Slides and example codes are available:
https://github.com/mint-lab/cv_tutorial

Image Geometry

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Review) Camera Pose Estimation

- Example) **Pose estimation (book)**

- Load the cover image
- Extract ORB features
- Build **3D object points** $\mathbf{X}_1, \mathbf{X}_2, \ldots$

Pass tentative matches

Pass correct matches

- Grab an input image
- Extract **ORB features** $\mathbf{x}_1, \mathbf{x}_2, \ldots$
- Match them to the object features

[Outlier Rejection]
- Remove wrong matches using `cv.solvePnPRansac()`

[Camera Pose Estimation]
- Estimate camera pose using `cv.solvePnP()`

[Camera Pose Update]
- Intrinsic: K (given and fixed)
- Extrinsic: R, $\mathbf{t}$

Draw the box using `cv::projectPoints()`

Review) Camera Pose Estimation

(∵ unknown, autofocus)

- Example) **Pose estimation (book) + camera calibration**

- Load the cover image
- Extract ORB features
- Build **3D object points** $\mathbf{X}_1, \mathbf{X}_2, \ldots$

Pass tentative matches

Pass correct matches

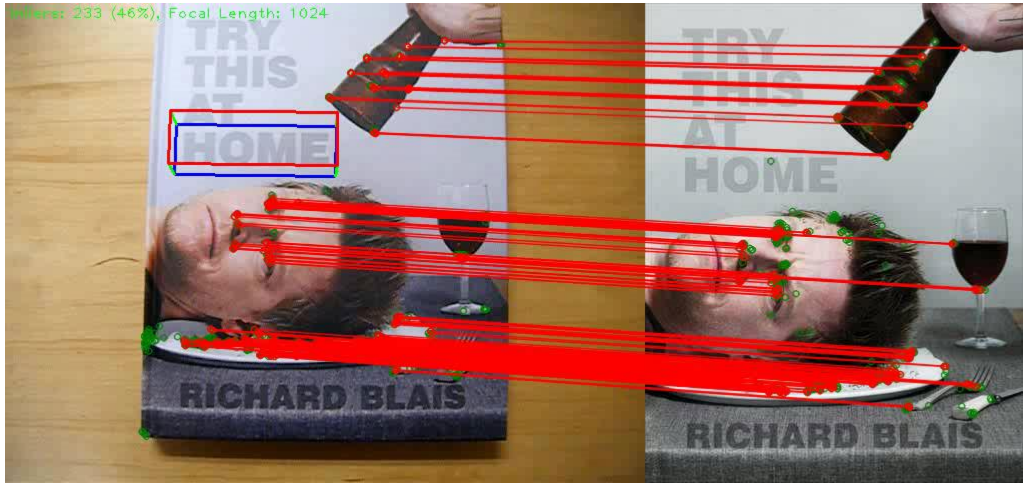
- Grab an input image
- Extract **ORB features** $\mathbf{x}_1, \mathbf{x}_2, \ldots$
- Match them to the object features

[Outlier Rejection]
- Remove wrong matches using `cv.solvePnPRansac()`

[Camera Pose Estimation]
- Estimate camera parameters using `cv.calibrateCamera()`

[Camera Pose Update]
- Intrinsic: K (initially known)
- Extrinsic: R, $\mathbf{t}$

Draw the box using `cv.projectPoints()`



Review) Camera Pose Estimation

(∵ unknown)

- Example) **Pose estimation (book) + camera calibration – initially given** K

- Load the cover image
- Extract ORB features
- Build **3D object points** $\mathbf{X}_1, \mathbf{X}_2, \ldots$

Pass tentative matches

- Grab an input image
- Extract **ORB features** $\mathbf{x}_1, \mathbf{x}_2, \ldots$
- Match them to the object features

[Outlier Rejection]
- Remove wrong matches using `cv.findHomography()`

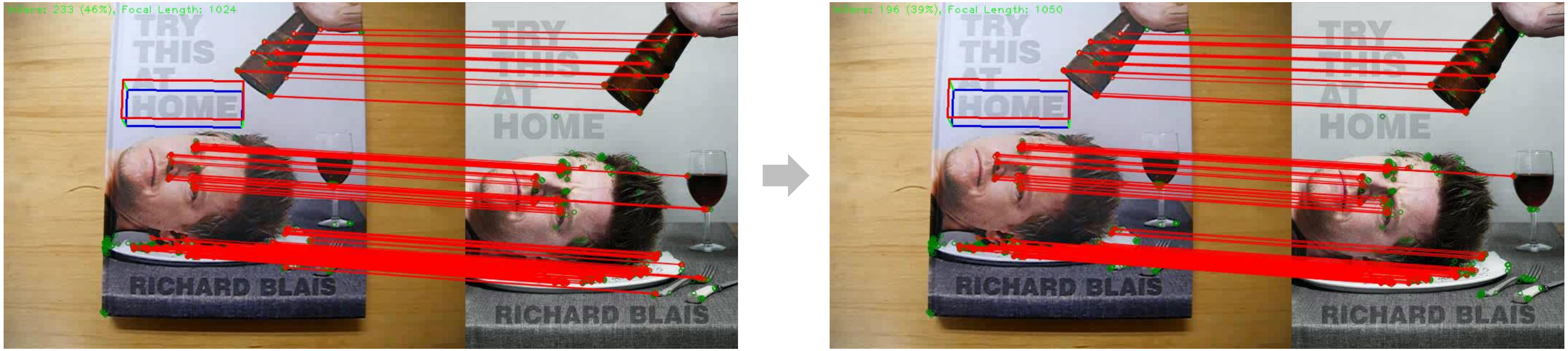
Free from K

Pass correct matches

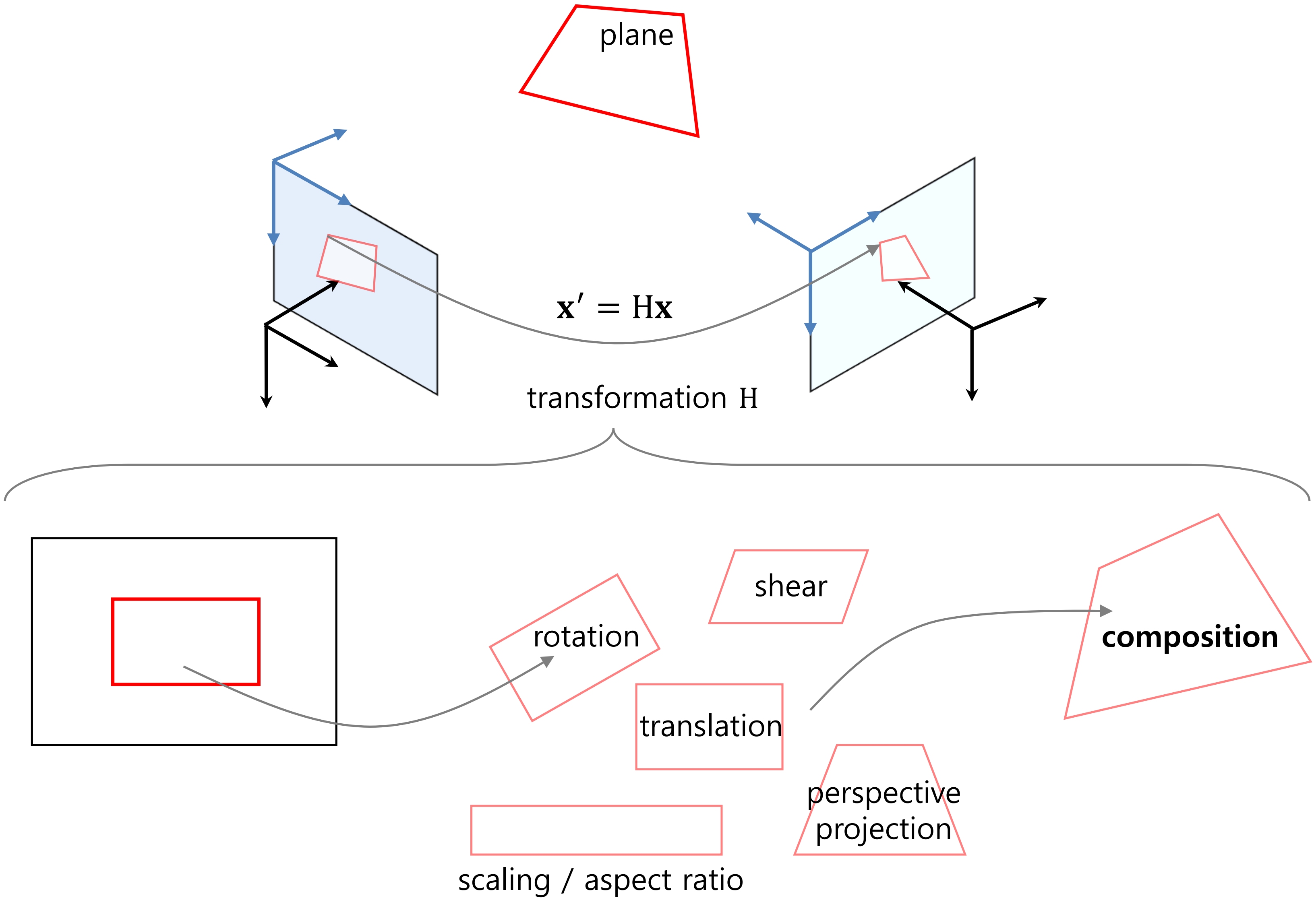
[Camera Pose Estimation]
- Estimate camera parameters using `cv.calibrateCamera()`

[Camera Pose Update]
- Intrinsic: K (initially known)
- Extrinsic: R, $\mathbf{t}$

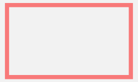
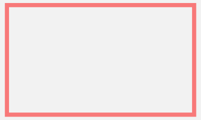
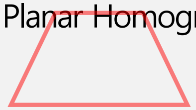
Draw the box using `cv.projectPoints()`



Planar Homography



Planar Homography

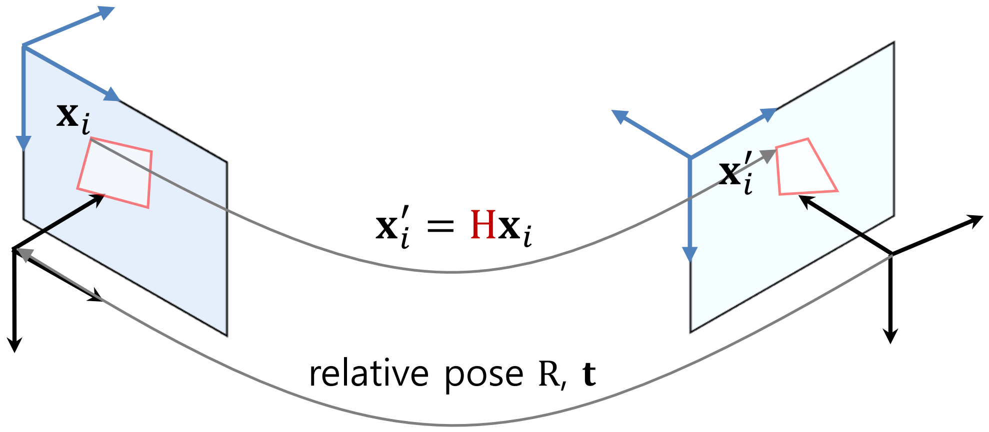
	**Euclidean Transform** (a.k.a. Rigid Transform) 	**Similarity Transform** 	**Affine Transform** 	**Projective Transform** (a.k.a. Planar Homography) 
Matrix Forms H	$\begin{bmatrix} \cos\theta & -\sin\theta & t_x \\ \sin\theta & \cos\theta & t_y \\ 0 & 0 & 1 \end{bmatrix}$	$\begin{bmatrix} s\cos\theta & -s\sin\theta & t_x \\ s\sin\theta & s\cos\theta & t_y \\ 0 & 0 & 1 \end{bmatrix}$	$\begin{bmatrix} a_{11} & a_{12} & t_x \\ a_{21} & a_{22} & t_y \\ 0 & 0 & 1 \end{bmatrix}$	$\begin{bmatrix} a_{11} & a_{12} & t_x \\ a_{21} & a_{22} & t_y \\ v_1 & v_2 & 1 \end{bmatrix}$
DoF	3	4	6	8
Transformations - rotation - translation - scaling - aspect ratio - shear - perspective projection	 O O X X X X	 O O O X X X	 O O O O O X	 O O O O O O
Invariants - length - angle - ratio of lengths - parallelism - incidence - cross ratio	 O O O O O O	 X O O O O O	 X X X O O O	 X X X X O O

OpenCV Functions			`cv::getAffineTransform()`
			`cv::estimateRigidTransform()`
			-
			`cv::warpAffine()`
				`cv::getPerspectiveTransform()`
				-
				`cv::findHomography()`
				`cv::warpPerspective()`

Note) Similarly **3D transformations** (3D-3D geometry) are represented as **4x4 matrices**.

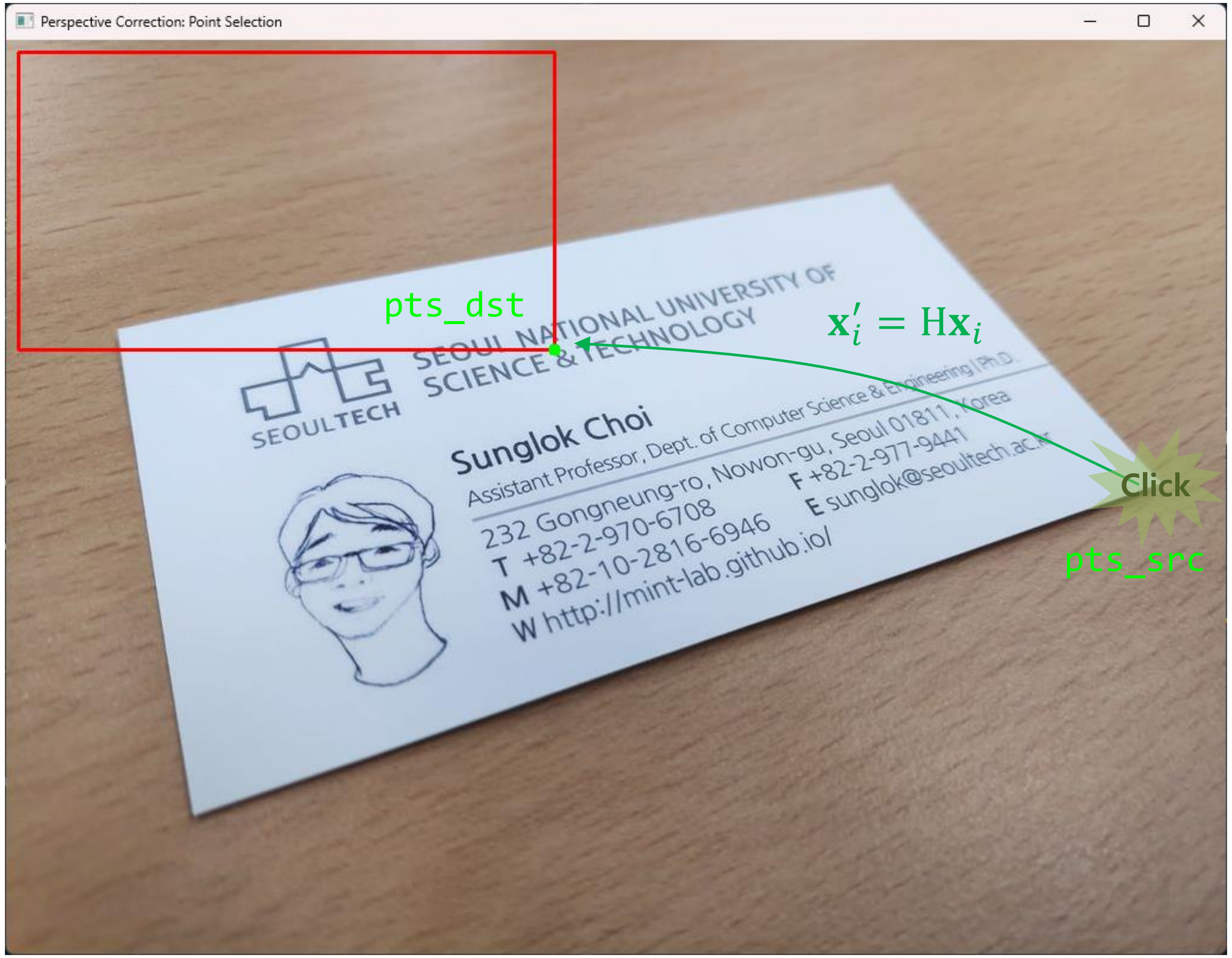
Planar Homography

- **Planar homography estimation**
  - Unknown: Planar homography H (8 DoF)
  - Given: Point correspondence $(\mathbf{x}_1, \mathbf{x}'_1)$, …, $(\mathbf{x}_n, \mathbf{x}'_n)$
  - Constraints: n x projective transformation $\mathbf{x}'_i = \mathrm{H}\mathbf{x}_i$
  - Solutions (n ≥ 4) → 4-point algorithm
    - OpenCV: `cv::getPerspectiveTransform()` and `cv::findHomography()`
    - Note) More simplified transformations need less number of minimal correspondence.
      - Affine (n ≥ 3), similarity (n ≥ 2), Euclidean (n ≥ 2)
  - Note) Planar homography can be decomposed as relative camera pose.
    - OpenCV `cv::decomposeHomographyMat()`
    - The decomposition needs to know camera matrices.



Planar Homography

- Example) **Perspective distortion correction**



Planar Homography

- Example) **Perspective distortion correction**

```python
def mouse_event_handler(event, x, y, flags, param):
    if event == cv.EVENT_LBUTTONDOWN:
        param.append((x, y))

if __name__ == '__main__':
    img_file = '../data/sunglok_card.jpg'
    card_size = (450, 250)
    offset = 10

    # Prepare the rectified points
    pts_dst = np.array([[0, 0], [card_size[0], 0], [0, card_size[1]], [card_size[0], card_size[1]]])

    # Load an image
    img = cv.imread(img_file)

    # Get the matched points from mouse clicks
    pts_src = []
    cv.namedWindow('Perspective Correction: Point Selection')
    cv.setMouseCallback('Perspective Correction: Point Selection', mouse_event_handler, pts_src)
    while len(pts_src) < 4:
        img_display = img.copy()
        cv.rectangle(img_display, (offset, offset), (offset + card_size[0], offset + card_size[1]), (0, 0, 255), 2)
        idx = min(len(pts_src), len(pts_dst))
        cv.circle(img_display, offset + pts_dst[idx], 5, (0, 255, 0), -1)
        cv.imshow('Perspective Correction: Point Selection', img_display)
        key = cv.waitKey(10)
```

Planar Homography

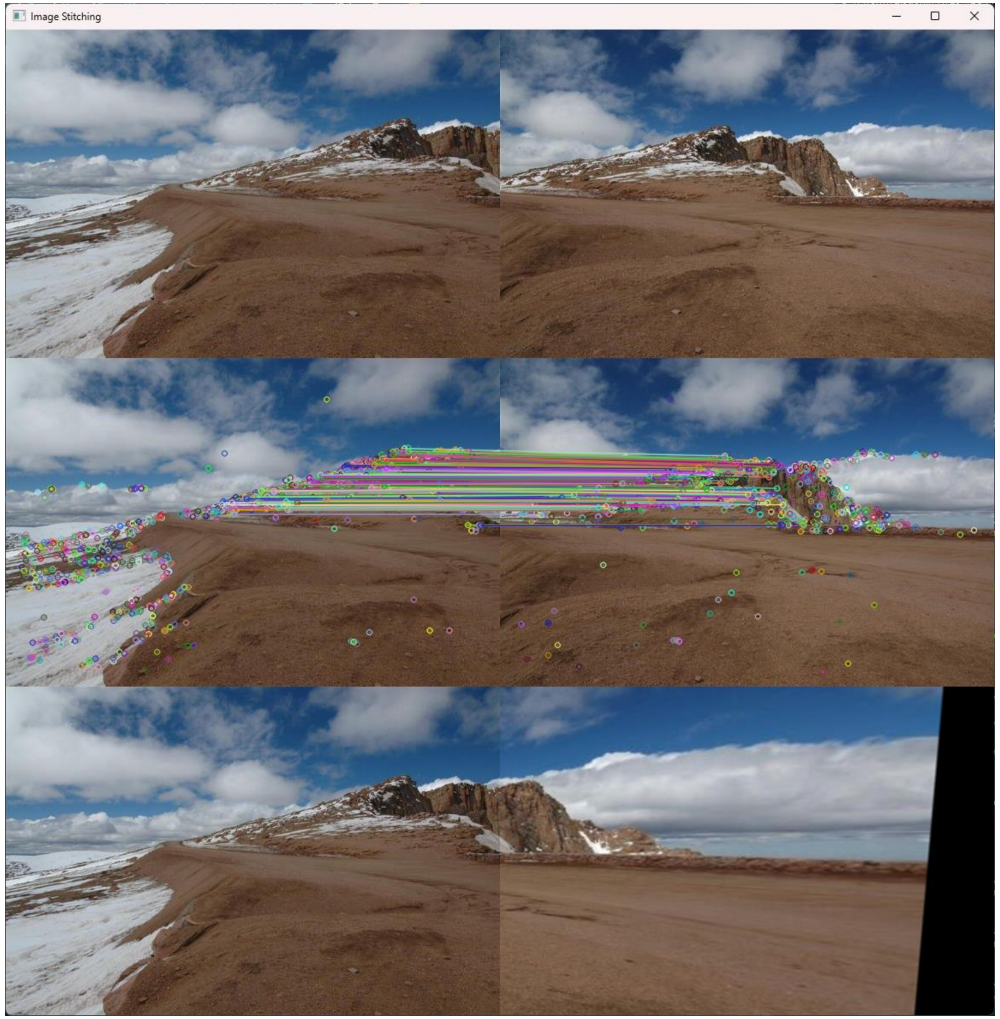
- Example) **Perspective distortion correction**

```python
if __name__ == '__main__':
    img_file = '../data/sunglok_card.jpg'
    card_size = (450, 250)
    offset = 10

    # Prepare the rectified points
    pts_dst = np.array([[0, 0], [card_size[0], 0], [0, card_size[1]], [card_size[0], card_size[1]]])

    # Load an image
    img = cv.imread(img_file)

    # Get the matched points from mouse clicks
    pts_src = []
    ...

    if len(pts_src) == 4:
        # Calculate planar homography and rectify perspective distortion
        H, _ = cv.findHomography(np.array(pts_src), pts_dst)
        img_rectify = cv.warpPerspective(img, H, card_size)

        # Show the rectified image
        cv.imshow('Perspective Correction: Rectified Image', img_rectify)
        cv.waitKey(0)

    cv.destroyAllWindows()
```

Planar Homography

- Example) **Planar Image Stitching**

```python
# Load two images
img1 = cv.imread('../data/hill01.jpg')
img2 = cv.imread('../data/hill02.jpg')

# Retrieve matching points
brisk = cv.BRISK_create()
keypoints1, descriptors1 = brisk.detectAndCompute(img1, None)
keypoints2, descriptors2 = brisk.detectAndCompute(img2, None)

fmatcher = cv.DescriptorMatcher_create('BruteForce-Hamming')
match = fmatcher.match(descriptors1, descriptors2)

# Calculate planar homography and merge them
pts1, pts2 = [], []
for i in range(len(match)):
    pts1.append(keypoints1[match[i].queryIdx].pt)
    pts2.append(keypoints2[match[i].trainIdx].pt)
pts1 = np.array(pts1, dtype=np.float32)
pts2 = np.array(pts2, dtype=np.float32)

H, inlier_mask = cv.findHomography(pts2, pts1, cv.RANSAC)
img_merged = cv.warpPerspective(img2, H, (img1.shape[1]*2, img1.shape[0]))
img_merged[:,:img1.shape[1]] = img1 # Copy

# Show the merged image
img_matched = cv.drawMatches(img1, keypoints1, img2, keypoints2, match, None, None, None,
```



Planar Homography

- Example) **2D Video Stabilization**

```
# Open a video and get the reference image and feature points
video = cv.VideoCapture('../data/traffic.avi')

_, gray_ref = video.read()
if gray_ref.ndim >= 3:
    gray_ref = cv.cvtColor(gray_ref, cv.COLOR_BGR2GRAY)
pts_ref = cv.goodFeaturesToTrack(gray_ref, 2000, 0.01, 10)

# Run and show video stabilization
while True:
    # Read an image from 'video'
    valid, img = video.read()
    if not valid:
        break
    if img.ndim >= 3:
        gray = cv.cvtColor(img, cv.COLOR_BGR2GRAY)
    else:
        gray = img.copy()

    # Extract optical flow and calculate planar homography
    pts, status, err = cv.calcOpticalFlowPyrLK(gray_ref, gray, pts_ref, None)
    H, inlier_mask = cv.findHomography(pts, pts_ref, cv.RANSAC)

    # Synthesize a stabilized image
    warp = cv.warpPerspective(img, H, (img.shape[1], img.shape[0]))
```

A shaking CCTV video

Planar Homography

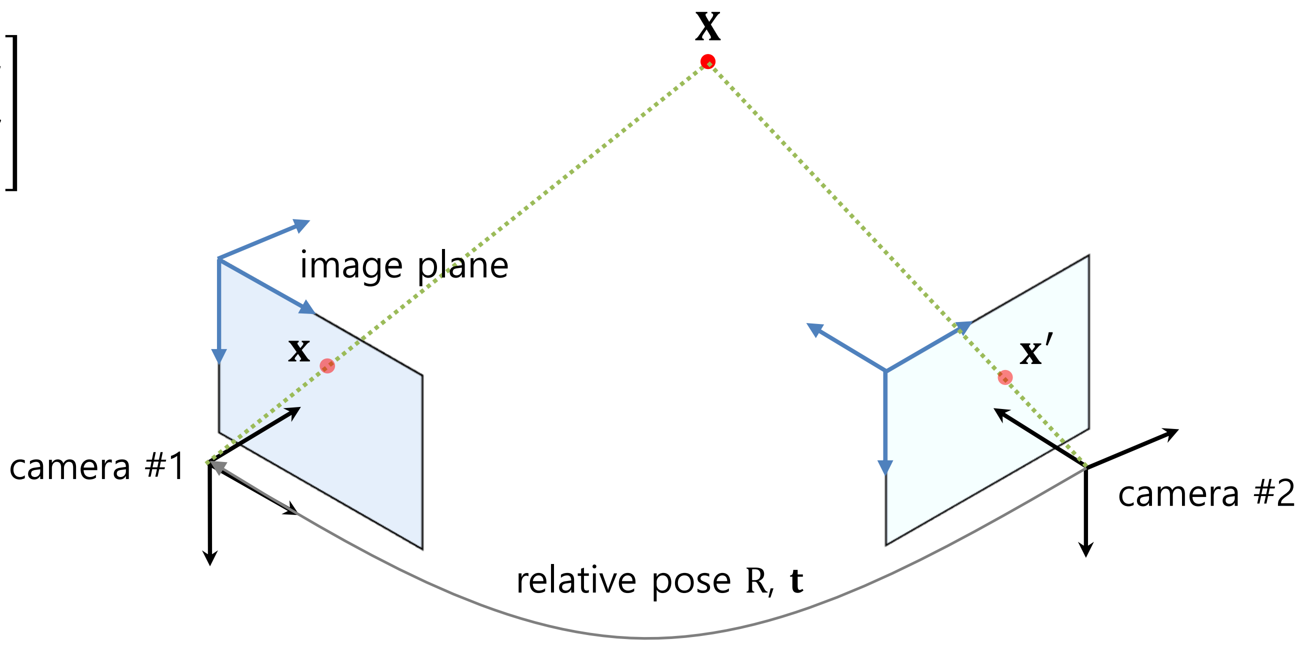
- Assumption) **A <u>plane</u> is observed by two views.**
  - Perspective distortion correction: Okay
  - Image stitching: Approximation (distance ≫ depth variation)
  - Video stabilization: Approximation (small motion)

Triangulation

- **Triangulation** (point localization)
  - Unknown: Position of a 3D point $\mathbf{X}$ (3 DoF)
  - Given: Point correspondence $(\mathbf{x}, \mathbf{x}')$, camera matrices $(\mathrm{K}, \mathrm{K}')$, and relative pose $(\mathrm{R}, \mathbf{t})$
  - Constraints: $\mathbf{x} = \mathrm{K}\,[\,\mathrm{I}\,|\,\mathbf{0}\,]\,\mathbf{X}$, $\mathbf{x}' = \mathrm{K}'\,[\,\mathrm{R}\,|\,\mathbf{t}\,]\,\mathbf{X}$
  - Solution (OpenCV): `cv::triangulatePoints()`
    - Special case) Stereo cameras

$$\mathrm{R} = \mathrm{I}_{3\times3},\ \mathbf{t} = \begin{bmatrix} -b \\ 0 \\ 0 \end{bmatrix},\ \text{and } \mathrm{K} = \mathrm{K}' = \begin{bmatrix} f & 0 & c_x \\ 0 & f & c_y \\ 0 & 0 & 1 \end{bmatrix}$$

$$\therefore Z = \frac{f}{x - x'} b$$



Triangulation

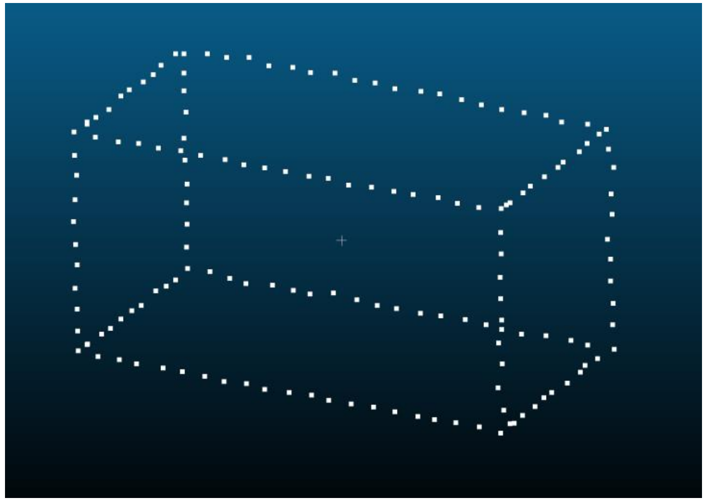
- Example) Triangulation

```
import cv2 as cv
import numpy as np

f, cx, cy = 1000., 320., 240.
pts0 = np.loadtxt('../data/image_formation0.xyz')[:,:2]
pts1 = np.loadtxt('../data/image_formation1.xyz')[:,:2]
output_file = '../data/triangulation.xyz'

# Estimate relative pose of two view
F, _ = cv.findFundamentalMat(pts0, pts1, cv.FM_8POINT)
K = np.array([[f, 0, cx], [0, f, cy], [0, 0, 1]])
E = K.T @ F @ K
_, R, t, _ = cv.recoverPose(E, pts0, pts1)

# Reconstruct 3D points (triangulation)
P0 = K @ np.eye(3, 4, dtype=np.float32)
Rt = np.hstack((R, t))
P1 = K @ Rt
X = cv.triangulatePoints(P0, P1, pts0.T, pts1.T)
X /= X[3]
X = X.T

# Write the reconstructed 3D points
np.savetxt(output_file, X)
```

$\because \mathbf{x} = \mathrm{K}\left[\mathrm{I} \,|\, \mathbf{0}\right]\mathbf{X}$

$\because \mathbf{x}' = \mathrm{K}'\left[\mathrm{R} \,|\, \mathbf{t}\right]\mathbf{X}$

Result: `data/triangulation.xyz`



CloudCompare