HW2 COLMAP & Camera Relocalization

Due: 2025/10/13 11:59 AM

3DCV 2025

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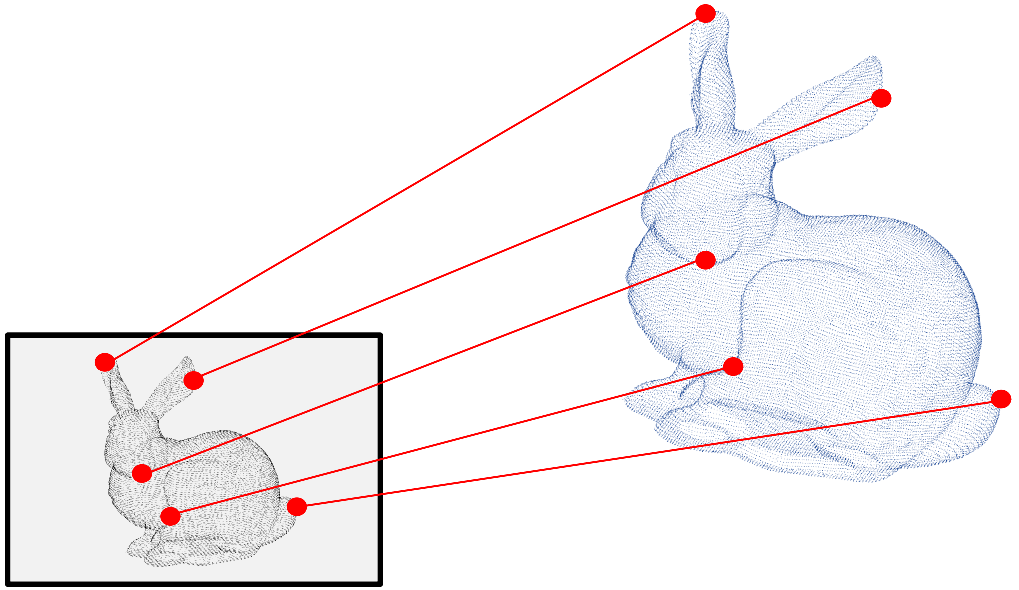
GitHub Classroom: https://classroom.github.com/a/lyfclldM

Outline

The goal of this homework is to gain practical experience in 3D reconstruction (Problem 1) and to develop an understanding of how a camera-relocalization system works (Problem 2).

- Introduction to COLMAP
- Problem 1: COLMAP (Q1-1 ~ Q1-2)
- Introduction to Camera Relocalization
- Dataset
- Problem 2: Camera Relocalization (Q2-1 ~ Q2-2)
- Grading Policy

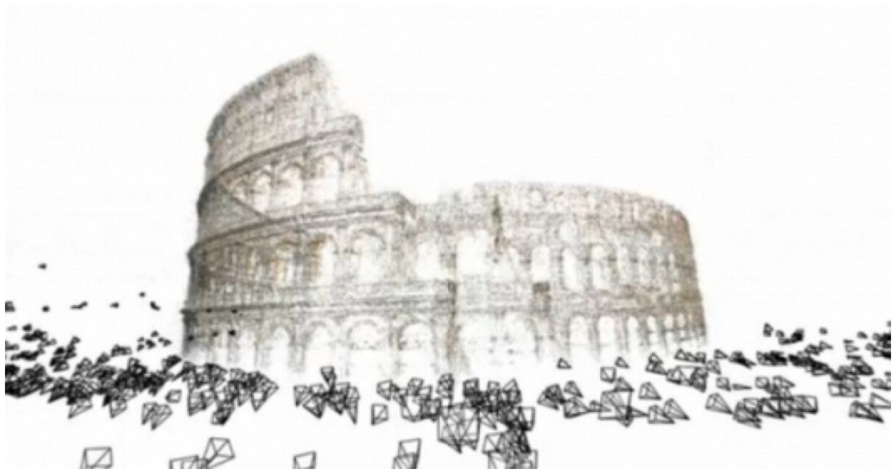


Introduction to COLMAP

Structure from Motion: Recover both the 3D scene structure (3D point cloud) and camera motion (camera poses) from a set of images.

Images

Structure from Motion

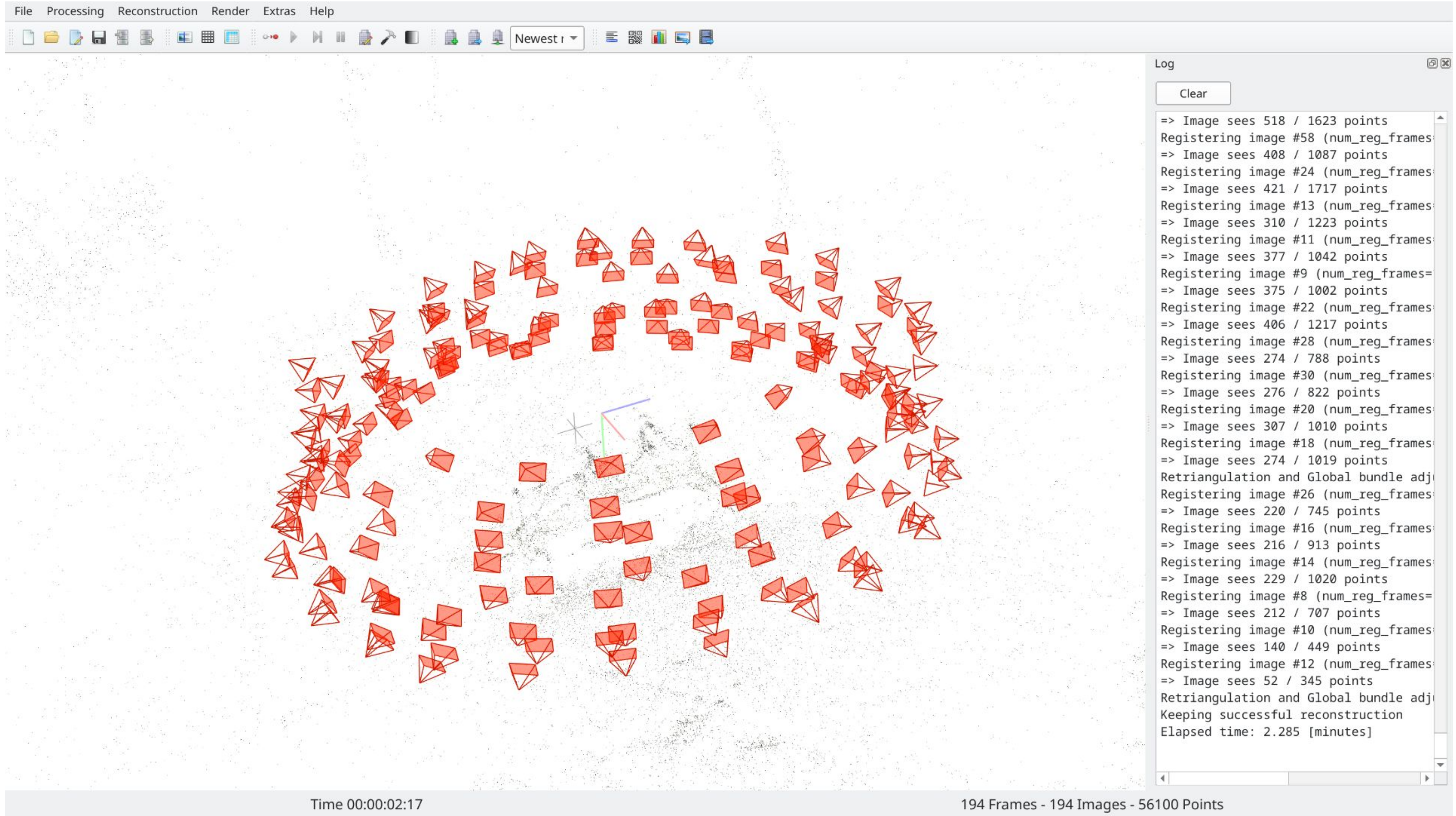


Reconstruction results

Introduction to COLMAP

COLMAP: An open-source software for Structure-from-Motion and Multi-View Stereo.

Documentation: https://colmap.github.io/



Problem 1

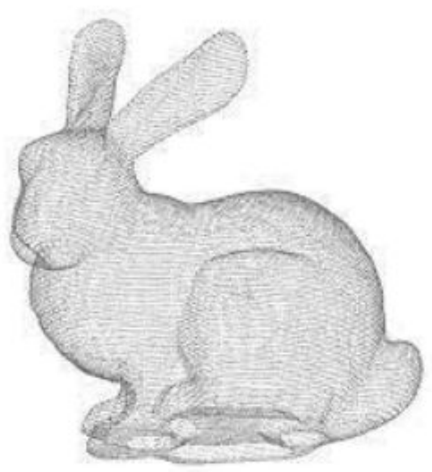
<u>Q1-1</u> Try using COLMAP with your own data! Please capture a video of a scene **on the NTU campus** using your phone or camera. Then use COLMAP to perform Structure from Motion. Show the reconstruction results in the COLMAP GUI.

Notes:

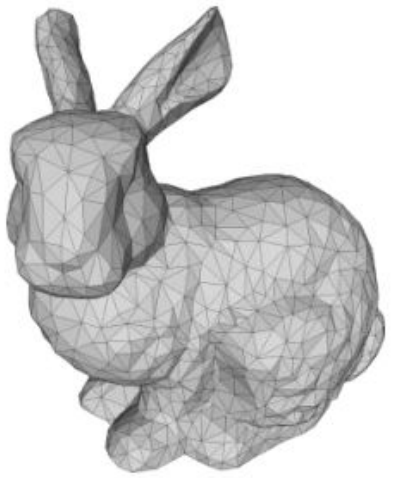
- Any scene on the campus is allowed, e.g. outdoor sculpture or indoor classroom.
- The dense reconstruction step in COLMAP is not required. Performing sparse reconstruction is sufficient.

Problem 1

<u>Q1-2</u> Convert the output point cloud into a 3D triangle mesh model. This can be done using appropriate 3D processing software. Try to make the mesh quality as good as possible. Provide a description of the software tools and methods you applied in the process.



Point cloud



Mesh

Report for Problem 1

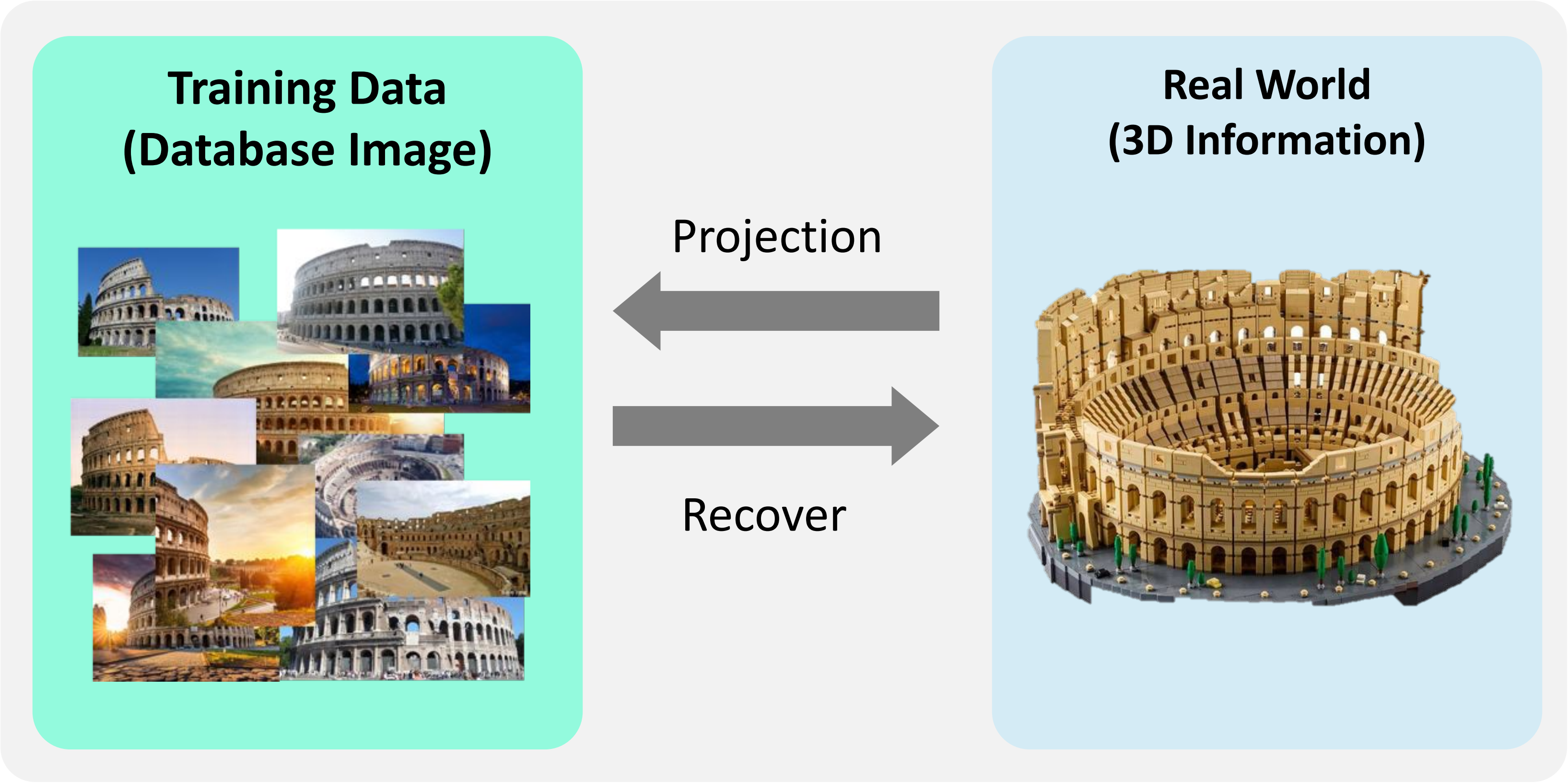
- In the report, briefly explain your method in each step, and provide screenshots of your results.
- Demonstrate your data and results in a video and provide the **YouTube link**.
- In the uploaded video, first show the full video of the scene you captured. For Q1-1, show the reconstruction results in the COLMAP GUI. For Q1-2, show the mesh conversion results.

Introduction to Camera Relocalization

Camera Relocalization: Determine the camera pose from the visual scene representation.

In other words, the scene is **seen** (and modeled) **beforehand**. Now, given a query image that is taken is this environment, we are able to find out where this image is taken.

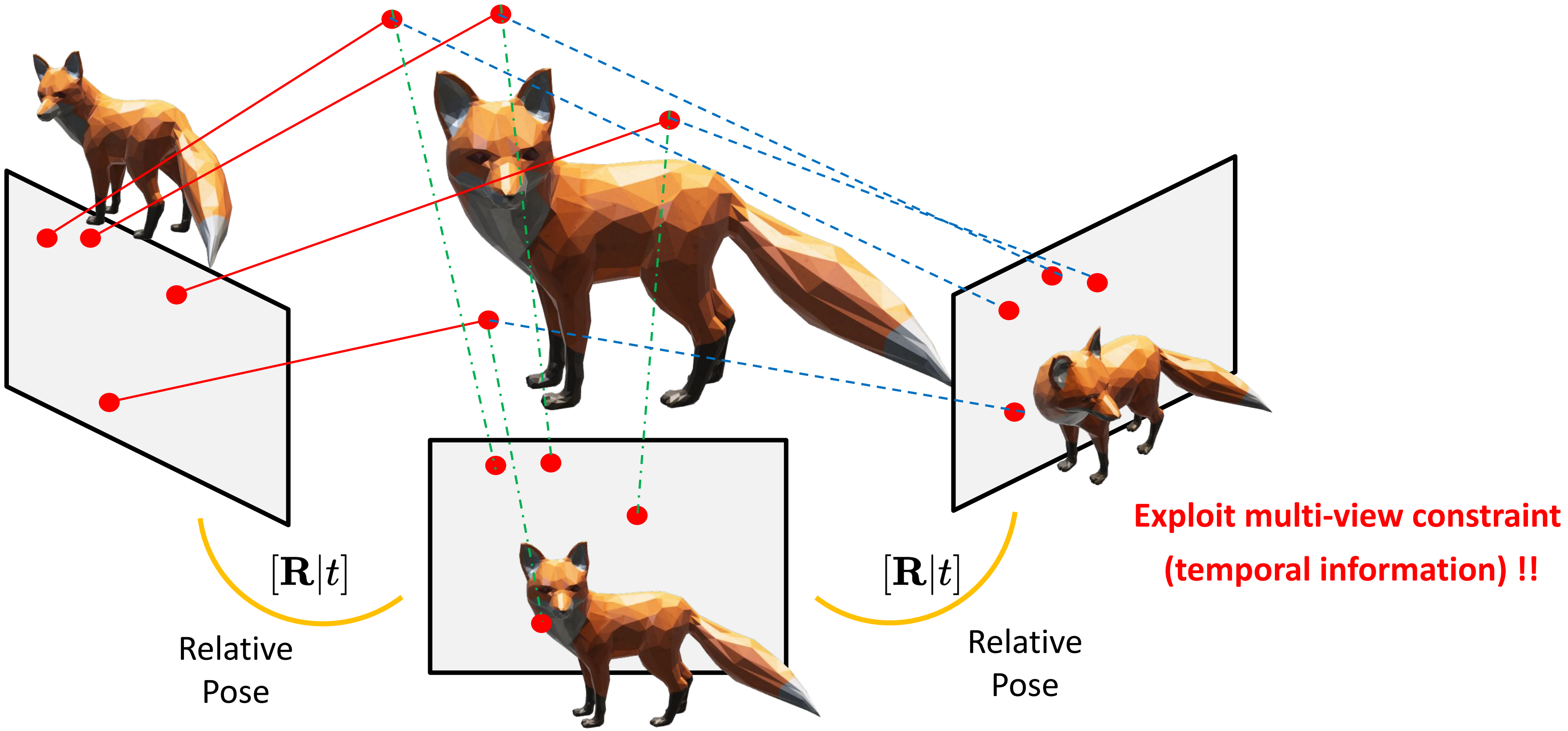
Query Image



Introduction to Camera Relocalization

One-shot relocalization: focus on a finding the pose of still image.

Temporal camera relocalization: estimates the poses of every frame in the video sequence.



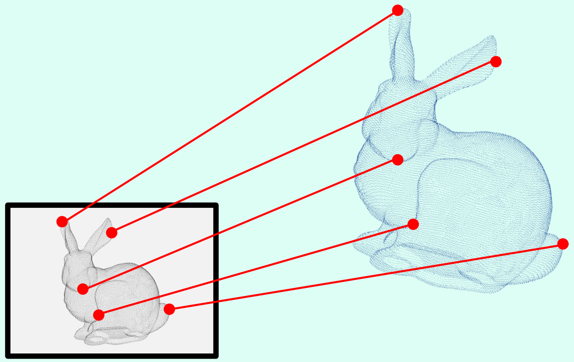
Methodology

Common strategies for camera relocalization. Note that there are some approaches utilize hybrid models to increase the efficiency and robustness.

Metric localization can only be achieved by machine (or deep) learning models.

2D-3D Matching Localization

3D scene models with local feature descriptors



Metric Localization (Absolute Pose Regression)

regresses the position and orientation of the camera

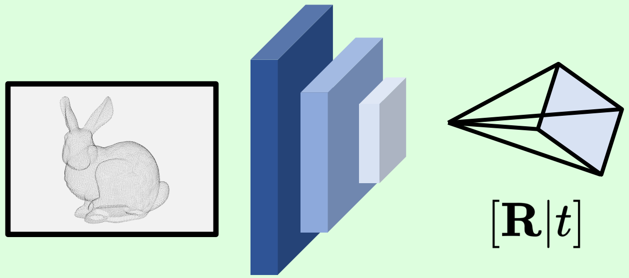
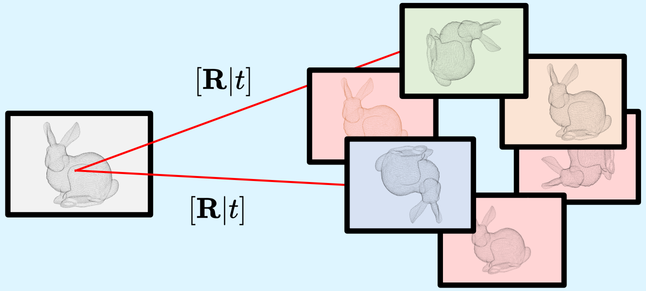


Image Retrieval Localization

pose approximation from top-k similar images



Welcome to the NTU Front Gate

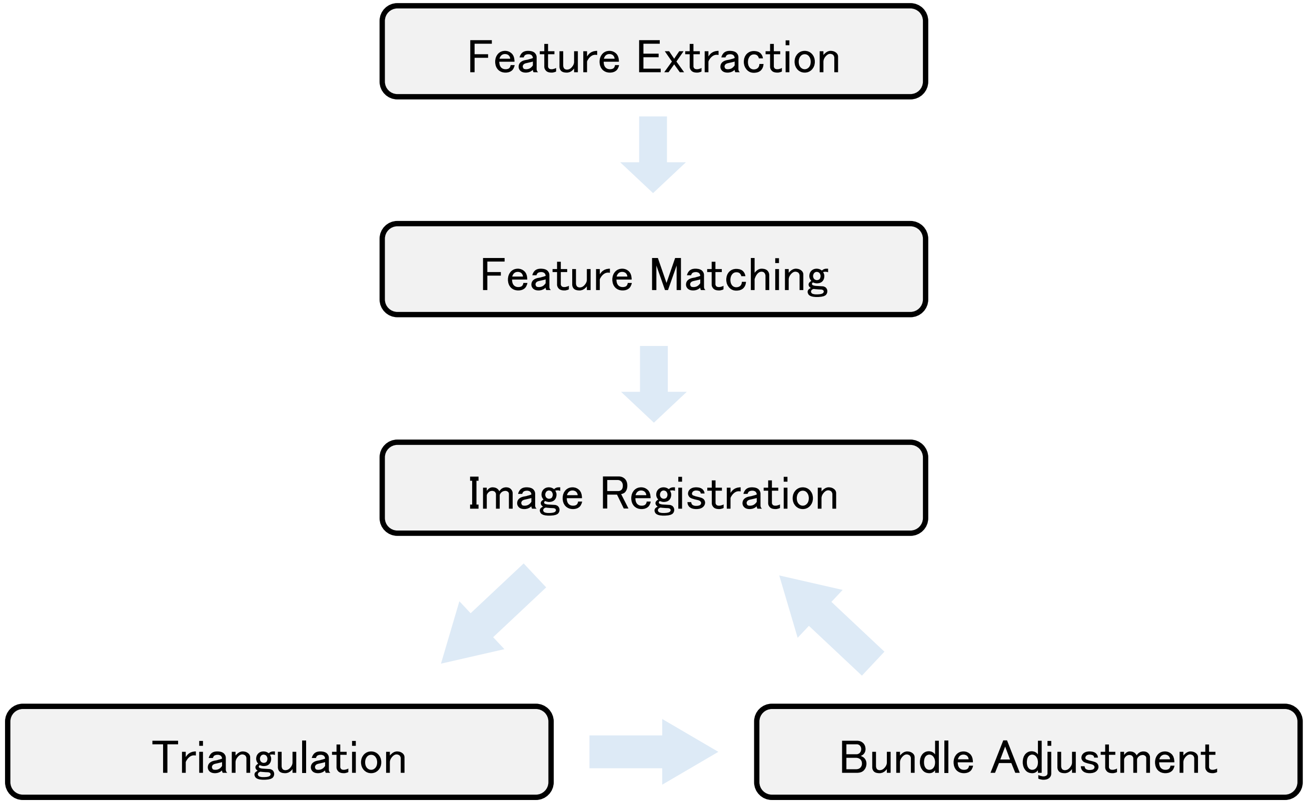
We collect multiple images of the NTU front gate, and reconstruct its 3D point cloud model via structure from motion.

About Dataset

293 color images (1920x1080x3): 163 images for training, 130 images for testing

111,518 points (in world coordinate) with 682,467 local image descriptors

Dataset images



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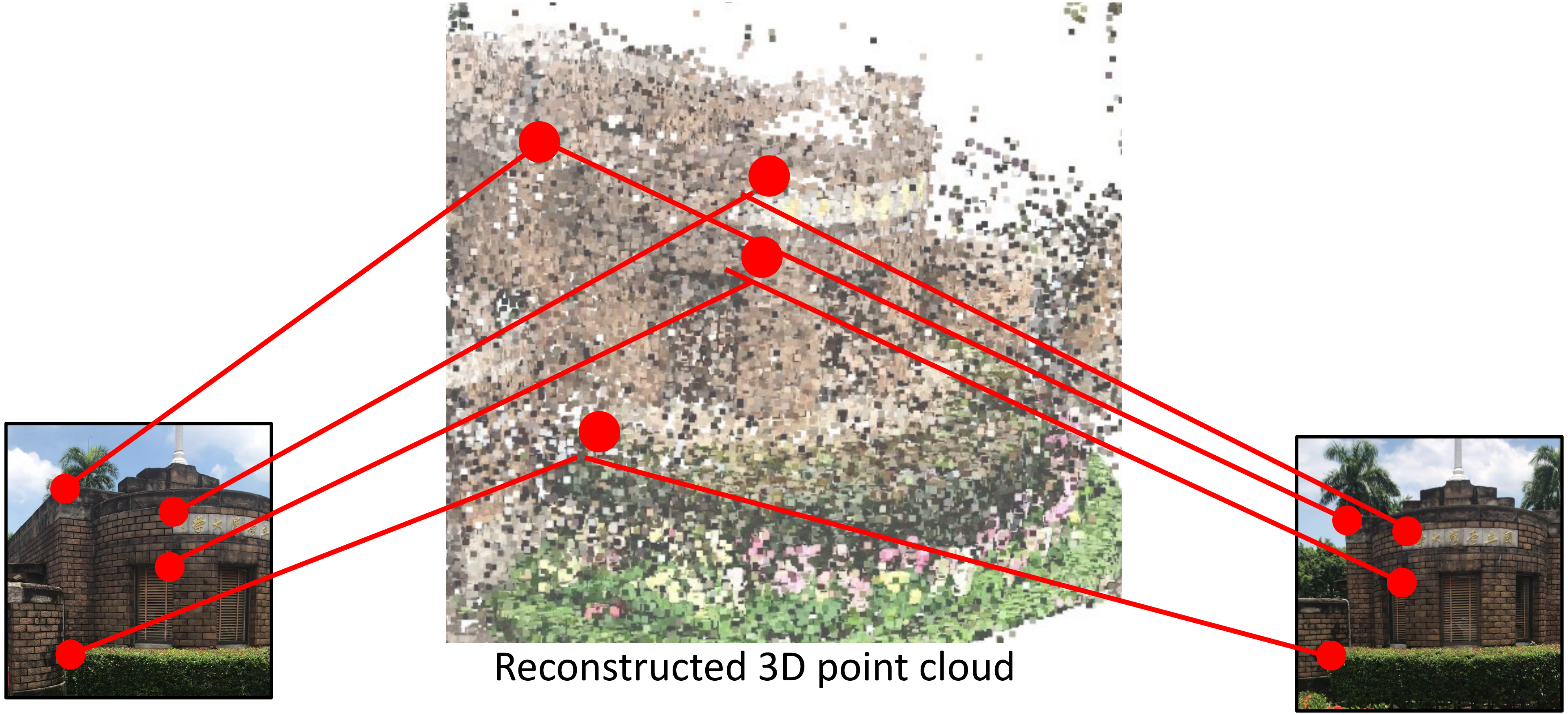


Reconstructed 3D point cloud

Data/image.pkl

⚠️ The pose of an image is represented as the projection **from world to the camera** coordinate system. That is, p=K[R|T]X.

Camera Position(x,y,z)

Rotation (in quaternion)

	IMAGE_ID	NAME	TX	TY	TZ	QW	QX	QY	QZ
0	1	train_img100.jpg	-3.12923	-0.273371	3.17218	0.969363	-0.003488	0.244797	0.019927
1	2	train_img104.jpg	-3.10598	-0.264036	3.12049	0.972423	-0.005048	0.232322	0.019880
2	3	train_img108.jpg	-3.06986	-0.270274	3.08285	0.975032	-0.004203	0.221007	0.021220
3	4	train_img112.jpg	-3.02027	-0.290710	3.07195	0.976940	-0.003627	0.212336	0.022091
4	5	train_img116.jpg	-2.98028	-0.307973	3.05439	0.979017	-0.002989	0.202524	0.022389
...	...	...	...	...	...	...	...	...	...
288	289	valid_img75.jpg	-2.86676	-0.366566	3.79563	0.931094	0.002295	0.363172	0.034118
289	290	valid_img80.jpg	-2.86618	-0.323873	3.72239	0.937160	-0.001973	0.347476	0.031431
290	291	valid_img85.jpg	-2.91426	-0.300918	3.59808	0.945271	-0.004261	0.325035	0.028210
291	292	valid_img90.jpg	-2.99320	-0.267023	3.46717	0.954254	-0.004443	0.298019	0.023733
292	293	valid_img95.jpg	-3.08001	-0.259334	3.30072	0.962891	-0.003862	0.269045	0.021006

293 rows × 9 columns

⚠️ Note that the order is (QW, QX, QY, QZ)

Data/point_desc.pkl

point_desc.pkl

Source Info

128D Descriptors

	POINT_ID	IMAGE_ID	XY	DESCRIPTORS
0	1	1	[94.94650268554688, 284.02899169921875]	[46, 43, 12, 11, 10, 5, 19, 37, 24, 16, 8, 9, ...
1	1	2	[99.05780029296875, 290.6889953613281]	[39, 42, 34, 14, 15, 12, 13, 31, 29, 11, 8, 7,...
2	1	3	[110.51899719238281, 291.7560119628906]	[47, 57, 39, 12, 12, 11, 9, 20, 43, 26, 13, 7,...
3	1	4	[131.70199584960938, 286.4880065917969]	[38, 58, 39, 12, 11, 11, 13, 16, 35, 20, 12, 8...
4	1	7	[156.52499389648438, 279.2149963378906]	[32, 38, 31, 19, 15, 6, 11, 32, 28, 14, 6, 10,...
...	...	...	...	...
1234453	129081	276	[816.5590209960938, 353.6910095214844]	[28, 20, 11, 16, 23, 18, 22, 25, 42, 11, 8, 24...
1234454	129081	278	[892.0490112304688, 384.6050109863281]	[30, 30, 15, 22, 28, 14, 15, 23, 47, 13, 10, 2...
1234455	129081	279	[965.5770263671875, 397.2950134277344]	[29, 22, 12, 18, 28, 16, 20, 30, 40, 12, 9, 27...
1234456	129081	280	[1039.56005859375, 405.864990234375]	[27, 24, 14, 15, 26, 16, 25, 33, 45, 12, 10, 2...
1234457	129081	280	[1045.989990234375, 404.6090087890625]	[23, 38, 24, 33, 28, 7, 3, 7, 52, 12, 12, 26, ...

⚠️ If Point_ID is -1, then its 3D position is not available.

Data/train.pkl

train.pkl

3D Point Position(x,y,z) | Source Info | 128D Descriptors

	POINT_ID	XYZ	RGB	IMAGE_ID	XY	DESCRIPTORS
0	1	[1.6093346, -1.1848674, 1.610395]	[87, 87, 77]	1	[94.94650268554688, 284.02899169921875]	[46, 43, 12, 11, 10, 5, 19, 37, 24, 16, 8, 9, ...
1	1	[1.6093346, -1.1848674, 1.610395]	[87, 87, 77]	2	[99.05780029296875, 290.6889953613281]	[39, 42, 34, 14, 15, 12, 13, 31, 29, 11, 8, 7,...
2	1	[1.6093346, -1.1848674, 1.610395]	[87, 87, 77]	3	[110.51899719238281, 291.7560119628906]	[47, 57, 39, 12, 12, 11, 9, 20, 43, 26, 13, 7,...
3	1	[1.6093346, -1.1848674, 1.610395]	[87, 87, 77]	4	[131.70199584960938, 286.4880065917969]	[38, 58, 39, 12, 11, 11, 13, 16, 35, 20, 12, 8...
4	1	[1.6093346, -1.1848674, 1.610395]	[87, 87, 77]	7	[156.52499389648438, 279.2149963378906]	[32, 38, 31, 19, 15, 6, 11, 32, 28, 14, 6, 10,...
...	...	...	...	...	...	...
682463	129081	[0.66382873, -1.3121917, 5.433149]	[33, 30, 28]	141	[834.9459838867188, 363.7510070800781]	[32, 26, 15, 19, 28, 14, 18, 30, 37, 12, 11, 2...
682464	129081	[0.66382873, -1.3121917, 5.433149]	[33, 30, 28]	142	[867.6019897460938, 366.8039855957031]	[33, 16, 6, 11, 25, 16, 18, 36, 41, 10, 7, 23,...
682465	129081	[0.66382873, -1.3121917, 5.433149]	[33, 30, 28]	144	[981.5599975585938, 398.8039855957031]	[25, 14, 7, 12, 27, 21, 24, 28, 50, 13, 8, 24,...
682466	129081	[0.66382873, -1.3121917, 5.433149]	[33, 30, 28]	145	[1039.56005859375, 405.864990234375]	[27, 24, 14, 15, 26, 16, 25, 33, 45, 12, 10, 2...
682467	129081	[0.66382873, -1.3121917, 5.433149]	[33, 30, 28]	145	[1045.989990234375, 404.6090087890625]	[23, 38, 24, 33, 28, 7, 3, 7, 52, 12, 12, 26, ...

682468 rows × 6 columns

About Dataset: Camera Parameters

- Review the Pinhole camera model:

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} \approx \begin{bmatrix} f_x & s & o_x \\ 0 & f_y & o_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} R & t \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

- Intrinsic Parameters:

$$K = \begin{bmatrix} f_x & s & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1868.27 & 0 & 540 \\ 0 & 1869.18 & 960 \\ 0 & 0 & 1 \end{bmatrix}$$

- Distortion Parameters (Brown-Conrady Model):

$$D = \begin{bmatrix} k_1 & k_2 & p_1 & p_2 \end{bmatrix} = [0.0847023, -0.192929, -0.000201144, -0.000725352]$$

Problem 2

Q2-1 [Step 1] For each validation image, compute its camera pose with respect to world coordinate. Find the 2D-3D correspondence by descriptor matching, and solve the camera pose.

Notes:

- You can use OpenCV functions. Choose any method for PnP computation.
  https://docs.opencv.org/4.x/d5/d1f/calib3d_solvePnP.html
- To obtain bonus points, implement P3P + RANSAC by yourself without using OpenCV.
  Briefly explain your implementation and write down the pseudo code in your report.

Problem 2

<u>Q2-1</u> [Step 2] For each camera pose you calculated, compute the median pose error (translation, rotation) with respect to ground truth camera pose. Provide some discussion.

Notes:

- Translation: median of all absolute pose differences (Euclidean Distance).

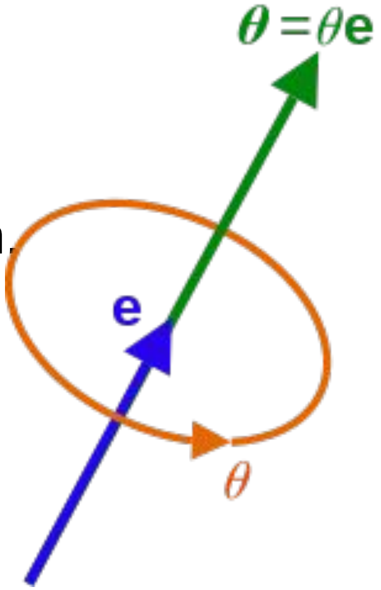
$$t_e = \|\mathbf{t} - \hat{\mathbf{t}}\|_2$$

- Rotation: median of relative rotation angle between estimation and ground-truth.

(1. Find out the relative rotation and represent it as axis angle representation.

2. Report the median of angles.)

$$\mathcal{R} = R_e \widehat{\mathcal{R}}$$

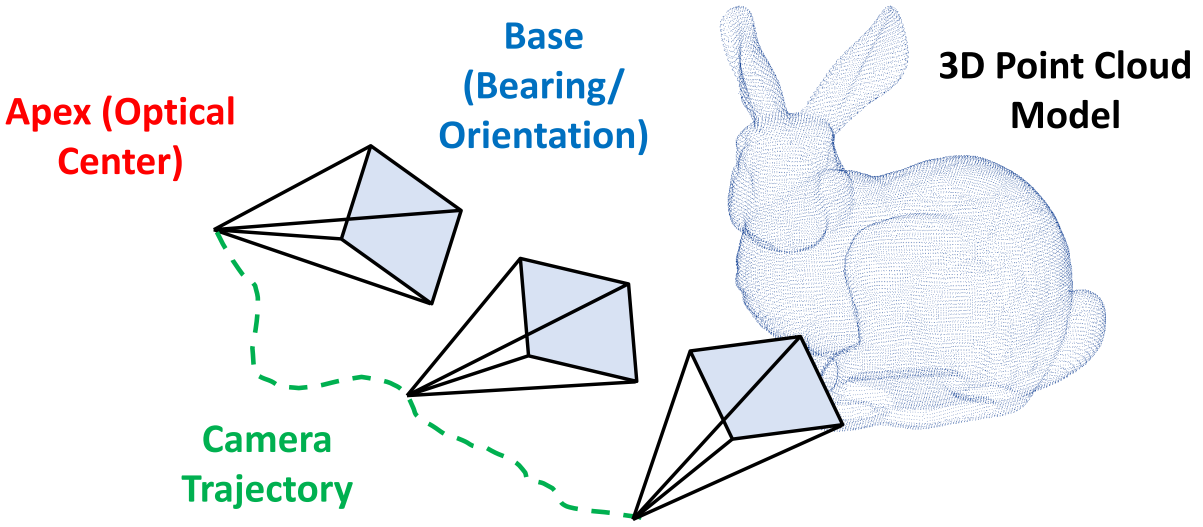


Problem 2

Q2-1 [Step 3] For each camera pose you calculated, plot the trajectory and camera poses along with 3d point cloud model using Open3D. Explain how you draw and provide some discussion.

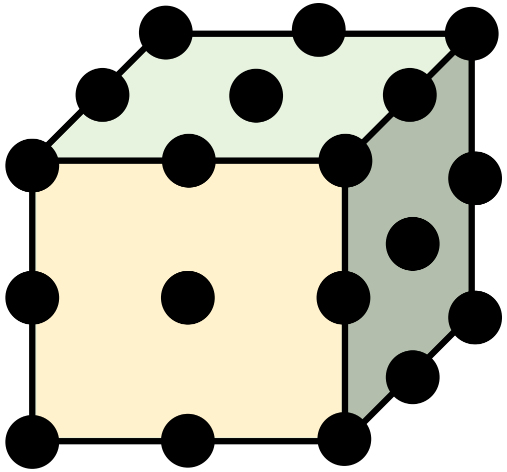
Notes:

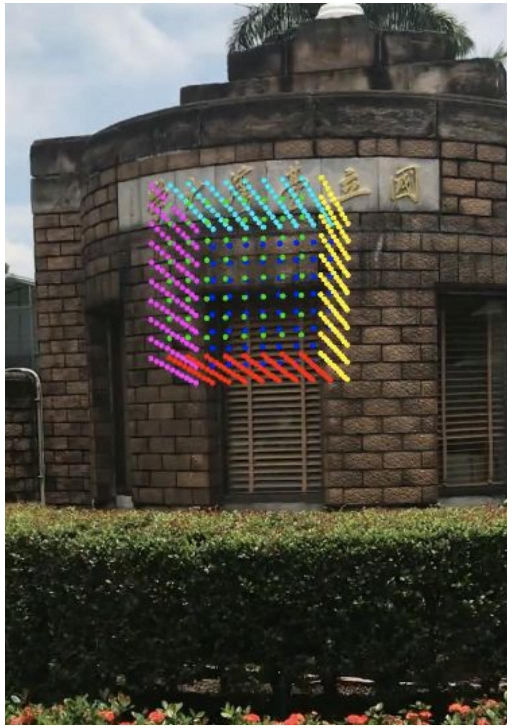
- Draw the camera pose as a quadrangular pyramid, where the apex is the position of the optical center, and the normal of base is the bearing (orientation) of the camera.



Problem 2

Q2-2 With camera intrinsic and extrinsic parameters, place a virtual cube in the validation image sequences to create an Augmented Reality video. Draw the virtual cube as a point set with different colors on its surface. Implement a simply but efficient painter's algorithm to determine the order of drawing.





Notes:

- You don't have to consider whether virtual cube will be occluded.
- Manually select the location, orientation, and scale of the virtual cube.
  (We provide a code that allows you to adjust the cube by keyboard.)
- **Painter's Algorithm:**
  1. Sort each voxel by depth
  2. Place each voxel from the furthest to the closest

Report for Problem 2

- In the report, briefly explain your method in each step, and provide screenshots of your results.
- Demonstrate your results in a video and provide the **YouTube link**.
  - You should record your demonstration, including the start time and the GitHub clone action. Example : https://youtu.be/-VnjVda7c8o?si=77nV7V1ngjZqoY5G
  - In the recording, run your code and then show the output results. For Q2-1, show the visualization result of step 3. For Q2-2, show the final output video.
- Please tell us **how to execute** your codes, including the package used and the environment.

Sample Code

You should read the pickle files with **pandas**.

```
>>> import pandas as pd
>>> images_df = pd.read_pickle("dataframes/images.pkl")
```

You may use **Scipy** to deal with 3D rotation representations.

```
>>> from scipy.spatial.transform import Rotation as R
>>> r = R.from_quat([0, 0, np.sin(np.pi/4), np.cos(np.pi/4)])
>>> r.as_rotvec()
array([0. , 0. , 1.57079633])
```

⚠️ Be aware of the order.

Parameters: **quat : *array_like, shape (N, 4) or (4,)***

Each row is a (possibly non-unit norm) quaternion in scalar-last (x, y, z, w) format. Each quaternion will be normalized to unit norm.

Returns: **rotation : *`Rotation` instance***

Object containing the rotations represented by input quaternions.

Introduction to Open3D

Install open3D

```
pip install open3d
```

Basic manipulation in open3D (Example Drawing):

```
points = [[0, 0, 0], [1, 0, 0], [0, 1, 0], [1, 1, 0],
         [0, 0, 1], [1, 0, 1], [0, 1, 1], [1, 1, 1]]
lines  = [[0, 1], [0, 2], [1, 3], [2, 3], [4, 5], [4, 6],
         [5, 7], [6, 7], [0, 4], [1, 5], [2, 6], [3, 7]]

import open3d as o3d
line_set = o3d.geometry.LineSet()
line_set.points = o3d.utility.Vector3dVector(points)
line_set.lines = o3d.utility.Vector2iVector(lines)

vis = o3d.visualization.Visualizer()
vis.create_window()
vis.add_geometry(line_set) o3d.visualization.ViewControl.set_zoom(vis.get_view_control(), 0.8)
vis.run()
```

⚠️ Please refer to the document to find the property you need.

http://www.open3d.org/docs/latest/tutorial/visualization/visualization.html

Grading

- We will evaluate both **the functionality of the code** and **the quality of the report**.
- **Functionality**: Can it run? How's the performance?
- **Quality**: theoretical/experimental analysis, observation, discussion, …
- Note that it **might be curved** based on overall performance of students.
- **Grade: (11+4 points)**
  - Q1-1: 4 points
  - Q1-2: 1 point
  - Q2-1: 4+4 points
    - 4 points if using OpenCV for PnP computation
    - 4 bonus points for implementing RANSAC (2 points) + P3P (2 points)
  - Q2-2: 2 points

Grading Policies

- Push your code and report to the GitHub classroom.
- Programming Languages: Python (Python>=3.8)
- Report Format: PDF or Markdown
  (Warning for Markdown users: Latex equations cannot be rendered properly in GitHub)
- Late Submission: **-10% from your score** / day
- Plagiarism: You have to **write your own codes**.
- Discussion: We encourage you to discuss with your classmates, but remember to **mention their names and contributions in the report**.
- **If an LLM is used, the report must specify the name of the LLM employed, the tasks it performed, and the extent of its contribution.**

Thanks

If you have any question, please email 3dcv@csie.ntu.edu.tw