vo_benchmark

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Notebook for two-view reconstruction without inertial data.

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[1]:

```
import symforce
symforce.set_epsilon_to_symbol()

import cv2
import numpy as np
import matplotlib.pyplot as plt
from pathlib import Path
from scipy.spatial.transform import Rotation as R
import time

import vo
# pose_metrics requires evo (see top of pose_metrics.py for install␣
 ↪instructions)
import pose_metrics
import utils

# Note: this notebook requires pandas in addition to all of Prof. Bretl's␣
 ↪dependencies
import pandas as pd
```

0.0.1 Read data

[2]:

```
# Specify the dataset (should be 'kitti' or 'euroc')
# chosen_dataset = 'euroc'
chosen_dataset = 'kitti'

assert(chosen_dataset in ['kitti', 'euroc'])
```

0.0.2 Provide settings

[3]:

```
# When matching (max threshold for ratio test)
if chosen_dataset == 'euroc':
    matching_threshold = 0.5
else:
    matching_threshold = 0.3

# When deciding if triangulated points are invalid
max_reprojection_err = 0.75

# Temporary folder for evo metrics
temporary_folder = Path('./temp')
temporary_folder.mkdir(parents=True, exist_ok=True)
```

[4]:

```
if chosen_dataset == 'euroc': # Note: euroc takes a bit longer to load.
    # Use EuRoC MAV

    mav_video_folder = Path('./data/mav0')

    # Read MAV data
    dataset_info = utils.read_data_mav(mav_video_folder)
    print("Read dataset with keys: {}".format(sorted(list(dataset_info.
 ↪keys()))))

    # Extract relevant data
    cam0_K = dataset_info['cam0_K']
    cam0_distortion = dataset_info['cam0_distortion']
    visual_inertial_data = dataset_info['visual_inertial_data']

    sigma_acc_wn = dataset_info['imu_accelerometer_noise_density']
    sigma_gyr_wn = dataset_info['imu_gyroscope_noise_density']
    sigma_acc_rw = dataset_info['imu_accelerometer_noise_density']
    sigma_gyr_rw = dataset_info['imu_gyroscope_random_walk']

    dt = 1/200 # IMU frequency

    # Get extrinsics
    T_inB_ofC = dataset_info['cam0_extrinsics']
    T_inC_ofB = np.block([[T_inB_ofC[:3,:3].T, (-T_inB_ofC[:3,:3].T @␣
 ↪T_inB_ofC[:3,-1])[:,np.newaxis]], [np.zeros(3), 1]])

    # Collate
    acc_meas, gyr_meas = utils.imu_collate(dataset_info['visual_inertial_data'])
    R_inR_ofB, v_inR_ofB, p_inR_ofB, b_a, b_w = utils.
 ↪groundtruth_collate(dataset_info['visual_inertial_data'], True)
```

```
    # As EuRoC's ground-truth (MoCap) is not aligned with gravity (i.e., in world frame), we identify the orientation of MoCap frame in world frame
    gravity = np.array([0., 0., -9.81])

    g_inB = - np.mean(acc_meas[:10], axis=0)
    g_inW = gravity

    def align_vectors(g_inB, g_inW):
        # Normalize input vectors
        g_inB_unit = g_inB / np.linalg.norm(g_inB)
        g_inW_unit = g_inW / np.linalg.norm(g_inW)

        # Compute the axis of rotation
        v = np.cross(g_inB_unit, g_inW_unit)

        # Compute the angle of rotation
        cos_theta = np.dot(g_inB_unit, g_inW_unit)
        sin_theta = np.linalg.norm(v)
        theta = np.arctan2(sin_theta, cos_theta)

        v /= np.linalg.norm(v)

        # Compute the rotation matrix
        Rot = R.from_rotvec(theta*v)
        return Rot

    # Compute rotation matrix
    R_inW_ofB = align_vectors(g_inB, g_inW)
    print("Rotation Matrix:\n", R_inW_ofB.as_matrix())

    R_inW_ofB.apply(g_inB)

    R_inW_ofR = R_inW_ofB * R_inR_ofB[:10].mean().inv()
    R_inW_ofB = R_inW_ofR * R_inR_ofB
    v_inW_ofB = R_inW_ofR.apply(v_inR_ofB)
    p_inW_ofB = R_inW_ofR.apply(p_inR_ofB)

else:
    # Use KITTI

    kitti_base_path = './data/kitti'
    kitti_date = '2011_09_26'
    kitti_drive = '0022'

    # Read KITTI data
    dataset_info = utils.read_data_kitti('./data/kitti', '2011_09_26', '0022')
    # Extract relevant data
    cam0_K = dataset_info['cam0_K']
    cam0_distortion = dataset_info['cam0_distortion']
    visual_inertial_data = dataset_info['visual_inertial_data']

    T_inC_ofB = dataset_info['cam0_extrinsics']
    R_inB_of_C = T_inC_ofB[:3, :3].T
    t_inB_of_C = R_inB_of_C @ T_inC_ofB[:3, 3]
    T_inB_ofC = np.block([[R_inB_of_C, t_inB_of_C[:,np.newaxis]], [np.zeros(3),␣
  ↪1]])

    R_inC_of_B = T_inC_ofB[:3, :3]
    t_inC_of_B = T_inC_ofB[:3, 3]


    # Collate
    acc_meas, gyr_meas = utils.imu_collate(visual_inertial_data)
    R_inW_ofB, v_inW_ofB, p_inW_ofB, b_a, b_w = utils.
  ↪groundtruth_collate(visual_inertial_data, False)
```

0.0.3 Create random generator

[5]:

```
rng = utils.create_rng(42)
```

```
seeding RNG with 42
```

0.0.4 Create image keypoint feature extractor

[6]:

```
feature_extractor = cv2.SIFT_create() # could also do ORB_create() for ORB␣
  ↪features
```

0.0.5 Two view reconstruction

Get initial solution

[7]:

```
if chosen_dataset == 'euroc': # Note: euroc takes a bit longer to load.
    # Use EuRoC MAV
    chosen_index = 500
    advance = 100
else:
    chosen_index = 50
    advance = 5

# Get first index closest to chosen index
```

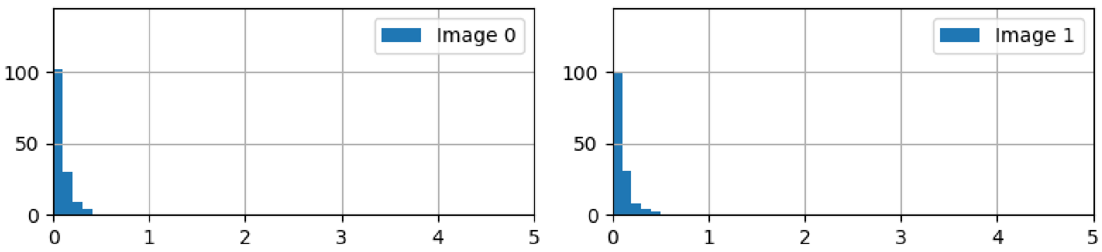
```
first_frame_idx = utils.get_index_of_next_image(visual_inertial_data,␣
 ↪chosen_index)
# Get second index
second_frame_idx = utils.get_index_of_next_image(visual_inertial_data,␣
 ↪first_frame_idx+advance)

# Create two views
views = [
    vo.create_view_data(utils.
 ↪read_image(visual_inertial_data[first_frame_idx]['image_file']),
                        first_frame_idx, feature_extractor, cam0_K,␣
 ↪cam0_distortion),
    vo.create_view_data(utils.
 ↪read_image(visual_inertial_data[second_frame_idx]['image_file']),
                        second_frame_idx, feature_extractor, cam0_K,␣
 ↪cam0_distortion)
]

# Perform two-view reconstruction
tic = time.time()
tracks = vo.vo_2view(views, matching_threshold, cam0_K, rng, use_opencv=False)
toc = time.time()

analyctical_guess = toc - tic
print(f"Analytical guess: {analyctical_guess:.2f} [s]")
```

```
found 145 good matches
found 145 inliers
Analytical guess: 2.84 [s]
```

[8]:

```
vo.show_reproj_results(views, tracks, cam0_K, cam0_distortion,␣
 ↪print_raw_reproj=True, show_reproj_histogram=True)
vo.visualize_predictions(views, tracks, cam0_K, cam0_distortion)
```

```
REPROJECTION ERRORS
 Image   0 (  145 points) : (mean, std, max, min) = (0.0868, 0.0800, 0.4026,
0.0004)
 Image (raw reprojection)  0 (  145 points) : (mean, std, max, min) = (0.0868,
0.0800, 0.4026, 0.0004)
 Image   1 (  145 points) : (mean, std, max, min) = (0.0931, 0.0883, 0.4769,
0.0004)
 Image (raw reprojection)  1 (  145 points) : (mean, std, max, min) = (0.0931,
0.0883, 0.4769, 0.0004)
```



Get post-optimization solution

Run below to keep the initial views and tracks

[9]:

```
views_ini = views.copy()
tracks_ini = tracks.copy()
```

[10]:

```
tic = time.time()

views, tracks, initial_values, results  = vo.vo_nonlinear_optimize(views_ini,␣
  ↪tracks_ini, cam0_K, max_reprojection_err)

toc = time.time()
nonlinear = toc - tic
print(f"{nonlinear:.2f} [s]")
```

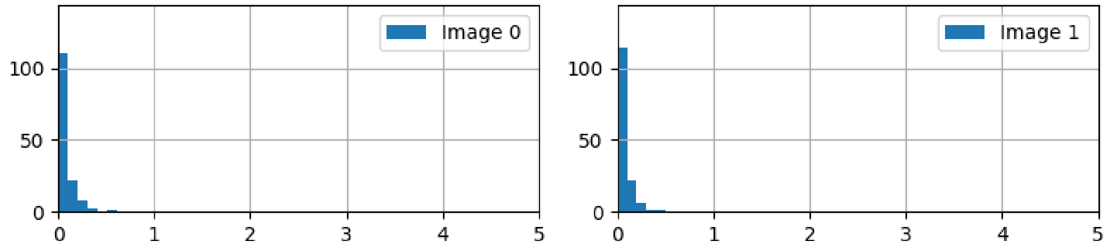
```
[2024-05-10 16:46:52.493] [info] LM<sym::Optimize> [iter    0] lambda:
1.000e+00, error prev/linear/new: 6.158e+00/0.000e+00/6.046e+00, rel reduction:
1.82341e-02
[2024-05-10 16:46:52.519] [info] LM<sym::Optimize> [iter    1] lambda:
1.000e-01, error prev/linear/new: 6.046e+00/0.000e+00/5.926e+00, rel reduction:
1.99465e-02
[2024-05-10 16:46:52.539] [info] LM<sym::Optimize> [iter    2] lambda:
1.000e-02, error prev/linear/new: 5.926e+00/0.000e+00/5.894e+00, rel reduction:
5.30232e-03
[2024-05-10 16:46:52.558] [info] LM<sym::Optimize> [iter    3] lambda:
1.000e-03, error prev/linear/new: 5.894e+00/0.000e+00/5.858e+00, rel reduction:
6.04853e-03
[2024-05-10 16:46:52.578] [info] LM<sym::Optimize> [iter    4] lambda:
```

```
1.000e-04, error prev/linear/new: 5.858e+00/0.000e+00/5.760e+00, rel reduction:
1.68508e-02
[2024-05-10 16:46:52.598] [info] LM<sym::Optimize> [iter    5] lambda:
1.000e-05, error prev/linear/new: 5.760e+00/0.000e+00/5.622e+00, rel reduction:
2.39643e-02
[2024-05-10 16:46:52.618] [info] LM<sym::Optimize> [iter    6] lambda:
1.000e-06, error prev/linear/new: 5.622e+00/0.000e+00/5.561e+00, rel reduction:
1.07297e-02
[2024-05-10 16:46:52.637] [info] LM<sym::Optimize> [iter    7] lambda:
1.000e-07, error prev/linear/new: 5.561e+00/0.000e+00/5.553e+00, rel reduction:
1.47557e-03
[2024-05-10 16:46:52.657] [info] LM<sym::Optimize> [iter    8] lambda:
1.000e-08, error prev/linear/new: 5.553e+00/0.000e+00/5.552e+00, rel reduction:
1.28544e-04
[2024-05-10 16:46:52.677] [info] LM<sym::Optimize> [iter    9] lambda:
1.000e-09, error prev/linear/new: 5.552e+00/0.000e+00/5.552e+00, rel reduction:
6.95137e-06
0.84 [s]
```

[11]:

```
vo.show_reproj_results(views, tracks, cam0_K, cam0_distortion,␣
 ↪print_raw_reproj=True, show_reproj_histogram=True)
vo.visualize_predictions(views, tracks, cam0_K, cam0_distortion)
```

```
REPROJECTION ERRORS
 Image  0 (  144 points) : (mean, std, max, min) = (0.0745, 0.0797, 0.5337,
0.0001)
 Image (raw reprojection)  0 (  144 points) : (mean, std, max, min) = (0.0745,
0.0797, 0.5337, 0.0001)
 Image  1 (  144 points) : (mean, std, max, min) = (0.0699, 0.0719, 0.4287,
0.0001)
 Image (raw reprojection)  1 (  144 points) : (mean, std, max, min) = (0.0699,
0.0719, 0.4287, 0.0001)
```



[12]:
```
print(f"\nTiming\n{'='*100}")
print(f"Analytical guess: {analyctical_guess:.2f} [s]")
print(f"Non linear (VO): {nonlinear:.2f} [s]")
```

```
Timing
================================================================================
====================
Analytical guess: 2.84 [s]
Non linear (VO): 0.84 [s]
```

[13]:
```
# This highlights the scale ambiguity seen in two-view reconstruction
print("Metric pose difference norm (gt) = {:.3f}".format(np.linalg.norm(
    # Note: while this is in world frame, the frames do not have any scaling,
    # so measuring displacement this way still should provide the correct␣
  ↪distance.
    np.linalg.norm(p_inW_ofB[first_frame_idx] - p_inW_ofB[second_frame_idx])
)))
print("Metric pose difference norm (ini) = {:.3f}".format(np.linalg.
  ↪norm(results.initial_values['T_inB1_ofA'].t)))
print("Metric pose difference norm (sf) = {:.3f}".format(np.linalg.norm(results.
  ↪optimized_values['T_inB1_ofA'].t)))
```

```
Metric pose difference norm (gt) = 2.784
Metric pose difference norm (ini) = 1.000
Metric pose difference norm (sf) = 1.000
```

Relative change in position (Δp) and rotation (ΔR) between frames (**NOT ERROR w.r.t Ground Truth**)

[14]:
```
# First frame results
frame0_key = 'T_inB0_ofA'
# Symforce - Initial values
R_inB0_ofA_ini = results.initial_values[frame0_key].R.to_rotation_matrix()
p_inB0_ofA_ini = results.initial_values[frame0_key].t

# Symforce - Optimized values
R_inB0_ofA_sf = results.optimized_values[frame0_key].R.to_rotation_matrix()
p_inB0_ofA_sf = results.optimized_values[frame0_key].t
```

```python
# ground truth
R_inW_ofB0_gt = R_inW_ofB[first_frame_idx].as_matrix()
p_inW_ofB0_gt = p_inW_ofB[first_frame_idx]
v_inW_ofB0_gt = v_inW_ofB[first_frame_idx]

# Second frame results
frame1_key = 'T_inB1_ofA'
# Symforce - Initial values
R_inB1_ofA_ini = results.initial_values[frame1_key].R.to_rotation_matrix()
p_inB1_ofA_ini = results.initial_values[frame1_key].t


# Symforce - Optimized values
R_inB1_ofA_sf = results.optimized_values[frame1_key].R.to_rotation_matrix()
p_inB1_ofA_sf = results.optimized_values[frame1_key].t

# Ground Truth
R_inW_ofB1_gt = R_inW_ofB[second_frame_idx].as_matrix()
p_inW_ofB1_gt = p_inW_ofB[second_frame_idx]
v_inW_ofB1_gt = v_inW_ofB[second_frame_idx]

print(f"RELATIVE CHANGE BETWEEN FRAMES (NOT ERROR)\n")
print(f'dp\n{"="*50}')
print('(Analytical guess) dp: {:.2f} [m]'.format( np.linalg.norm(␣
 ↪p_inB0_ofA_ini -  p_inB1_ofA_ini)))
print('(Non linear - VO) dp: {:.2f} [m]'.format( np.linalg.norm( p_inB0_ofA_sf ␣
 ↪-  p_inB0_ofA_sf)))
print('(Ground Truth)     dp: {:.2f} [m]'.format( np.linalg.norm( p_inW_ofB0_gt␣
 ↪ -  p_inW_ofB1_gt)))

print(f'\ndR\n{"="*50}')
print('(Analytical guess) dR scalar: {:.5f} [deg]'.format(pose_metrics.
 ↪rotational_error( R_inB0_ofA_ini, R_inB1_ofA_ini)))
print('(Non linear - VO) dR scalar: {:.5f} [deg]'.format(pose_metrics.
 ↪rotational_error( R_inB0_ofA_sf,  R_inB1_ofA_sf)))
print('(Ground Truth)     dR scalar: {:.5f} [deg]'.format(pose_metrics.
 ↪rotational_error( R_inW_ofB0_gt,  R_inW_ofB1_gt)))
```

```
RELATIVE CHANGE BETWEEN FRAMES (NOT ERROR)

dp
==================================================
(Analytical guess) dp: 1.00 [m]
(Non linear - VO) dp: 0.00 [m]
(Ground Truth)     dp: 2.78 [m]
```

```
dR
==================================================
(Analytical guess) dR scalar: 7.10949 [deg]
(Non linear - VO) dR scalar: 7.10223 [deg]
(Ground Truth)     dR scalar: 7.21199 [deg]
```