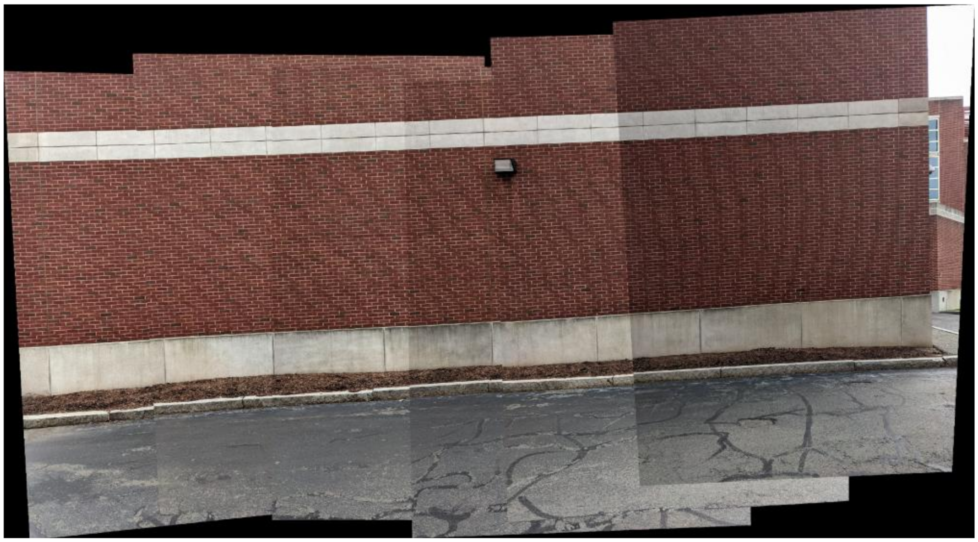

Figure 10: Merged panorama for plain brick wall

Reduced Image Overlap

Lastly, this mosaicking was repeated for a larger mural by the Ruggles T-Stop with a reduced overlap percentage between images. Using a set of 2000 Harris points of interest, the image stitching failed due to lack of common features. Increasing this up to 5000 points created the expected stitched image. This finding makes sense because as the amount of overlap decreases, there are fewer common corners to stitch the images together.

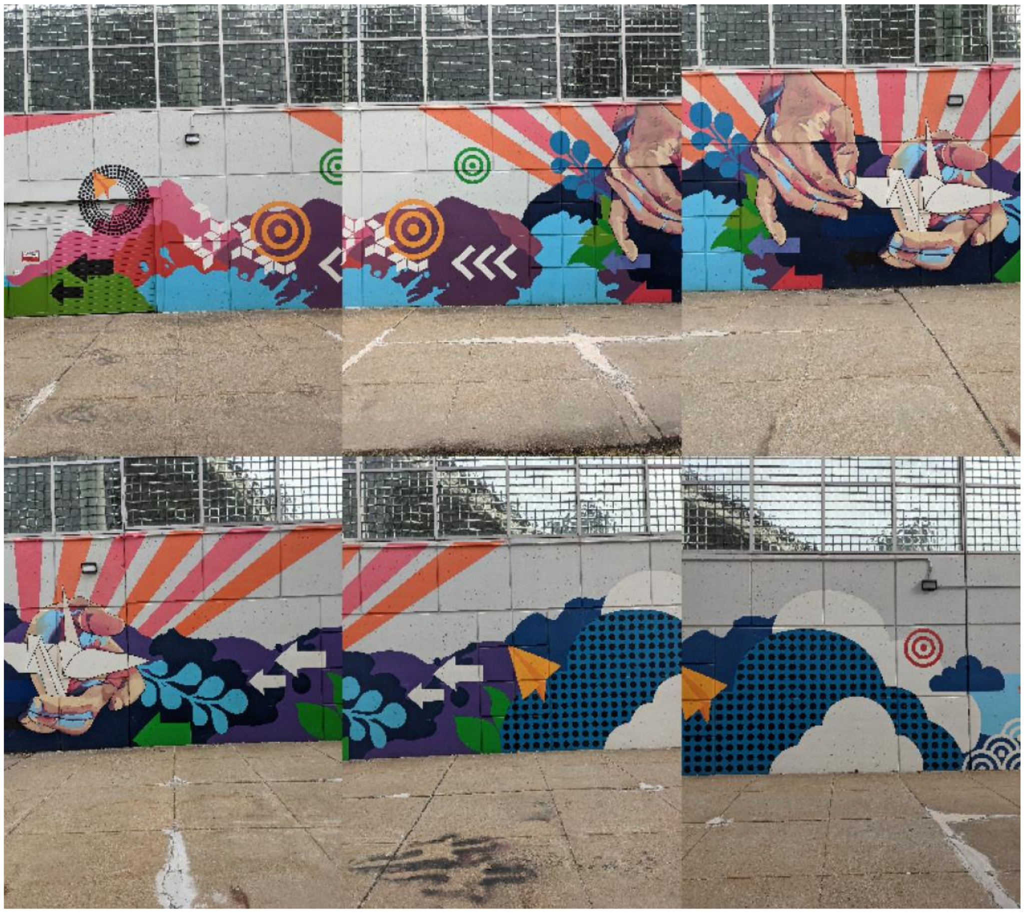

Figure 11: Images of Mural with lower % overlap

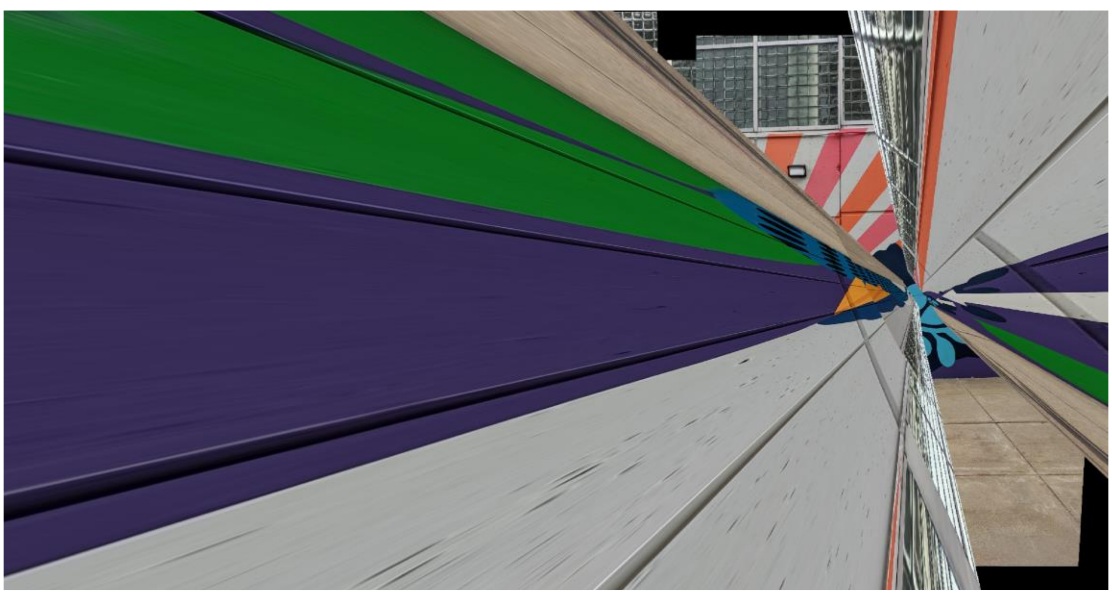

Figure 12: Mural with 15% overlap at 2000 Harris Interest Points

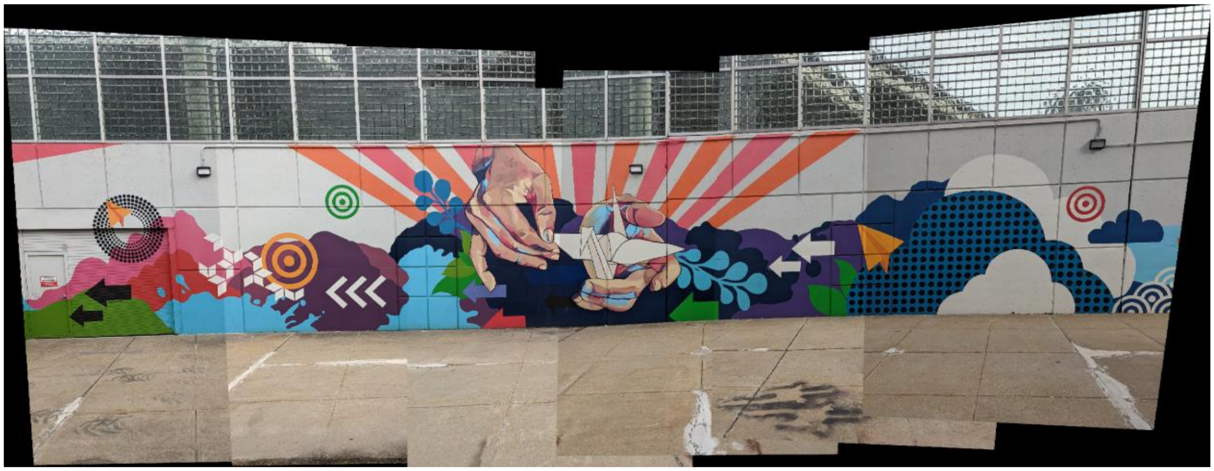

Figure 13: Mural with 15% overlap at 5000 Harris Interest Points