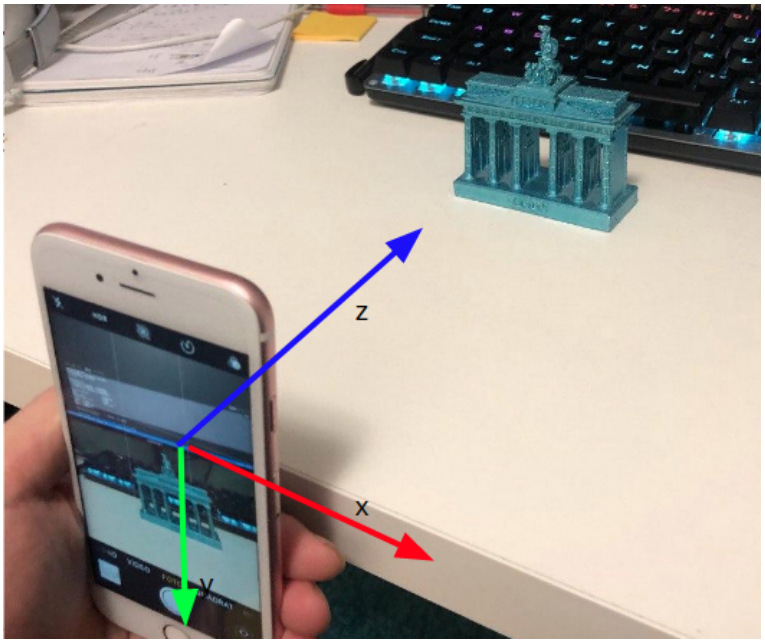

Figure 1: the world coordinate

Theory

1.)Image acquisition

Figure 2 shows the experiment configuration. The object in the center of the picture is the mini blue Brandenburg Tor. The approximate size of the Tor is $75 \cdot 55 \cdot 30$(mm). The drawback of this object is that the distance from front to back is not long enough so as to cause the selection of feature points not scattered enough. We use the digital camera of iPhone X to take the picture and it's focal length is 28mm, moreover, the photo we use for the processing is in the size of 817x817 pixels.

2.) Control point measurements

From the Figure 2 you could observe the object coordinate system, the original point is at the center of the cellphone, the mini Tor is in front of it with the distance 130mm. We use a normal ruler to measure the distance, the accuracy is in mm level.The control points and their order of selection are marked in the Figure 2

4.) Interpretation of the projection matrix

a) After the processing with the program, the parameters are calculated out.

$$K = \begin{bmatrix} 0.00023681088 & -0.000001392732 & 404.99991 \\ 0 & 0.00023889562 & 174.99965 \\ 0 & 0 & 1 \end{bmatrix} \tag{1}$$

$$R = \begin{bmatrix} 0.99960512 & 0.027980646 & -0.0025907925 \\ -0.028100334 & 0.99534744 & -0.092161812 \\ -8.2565021e^{-9} & 0.092198215 & 0.99574065 \end{bmatrix} \tag{2}$$

Figure 2: the selected control points

Skew: 89.663
Skew is the angle(degree) between x and y axis in the image plane.

Aspect ratio: 1.0088
Aspect ratio is the proportion between the length in pixel in x and y direction

Principal point (x,y): [405, 175]
Principal distance means the distance from imaging plane to the projection center or the principle plane
The principal point is the point on the image plane onto which the perspective center is projected

omega: -5.29008
phi: -4.73063e-07
kappa: 1.61024
These three variables are the camera rotation angle in degree at 3D space.

b) The whole calibration process can be summarized as following:
1. Select 6(or more) point pairs and record their corresponding coordinates in the world frame and camera frame.
2. Get the corresponding design matrix and use Direct Linear Transformation with the method like SVD to calculate out the projection matrix and decondition it.
3. Use RQ decomposition to derive calibration,matrix rotation matrix etc.
From the observation of the outcome parameters we could see the rotation matrix is almost a diagonal matrix, since we took the photo in front of the object and set the world coordinate based at the same place, which means that there is almost no rotation between world

and camera frame, so the value of rotation matrix, omega phi and kappa are reasonable. Also,the skew is almost 90 degree, which means the shearing happens very slightly. Besides, the scaling is mostly isotropic during internal calibration, which explains the aspect ratio is close to 1.

The metric of calibration matrix arouses our attention, because the principle length is surprisingly small, the reason behind that could be following: The feature points we select has not much difference in the z direction, after the SVD and RQ decomposition, the value could be hugely inaccurate. For improvement, the optimal point selection should be scattered in all of the three axes, it could be also possible that the positions of selected point in world frame and image frame are not accurate enough. After that, the ruler might give measurement errors of up to a full mm, which can have quite a big impact on the estimation error.