Lund University

Center for Mathematical Sciences

FMAN95

Computer Vision

Assignment 3

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2 The Fundamental Matrix

Exercise 1

We have

$$P_1 = [I \ 0], \quad P_2 = \begin{pmatrix} 1 & 1 & 0 & 0 \\ 0 & 2 & 0 & 2 \\ 0 & 0 & 1 & 0 \end{pmatrix} = [A \ t]$$

The fundamental matrix then will be

$$F = [t]_\times A = \begin{pmatrix} 0 & 0 & 2 \\ 0 & 0 & 0 \\ -2 & 0 & 0 \end{pmatrix} \begin{pmatrix} 1 & 1 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 2 \\ 0 & 0 & 0 \\ -2 & -2 & 0 \end{pmatrix}$$

The epipolar line is given by

$$l = \lambda A x + t = \lambda \begin{pmatrix} 1 & 1 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} + \begin{pmatrix} 0 \\ 2 \\ 0 \end{pmatrix} = \lambda \begin{pmatrix} 2 \\ 2 \\ 1 \end{pmatrix} + \begin{pmatrix} 0 \\ 2 \\ 0 \end{pmatrix}$$

In a vector representation it would be

$$l = t \times (Ax) = \begin{pmatrix} 2 \\ 2 \\ 1 \end{pmatrix} \times \begin{pmatrix} 0 \\ 2 \\ 0 \end{pmatrix} = \begin{pmatrix} 2 \\ 0 \\ -4 \end{pmatrix}$$

$\begin{pmatrix} 2 & 0 & -4 \end{pmatrix} \begin{pmatrix} 2 \\ 0 \\ 1 \end{pmatrix} = 0 \Rightarrow$ could be a match. $\begin{pmatrix} 2 & 0 & -4 \end{pmatrix} \begin{pmatrix} 2 \\ 1 \\ 1 \end{pmatrix} = 0 \Rightarrow$ could be a match.

$\begin{pmatrix} 2 & 0 & -4 \end{pmatrix} \begin{pmatrix} 4 \\ 2 \\ 1 \end{pmatrix} = 4 \neq 0 \Rightarrow$ could **not** be a match.

Exercise 2

To compute the camera centers we first find the nullspaces of the camera matrices. For P_1 it is easy to see that $C_1 \sim \begin{pmatrix}0,0,0,1\end{pmatrix}$. The nullspace of P_2 is given by the system

$$\begin{cases} X+Y+Z+2W=0 \\ 2Y+2W=0 \\ Z=0 \end{cases} \qquad \Leftrightarrow \qquad \begin{cases} X=-t \\ Y=-t \\ Z=0 \\ W=t \end{cases}, \tag{1}$$

which gives $C_2 \sim \begin{pmatrix}-1,-1,0,1\end{pmatrix}$. This gives

$$e_1 \sim P_1C_2 = [I\ 0]\begin{pmatrix}-1\\-1\\0\\1\end{pmatrix} = \begin{pmatrix}-1\\-1\\0\end{pmatrix},$$

$$e_2 \sim P_2C_1 = \begin{pmatrix}1&1&1&2\\0&2&0&2\\0&0&1&0\end{pmatrix}\begin{pmatrix}0\\0\\0\\1\end{pmatrix} = \begin{pmatrix}2\\2\\0\end{pmatrix}.$$

The Fundamental matrix is

$$F = [t]_\times A = \begin{pmatrix}0&0&2\\0&0&-2\\-2&2&0\end{pmatrix}\begin{pmatrix}1&1&1\\0&2&0\\0&0&1\end{pmatrix} = \begin{pmatrix}0&0&2\\0&0&-2\\-2&2&-2\end{pmatrix}.$$

We can see that $det(F) = 0$.

$$e_2^TF = \begin{pmatrix}2&2&0\end{pmatrix}\begin{pmatrix}0&0&2\\0&0&-2\\-2&2&-2\end{pmatrix} = \begin{pmatrix}0&0&0\end{pmatrix}.$$

$$Fe_1 = \begin{pmatrix}0&0&2\\0&0&-2\\-2&2&-2\end{pmatrix}\begin{pmatrix}-1\\-1\\0\end{pmatrix} = \begin{pmatrix}0\\0\\0\end{pmatrix}.$$

Optional solution: For a general camera pair $P_1 = [I\ 0]$ and $P_2 = [A\ t]$. Assuming A is invertible we have that $C_1 = \begin{pmatrix}0,0,0,1\end{pmatrix}$ and $C_2 = \begin{bmatrix}-A^{-1}t\\1\end{bmatrix}$ in homogeneous coordinates.

Projecting into the two cameras gives $e_1 \sim P_1 C_2 = \begin{bmatrix} I & 0 \end{bmatrix} \begin{bmatrix} -A^{-1}t \\ 1 \end{bmatrix} = -A^{-1}t$, and $e_2 \sim P_2 C_1 = t$.

Let's compute $e_2^T F$ and $F e_1$, where $F = [t]_\times A$:

Since $[t]_\times$ is skew symmetric, we have that $[t]_\times = -[t]_\times^T$.

$$e_2^T F = t^T [t]_\times A = -([t]_\times t)^T A = -(t \times t)^T A = 0,$$

$$F e_1 = [t]_\times A(-A^{-1}t) = -[t]_\times t = -t \times t = 0.$$

To show that $det(F) = 0$, we can show that 0 is an eigenvalue of F. We have that $F e_1 = 0 e_1$, where e_1 can be any arbitrary vector. This means that e_1 is an eigenvector of F and the eigenvalue is 0. Hence, $\det(F) = 0$ as 0 is a root to the characteristic equation.

Exercise 3

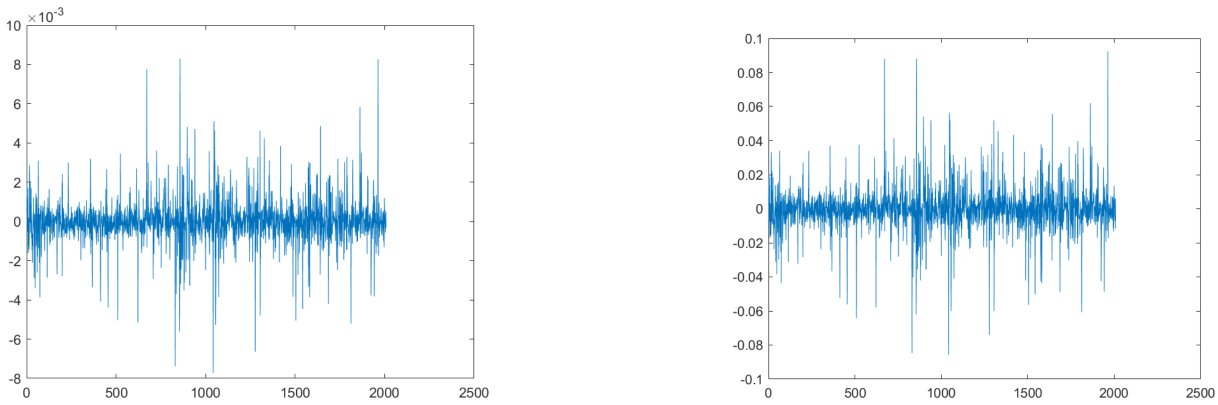
The Fundamental matrix for the original (un-normalized) points will be: $F \sim N_2^T \tilde{F} N_1$.

Computer Exercise 1

The fundamental matrix for the original (un-normalized) points is:

$F = \begin{pmatrix} 0 & 0 & 0.0058 \\ 0 & 0 & -0.027 \\ -0.0072 & 0.026 & 1 \end{pmatrix}.$

The mean epipolar distance obtained when F is computed with normalization is 0.36123, and without normalization it is 0.48784.



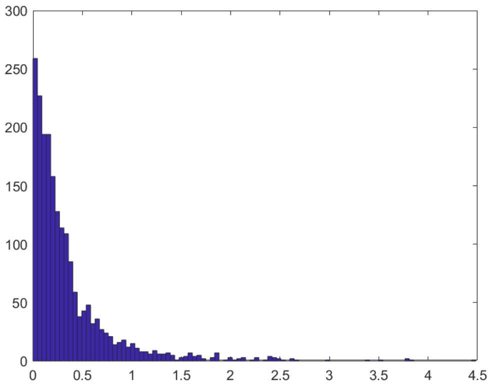
(a) With normalization. (b) Without normalization.

Figure 1: Epipolar constraints.

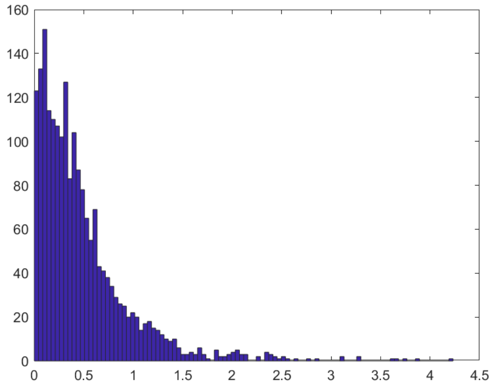
(a) With normalization.

(b) Without normalization.

Figure 2: The plot of the epipolar lines.



(a) With normalization.



(b) Without normalization.

Figure 3: Histogram.

Exercise 4

Since we know that $F^T e_2 = 0$ we can find e_2 by computing the null space of F^T.

$$F^T = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 1 & 0 & 1 \end{pmatrix}.$$

To find e_2 we find the nullspace of F^T by solving

$$\begin{cases} y = 0 \\ x + z = 0 \end{cases} \quad \Leftrightarrow \quad \begin{cases} x = -t \\ y = 0 \\ z = t \end{cases}, \tag{2}$$

Hence $e_2 \sim \begin{pmatrix} -1, 0, 1 \end{pmatrix}$ and we get

$$[e_2]_\times F = \begin{pmatrix} 0 & -1 & 0 \\ 1 & 0 & 1 \\ 0 & -1 & 0 \end{pmatrix} \begin{pmatrix} 0 & 1 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 1 \end{pmatrix} = \begin{pmatrix} -1 & 0 & 0 \\ 0 & 2 & 2 \\ -1 & 0 & 0 \end{pmatrix}.$$

$$P_2 = \begin{pmatrix} [e_2]_\times F & e_2 \end{pmatrix} = \begin{pmatrix} -1 & 0 & 0 & -1 \\ 0 & 2 & 2 & 0 \\ -1 & 0 & 0 & 1 \end{pmatrix}.$$

Camera center for P_2 then will be its nullspace:

$$\begin{cases} -X - W = 0 \\ 2Y + 2Z = 0 \\ -X + W = 0 \end{cases} \quad \Leftrightarrow \quad \begin{cases} X = 0 \\ Y = -t \\ Z = t \\ W = 0 \end{cases}, \tag{3}$$

which gives $C_2 \sim \begin{pmatrix} 0, -1, 1, 0 \end{pmatrix}$, which is a point at infinity.
For $X_1 = \begin{pmatrix} 1, 2, 3, 1 \end{pmatrix}$ we get

$$x_1 = P_1 X_1 = \begin{pmatrix} I & 0 \end{pmatrix} \begin{pmatrix} 1 \\ 2 \\ 3 \\ 1 \end{pmatrix} = \begin{pmatrix} 1 \\ 2 \\ 3 \end{pmatrix},$$

$$x_2 = P_2 X_1 = \begin{pmatrix} -1 & 0 & 0 & -1 \\ 0 & 2 & 2 & 0 \\ -1 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 \\ 2 \\ 3 \\ 1 \end{pmatrix} = \begin{pmatrix} -2 \\ 10 \\ 0 \end{pmatrix}.$$

The epipolar constraint then is

$$x_2^T F x_1 = \begin{pmatrix} -2 & 10 & 0 \end{pmatrix} \begin{pmatrix} 0 & 1 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 1 \end{pmatrix} \begin{pmatrix} 1 \\ 2 \\ 3 \end{pmatrix} = \begin{pmatrix} -2 & 10 & 0 \end{pmatrix} \begin{pmatrix} 5 \\ 1 \\ 5 \end{pmatrix} = 0.$$

Similarly for $X_2 = \begin{pmatrix} 3, 2, 1, 1 \end{pmatrix}$ we get

$$x_1 = P_1 X_2 = \begin{pmatrix} I & 0 \end{pmatrix} \begin{pmatrix} 3 \\ 2 \\ 1 \\ 1 \end{pmatrix} = \begin{pmatrix} 3 \\ 2 \\ 1 \end{pmatrix},$$

$$x_2 = P_2 X_2 = \begin{pmatrix} -1 & 0 & 0 & -1 \\ 0 & 2 & 2 & 0 \\ -1 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 3 \\ 2 \\ 1 \\ 1 \end{pmatrix} = \begin{pmatrix} -4 \\ 6 \\ -2 \end{pmatrix}.$$

The epipolar constraint then is

$$x_2^T F x_1 = \begin{pmatrix} -4 & 6 & -2 \end{pmatrix} \begin{pmatrix} 0 & 1 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 1 \end{pmatrix} \begin{pmatrix} 3 \\ 2 \\ 1 \end{pmatrix} = \begin{pmatrix} -4 & 6 & -2 \end{pmatrix} \begin{pmatrix} 3 \\ 3 \\ 3 \end{pmatrix} = 0.$$

Lastly for $X_3 = \begin{pmatrix} 1, 0, 1, 1 \end{pmatrix}$ we get

$$x_1 = P_1 X_3 = \begin{pmatrix} I & 0 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 1 \\ 1 \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \\ 1 \end{pmatrix},$$

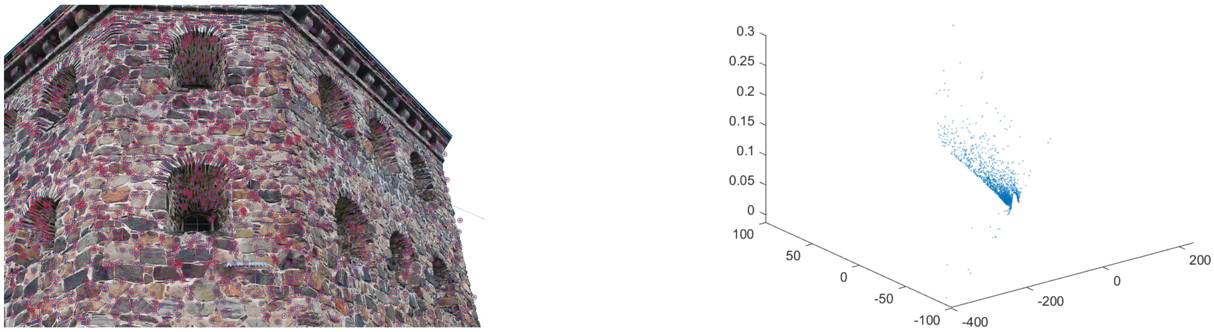
$$x_2 = P_2 X_3 = \begin{pmatrix} -1 & 0 & 0 & -1 \\ 0 & 2 & 2 & 0 \\ -1 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 1 \\ 1 \end{pmatrix} = \begin{pmatrix} -2 \\ 2 \\ 0 \end{pmatrix}.$$

The epipolar constraint then is

$$x_2^T F x_1 = \begin{pmatrix} -2 & 2 & 0 \end{pmatrix} \begin{pmatrix} 0 & 1 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 1 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 1 \end{pmatrix} = \begin{pmatrix} -2 & 2 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} = 0.$$

We see that epipolar constraints are fulfilled for all 3D points.

Computer Exercise 2



(a) 2D plot. (b) 3D plot.

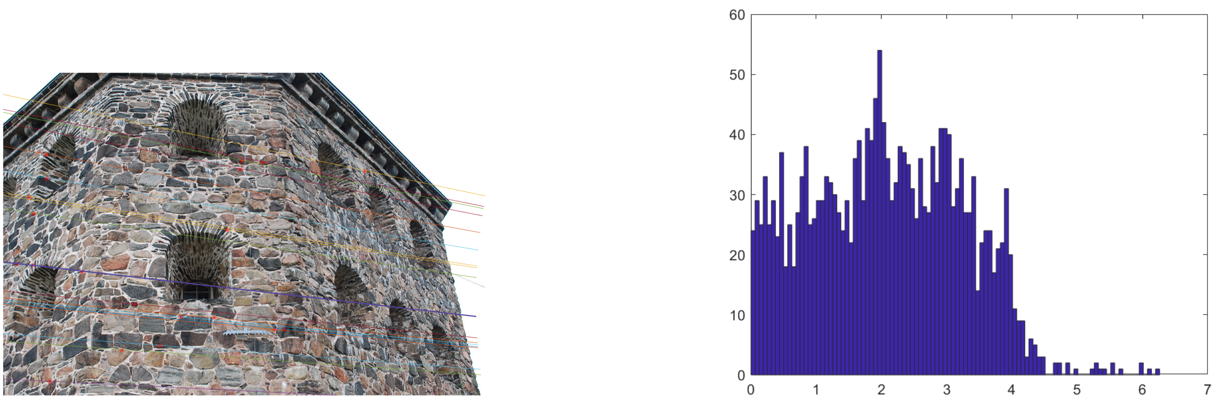
Figure 4: Plots for Computer Exercise 2.

3 The Essential Matrix

Computer Exercise 3

Essential matrix is:

$$E = \begin{pmatrix} -8.89 & -1005.81 & 377.08 \\ 1252.52 & 78.37 & -2448.17 \\ -472.79 & 2550.19 & 1 \end{pmatrix}.$$



(a) Epipolar Lines. (b) The histogram.

Figure 5: Plots for Computer Exercise 3.

Exercise 6

$$UV^T = \begin{pmatrix} 1/\sqrt{2} & -1/\sqrt{2} & 0 \\ 1/\sqrt{2} & 1/\sqrt{2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & -1 & 0 \end{pmatrix} = \begin{pmatrix} 1/\sqrt{2} & 0 & -1/\sqrt{2} \\ 1/\sqrt{2} & 0 & 1/\sqrt{2} \\ 0 & -1 & 0 \end{pmatrix}.$$

$$det(UV^T) = det\begin{pmatrix} 1/\sqrt{2} & 0 & -1/\sqrt{2} \\ 1/\sqrt{2} & 0 & 1/\sqrt{2} \\ 0 & -1 & 0 \end{pmatrix} = det\begin{pmatrix} 1/\sqrt{2} & -1/\sqrt{2} \\ 1/\sqrt{2} & 1/\sqrt{2} \end{pmatrix} = 1.$$

$$E = \begin{pmatrix} 1/\sqrt{2} & -1/\sqrt{2} & 0 \\ 1/\sqrt{2} & 1/\sqrt{2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & -1 & 0 \end{pmatrix} = \begin{pmatrix} 1/\sqrt{2} & -1/\sqrt{2} & 0 \\ 1/\sqrt{2} & 1/\sqrt{2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix}$$
$$= \begin{pmatrix} 1/\sqrt{2} & 0 & -1/\sqrt{2} \\ 1/\sqrt{2} & 0 & 1/\sqrt{2} \\ 0 & 0 & 0 \end{pmatrix}.$$

$$x_2^T E x_1 = \begin{pmatrix} 1 & 1 & 1 \end{pmatrix} \begin{pmatrix} 1/\sqrt{2} & 0 & -1/\sqrt{2} \\ 1/\sqrt{2} & 0 & 1/\sqrt{2} \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} = \begin{pmatrix} 1 & 1 & 1 \end{pmatrix} \begin{pmatrix} -1/\sqrt{2} \\ 1/\sqrt{2} \\ 0 \end{pmatrix} = 0.$$

Hence x_1 and x_2 is a plausible correspondence.
From camera equation we have

$$x_1 \sim P_1 X,$$
$$\begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \sim \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \\ W \end{pmatrix}.$$

Hence X must be one of the points: $X(s) = \begin{pmatrix} 0 \\ 0 \\ 1 \\ s \end{pmatrix}$.

$$W = \begin{pmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix},\ u_3 = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}.$$

First solution:

$$UWV^T = \begin{pmatrix} 1/\sqrt{2} & -1/\sqrt{2} & 0 \\ 1/\sqrt{2} & 1/\sqrt{2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & -1 & 0 \end{pmatrix} = \begin{pmatrix} 1/\sqrt{2} & -1/\sqrt{2} & 0 \\ 1/\sqrt{2} & 1/\sqrt{2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 0 & 0 & -1 \\ 1 & 0 & 0 \\ 0 & -1 & 0 \end{pmatrix}$$
$$= \begin{pmatrix} -1/\sqrt{2} & 0 & -1/\sqrt{2} \\ 1/\sqrt{2} & 0 & -1/\sqrt{2} \\ 0 & -1 & 0 \end{pmatrix}.$$

$$P_2 = \begin{bmatrix} UWV^T & u_3 \end{bmatrix} = \begin{bmatrix} -1/\sqrt{2} & 0 & -1/\sqrt{2} & 0 \\ 1/\sqrt{2} & 0 & -1/\sqrt{2} & 0 \\ 0 & -1 & 0 & 1 \end{bmatrix}.$$

$$P_2X(s) = \begin{pmatrix} -1/\sqrt{2} & 0 & -1/\sqrt{2} & 0 \\ 1/\sqrt{2} & 0 & -1/\sqrt{2} & 0 \\ 0 & -1 & 0 & 1 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 1 \\ s \end{pmatrix} = \begin{pmatrix} -1/\sqrt{2} \\ -1/\sqrt{2} \\ s \end{pmatrix} = \lambda x_2 = \lambda \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}.$$

Hence, $s = -1/\sqrt{2}$.
To determine if a point is in front of a camera we will compute its depth with respect to that camera.

$$depth(P_2, \mathbf{X}) = \frac{sign(det(A))\lambda}{||A_3||s} = \frac{sign(1) * (-1/\sqrt{2})}{(-1/\sqrt{2})} = 1.$$
$$depth(P_1, \mathbf{X}) = \frac{sign(det(A))\lambda}{||A_3||s} = \frac{1}{-1/\sqrt{2}} = -\sqrt{2}.$$

Hence the point $X(s)$ is **not** in front of **both** cameras.
Second solution:

$$P_2 = \begin{bmatrix} UWV^T & -u_3 \end{bmatrix} = \begin{bmatrix} -1/\sqrt{2} & 0 & -1/\sqrt{2} & 0 \\ 1/\sqrt{2} & 0 & -1/\sqrt{2} & 0 \\ 0 & -1 & 0 & -1 \end{bmatrix}.$$

$$P_2X(s) = \begin{pmatrix} -1/\sqrt{2} & 0 & -1/\sqrt{2} & 0 \\ 1/\sqrt{2} & 0 & -1/\sqrt{2} & 0 \\ 0 & -1 & 0 & -1 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 1 \\ s \end{pmatrix} = \begin{pmatrix} -1/\sqrt{2} \\ -1/\sqrt{2} \\ -s \end{pmatrix} = \lambda x_2 = \lambda \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}.$$

Hence, $s = 1/\sqrt{2}$.

$$depth(P_2, \mathbf{X}) = \frac{sign(det(A))\lambda}{||A_3||s} = \frac{sign(1) * (-1/\sqrt{2})}{1/\sqrt{2}} = -1.$$

Hence the point is **not** in front of the camera.

Third solution:

$$UW^TV^T = \begin{pmatrix} 1/\sqrt{2} & -1/\sqrt{2} & 0 \\ 1/\sqrt{2} & 1/\sqrt{2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & -1 & 0 \end{pmatrix} = \begin{pmatrix} 1/\sqrt{2} & -1/\sqrt{2} & 0 \\ 1/\sqrt{2} & 1/\sqrt{2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 0 & 0 & 1 \\ -1 & 0 & 0 \\ 0 & -1 & 0 \end{pmatrix}$$
$$= \begin{pmatrix} 1/\sqrt{2} & 0 & 1/\sqrt{2} \\ -1/\sqrt{2} & 0 & 1/\sqrt{2} \\ 0 & -1 & 0 \end{pmatrix}.$$

$$P_2 = \begin{bmatrix} UW^TV^T & u_3 \end{bmatrix} = \begin{bmatrix} 1/\sqrt{2} & 0 & 1/\sqrt{2} & 0 \\ -1/\sqrt{2} & 0 & 1/\sqrt{2} & 0 \\ 0 & -1 & 0 & 1 \end{bmatrix}.$$

$$P_2X(s) = \begin{pmatrix} 1/\sqrt{2} & 0 & 1/\sqrt{2} & 0 \\ -1/\sqrt{2} & 0 & 1/\sqrt{2} & 0 \\ 0 & -1 & 0 & 1 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 1 \\ s \end{pmatrix} = \begin{pmatrix} 1/\sqrt{2} \\ 1/\sqrt{2} \\ s \end{pmatrix} = \lambda x_2 = \lambda \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}.$$

Hence, $s = 1/\sqrt{2}$.

$$depth(P_2, \mathbf{X}) = \frac{sign(det(A))\lambda}{||A_3||s} = \frac{sign(1) * (1/\sqrt{2})}{(1/\sqrt{2})} = 1.$$
$$depth(P_1, \mathbf{X}) = \frac{sign(det(A))\lambda}{||A_3||s} = \frac{1}{1/\sqrt{2}} = \sqrt{2}.$$

Hence the point $X(s)$ is in front of **both** cameras.

Fourth solution:

$$P_2 = \begin{bmatrix} UW^TV^T & -u_3 \end{bmatrix} = \begin{bmatrix} 1/\sqrt{2} & 0 & 1/\sqrt{2} & 0 \\ -1/\sqrt{2} & 0 & 1/\sqrt{2} & 0 \\ 0 & -1 & 0 & -1 \end{bmatrix}.$$

$$P_2X(s) = \begin{pmatrix} 1/\sqrt{2} & 0 & 1/\sqrt{2} & 0 \\ -1/\sqrt{2} & 0 & 1/\sqrt{2} & 0 \\ 0 & -1 & 0 & -1 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 1 \\ s \end{pmatrix} = \begin{pmatrix} 1/\sqrt{2} \\ 1/\sqrt{2} \\ -s \end{pmatrix} = \lambda x_2 = \lambda \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}.$$

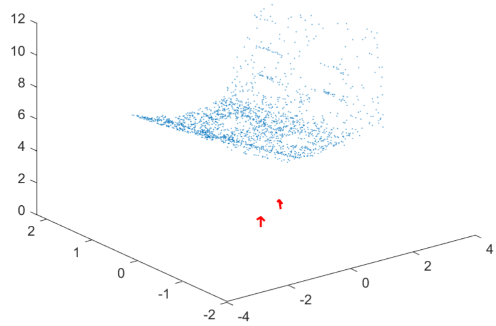
Hence, $s = -1/\sqrt{2}$.

$$depth(P_2, \mathbf{X}) = \frac{sign(det(A))\lambda}{||A_3||s} = \frac{sign(1) * (1/\sqrt{2})}{(-1/\sqrt{2})} = -1.$$

Hence the point is **not** in front of the camera.

Computer Exercise 4

(a) projected 3D-points.



(b) 3D points with camera centers.

Figure 6: Plots for Computer Exercise 4.