

# pySLAM: An Open-Source, Modular, and Extensible Framework for SLAM

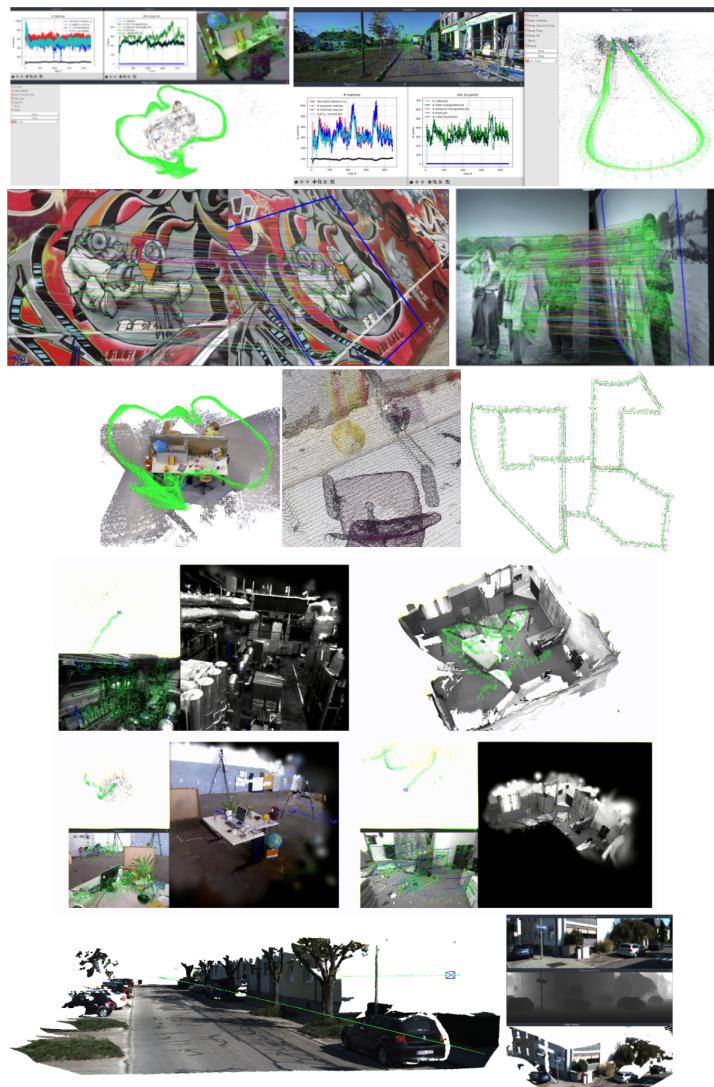
Luigi Freda

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[github.com/luigifreda/pyslam](https://github.com/luigifreda/pyslam)

## Abstract

pySLAM is an open-source Python framework for Visual SLAM, supporting monocular, stereo, and RGB-D cameras. It provides a flexible interface for integrating both classical and modern local features, making it adaptable to various SLAM tasks. The framework includes different loop closure methods, a volumetric reconstruction pipeline, and support for depth prediction models. Additionally, it offers a suite of tools for visual odometry and SLAM applications. Designed for both beginners and experienced researchers, pySLAM encourages community contributions, fostering collaborative development in the field of Visual SLAM.



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# Introduction

The goal of this document is to present the pySLAM framework, its main features, and usage. **pySLAM** is a python implementation of a *Visual SLAM* pipeline that supports **monocular**, **stereo** and **RGBD** cameras. It provides the following **features**:

- A wide range of classical and modern **local features** with a convenient interface for their integration.
- Various loop closing methods, including **descriptor aggregators** such as visual Bag of Words (BoW, iBow), Vector of Locally Aggregated Descriptors (VLAD), and modern **global descriptors** (image-wise descriptors).
- A **volumetric reconstruction pipeline** that processes available depth and color images with volumetric integration and provides an output dense reconstruction. This can use **TSDF** with voxel hashing or incremental **Gaussian Splatting**.
- Integration of **depth prediction models** within the SLAM pipeline. These include DepthPro, DepthAnythingV2, RAFT-Stereo, CREStereo, MAST3R, MVDUST3R, etc.
- A collection of other useful tools for VO and SLAM.

A convenient entry-point are the following **main scripts**:

- `main_vo.py` combines the simplest VO ingredients without performing any image point triangulation or windowed bundle adjustment. At each step  $k$ , `main_vo.py` estimates the current camera pose  $C_k$  with respect to the previous one  $C_{k-1}$ . The inter-frame pose estimation returns  $[R_{k-1,k}, t_{k-1,k}]$  with  $\|t_{k-1,k}\| = 1$ . With this very basic approach, you need to use a ground truth in order to recover a correct inter-frame scale  $s$  and estimate a valid trajectory by composing  $C_k = C_{k-1}[R_{k-1,k}, st_{k-1,k}]$ . This script is a first start to understand the basics of inter-frame feature tracking and camera pose estimation.
- `main_slam.py` adds feature tracking along multiple frames, point triangulation, keyframe management, bundle adjustment, loop closing, dense mapping and depth inference in order to estimate the camera trajectory and build both a sparse and dense map. It's a full SLAM pipeline and includes all the basic and advanced blocks which are necessary to develop a real visual SLAM pipeline.
- `main_feature_matching.py` shows how to use the basic feature tracker capabilities (*feature detector + feature descriptor + feature matcher*) and allows to test the different available local features.
- `main_depth_prediction.py` shows how to use the available depth inference models to get depth estimations from input color images.
- `main_map_viewer.py` reloads a saved map and visualizes it. Further details on how to save a map [here](#).
- `main_map_dense_reconstruction.py` reloads a saved map and uses a configured volumetric integrator to obtain a dense reconstruction (see [here](#)).

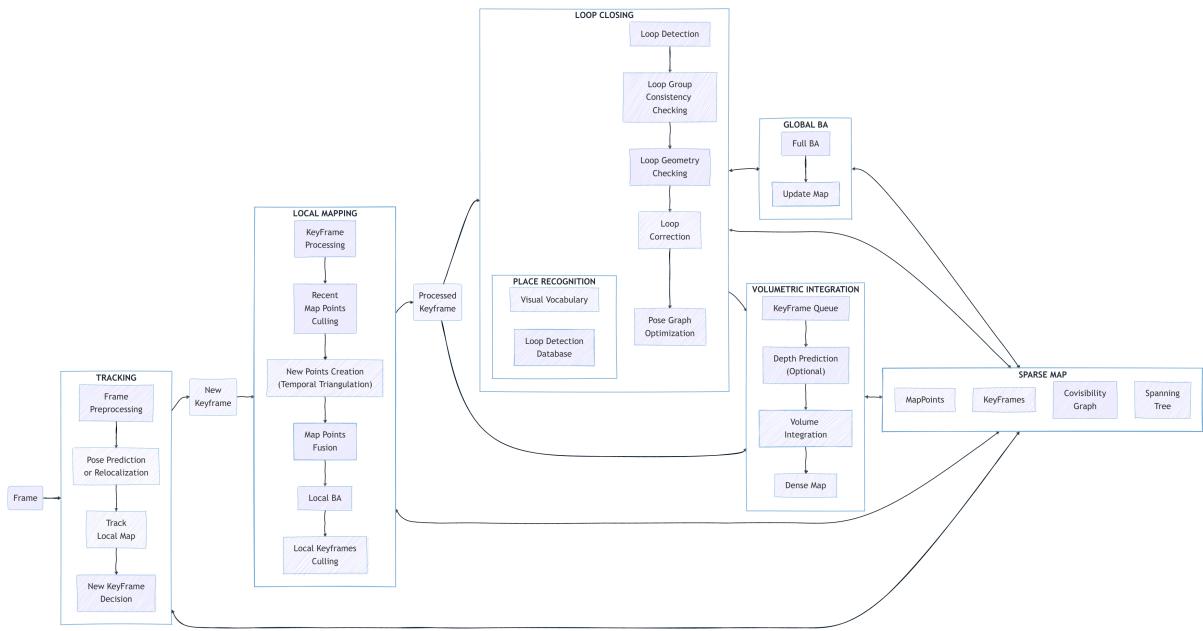
pySLAM can be used as flexible baseline framework to experiment with VO/SLAM techniques, **local features**, **descriptor aggregators**, **global descriptors**, **volumetric integration** and **depth prediction**. It allows to quickly explore, prototype and develop VO/SLAM pipelines. Users should note that pySLAM is a research framework and a work in progress. It is not optimized for real-time performances.

Enjoy it!

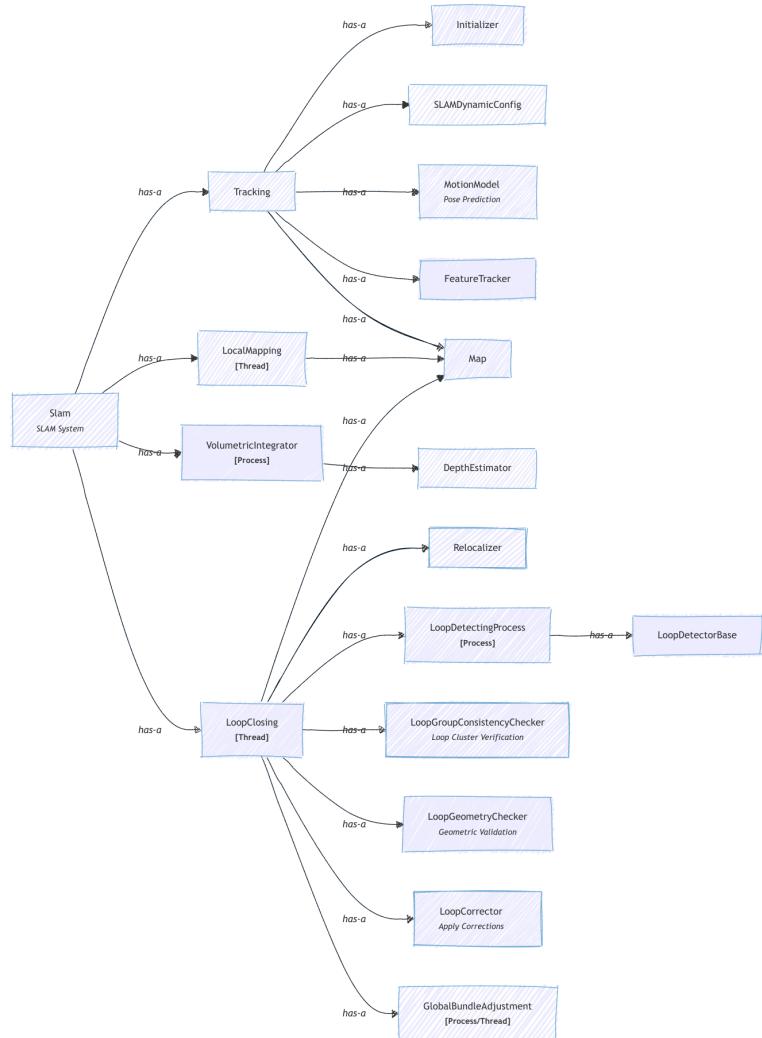
## System overview

This section presents some diagram sketches that provide an overview of the main workflow, system components, and class relationships/dependencies. To make the diagrams more readable, some minor components and arrows have been omitted.

## SLAM Workflow



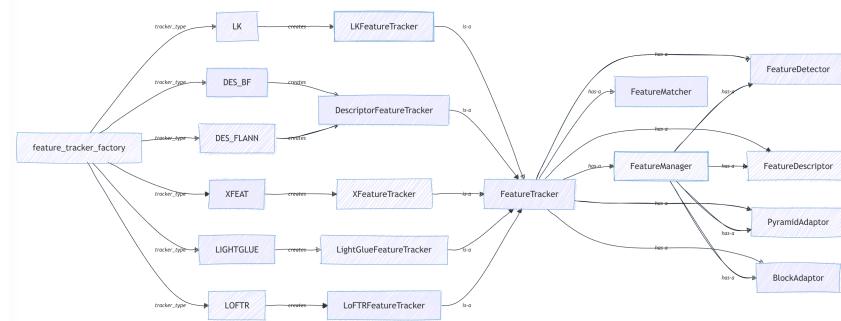
## SLAM Components



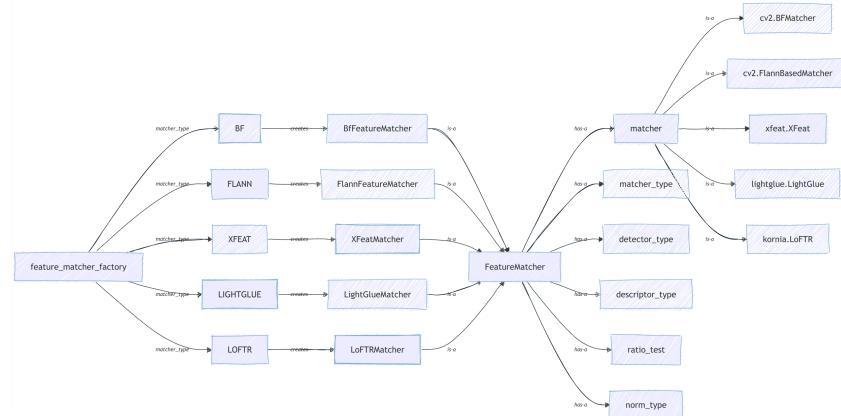
**Note:** In some case, I used **Processes** instead of **Threads** because in Python 3.8 (used by pySLAM) the Global Interpreter Lock (GIL) allows only one thread can execute at a time within a single process. Multiprocessing avoids this limitation and enables better parallelism, though it involves data duplication via pickling. See this related nice [post](#).

## Main System Components

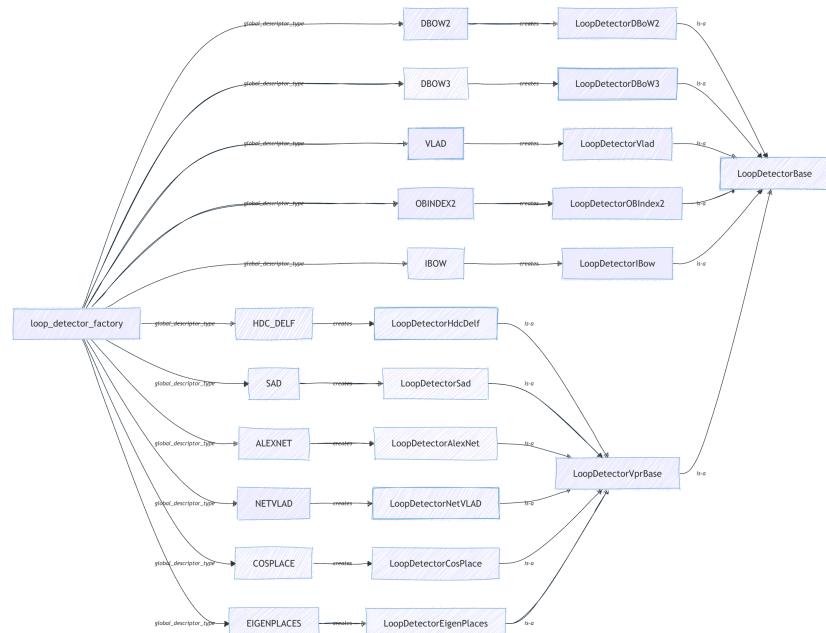
### Feature Tracker



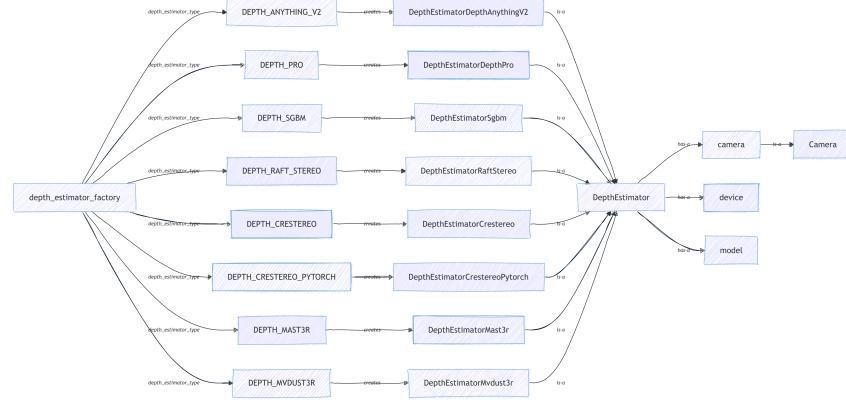
### Feature Matcher



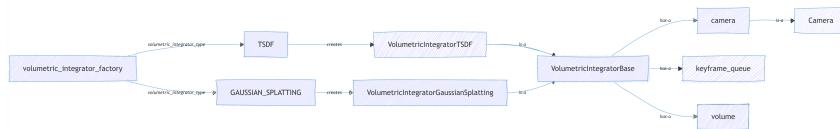
### Loop Detector



### Depth Estimator



## Volumetric Integrator



## Usage

Once you have run the script `install_all_venv.sh` / `install_all_conda.sh` (follow the instructions [above](#) according to your OS), you can open a new terminal and start testing the basic **Visual Odometry (VO)**:

```
$ . pyenv-activate.sh # Activate pyslam python virtual environment. This is only needed once in a new terminal.
$ ./main_vo.py
```

This will process a default **KITTI** video (available in the folder `data/videos`) by using its corresponding camera calibration file (available in the folder `settings`), and its groundtruth (available in the same `data/videos` folder). If matplotlib windows are used, you can stop `main_vo.py` by focusing/clicking on one of them and pressing the key 'Q'. As explained above, this very *basic* script `main_vo.py` **strictly requires a ground truth**. Now, with RGBD datasets, you can also test the **RGBD odometry** with the classes `VisualOdometryRgbd` or `VisualOdometryRgbdTensor` (ground truth is not required here).

Similarly, you can test the **full SLAM** by running `main_slam.py`:

```
$ . pyenv-activate.sh # Activate pyslam python virtual environment. This is only needed once in a new terminal.
$ ./main_slam.py
```

This will process the same default **KITTI** video (available in the folder `data/videos`) by using its corresponding camera calibration file (available in the folder `settings`). You can stop it by focusing/clicking on one of the opened windows and pressing the key 'Q' or closing the 3D pangolin GUI.

With both scripts, in order to process a different **dataset**, you need to update the file `config.yaml`: \* Select your dataset **type** in the section **DATASET** (further details in the section [Datasets](#) below for further details). This identifies a corresponding dataset section (e.g. **KITTI\_DATASET**, **TUM\_DATASET**, etc). \* Select the **sensor\_type** (**mono**, **stereo**, **rgbd**) in the chosen dataset section.

\* Select the camera **settings** file in the dataset section (further details in the section [Camera Settings](#) below). \* The **groundtruth\_file** accordingly (further details in the section [Datasets](#) below and check the files `io/ground_truth.py` and `io/convert_groundtruth.py`).

## Feature tracking

If you just want to test the basic feature tracking capabilities (*feature detector + feature descriptor + feature matcher*) and get a taste of the different available local features, run

```
$ . pyenv-activate.sh # Activate pyslam python virtual environment. This is only needed once in a new terminal.
$ ./main_feature_matching.py
```

In any of the above scripts, you can choose any detector/descriptor among **ORB**, **SIFT**, **SURF**, **BRISK**, **AKAZE**, **SuperPoint**, etc. (see the section [Supported Local Features](#) below for further information).

Some basic examples are available in the subfolder `test/loopclosing`. In particular, as for feature detection/description, you may want to take a look at `test/cv/test_feature_manager.py` too.

## Loop closing

Different [loop closing methods](#) are available, combining [aggregation methods](#) and [global descriptors](#).

While running full SLAM, loop closing is enabled by default and can be disabled by setting `kUseLoopClosing=False` in `config_parameters.py`. Configuration options can be found in `loop_closing/loop_detector_configs.py`.

**Examples:** Start with the examples in `test/loopclosing`, such as `test/loopclosing/test_loop_detector.py`.

### Vocabulary management

`DBoW2`, `DBoW3`, and `VLAD` require pre-trained vocabularies. ORB-based vocabularies are automatically downloaded in the `data` folder (see `loop_closing/loop_detector_configs.py`).

To create a new vocabulary, follow these steps:

1. **Generate an array of descriptors:** Use the script `test/loopclosing/test_gen_des_array_from_imgs.py` to generate the array of descriptors that will be used to train the new vocabulary. Select your desired descriptor type via the tracker configuration.
2. **DBOW vocabulary generation:** Train your target DBOW vocabulary by using the script `test/loopclosing/test_gen_dbow_voc_from_des_array.py`.
3. **VLAD vocabulary generation:** Train your target VLAD “vocabulary” by using the script `test/loopclosing/test_gen_vlad_voc_from_des_array.py`.

### Vocabulary-free loop closing

Most methods do not require pre-trained vocabularies. Specifically:  
- `iBoW` and `OBindex2`: These methods incrementally build bags of binary words and, if needed, convert (front-end) non-binary descriptors into binary ones.  
- Others: Methods like `HDC_DELF`, `SAD`, `AlexNet`, `NetVLAD`, `CosPlace`, and `EigenPlaces` directly extract global descriptors and process them using dedicated aggregators, independently from the used front-end descriptors.

As mentioned above, only `DBoW2`, `DBoW3`, and `VLAD` require pre-trained vocabularies.

### Double-check your loop detection configuration and verify vocabulary compatibility

When selecting a loop detection method based on a pre-trained vocabulary (such as `DBoW2`, `DBoW3`, and `VLAD`), ensure the following:

1. The back-end and the front-end are using the same descriptor type (this is also automatically checked for consistency).
2. A corresponding pre-trained vocabulary is available.

For more details, refer to the [vocabulary management section](#).

If you lack a compatible vocabulary for the selected front-end descriptor type, no loop closing method will be used. You have the following options:

- a. Create and load the vocabulary (refer to the [vocabulary management section](#)).
- b. Choose an `*_INDEPENDENT` loop detector method, which works with an independent `local_feature_manager`.
- c. Select a vocabulary-free loop closing method.

See the file `loopclosing/loop_detector_configs.py` for further details.

---

## Volumetric reconstruction

### Dense reconstruction while running SLAM

The SLAM back-end hosts a volumetric reconstruction pipeline. This is disabled by default. You can enable it by setting `kUseVolumetricIntegration=True` and selecting your preferred method `kVolumetricIntegrationType` in `config_parameters.py`. At present, two methods are available: `TSDF` and `GAUSSIAN_SPLATTING` (see `dense/volumetric_integrator_factory.py`). Note that you need CUDA in order to run `GAUSSIAN_SPLATTING` method.

At present, the volumetric reconstruction pipeline works with:

- RGBD datasets
- When a [depth estimator](#) is used in the back-end or front-end and a depth prediction/estimation gets available for each processed keyframe.

If you want a mesh as output then set `kVolumetricIntegrationExtractMesh=True` in `config_parameters.py`.

### Reload a saved sparse map and perform dense reconstruction

Use the script `main_map_dense_reconstruction.py` to reload a saved sparse map and to perform dense reconstruction by using its posed keyframes as input. You can select your preferred dense reconstruction method directly in the script.

- To check what the volumetric integrator is doing, run in another shell `tail -f logs/volumetric_integrator.log` (from repository root folder).
- To save the obtained dense and sparse maps, press the **Save** button on the GUI.

### Reload and check your dense reconstruction

You can check the output pointcloud/mesh by using [CloudCompare](#).

In the case of a saved Gaussian splatting model, you can visualize it by:

1. Using the [supersplat editor](#) (drag and drop the saved Gaussian splatting .ply pointcloud in the editor interface).
2. Getting into the folder `test/gaussian_splatting` and running:  
`$ python test_gsm.py --load <gs_checkpoint_path>`

### Controlling the spatial distribution of keyframe FOV centers

If you are targeting volumetric reconstruction while running SLAM, you can enable a **keyframe generation policy** designed to manage the spatial distribution of keyframe field-of-view (FOV) centers. The *FOV center of a camera* is defined as the backprojection of its image center, calculated using the median depth of the frame. With this policy, a new keyframe is generated only if its FOV center is farther than a predefined distance from the nearest existing keyframe's FOV center. You can enable this policy by setting the following parameters in the yaml setting:

```
KeyFrame.useFovCentersBasedGeneration: 1    # compute 3D fov centers of camera frames by using median depth and use their distances to control keyframe generation
KeyFrame.maxFovCentersDistance: 0.2          # max distance between fov centers in order to generate a keyframe
```

## Depth prediction

The available depth prediction models can be utilized both in the SLAM back-end and front-end.

- Back-end: Depth prediction can be enabled in the [volumetric reconstruction](#) pipeline by setting the parameter `kVolumetricIntegrationUseDepthEstimator=True` and selecting your preferred `kVolumetricIntegrationDepthEstimatorType` in `config_parameters.py`.
- Front-end: Depth prediction can be enabled in the front-end by setting the parameter `kUseDepthEstimatorInFrontEnd` in `config_parameters.py`. This feature estimates depth images from input color images to emulate a RGBD camera. Please, note this functionality is still *experimental* at present time.

Refer to the file `depth_estimation/depth_estimator_factory.py` for further details. Both stereo and monocular prediction approaches are supported. You can test depth prediction/estimation by using the script `main_depth_prediction.py`.

**Notes:** \* In the case of a monocular SLAM configuration, do NOT use depth prediction in the back-end volumetric integration: The SLAM (fake) scale will conflict with the absolute metric scale of depth predictions. With monocular datasets, enable depth prediction to run in the front-end. - The depth inference may be very slow (for instance, with DepthPro it takes ~1s per image on my machine). Therefore, the resulting volumetric reconstruction pipeline may be very slow.

## Saving and reloading

### Save the a map

When you run the script `main_slam.py` (`main_map_dense_reconstruction.py`):

- You can save the current map state by pressing the button **Save** on the GUI. This saves the current map along with front-end, and backend configurations into the default folder `results/slam_state` (`results/slam_state_dense_reconstruction`).
- To change the default saving path, open `config.yaml` and update target `folder_path` in the section:

```
bash SYSTEM_STATE:      folder_path: results/slam_state    # default folder path (relative to repository root) where the system state is saved or reloaded
```

### Reload a saved map and relocalize in it

- A saved map can be loaded and visualized in the GUI by running:

```
$ . pyenv-activate.sh  # Activate pyslam python virtual environment. This is only needed once in a new terminal.  
$ ./main_map_viewer.py # Use the --path options to change the input path
```

- To enable map reloading and relocalization when running `main_slam.py`, open `config.yaml` and set

```
SYSTEM_STATE:  
  load_state: True          # flag to enable SLAM state reloading (map state + loop closing state)  
  folder_path: results/slam_state  # default folder path (relative to repository root) where the system state is saved or reloaded
```

Note that pressing the **Save** button saves the current map, front-end, and backend configurations. Reloading a saved map overwrites the current system configurations to ensure descriptor compatibility.

### Trajectory saving

Estimated trajectories can be saved in three different formats: *TUM* (The Open Mapping format), *KITTI* (KITTI Odometry format), and *EuRoC* (EuRoC MAV format). `pyslam` saves two **types** of trajectory estimates:

- **Online**: In *online* trajectories, each pose estimate depends only on past poses. A pose estimate is saved at the end of each front-end iteration on current frame.
- **Final**: In *final* trajectories, each pose estimate depends on both past and future poses. A pose estimate is refined multiple times by LBA windows that cover it and by GBA during loop closures.

To enable trajectory saving, open `config.yaml` and search for the `SAVE_TRAJECTORY`: set `save_trajectory: True`, select your `format_type` (`tum`, `kitti`, `euroc`), and the output filename. For instance for a `tum` format output:

```
SAVE_TRAJECTORY:  
  save_trajectory: True  
  format_type: kitti        # supported formats: `tum`, `kitti`, `euroc`  
  output_folder: results/metrics # relative to pyslam root folder  
  basename: trajectory       # basename of the trajectory saving output
```

## SLAM GUI

Some quick information about the non-trivial GUI buttons of `main_slam.py`:

- **Step**: Enter the *Step by step mode*. Press the button **Step** a first time to pause. Then, press it again to make the pipeline process a single new frame.
- **Save**: Save the map into the file `map.json`. You can visualize it back by using the script `/main_map_viewer.py` (as explained above).
- **Reset**: Reset SLAM system.
- **Draw Ground Truth**: If a ground truth dataset is loaded (e.g., from KITTI, TUM, EUROC, or REPLICA), you can visualize it by pressing this button. The ground truth trajectory will be displayed in 3D and progressively aligned (approximately every 30 frames) with the estimated trajectory. The alignment improves as more samples are added to the estimated trajectory. After ~20 frames, if the button is pressed, a window will appear showing the Cartesian alignment errors (ground truth vs. estimated trajectory) along the axes.

## Monitor the logs for tracking, local mapping, and loop closing simultaneously

The logs generated by the modules `local_mapping.py`, `loop_closing.py`, `loop_detecting_process.py`, and `global_bundle_adjustments.py` are collected in the files `local_mapping.log`, `loop_closing.log`, `loop_detecting.log`, and `gba.log`, which are all stored in the folder `logs`. For debugging, you can monitor a parallel flow by running the following command in a separate shell:

```
$ tail -f logs/<log file name>
```

Otherwise, to check all parallel logs with tmux, run:

```
$ ./scripts/launch_tmux_logs.sh
```

To launch slam and check all logs in a single tmux, run:

```
$ ./scripts/launch_tmux_slam.sh
```

Press **CTRL+A** and then **CTRL+Q** to exit from `tmux` environment.

# Supported components and models

## Supported local features

At present time, the following feature **detectors** are supported:

- [FAST](#) [46]
- [Good features to track](#) [49]
- [ORB](#) [47]
- [ORB2](#) (improvements of ORB-SLAM2 to ORB detector)
- [SIFT](#) [26]
- [SURF](#) [8]
- [KAZE](#) [1]
- [AKAZE](#) [2]
- [BRISK](#) [20]
- [AGAST](#)
- [MSER](#) [31]
- [StarDetector/CenSurE](#)
- [Harris-Laplace](#)
- [SuperPoint](#)
- [D2-Net](#) [13]
- [DELF](#) [39]
- [Contextdesc](#) [29]
- [LFNet](#) [40]
- [R2D2](#) [44]
- [Key.Net](#) [5]
- [DISK](#) [59]
- [ALIKED](#) [6]
- [Xfeat](#) [7]
- [KeyNetAffNetHardNet](#) (KeyNet detector + AffNet + HardNet descriptor)

The following feature **descriptors** are supported:

- [ORB](#) [47]
- [SIFT](#) [26]
- [ROOT SIFT](#)
- [SURF](#) [8]
- [AKAZE](#) [2]
- [BRISK](#) [20]
- [FREAK](#)
- [SuperPoint](#)
- [Tfeat](#)
- [BOOST-DESC](#) [58]
- [DAISY](#) [57]
- [LATCH](#) [21]
- [LUCID](#)

- [VGG](#) [50]
- [Hardnet](#) [33]
- [GeoDesc](#) [62]
- [SOSNet](#)
- [L2Net](#)
- Log-polar descriptor
- [D2-Net](#) [13]
- [DELF](#) [39]
- [Contextdesc](#) [29]
- [LFNet](#) [40]
- [R2D2](#) [44]
- [BEBLID](#)
- [DISK](#) [59]
- [ALIKED](#) [6]
- [Xfeat](#) [7]
- [KeyNetAffNetHardNet](#) (KeyNet detector + AffNet + HardNet descriptor)

For more information, refer to `local_features/feature_types.py` file. Some of the local features consist of a *joint detector-descriptor*. You can start playing with the supported local features by taking a look at `test/cv/test_feature_manager.py` and `main_feature_matching.py`.

In both the scripts `main_vo.py` and `main_slam.py`, you can create your preferred detector-descriptor configuration and feed it to the function `feature_tracker_factory()`. Some ready-to-use configurations are already available in the file `local_features/feature_tracker.configs.py`.

The function `feature_tracker_factory()` can be found in the file `local_features/feature_tracker.py`. Take a look at the file `local_features/feature_manager.py` for further details.

**N.B.:** You just need a *single* python environment to be able to work with all the [supported local features](#)!

## Supported matchers

- BF: Brute force matcher on descriptors (with KNN).
- [FLANN](#) [35]
- [XFeat](#) [7]
- [LightGlue](#)
- [LoFTR](#)

See the file `local_features/feature_matcher.py` for further details.

## Supported global descriptors and local descriptor aggregation methods

### Local descriptor aggregation methods

- Bag of Words (BoW): [DBoW2](#) [16], [DBoW3](#). [\[paper\]](#)
- Vector of Locally Aggregated Descriptors: [VLAD](#) [3]. [\[paper\]](#)
- Incremental Bags of Binary Words (iBoW) via Online Binary Image Index: [iBoW](#), [OBIndex2](#). [\[paper\]](#)
- Hyperdimensional Computing: [HDC](#) [37]. [\[paper\]](#)

**NOTE:** *iBoW* and *OBIndex2* incrementally build a binary image index and do not need a prebuilt vocabulary. In the implemented classes, when needed, the input non-binary local descriptors are transparently transformed into binary descriptors.

## Global descriptors

Also referred to as *holistic descriptors*:

- [SAD](#)
- [AlexNet](#)
- [NetVLAD \[3\]](#)
- [HDC-DELF](#)
- [CosPlace \[9\]](#)
- [EigenPlaces \[10\]](#)

Different [loop closing methods](#) are available. These combines the above aggregation methods and global descriptors. See the file [loop\\_closing/loop\\_detector\\_configs.py](#) for further details.

## Supported depth prediction models

Both monocular and stereo depth prediction models are available. SGBM algorithm has been included as a classic reference approach.

- [SGBM](#): Depth SGBM from OpenCV (Stereo, classic approach) [17]
- [Depth-Pro](#) (Monocular) [11]
- [DepthAnythingV2](#) (Monocular) [53]
- [RAFT-Stereo](#) (Stereo) [54]
- [CREStereo](#) (Stereo) [23]
- [MASt3R](#) (Monocular/Stereo) [19]
- [MV-DUSt3R](#) (Monocular/Stereo) [52]

## Supported volumetric mapping methods

- [TSDF](#) with voxel block grid (parallel spatial hashing)
- Incremental 3D Gaussian Splatting. See [here](#) and [MonoGS](#) for a description of its backend [18].

## Camera Settings

The folder **settings** contains the camera settings files which can be used for testing the code. These are the same used in the framework [ORB-SLAM2](#) [36]. You can easily modify one of those files for creating your own new calibration file (for your new datasets).

In order to calibrate your camera, you can use the scripts in the folder **calibration**. In particular: 1. Use the script [grab\\_chessboard\\_images.py](#) to collect a sequence of images where the chessboard can be detected (set the chessboard size therein, you can use the calibration pattern [calib\\_pattern.pdf](#) in the same folder) 2. Use the script [calibrate.py](#) to process the collected images and compute the calibration parameters (set the chessboard size therein)

For more information on the calibration process, see this [tutorial](#) [30] or this other [link](#) [42].

If you want to **use your camera**, you have to:

- Calibrate it and configure [WEBCAM.yaml](#) accordingly.
- Record a video (for instance, by using [save\\_video.py](#) in the folder **calibration**).
- Configure the **VIDEO\_DATASET** section of [config.yaml](#) in order to point to your recorded video.

## Comparison pySLAM vs ORB-SLAM3

For a comparative evaluation, *online* trajectory estimated by pySLAM vs *final* trajectories estimated by ORB-SLAM3, see this nice [notebook](#). Note that pySLAM is able to save both online and final pose estimates. On the other end, ORB-SLAM3 pose estimates are saved at the end of the full dataset playback. For further details about online/final trajectories and trajectory saving, see the section .

## Credits

The following is a list of frameworks that inspired or has been integrated into pySLAM. Many thanks to their Authors for their great work.

- Pangolin
- g2opy
- ORBSLAM2 [36]
- SuperPointPretrainedNetwork [12]
- Tfeat [4]
- Image Matching Benchmark Baselines [61]
- Hardnet [34]
- GeoDesc [28]
- SOSNet [56]
- L2Net [55]
- Log-polar descriptor [15]
- D2-Net [14]
- DELF [38]
- Contextdesc [27]
- LFNet [41]
- R2D2 [45]
- BEBLID [51]
- DISK [60]
- Xfeat [43]
- LightGlue [24]
- Key.Net [5]
- Twitchslam
- MonoVO
- VPR\_Tutorial [48]
- DepthAnythingV2 [63]
- DepthPro [11]
- RAFT-Stereo [25]
- CREStereo and CREStereo-Pytorch [22]
- MonoGS [32]
- MASt3R [19]
- MV-DUSt3R [52]
- Many thanks to Anathonic for adding the trajectory-saving feature and for the comparison notebook: pySLAM vs ORB-SLAM3.

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