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END SEM – Mobile Robotics

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ENDSEM – MOBILE ROBOTICS

Rajat Kumar 2019101020

Q1.

(a) $Fe = 0$ $e \rightarrow$ epipole of 1^{st} camera seen in second image

$F \rightarrow$ Fundamental Matrix

We Know

$\cancel{F = K^{-T}[T_x]RK^{-1} \neq K^{-T}[T\times(Rp')]K^{-1}}$

~~$R \rightarrow$ Rotation Matrix~~

$$F = K^{-T}[T_x]RK^{-1}e$$

In the proof of Fundamental Matrix we got that

$$p^T \cdot [T \times (Rp')] = 0$$

where p^T and p' are normalized coordinates.

$\therefore$

$$(K^{-1}p_1)^T \cdot [T\times R\, K^{-1}p_1'] = 0$$

$$p_1^T \cdot K^{-T} \cdot [T\times(RK^{-1}p_1')] = 0 \quad -(1)$$

It resulted in

$$p_1^T \cdot F \cdot p_1' = 0 \quad -(2)$$

p_1^T & p_1' are original image coordinates.

$\therefore$ By comparing eqn (1) and (2) we got

$$F \cdot p_1' = K^{-1} \cdot [T\times(RK^{-1}p_1')] = 0$$

Now putting $p_1' = e$ i.e epipole of 1^{st} camera seen in 2^{nd} Image.

Q(1) extended (a)

$$F \cdot e = K^{-1} \cdot [T \times (R K^{-1} e)] = 0$$

Here we can see $(R K^{-1} e) \parallel OO'$ i.e. $(R K^{-1} e) \parallel T$

$$\therefore \quad [T \times (R K^{-1} e)] = 0$$

$$F \cdot e = K^{-1} \cdot [0] = 0.$$

$\therefore$ Hence prooved $\boxed{Fe = 0}$

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(4) Fundamental Matrix between I_2 and I_1 is F^T.

It is different Because.

we Know $F = K^{-T} [T_x] R K'^{-1}$

When we want I_2 and I_1 Fundamental Matrix than Rotation Matrix (R) changes and K' and K get ~~interc~~ changed

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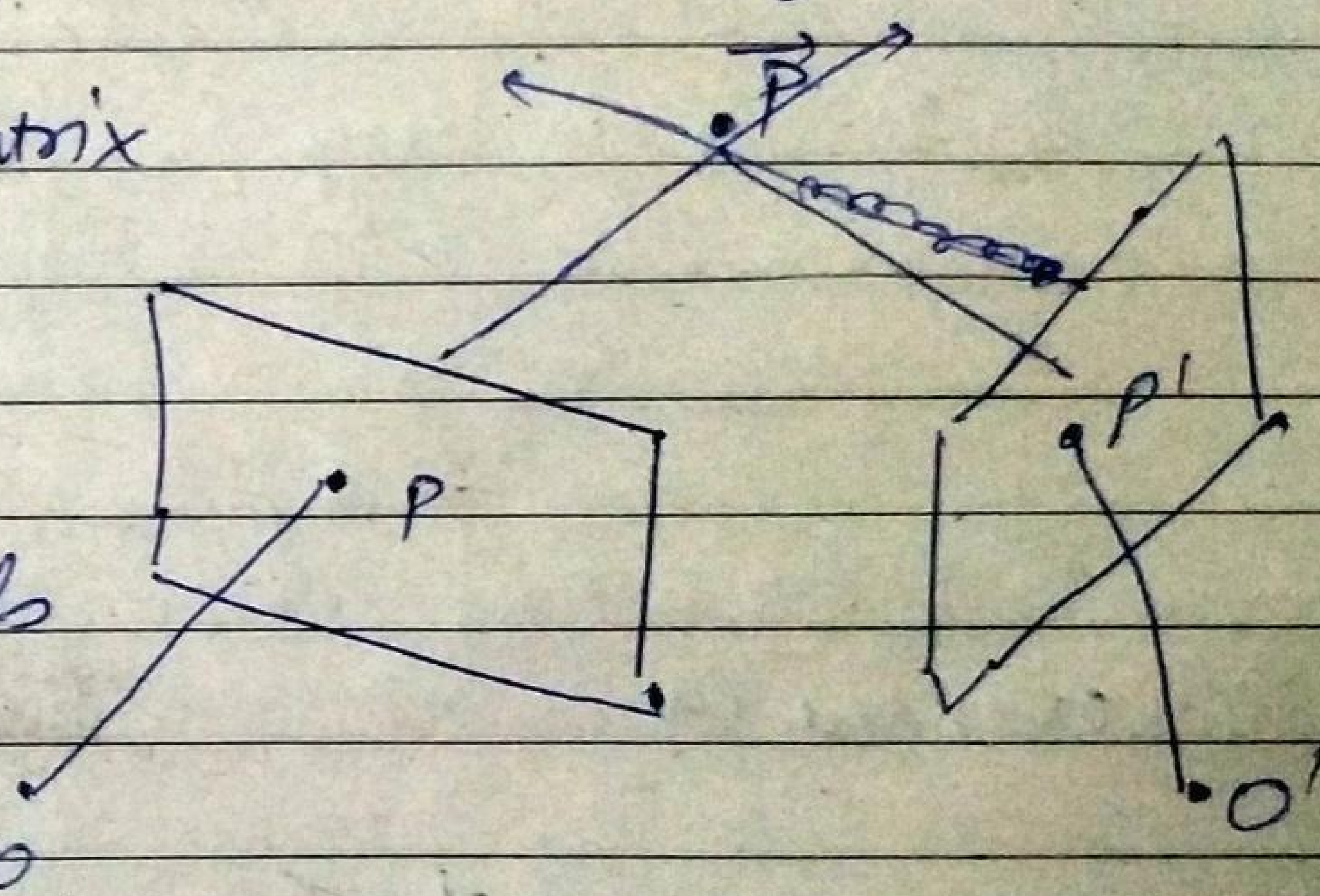
(C) The difference between Fundamental matrix and Essential matrix is that

* Fundamental Matrix relates two Corresponding pixels in the Original Image. Have 9 Degree of freedom. whereas
* Essential Matrix relates two corresponding pixels in the Normalized Image. Have 5 Degree of Freedom.

Eg Fundamenta Matrix

$$\boxed{p^T F p' = 0}$$



Here P and p' are Original Image Pixels

$K^{-1}P \parallel \vec{P}$

For Essential Matrix

$\cancel{p_1 = K^{-1}[I\ 0]P}$ $\cancel{p_1' = K'^{-1}[R\ T]P}$

$$\boxed{p_1^T E p_1' = 0}$$

Here $p_1 \parallel \vec{P}$

* $F = (K^{-1})^T E K^{-1}$ or $K^T F K = E$

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Q3 Camera Calibration

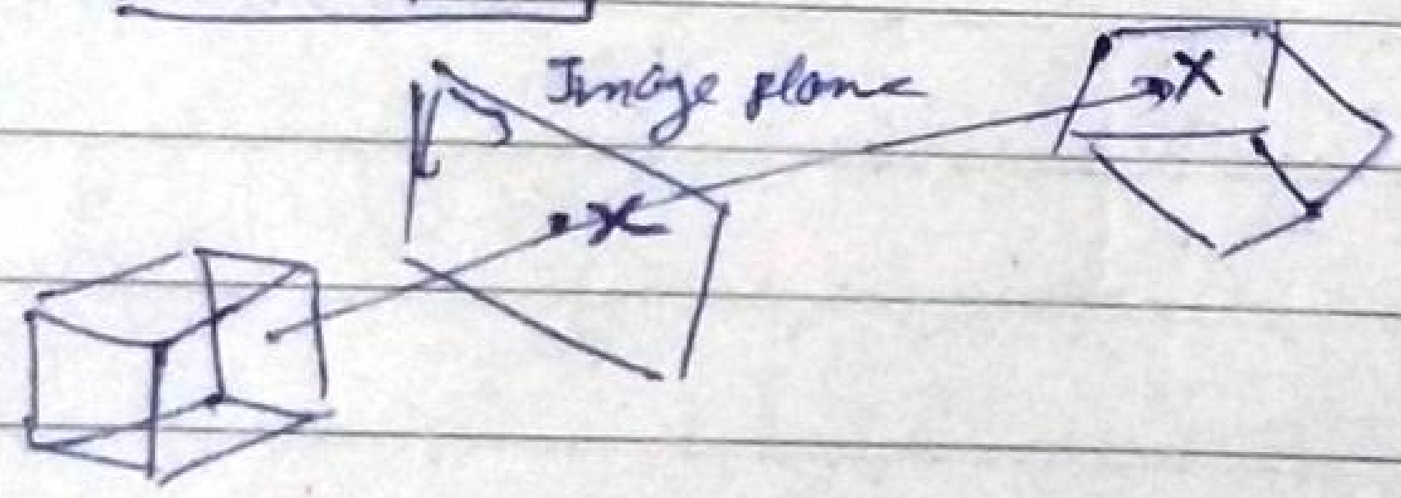
(a) DLT Algorithm proof :-

1) DLT Algorithm is used for Estimating the pose of a camera given coordinates of object points and coordinates (x,y) of those object points in an image.

DLT maps any object point X to image point x

$$x = KR[I_3 | -X_0]X$$

$$\boxed{x = PX}$$



$$\underset{3\times1}{x} = \underset{3\times3}{K}\ \underset{3\times3}{R}\ \underbrace{[\underset{3\times3}{I_3} | \underset{3\times1}{-X_0}]}_{3\times4}\ \underset{4\times1}{X}$$

$$= \underset{3\times4}{P}\ \underset{4\times1}{X}$$

$K \rightarrow$ Intrinsic parameter of camera
$X_0 \rightarrow$ origin of camera
$R \rightarrow$ Rotation matrix

$K \rightarrow c, s, m, x_H, y_H \rightarrow$ 5 parameters
$X_0 \rightarrow$ 3 translation parameters
$R \rightarrow$ 3 Rotation parameters.

So we require to the

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = P \begin{bmatrix} X \\ Y \\ W \\ T \end{bmatrix}$$

Normalising the points

$$\begin{bmatrix} u/w \\ v/w \\ 1 \end{bmatrix} = P \cancel{\begin{bmatrix} u/T \\ v/T \\ 1 \end{bmatrix}} \begin{bmatrix} X/T \\ Y/T \\ W/T \\ 1 \end{bmatrix} \quad -(1)$$

Let $P = \begin{bmatrix} p_{11} & p_{12} & p_{13} & p_{14} \\ p_{21} & p_{22} & p_{23} & p_{24} \\ p_{31} & p_{32} & p_{33} & p_{34} \end{bmatrix}$

$\therefore$ Rewriting eqn (1)

$$\begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \begin{bmatrix} p_{11} & p_{12} & p_{13} & p_{14} \\ p_{21} & p_{22} & p_{23} & p_{24} \\ p_{31} & p_{32} & p_{33} & p_{34} \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} \quad -(2)$$

Solving eqn (2) we get

$$x = \frac{p_{11} X + p_{12} Y + p_{13} Z + p_{14}}{p_{31} X + p_{32} Y + p_{33} Z + p_{34}} \quad - \text{II}$$

$$y = \frac{p_{21} X + p_{22} Y + p_{23} Z + p_{24}}{p_{31} X + p_{32} Y + p_{33} Z + p_{34}} \quad - \text{III}$$

So for uncalibrated camera we have 11 unknown and DLT is used

So we see from any particular x_i, X_i correspond-ing points we get 2 eqn i.e. eqn II, III.

So to solve for 11 parameters we require minimum $\{(11/2) = 5.5\}$ 6 points.

So let we have 6 points $(x_1, x_2, x_3, x_4, x_5, x_6)$ $(X_1, X_2, X_3, X_4, X_5, X_6)$ respectively correspondence

$$\therefore \quad x_i = \underset{3\times4}{P} X_i = \begin{bmatrix} p_{11} & p_{12} & p_{13} & p_{14} \\ p_{21} & p_{22} & p_{23} & p_{24} \\ p_{31} & p_{32} & p_{33} & p_{34} \end{bmatrix} X_i$$

$$\left\{ \text{let} \quad A = \begin{bmatrix} p_{11} \\ p_{12} \\ p_{13} \\ p_{14} \end{bmatrix}, \quad B = \begin{bmatrix} p_{21} \\ p_{22} \\ p_{23} \\ p_{24} \end{bmatrix}, \quad C = \begin{bmatrix} p_{31} \\ p_{32} \\ p_{33} \\ p_{34} \end{bmatrix} \right\}$$

$$\Rightarrow \quad \therefore \quad x_i = \begin{bmatrix} A^T \\ B^T \\ C^T \end{bmatrix} X_i$$

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⇒ Multiplying RHS

⇒ $$x_i = \begin{bmatrix} A^T X_i \\ B^T X_i \\ C^T X_i \end{bmatrix}$$

as x_i is a homogenous coordinates
Finding Euclidean Coordinates

⇒ ∴ $$\begin{bmatrix} x_i \\ y_i \\ 1 \end{bmatrix} = \begin{bmatrix} u_i \\ v_i \\ w_i \end{bmatrix} = \begin{bmatrix} A^T X_i \\ B^T X_i \\ C^T X_i \end{bmatrix}$$

Comparing LHS = RHS

⇒ $x_i = \frac{u_i}{w_i} = \frac{A^T X_i}{C^T X_i}$ | $y_i = \frac{v_i}{w_i} = \frac{B^T X_i}{C^T X_i}$

⇒ ∴ $x_i C^T X_i - A^T X_i = 0$ | $y_i C^T X_i - B^T X_i = 0$ — (3)

⇒ This leads to systems of equation linear in A, B, C.

⇒ we rewrite equation (3) as

⇒ $$-X_i^T A + x_i X_i^T C = 0$$

$$-X_i^T B + y_i X_i^T C = 0$$

{ we are writing like this because to match it with system of linear equation where coefficients are known and A, B, C are unknown }

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Now let p be a vector such that

$$p = (p_x) = \begin{bmatrix} A \\ B \\ C \end{bmatrix}_{12\times1} = vec(P^T)$$

rows of P as column - vectors one below the other

$\Rightarrow$ So now we can rewrite system of equation derived in eq^n ③ as

$$-X_i^T A + x_i X_i^T C = 0 \longrightarrow a_{x_i}^T p = 0$$

$$-X_i^T B + y_i X_i^T C = 0 \rightarrow a_{y_i}^T p = 0$$

$\therefore$

$$\Rightarrow a_{x_i}^T \begin{bmatrix} A \\ B \\ C \end{bmatrix} = -X_i^T A + x_i X_i^T C$$

And

$$a_{y_i}^T \begin{bmatrix} A \\ B \\ C \end{bmatrix} = -X_i^T B + y_i X_i^T C$$

$\Rightarrow$ Comparing LHS and RHS above

$$a_{x_i}^T = (-X_i^T, 0^T, x_i X_i^T)$$

$$a_{y_i}^T = (0^T, -X_i^T, y_i X_i^T)$$

$\Rightarrow$ i.e.

$$a_{x_i}^T = (-X_i, -Y_i, -Z_i, -1, 0, 0, 0, 0, x_iX_i, x_iY_i, x_iZ_i, x_i)$$

$$a_{y_i}^T = (0, 0, 0, 0, -X_i, -Y_i, -Z_i, -1, y_iX_i, y_iY_i, y_iZ_i, y_i)$$

This is the step which will fail if all the corresponding points lie on a plane.
In the next step we will be collecting everything together.
i.e. for all $(x_1, x_2 \dots x_\ell)$ ℓ number of points.

$$\begin{bmatrix} a_{x_1}^T \\ a_{y_1}^T \\ a_{x_2}^T \\ \vdots \\ a_{y_\ell}^T \end{bmatrix} p = \underset{2\ell \times 12}{M} \; \underset{12\times 1}{p} = 0$$

So

$$M = \begin{array}{c} \begin{array}{cccccccccccc} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 \end{array} \\ \begin{bmatrix} -X_i & -Y_i & -Z_i & -1 & 0 & 0 & 0 & 0 & x_iX_i & x_iY_i & x_iZ_i & x_i \\ 0 & 0 & 0 & 0 & -X_i & -Y_i & -Z_i & -1 & y_iX_i & y_iY_i & y_iZ_i & y_i \\ \vdots & \vdots & \vdots & & & & & & \vdots & & & \end{bmatrix} \end{array}$$

If all points lie on a plane.
eg: $Z = 0$
then column 3, 8, 10 will become 0
So only 9 column will remain non-zero
which will lead to rank deficiency.

$\Rightarrow$ $Mp = 0$

This system is called Homogenous system and could be found using SVD. i.e. finding Null space of matrix M.

$\Rightarrow$ Due to redundant observations ($Mp \neq 0$)

$$Mp = w \quad - (5)$$

So we have to find p which minimizes w. or $w^T w$.

Let $\Omega = w w^T$

$$\hat{p} = \underset{p}{\arg\min}\ w^T w$$

From (5)

$$\hat{p} = \arg\min\ p^T M^T M p$$

So we find this using SVD on M

$$\underset{21 \times 12}{M} = \underset{21 \times 12}{U}\ \underset{12 \times 12}{S}\ \underset{12 \times 12}{V^T} = \sum_{i=1}^{12} s_i u_i v_i^T$$

Eigen singular vector v_{12} in V corresponding to least eigen value is the vector which minimiser singular value. So we ~~select~~ V_{12} as singular vector.

So $p = V_{12} = \begin{bmatrix} p_{11} \\ p_{\cdot} \\ \vdots \\ p_{34} \end{bmatrix}$

Which we can arrange as

$$P_{3\times4} = \begin{bmatrix} p_{11} & \cdots & p_{14} \\ & \cdots & p_{34} \end{bmatrix}$$

⇒ Deriving Intrinsic and Extrinsic parameters.

$$\underset{3\times4}{P} = [KR \mid -KRX_0] = [H \mid h]$$

$H = KR \qquad h = -KRX_0$

we have H and h now

so $\boxed{X_0 = -H^{-1}h}$

For finding K and R
we can use q^n $H = KR$
Decompose H^{-1} using QR Decomposition matrix.
as $K \rightarrow$ triangular matrix
$R \rightarrow$ Rotation Matrix.
∴ Hence DII proof.

Coding Question :

(1) $f(x) = e^{-ax} \sin x + b$

Jacobian $= \begin{bmatrix} \frac{\partial f}{\partial a} & \frac{\partial f}{\partial b} \end{bmatrix}$

parameters (a, b)

$$\boxed{\text{Jacobian} = \begin{bmatrix} -xe^{-ax} \sin x & 1 \end{bmatrix}}$$

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Q(2)

(a) Let C_1 and C_2 be two camera frames
Let there be a point X_i in 3D whose homogeneous coordinates w.r.t. C_1 and C_2 be X_{iC_1}, X_{iC_2} respectively.
And they form image point for X_{iC_1}, X_{iC_2} at x_{iC_1}, x_{iC_2} respectively.

$$\therefore \quad x_{iC_1} = K X_{iC_1} \quad -(1)$$

$$x_{iC_2} = K X_{iC_2} \quad -(2)$$

We know T be the transformation matrix from C_1 to C_2 in pure rotation

$$\therefore \quad T = [R \;\; 0]$$

putting in eqns

$$X_{iC_2} = T X_{iC_1} = [R \;\; 0] X_{iC_1} = R X_{iC_1} \quad -(3)$$

from eqn (1), (2), (3)

$$x_{iC_2} = K X_{iC_2} \Rightarrow x_{iC_2} = K R X_{iC_1}$$

As $X_{iC_1} = K^{-1} x_{iC_1}$

$$\boxed{x_{iC_2} = K R K^{-1} x_{iC_1}}$$

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putting $H = K R K^{-1}$

$$\boxed{x_{j c_2} = H x_{i c_1}}$$

H is the Homography Matrix.

This homography matrix does not hold for translation as in that case epipolar geometry is involved.

In case of Translation Matrix

$$T = [R \; t]$$

$\therefore$ putting in eq^{n}s derived above we get

$$x_{ic_2} = [R \; t] \, x_{ic_1} = R x_{ic_1} + t$$

$\therefore$ $x_{ic_2} = H x_{ic_1} + Kt$

is no longer a Homography eq^n.

(b) Three ways to relate pixels are:

(1) Homography:

In this formation, frames I_1 and I_2 are seperated by rotation R from I_1 to I_2

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Relation given is

$$\boxed{x_{i_2} = (K_2 R K_1^{-1})\, x_{i_1}}$$

K_2 and K_1 are intrisic parameters.

(2) ~~Epipolar~~ Epipolar Geometry:

Here we have matrix called Fundamental Matrix

Relation i.e. $\boxed{x_{i_1}^T F x_{i_2} = 0}$

where $F = K_1^{-T} [Tx] R K_2^{-1}$

$K_1 - K_2 \rightarrow$ intric calmera calibration matrix for Camera 1 and 2.

$[Tx]$ is a skew symmetrix matrix

(3) ~~Stereo~~:- representation of translation b/w I_1 & I_2

$[Tx] R = E$ i.e. ~~ei~~ essential matrix

(3) Stereo:-

When I_1 and I_2 are seperated by translation i.e. $R = 0$, $t = (T, 0, 0)$ we have ||'l eppipolar lines and epi. epipoles lie at ∞.

For given x_{i_1}, x_{i_2} can be directly related as both of their y-coordinate will be same. & we have to search for x_{j_2} on same row as x_{i_1}

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So Mathematically

$\Rightarrow R = I.$ & $t = (T, 0, 0)$

$$\Rightarrow E = t \times R = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -T \\ 0 & T & 0 \end{bmatrix}$$

$\Rightarrow x_{i_1}^T \; K_1^{-T} E K_2^{-1} x_{j_2} = 0 \quad [x_{i_1}^T F x_{i_1} = 0]$

$x_{i_1}^T K_1^{-1} = [u \; v \; 1]$

& $K_2^{-1} x_{i_2} = (u' \; v' \; 1)^T$

$$[u \; v \; 1] \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -T \\ 0 & T & 0 \end{bmatrix} \begin{bmatrix} u' \\ v' \\ 1 \end{bmatrix} = 0$$

$Tv = Tv' \Rightarrow$ Same y-coordinates

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(c)

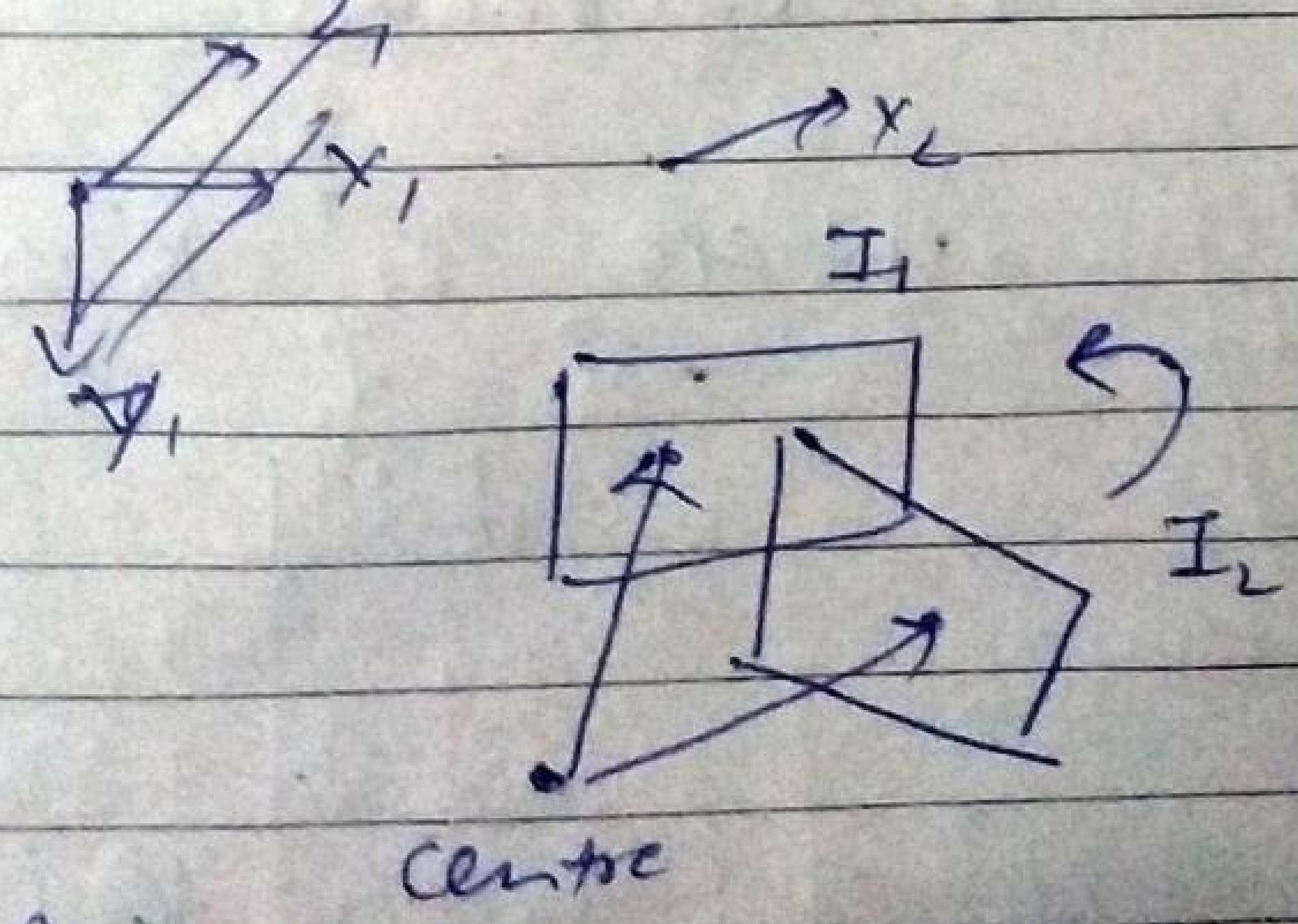
In Stereo rectification, we project the two images formed by camera's on plane ‖'e to line between camera centres.

For that we need two homographies one for each input image reprojection.

(1) H1 → Rotation Homography is applied to only second frame I_2 such that it becomes parallel to I_1 and this Homography can be found by finding essential matrix E using 8 point algorithm & then decompose it to get homography H i.e. R

So eqn $\boxed{x_{i_2} = R\, x_{i_1}}$

Now as I_1 & I_2 are parallel i.e. their axis & image plane are parallel.



⇒ Applying rot. R or we can say rotational homography that relates two camera that suffer from pure rotation w.r.t. each other

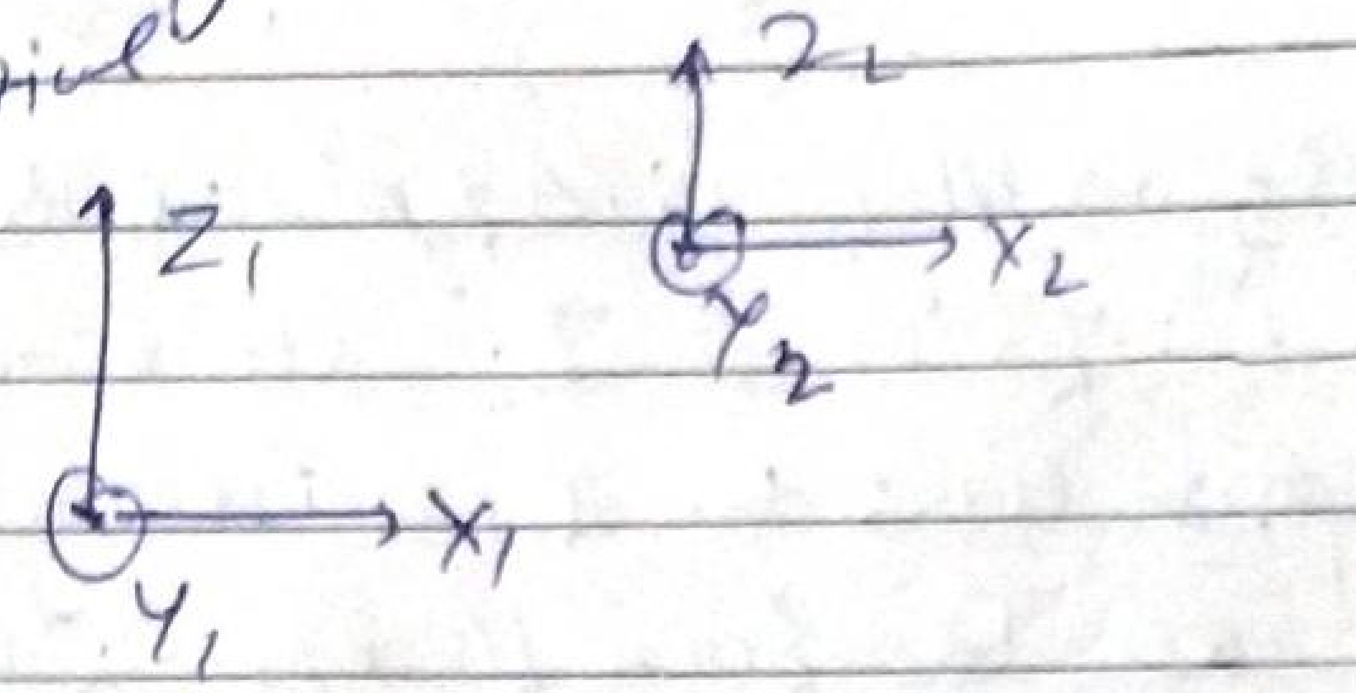
$$\boxed{H = KRK^{-1}}$$

Axis ~~centre~~ of Both can be different.

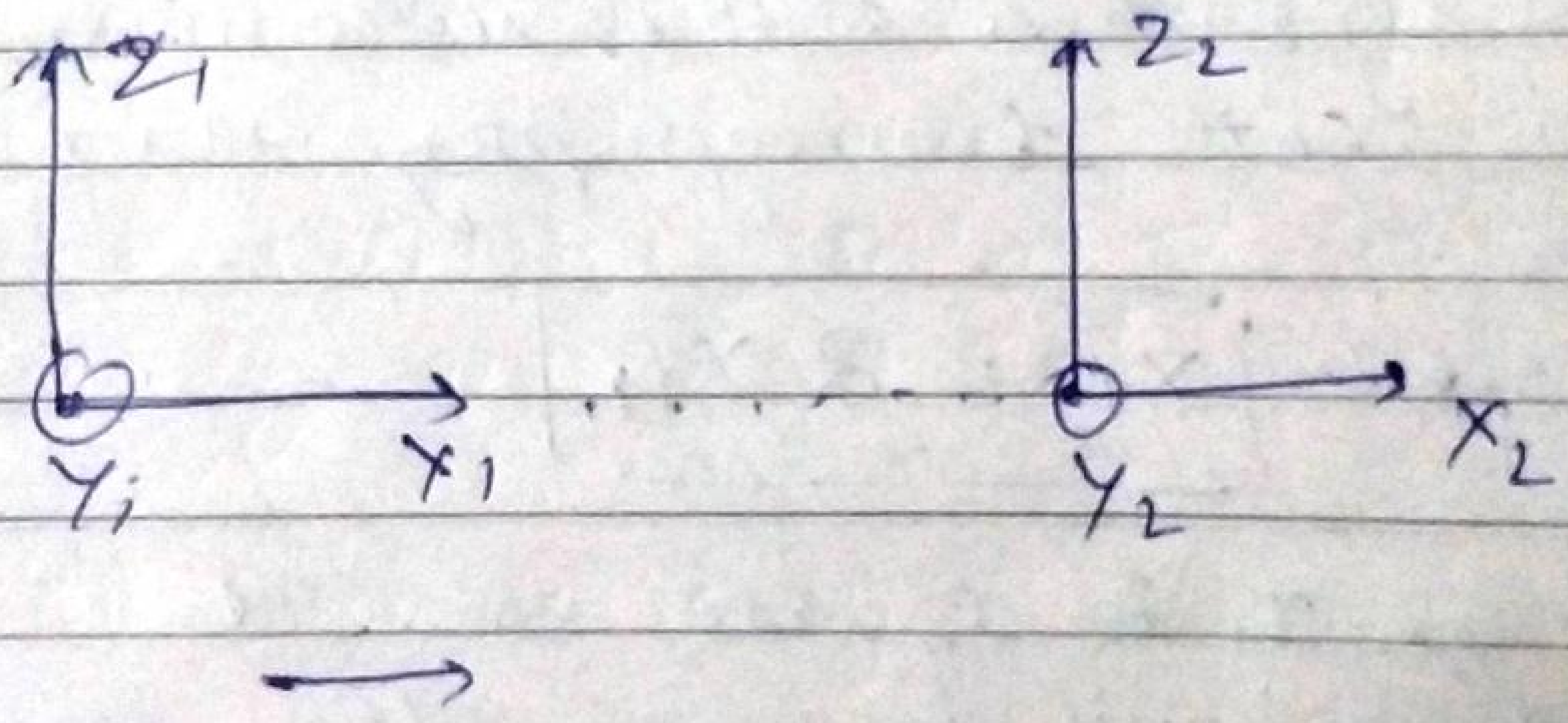
Homography 2 →

making the axis of ~~$\not\!\!X$~~ I_1 & I_2 to colinear i.e. epipoles at ∞ and epipolar lines become ll'e. and the transformed frame only be seperated by translation along x-axis.

initial



Final



translation $= (T, 0, 0)$

Let $R_{rect} = \begin{bmatrix} r_1^T \\ r_2^T \\ r_3^T \end{bmatrix}$ where $r_1^T = K^{-1} e_2$

$= \hat{t} = \dfrac{\vec{t}}{\|\vec{t}\|}$

& $r_2^T = \hat{t} \cdot [0\ 0\ 1]^T = [\hat{t}_x\ \hat{t}_y\ 0]^T$

where $\hat{t} = [\hat{t}_x\ \hat{t}_y\ \hat{t}_z]$

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$r_3^T = r_1^T \times r_2^T$ as Rrect is orthogonal

$\therefore$ Rect $\widehat{K^{-1}e_2} = \begin{bmatrix} r_1^T \\ r_2^T \\ r_3^T \end{bmatrix} \widehat{K^{-1}e_2} = \begin{bmatrix} \|\widehat{K^{-1}e_2}\|^2 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$

$\therefore$ image of the point $[1\ 0\ 0]^T =$

$K[I\ 0]\begin{bmatrix} 1 \\ 0 \\ 0 \\ 1 \end{bmatrix} = K\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} f_x \\ 0 \\ 0 \end{bmatrix} = f_x\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \Rightarrow$

point at ∞ in the image

This is precisely what we want i.e. epipole at ∞

So

we found homography

$$\boxed{H_2 = K\ \text{Rect}\ K^{-1}}$$

that takes $e_2 = [e_{2x}\ e_{2y}\ 1]^T$ to $[1\ 0\ 0]^T$ i.e. pt at ∞.

$\therefore$ Final x_{i1}, x_{i2}

$x_{i1} \rightarrow (K\ \text{Rrect}\ K^{-1})\, x_{i1}$

$x_{j2} \rightarrow (K\ \text{Rect}\ R\ K^{-1})\, x_{j2}$

Rotation R & R_{rect} corresponds to Homography H_1 & H_2 as they simply rotate the frame. Here frame are from same camera but from different angle which is definition of Homography. ~~Hence they are cal~~

Q(4)
$\rightarrow$

(a) Variables :-

Robot State $\Rightarrow$ $u_0, u_1, u_2, \ldots u_n$

where $u_i = [\, u_{xi} \cdot u_{yi} \;\; u_{\theta i} \,]^T$

$u_1, u_2, u_3 \ldots, u_n \rightarrow$ controls

typically $u_1 = [\Delta\Phi, T]^T$

$\Delta\phi$ and Move by T.

$l_1, l_2, l_3 \ldots, l_m \rightarrow$ landmarks

$l_i = [\, u_{mix} \,, \; u_{miy} \,]^T$

Motion Model

$$\hat{u}_{i+1} = f(\hat{u}_i, \cancel{u_{i+1}}) = \begin{bmatrix} \hat{u}_{xi} \\ \hat{u}_{yi} \\ \hat{u}_{\theta i} \end{bmatrix} + \begin{bmatrix} T\cos(\hat{u}_\theta + \Delta\phi) \\ T\sin(\hat{u}_\theta + \Delta\phi) \\ \Delta\phi \end{bmatrix}$$

$\downarrow$

typically from odometry

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SAM optimizes cost function

$$\sum_{i=0}^{n-1} \| f(\hat{u}_i, u_{i+1}) - u_{i+1} \|_2^2$$

$$+ \sum_{i=1}^{n} \sum_{K=1}^{m} \| \hat{z}_{ik} - z_{ik} \|_2^2 \rightarrow (4)$$

Linearising odometry term:-

$$OT = f(\hat{u}_i, u_{i+1}) - \hat{u}_{i+1} = F_i \delta \hat{u}_i - a_i$$

where $a_i = f(\hat{u}_i, u_{i+1})$

a_i is the odometry error term and F_i is the 3x3 motion Jacobian

Linearising measurement term:

$$MT = h(\hat{u}_i, \hat{u}_{mk}) + \frac{\partial h}{\partial u_i} \delta u_i \Big|_{\hat{u}_i} + \frac{\partial h}{\partial u_{mk}} \delta u_{mk} \Big|_{\hat{u}_{mk}} - z_{ik}$$

$$= h(u_i, u_{mk}) + H_{ik} \delta \hat{u}_i + J_{ik} \delta \hat{u}_{mk} - z_{ik}$$

$$= H_{ik} \delta \hat{u}_i + J_{ik} \delta u_{mk} - c_{ik}$$

where $c_{ik} = h(u_i - u_{mk})$ is the measurement and $u_i, u_{mk} \rightarrow$ current estimate of u_i, u_{mk}

& if it is correct $c_{ik} \rightarrow 0$

So, $MT = H_{ik} \delta \hat{u}_i + J_{k} \delta \hat{u}_{mk} - c_{ik}$

Hence, eqn (4) becomes:-

$$\sum_{i=1}^{n-1} \| F_i \, \delta\hat{u}_i - a_i \|_2^2 + \sum_{i=1}^{m} \sum_{k=1}^{n} \| H_{ik} \, \delta\hat{u}_i + J_{ik} \, \delta\hat{l}_k - c_{ik} \|_2^2 \quad -(5)$$

where F_i is 3x3 motion Jacobian

H_{ik} is 3x3 landmark Jacobian w.r.t. poses &

J_{ik} is 3x3 landmark Jacobian w.r.t. landmark

rewriting eqn (5)

$$\underbrace{\begin{bmatrix} F_1 & 0 & \cdots & & & 0 \\ H_{11} & 0 & & 0 & J_{11} & 0 \\ H_{12} & 0 & & 0 & 0 \; J_{12} & 0 \\ \vdots & & & & & \\ H_{1m} & 0 & & & & J_{1m} \\ 0 & F_2 & & & & \\ 0 & H_{21} & & 0 & J_{21} & 0 \\ \vdots & & & & & \\ 0 & H_{2m} & & 0 & 0 & J_{2m} \\ \vdots & & & & & \\ 0 & & & F_N & 0 & 0 \\ 0 & & & H_{M1} & J_{M1} & 0 \\ \vdots & & & & & \\ 0 & & & H_{NM} & & J_{NM} \end{bmatrix}}_{m(n+1) \times (m+1)} \underbrace{\begin{bmatrix} \delta\hat{u}_1 \\ \delta\hat{u}_2 \\ \\ \delta\hat{u}_n \\ \\ \\ \delta u_{nm} \end{bmatrix}}_{(n+m) \times 1} = \begin{bmatrix} a_1 \\ c_1 \\ c_2 \\ \\ c_m \\ \vdots \\ c_{2m} \\ a_n \\ c_{N1} \\ c_{NM} \end{bmatrix}$$

(c)(a)

(b) Given RGB images across trajectory

~~$y = f(x)$~~

Let the starting point of trajectory will be X_0.

i.e. $X_0 = \begin{bmatrix} x_0 \\ y_0 \\ z_0 \\ 1 \end{bmatrix}$ ~~or in homogeneous coordinates~~

Firstly we will take two ~~con~~ consecuti trajectory images. and using SIFT for image matching we will find the correspon points in the two image.

~~be~~ Let Corresponding points be

$$\{x_i, y_i\}_{i=1}^{n} \Leftrightarrow \{x_i', y_i'\}_{i=1}^{n}$$

~~So~~ So after finding the points we are SVD to find ~~for~~ Fundamental Matrix between the two images.

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As we find Fundamental Matrix F

& so $\boxed{X^T F X' = 0}$

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Using F matrix and triangulation, we can now get a rough estimation of landmark postures.

So now we know F and K we can compute e and qr decomposition, which will give us R and T estimations between camera postures. We obtain four potential camera stances. However we can estimate poses when neither camera has the point on the front. We now have an approximate estimatic of for the camera postures and 3D coordin

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for the same landmark locations, and we will us bundle adjustment to spacify these coordinates.