stella_vslam

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GETTING STARTED

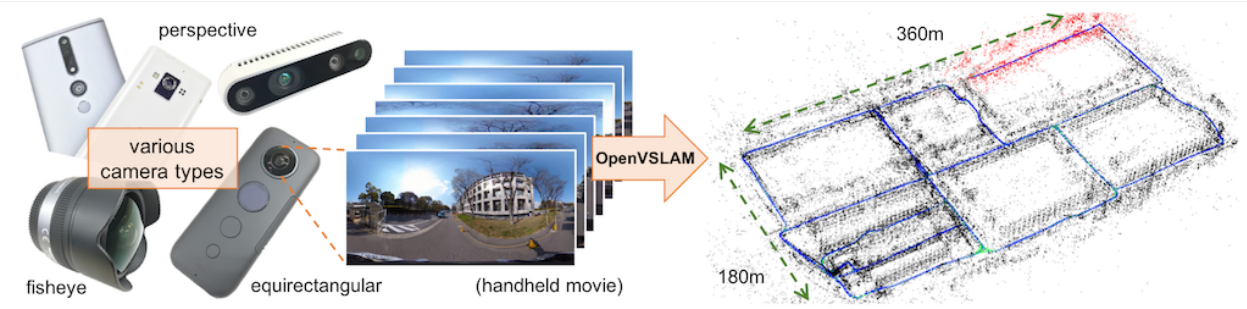
This is the stella_vslam documentation.

NOTE: This is a community fork of xdspacelab/openvslam. It was created to continue active development of OpenVSLAM on Jan 31, 2021. The original repository is no longer available. Please read README.md in stella_vslam.

CHAPTER

ONE

OVERVIEW



stella_vslam is a monocular, stereo, and RGBD visual SLAM system. The notable features are:

- It is compatible with **various type of camera models** and can be easily customized for other camera models.
- Created maps can be **stored and loaded**, then stella_vslam can **localize new images** based on the prebuilt maps.
- The system is fully modular. It is designed by encapsulating several functions in separated components with easy-to-understand APIs.
- We provided **some code snippets** to understand the core functionalities of this system.

stella_vslam is based on an indirect SLAM algorithm with sparse features, such as ORB-SLAM, ProSLAM, and UcoSLAM. One of the noteworthy features of stella_vslam is that the system can deal with various type of camera models, such as perspective, fisheye, and equirectangular. If needed, users can implement extra camera models (e.g. dual fisheye, catadioptric) with ease. For example, visual SLAM algorithm using **equirectangular camera models** (e.g. RICOH THETA series, insta360 series, etc) is shown above.

Some code snippets to understand the core functionalities of the system are provided. You can employ these snippets for in your own programs. Please see the `*.cc` files in `./example` directory or check *Simple Tutorial* and *Example*.

Also, some examples to run stella_vslam on ROS framework are provided. Please check *ROS Package*.

Please contact us via GitHub issues if you have any questions or notice any bugs about the software.

1.1 Installation

Please see *Installation* chapter.

The instructions for Docker users are also provided.

1.2 Tutorial

Please see *Simple Tutorial*.

A sample ORB vocabulary file can be downloaded from here.
Sample datasets are also provided at here.

If you would like to run visual SLAM with standard benchmarking datasets (e.g. KITTI Odometry dataset), please see *SLAM with standard datasets*.

1.3 Reference

- Raul Mur-Artal, J. M. M. Montiel, and Juan D. Tardos. 2015. ORB-SLAM: a Versatile and Accurate Monocular SLAM System. IEEE Transactions on Robotics 31, 5 (2015), 1147–1163.
- Raul Mur-Artal and Juan D. Tardos. 2017. ORB-SLAM2: an Open-Source SLAM System for Monocular, Stereo and RGB-D Cameras. IEEE Transactions on Robotics 33, 5 (2017), 1255–1262.
- Dominik Schlegel, Mirco Colosi, and Giorgio Grisetti. 2018. ProSLAM: Graph SLAM from a Programmer's Perspective. In Proceedings of IEEE International Conference on Robotics and Automation (ICRA). 1–9.
- Rafael Munoz-Salinas and Rafael Medina Carnicer. 2019. UcoSLAM: Simultaneous Localization and Mapping by Fusion of KeyPoints and Squared Planar Markers. arXiv:1902.03729.
- Mapillary AB. 2019. OpenSfM. https://github.com/mapillary/OpenSfM.
- Giorgio Grisetti, Rainer Kümmerle, Cyrill Stachniss, and Wolfram Burgard. 2010. A Tutorial on Graph-Based SLAM. IEEE Transactions on Intelligent Transportation SystemsMagazine 2, 4 (2010), 31–43.
- Rainer Kummerle, Giorgio Grisetti, Hauke Strasdat, Kurt Konolige, and Wolfram Burgard. 2011. g2o: A general framework for graph optimization. In Proceedings of IEEE International Conference on Robotics and Automation (ICRA). 3607–3613.

CHAPTER

TWO

INSTALLATION

2.1 Source code

The source code can be viewed from this GitHub repository.

Cloning the repository:

```
git clone --recursive https://github.com/stella-cv/stella_vslam.git
```

If you are Windows 10 user, please install the dependencies and stella_vslam with *SocketViewer support* on Windows Subsystem for Linux (WSL).

Docker systems can be used instead of preparing the dependencies manually.

2.2 Dependencies

stella_vslam requires a **C++11-compliant** compiler. It relies on several open-source libraries as shown below.

2.2.1 Requirements for stella_vslam

- Eigen : version 3.3.0 or later.
- g2o : Please use the latest release. Tested on commit ID ed40a5b.
- SuiteSparse : Required by g2o.
- FBoW : **Please use the custom version of FBoW** released in https://github.com/stella-cv/FBoW.
- yaml-cpp : version 0.6.0 or later.
- OpenCV : version 3.3.1 or later.

Note: OpenCV with GUI support is necessary for using the built-in viewer (Pangolin Viewer). OpenCV with video support is necessary if you plan on using video files (e.g. `.mp4`) as inputs. If your CPU has many cores, it is recommended to enable TBB.

2.2.2 Requirements for PangolinViewer

We provided an OpenGL-based simple viewer.
This viewer is implemented with Pangolin. Thus, we call it **PangolinViewer**.
Please install the following dependencies if you plan on using PangolinViewer.

- Pangolin : Please use the latest release. Tested on commit ID eab3d34.
- GLEW : Required by Pangolin.

Note: If Pangolin version 0.7 or higher, C++17 is required.

2.2.3 Requirements for SocketViewer

We provided an WebGL-based simple viewer running on web browsers.
The SLAM systems publish the map and the frame to the server implemented with Node.js via WebSocket. Thus, we call it **SocketViewer**.
Please install the following dependencies if you plan on using SocketViewer.

- socket.io-client-cpp : **Please use the custom version of socket.io-client-cpp** released in https://github.com/shinsumicco/socket.io-client-cpp.
- Protobuf : version 3 or later.

The following libraries are the dependencies for the server.

- Node.js : version 6 or later.
- npm : Tested on version 3.5.2.

2.2.4 Recommended

- backward-cpp : Used for stack-trace logger.

2.3 Prerequisites for Unix

Note: If your PC is frozen during the build, please reduce the number of parallel compile jobs when executing `make` (e.g. `make -j2`).

2.3.1 Installing for Linux

Tested for **Ubuntu 18.04**.

Install the dependencies via `apt`.

```
apt update -y
apt upgrade -y --no-install-recommends
# basic dependencies
apt install -y build-essential pkg-config cmake git wget curl unzip
# g2o dependencies
apt install -y libatlas-base-dev libsuitesparse-dev
# OpenCV dependencies
apt install -y libgtk-3-dev ffmpeg libavcodec-dev libavformat-dev libavutil-dev␣
↪libswscale-dev libavresample-dev libtbb-dev
# eigen dependencies
apt install -y gfortran
# backward-cpp dependencies (optional)
apt install -y binutils-dev
# other dependencies
apt install -y libyaml-cpp-dev libgflags-dev sqlite3 libsqlite3-dev

# (if you plan on using PangolinViewer)
# Pangolin dependencies
apt install -y libglew-dev

# (if you plan on using SocketViewer)
# Protobuf dependencies
apt install -y autogen autoconf libtool
# Node.js
curl -sL https://deb.nodesource.com/setup_12.x | sudo -E bash -
apt install -y nodejs
```

Download and install Eigen from source.

```
cd /path/to/working/dir
wget -q https://gitlab.com/libeigen/eigen/-/archive/3.3.7/eigen-3.3.7.tar.bz2
tar xf eigen-3.3.7.tar.bz2 && rm -rf eigen-3.3.7.tar.bz2
cd eigen-3.3.7
mkdir -p build && cd build
cmake \
    -DCMAKE_BUILD_TYPE=Release \
    -DCMAKE_INSTALL_PREFIX=/usr/local \
    ..
make -j4 && make install
```

Download, build and install OpenCV from source.

```
cd /path/to/working/dir
# Download OpenCV
wget -q https://github.com/opencv/opencv/archive/4.5.5.zip
unzip -q 4.5.5.zip && rm -rf 4.5.5.zip
# Download aruco module (optional)
wget -q https://github.com/opencv/opencv_contrib/archive/refs/tags/4.5.5.zip -O opencv_
```

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```
↪contrib-4.5.5.zip
unzip -q opencv_contrib-4.5.5.zip && rm -rf opencv_contrib-4.5.5.zip
mkdir -p extra && mv opencv_contrib-4.5.5/modules/aruco extra
rm -rf opencv_contrib-4.5.5
# Build and install OpenCV
cd opencv-4.5.5
mkdir -p build && cd build
cmake \
    -DCMAKE_BUILD_TYPE=Release \
    -DCMAKE_INSTALL_PREFIX=/usr/local \
    -DBUILD_DOCS=OFF \
    -DBUILD_EXAMPLES=OFF \
    -DBUILD_JASPER=OFF \
    -DBUILD_OPENEXR=OFF \
    -DBUILD_PERF_TESTS=OFF \
    -DBUILD_TESTS=OFF \
    -DBUILD_PROTOBUF=OFF \
    -DBUILD_opencv_apps=OFF \
    -DBUILD_opencv_dnn=OFF \
    -DBUILD_opencv_ml=OFF \
    -DBUILD_opencv_python_bindings_generator=OFF \
    -DENABLE_CXX11=ON \
    -DENABLE_FAST_MATH=ON \
    -DWITH_EIGEN=ON \
    -DWITH_FFMPEG=ON \
    -DWITH_TBB=ON \
    -DWITH_OPENMP=ON \
    -DOPENCV_EXTRA_MODULES_PATH=/tmp/extra \
    ..
make -j4 && make install
```

Jump to *Common Installation Instructions* for the next step.

2.3.2 Installing for macOS

Tested for **macOS High Sierra**.

Install the dependencies via `brew`.

```
brew update
# basic dependencies
brew install pkg-config cmake git
# g2o dependencies
brew install suite-sparse
# OpenCV dependencies and OpenCV
brew install eigen ffmpeg opencv
# other dependencies
brew install yaml-cpp glog gflags sqlite3

# (if you plan on using PangolinViewer)
# Pangolin dependencies
brew install glew
```

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```
# (if you plan on using SocketViewer)
# Protobuf dependencies
brew install automake autoconf libtool
# Node.js
brew install node
```

Jump to *Common Installation Instructions* for the next step.

2.3.3 Common Installation Instructions

Download, build and install **the custom FBoW** from source.

```
cd /path/to/working/dir
git clone https://github.com/stella-cv/FBoW.git
cd FBoW
mkdir build && cd build
cmake \
    -DCMAKE_BUILD_TYPE=Release \
    -DCMAKE_INSTALL_PREFIX=/usr/local \
    ..
make -j4 && make install
```

Download, build and install g2o.

```
cd /path/to/working/dir
git clone https://github.com/RainerKuemmerle/g2o.git
cd g2o
git checkout ed40a5bb028566fd56a78fd7b04921b613492d6f
mkdir build && cd build
cmake \
    -DCMAKE_BUILD_TYPE=Release \
    -DCMAKE_INSTALL_PREFIX=/usr/local \
    -DBUILD_SHARED_LIBS=ON \
    -DBUILD_UNITTESTS=OFF \
    -DG2O_USE_CHOLMOD=OFF \
    -DG2O_USE_CSPARSE=ON \
    -DG2O_USE_OPENGL=OFF \
    -DG2O_USE_OPENMP=OFF \
    -DG2O_BUILD_APPS=OFF \
    -DG2O_BUILD_EXAMPLES=OFF \
    -DG2O_BUILD_LINKED_APPS=OFF \
    ..
make -j4 && make install
```

(**if you plan on using PangolinViewer**)
Download, build and install Pangolin from source.

```
cd /path/to/working/dir
git clone https://github.com/stevenlovegrove/Pangolin.git
cd Pangolin
git checkout eab3d3449a33a042b1ee7225e1b8b593b1b21e3e
mkdir build && cd build
cmake \
    -DCMAKE_BUILD_TYPE=Release \
    -DCMAKE_INSTALL_PREFIX=/usr/local \
    -DBUILD_EXAMPLES=OFF \
    -DBUILD_PANGOLIN_DEPTHSENSE=OFF \
    -DBUILD_PANGOLIN_FFMPEG=OFF \
    -DBUILD_PANGOLIN_LIBDC1394=OFF \
    -DBUILD_PANGOLIN_LIBJPEG=OFF \
    -DBUILD_PANGOLIN_LIBOPENEXR=OFF \
    -DBUILD_PANGOLIN_LIBPNG=OFF \
    -DBUILD_PANGOLIN_LIBTIFF=OFF \
    -DBUILD_PANGOLIN_LIBUVC=OFF \
    -DBUILD_PANGOLIN_LZ4=OFF \
    -DBUILD_PANGOLIN_OPENNI=OFF \
    -DBUILD_PANGOLIN_OPENNI2=OFF \
    -DBUILD_PANGOLIN_PLEORA=OFF \
    -DBUILD_PANGOLIN_PYTHON=OFF \
    -DBUILD_PANGOLIN_TELICAM=OFF \
    -DBUILD_PANGOLIN_UVC_MEDIAFOUNDATION=OFF \
    -DBUILD_PANGOLIN_V4L=OFF \
    -DBUILD_PANGOLIN_ZSTD=OFF \
    ..
make -j4 && make install
```

(**if you plan on using SocketViewer**)
Download, build and install socket.io-client-cpp from source.

```
cd /path/to/working/dir
git clone https://github.com/shinsumicco/socket.io-client-cpp.git
cd socket.io-client-cpp
git submodule init
git submodule update
mkdir build && cd build
cmake \
    -DCMAKE_BUILD_TYPE=Release \
    -DCMAKE_INSTALL_PREFIX=/usr/local \
    -DBUILD_UNIT_TESTS=OFF \
    ..
make -j4
make install
```

(**if you plan on using SocketViewer**)
Install Protobuf.

If you use Ubuntu 18.04 or macOS, Protobuf 3.x can be installed via `apt` or `brew`.

```
# for Ubuntu 18.04 (or later)
apt install -y libprotobuf-dev protobuf-compiler
# for macOS
brew install protobuf
```

Otherwise, please download, build and install Protobuf from source.

```
wget -q https://github.com/google/protobuf/archive/v3.6.1.tar.gz
tar xf v3.6.1.tar.gz
cd protobuf-3.6.1
./autogen.sh
./configure \
    --prefix=/usr/local \
    --enable-static=no
make -j4
make install
```

2.4 Build Instructions

When building with support for PangolinViewer, please specify the following cmake options: `-DUSE_PANGOLIN_VIEWER=ON` and `-DUSE_SOCKET_PUBLISHER=OFF`.

```
cd /path/to/stella_vslam
mkdir build && cd build
cmake \
    -DUSE_PANGOLIN_VIEWER=ON \
    -DINSTALL_PANGOLIN_VIEWER=ON \
    -DUSE_SOCKET_PUBLISHER=OFF \
    -DBUILD_TESTS=ON \
    -DBUILD_EXAMPLES=ON \
    ..
make -j4 && make install
```

When building with support for SocketViewer, please specify the following cmake options: `-DUSE_PANGOLIN_VIEWER=OFF` and `-DUSE_SOCKET_PUBLISHER=ON`.

```
cd /path/to/stella_vslam
mkdir build && cd build
cmake \
    -DUSE_PANGOLIN_VIEWER=OFF \
    -DUSE_SOCKET_PUBLISHER=ON \
    -DINSTALL_SOCKET_PUBLISHER=ON \
    -DBUILD_TESTS=ON \
    -DBUILD_EXAMPLES=ON \
    ..
make -j4 && make install
```

After building, check to see if it was successfully built by executing `./run_kitti_slam -h`.

```
$ ./run_kitti_slam -h
Allowed options:
-h, --help                produce help message
-v, --vocab arg           vocabulary file path
-d, --data-dir arg        directory path which contains dataset
-c, --config arg          config file path
--frame-skip arg (=1)     interval of frame skip
--no-sleep                not wait for next frame in real time
--auto-term               automatically terminate the viewer
--log-level arg (=info)   log level
```

2.5 Server Setup for SocketViewer

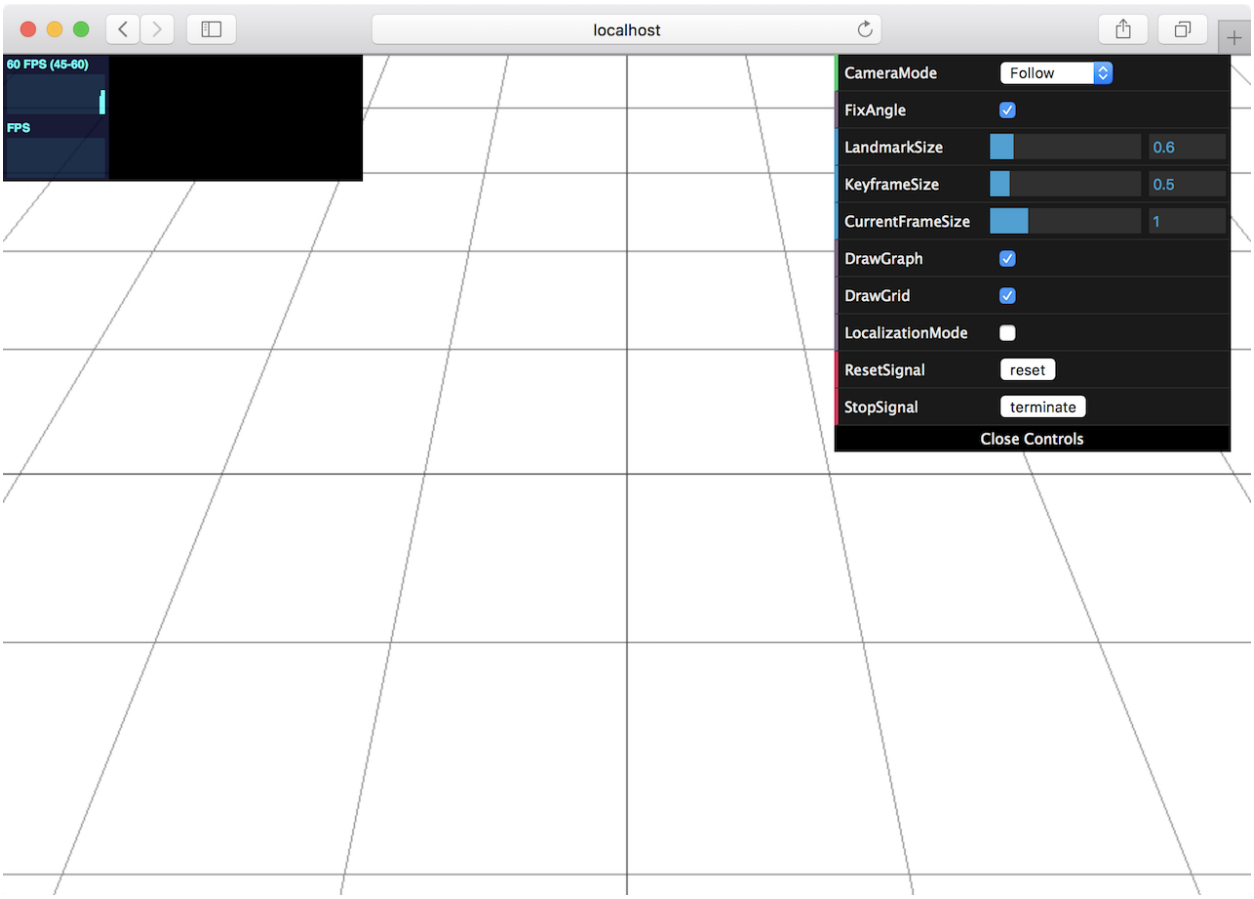
If you plan on using SocketViewer, please setup the environment for the server with `npm`.

```
$ cd /path/to/stella_vslam/viewer
$ ls
Dockerfile  app.js  package.json  public  views
$ npm install
added 88 packages from 60 contributors and audited 204 packages in 2.105s
found 0 vulnerabilities
$ ls
Dockerfile  app.js  node_modules  package-lock.json  package.json  public  views
```

Then, launch the server with `node app.js`.

```
$ cd /path/to/stella_vslam/viewer
$ ls
Dockerfile  app.js  node_modules  package-lock.json  package.json  public  views
$ node app.js
WebSocket: listening on *:3000
HTTP server: listening on *:3001
```

After launching, please access to `http://localhost:3001/` to check whether the server is correctly launched.



Note: When you try *the tutotial* and *the examples* with SocketViewer, please launch the server in the other terminal and access to it with the web browser **in advance**.

CHAPTER

THREE

SIMPLE TUTORIAL

3.1 TL; DR

Note: If you use *SocketViewer*, please launch the server in the other terminal and access to it with the web browser **in advance**.

Running the following commands will give a feel for what stella_vslam can do. The later parts of this chapter explains what each of the commands do in more detail.

```
# at the build directory of stella_vslam ...
$ pwd
/path/to/stella_vslam/build/
$ ls
run_video_slam   lib/   ...

# download an ORB vocabulary from GitHub
curl -sL "https://github.com/stella-cv/FBoW_orb_vocab/raw/main/orb_vocab.fbow" -o orb_
↪vocab.fbow

# download a sample dataset from Google Drive
FILE_ID="1d8kADKWBptEqTF7jEVhKatBEdN7g0ikY"
curl -sc /tmp/cookie "https://drive.google.com/uc?export=download&id=${FILE_ID}" > /dev/
↪null
CODE="$(awk '/_warning_/ {print $NF}' /tmp/cookie)"
curl -sLb /tmp/cookie "https://drive.google.com/uc?export=download&confirm=${CODE}&id=$
↪{FILE_ID}" -o aist_living_lab_1.zip
unzip aist_living_lab_1.zip

# download a sample dataset from Google Drive
FILE_ID="1TVf2D2QvMZPHsFoTb7HNxbXclPoFMGLX"
curl -sc /tmp/cookie "https://drive.google.com/uc?export=download&id=${FILE_ID}" > /dev/
↪null
CODE="$(awk '/_warning_/ {print $NF}' /tmp/cookie)"
curl -sLb /tmp/cookie "https://drive.google.com/uc?export=download&confirm=${CODE}&id=$
↪{FILE_ID}" -o aist_living_lab_2.zip
unzip aist_living_lab_2.zip

# run tracking and mapping
./run_video_slam -v ./orb_vocab.fbow -m ./aist_living_lab_1/video.mp4 -c ../example/aist/
```

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```
↪equirectangular.yaml --frame-skip 3 --no-sleep --map-db-out map.msg
# click the [Terminate] button to close the viewer
# you can find map.msg in the current directory

# run localization
./run_video_slam --disable-mapping -v ./orb_vocab.fbow -m ./aist_living_lab_2/video.mp4 -
↪c ../example/aist/equirectangular.yaml --frame-skip 3 --no-sleep --map-db-in map.msg
```

3.2 Sample Datasets

You can use stella_vslam with various video datasets. If you want to run stella_vslam with standard benchmarking detasets, please see *this section*.

Start by downloading some datasets you like.

3.2.1 Equirectangular Datasets

name	camera model	length	Google Drive	Baidu Wangpan
aist_entrance_hall_1	equirectangular (mono)	0:54	link	link (Pass: r7r4)
aist_entrance_hall_2	equirectangular (mono)	0:54	link	link (Pass: 4qma)
aist_factory_A_1	equirectangular (mono)	1:55	link	link (Pass: yy2u)
aist_factory_A_2	equirectangular (mono)	1:54	link	link (Pass: 9vey)
aist_factory_B_1	equirectangular (mono)	1:04	link	link (Pass: gpec)
aist_factory_B_2	equirectangular (mono)	1:34	link	link (Pass: ugrx)
aist_living_lab_1	equirectangular (mono)	2:16	link	link (Pass: 434m)
aist_living_lab_2	equirectangular (mono)	1:47	link	link (Pass: 549f)
aist_living_lab_3	equirectangular (mono)	2:06	link	link (Pass: cc2p)
aist_stairs_A_1	equirectangular (mono)	2:27	link	link (Pass: ncdr)
aist_stairs_B_1	equirectangular (mono)	2:55	link	link (Pass: xr5t)
aist_store_1	equirectangular (mono)	1:12	link	link (Pass: 47vq)
aist_store_2	equirectangular (mono)	1:44	link	link (Pass: xt8u)
aist_store_3	equirectangular (mono)	1:18	link	link (Pass: kghc)
ALL	equirectangular (mono)		link	link (Pass: vsv7)

3.2.2 Fisheye Datasets

name	camera model	length	Google Drive	Baidu Wangpan
aist_entrance_hall_1	fisheye (mono)	1:05	link	link (Pass: u86e)
aist_entrance_hall_2	fisheye (mono)	1:06	link	link (Pass: 9iyc)
aist_entrance_hall_3	fisheye (mono)	1:23	link	link (Pass: qaqc)
aist_entrance_hall_4	fisheye (mono)	1:27	link	link (Pass: em43)
aist_living_lab_1	fisheye (mono)	1:20	link	link (Pass: wcw4)
aist_living_lab_2	fisheye (mono)	2:26	link	link (Pass: dxns)
aist_living_lab_3	fisheye (mono)	3:43	link	link (Pass: 7n4q)
nu_eng2_corridor_1	fisheye (mono)	2:56	link	link (Pass: 71ws)
nu_eng2_corridor_2	fisheye (mono)	2:45	link	link (Pass: yrtj)
nu_eng2_corridor_3	fisheye (mono)	2:04	link	link (Pass: btpj)
ALL	fisheye (mono)		link	link (Pass: gumj)

After downloading and uncompressing a zip file, you will find a video file and a config file (old format) under the uncompressed directory.

```
$ ls dataset_name_X/
config.yaml  video.mp4
```

You can put the dataset in any directory where you have access to.

Additionally, please download a vocabulary file for FBoW from here.

For the rest of this chapter, we will use `aist_living_lab_1` and `aist_living_lab_2` datasets for our example.

3.3 Tracking and Mapping

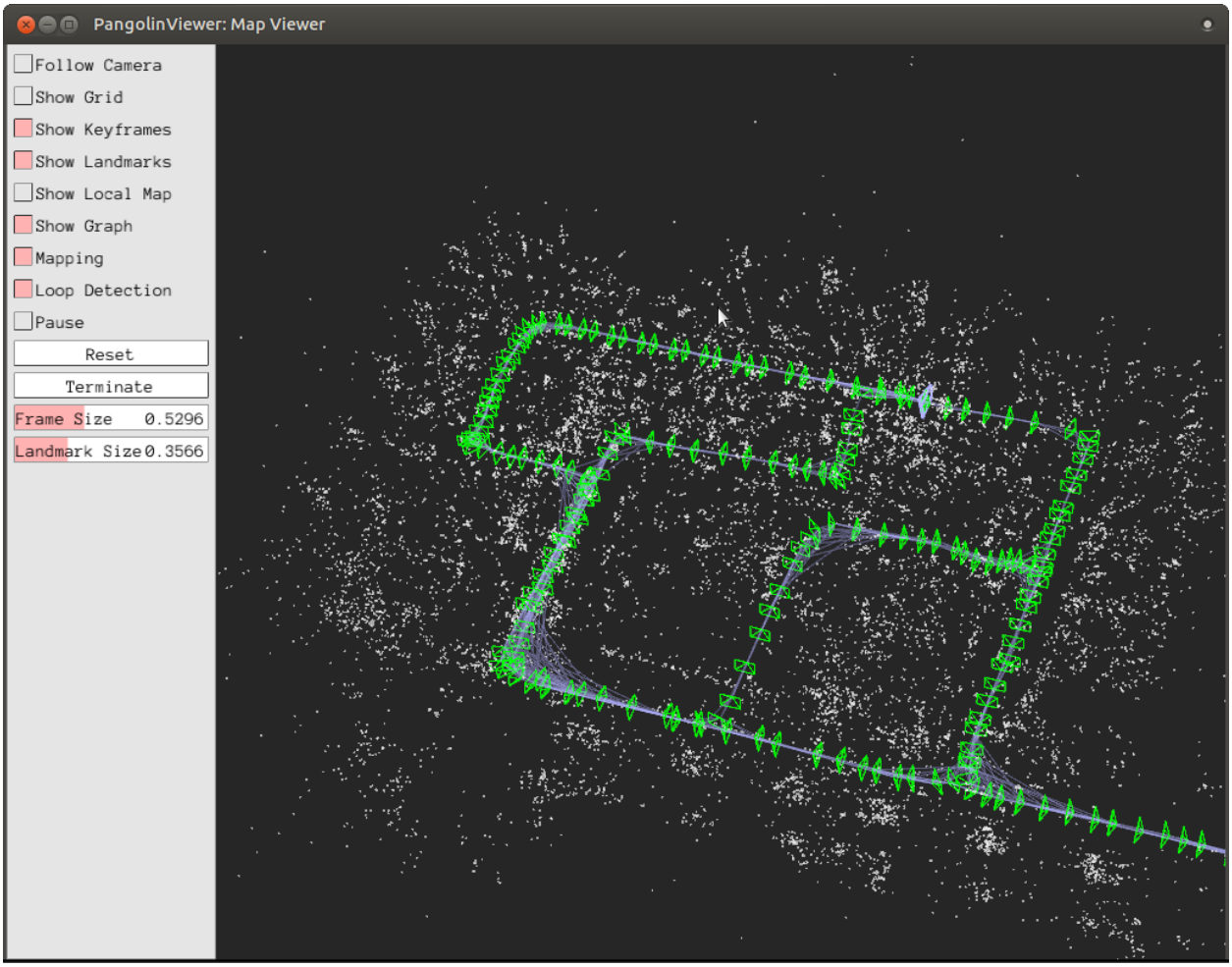
Here we should know how to run SLAM and create a map database file with `aist_living_lab_1` dataset. You can use `./run_video_slam` to run SLAM with the video file.

```
# at the build directory of stella_vslam
$ ls
...
run_video_slam
...
$ ./run_video_slam -h
Allowed options:
  -h, --help               produce help message
  -v, --vocab arg          vocabulary file path
  -m, --video arg          video file path
  -c, --config arg         config file path
  --mask arg               mask image path
  --frame-skip arg (=1)    interval of frame skip
  --no-sleep               not wait for next frame in real time
  --auto-term              automatically terminate the viewer
  --log-level arg (=info)  log level
```

Execute the following command to run SLAM. The paths should be changed accordingly.

```
$ ./run_video_slam \
    -v /path/to/orb_vocab/orb_vocab.fbow \
    -c /path/to/stella_vslam/example/aist/equirectangular.yaml \
    -m /path/to/aist_living_lab_1/video.mp4 \
    --frame-skip 3 \
    --map-db-out aist_living_lab_1_map.msg
```

The frame viewer and map viewer should launch as well. If the two viewers are not launching correctly, check if you launched the command with the appropriate paths.




```
[2019-05-20 17:52:41.677] [I] config file loaded: /path/to/stella_vslam/example/aist/
↪equirectangular.yaml
  ___                  __   _____ _       _   __  __
 / _ \ _ __  ___ _ _\ \ / / __| |    /_\ |  \/  |
| (_) | '_ \/ -_) ' \\ V /\__ \ |__ / _ \| |\/| |
 \___/| .__/\___|_||_|\_/ |___/____/_/ \_\_|  |_|
      |_|

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For the changes after forking,
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Camera Configuration:
- name: RICOH THETA S 960
- setup: Monocular
- fps: 30
```

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```
- cols: 1920
- rows: 960
- color: RGB
- model: Equirectangular
ORB Configuration:
- number of keypoints: 2000
- scale factor: 1.2
- number of levels: 8
- initial fast threshold: 20
- minimum fast threshold: 7
- edge threshold: 19
- patch size: 31
- half patch size: 15
- mask rectangles:
  - [0, 1, 0, 0.1]
  - [0, 1, 0.84, 1]
  - [0, 0.2, 0.7, 1]
  - [0.8, 1, 0.7, 1]
Tracking Configuration:

[2019-05-20 17:52:41.678] [I] loading ORB vocabulary: /path/to/orb_vocab/orb_vocab.fbow
[2019-05-20 17:52:42.037] [I] startup SLAM system
[2019-05-20 17:52:42.038] [I] start local mapper
[2019-05-20 17:52:42.038] [I] start loop closer
[2019-05-20 17:52:42.395] [I] initialization succeeded with E
[2019-05-20 17:52:42.424] [I] new map created with 191 points: frame 0 - frame 2
[2019-05-20 17:53:39.092] [I] detect loop: keyframe 36 - keyframe 139
[2019-05-20 17:53:39.094] [I] pause local mapper
[2019-05-20 17:53:39.303] [I] resume local mapper
[2019-05-20 17:53:39.303] [I] start loop bundle adjustment
[2019-05-20 17:53:40.186] [I] finish loop bundle adjustment
[2019-05-20 17:53:40.186] [I] updating map with pose propagation
[2019-05-20 17:53:40.194] [I] pause local mapper
[2019-05-20 17:53:40.199] [I] resume local mapper
[2019-05-20 17:53:40.199] [I] updated map
[2019-05-20 17:55:36.218] [I] shutdown SLAM system
[2019-05-20 17:55:36.218] [I] encoding 1 camera(s) to store
[2019-05-20 17:55:36.218] [I] encoding 301 keyframes to store
[2019-05-20 17:55:37.906] [I] encoding 19900 landmarks to store
[2019-05-20 17:55:38.819] [I] save the MessagePack file of database to aist_living_lab_1_
↪map.msg
median tracking time: 0.045391[s]
mean tracking time: 0.0472221[s]
[2019-05-20 17:55:40.087] [I] clear BoW database
[2019-05-20 17:55:40.284] [I] clear map database
```

Please click the **Terminate** button to close the viewer.

After terminating, you will find a map database file `aist_living_lab_1_map.msg`.

```
$ ls
...
aist_living_lab_1_map.msg
```

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```
...
```

The format of map database files is MessagePack, so you can reuse created maps for any third-party applications other than stella_vslam.

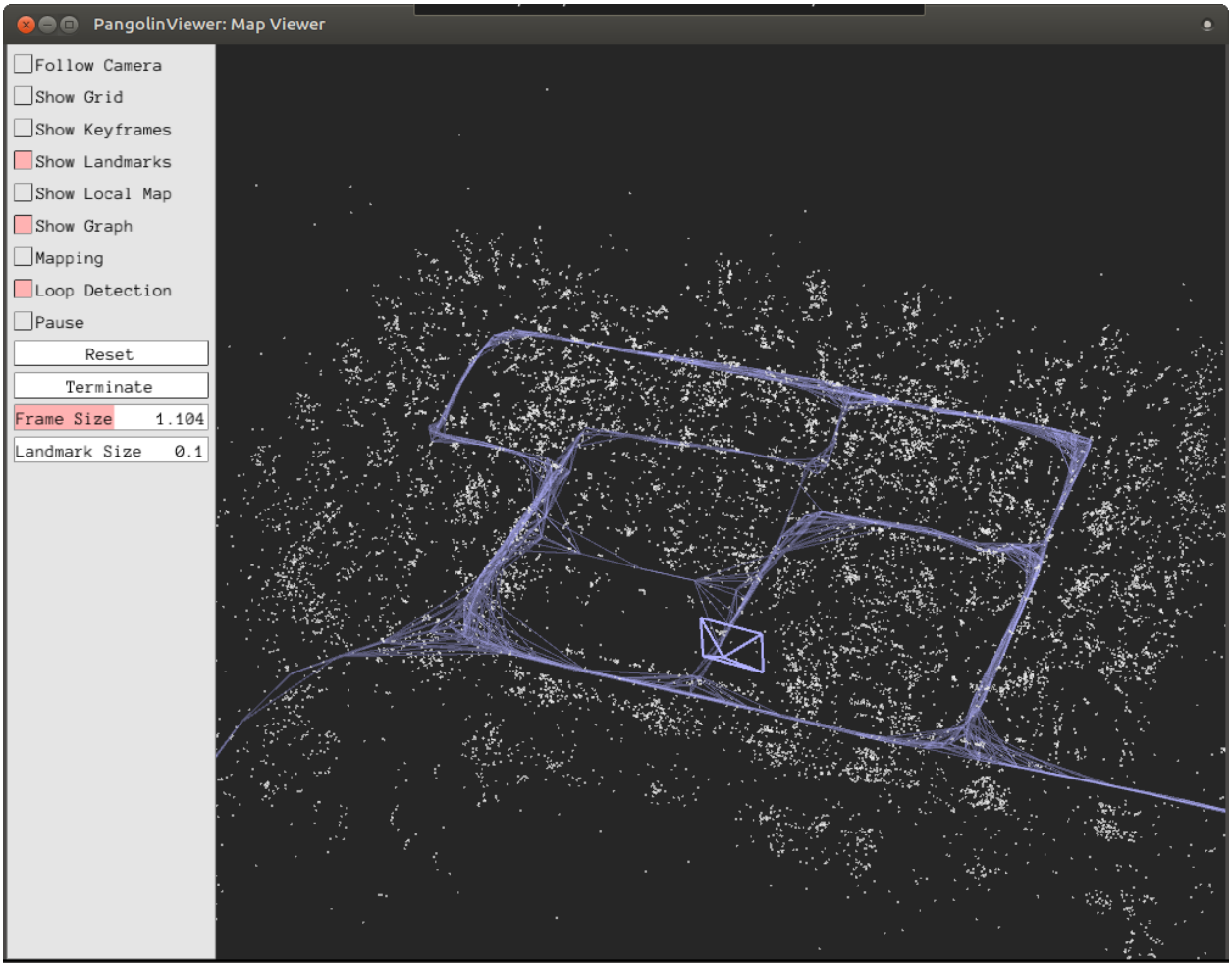
3.4 Localization

In this section, we will localize the frames in `aist_living_lab_2` dataset using the created map file `aist_living_lab_1_map.msg`. You can use `./run_video_slam` with `--map-db-in aist_living_lab_1_map.msg --disable-mapping` to run localization. Execute the following command to start localization. The paths should be changed accordingly.

```
$ ./run_video_slam --disable-mapping \
    -v /path/to/orb_vocab/orb_vocab.fbow \
    -c /path/to/stella_vslam/example/aist/equirectangular.yaml \
    -m /path/to/aist_living_lab_2/video.mp4 \
    --frame-skip 3 \
    --map-db-in aist_living_lab_1_map.msg
```

The frame viewer and map viewer should launch as well. If the two viewers are not launching correctly, check if you launched the command with the appropriate paths.

You can see if the current frame is being localized, based on the prebuild map.




```
[2019-05-20 17:58:54.728] [I] config file loaded: /path/to/stella_vslam/example/aist/
↪equirectangular.yaml
  ___                  __   _____ _       _   __  __
 / _ \ _ __  ___ _ _\ \ / / __| |    /_\ |  \/  |
| (_) | '_ \/ -_) ' \\ V /\__ \ |__ / _ \| |\/| |
 \___/| .__/\___|_||_|\_/ |___/____/_/ \_\_|  |_|
      |_|

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See the LICENSE file.

Camera Configuration:
- name: RICOH THETA S 960
- setup: Monocular
- fps: 30
```

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```
- cols: 1920
- rows: 960
- color: RGB
- model: Equirectangular
ORB Configuration:
- number of keypoints: 2000
- scale factor: 1.2
- number of levels: 8
- initial fast threshold: 20
- minimum fast threshold: 7
- edge threshold: 19
- patch size: 31
- half patch size: 15
- mask rectangles:
  - [0, 1, 0, 0.1]
  - [0, 1, 0.84, 1]
  - [0, 0.2, 0.7, 1]
  - [0.8, 1, 0.7, 1]
Tracking Configuration:

[2019-05-20 17:58:54.729] [I] loading ORB vocabulary: /path/to/orb_vocab/orb_vocab.fbow
[2019-05-20 17:58:55.083] [I] clear map database
[2019-05-20 17:58:55.083] [I] clear BoW database
[2019-05-20 17:58:55.083] [I] load the MessagePack file of database from aist_living_lab_
↪1_map.msg
[2019-05-20 17:58:57.832] [I] decoding 1 camera(s) to load
[2019-05-20 17:58:57.832] [I] load the tracking camera "RICOH THETA S 960" from JSON
[2019-05-20 17:58:58.204] [I] decoding 301 keyframes to load
[2019-05-20 17:59:02.013] [I] decoding 19900 landmarks to load
[2019-05-20 17:59:02.036] [I] registering essential graph
[2019-05-20 17:59:02.564] [I] registering keyframe-landmark association
[2019-05-20 17:59:03.161] [I] updating covisibility graph
[2019-05-20 17:59:03.341] [I] updating landmark geometry
[2019-05-20 17:59:04.189] [I] startup SLAM system
[2019-05-20 17:59:04.190] [I] start local mapper
[2019-05-20 17:59:04.191] [I] start loop closer
[2019-05-20 17:59:04.195] [I] pause local mapper
[2019-05-20 17:59:04.424] [I] relocalization succeeded
[2019-05-20 18:01:12.387] [I] shutdown SLAM system
median tracking time: 0.0370831[s]
mean tracking time: 0.0384683[s]
[2019-05-20 18:01:12.390] [I] clear BoW database
[2019-05-20 18:01:12.574] [I] clear map database
```

If you set the `--mapping` option, the mapping module is enabled to extend the prebuild map.

CHAPTER

FOUR

RUNNING ON DOCKER

4.1 Instructions for PangolinViewer

`Dockerfile.desktop` can be used for easy installation. This chapter provides instructions on building and running examples with PangolinViewer support using Docker.

The instructions are tested on Ubuntu 18.04 and 20.04. Docker for Mac are NOT supported due to OpenGL forwarding.

Note: If you're using Ubuntu, there are easy setup scripts in scripts/ubuntu. see scripts/ubuntu/README.md

If you plan on using a machine with NVIDIA graphics card(s), please use nvidia-docker2 and the version 390 or later of NVIDIA driver. These examples depend on X11 forwarding with OpenGL for visualization.

If the viewer cannot be lanched at all or you are using macOS, please *install the dependencies manually* or use *the docker images for SocketViewer*.

4.1.1 Building Docker Image

Execute the following commands:

```
git clone --recursive https://github.com/stella-cv/stella_vslam.git
cd stella_vslam
docker build -t stella_vslam-desktop -f Dockerfile.desktop .
```

You can accelerate the build of the docker image with `--build-arg NUM_THREADS=<number of parallel builds>` option. For example:

```
# building the docker image with four threads
docker build -t stella_vslam-desktop -f Dockerfile.desktop . --build-arg NUM_
↪THREADS=`expr $(nproc) - 1`
```

4.1.2 Starting Docker Container

In order to enable X11 forwarding, supplemental options (`-e DISPLAY=$DISPLAY` and `-v /tmp/.X11-unix/:/tmp/.X11-unix:ro`) are needed for `docker run`.

```
# before launching the container, allow display access from local users
xhost +local:
# launch the container
docker run -it --rm -e DISPLAY=$DISPLAY -v /tmp/.X11-unix/:/tmp/.X11-unix:ro stella_
↪vslam-desktop
```

Note: Additional option `--runtime=nvidia` is needed if you use NVIDIA graphics card(s). If you're using Docker with **Native GPU Support** then the options are `--gpus all`. Please see here for more details.

After launching the container, the shell interface will be launched in the docker container.

```
root@ddad048b5fff:/stella_vslam/build# ls
lib                     run_image_slam          run_video_slam
run_euroc_slam          run_kitti_slam          run_tum_slam
```

See *Tutorial* to run SLAM examples in the container.

Note: If the viewer does not work, please *install the dependencies manually* on your host machine or use *the docker images for SocketViewer* instead.

If you need to access to any files and directories on a host machine from the container, *bind directories* between the host and the container.

4.2 Instructions for SocketViewer

`Dockerfile.socket` and `viewer/Dockerfile` can be used for easy installation. This chapter provides instructions on building and running examples with SocketViewer support using Docker.

4.2.1 Building Docker Images

Docker Image of stella_vslam

Execute the following commands:

```
cd /path/to/stella_vslam
docker build -t stella_vslam-socket -f Dockerfile.socket .
```

You can accelerate the build of the docker image with `--build-arg NUM_THREADS=<number of parallel builds>` option. For example:

```
# building the docker image with four threads
docker build -t stella_vslam-socket -f Dockerfile.socket . --build-arg NUM_THREADS=`expr
↪$(nproc) - 1`
```

Docker Image of Server

Execute the following commands:

```
cd /path/to/stella_vslam
cd viewer
docker build -t stella_vslam-viewer .
```

4.2.2 Starting Docker Containers

On Linux

Launch the server container and access to it with the web browser in advance. Please specify `--net=host` in order to share the network with the host machine.

```
$ docker run --rm -it --name stella_vslam-viewer --net=host stella_vslam-viewer
WebSocket: listening on *:3000
HTTP server: listening on *:3001
```

After launching, access to `http://localhost:3001/` with the web browser.

Next, launch the container of stella_vslam. The shell interface will be launched in the docker container.

```
$ docker run --rm -it --name stella_vslam-socket --net=host stella_vslam-socket
root@hostname:/stella_vslam/build#
```

See *Tutorial* to run SLAM examples in the container.

If you need to access to any files and directories on a host machine from the container, *bind directories* between the host and the container.

On macOS

Launch the server container and access to it with the web browser in advance. Please specify `-p 3001:3001` for port-forwarding.

```
$ docker run --rm -it --name stella_vslam-viewer -p 3001:3001 stella_vslam-viewer
WebSocket: listening on *:3000
HTTP server: listening on *:3001
```

After launching, access to `http://localhost:3001/` with the web browser.

Then, inspect the container's IP address and append the `SocketPublisher.server_uri` entry to the YAML config file of stella_vslam.

```
# inspect the server's IP address
$ docker inspect stella_vslam-viewer | grep -m 1 \"IPAddress\" | sed 's/ //g' | sed 's/,/
↪/g'
"IPAddress": "172.17.0.2"
```

```
# config file of stella_vslam

...
```

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```
#============================#
# SocketPublisher Parameters #
#============================#

# append this entry
SocketPublisher.server_uri: "http://172.17.0.2:3000"
```

Next, launch the container of stella_vslam. The shell interface will be launched in the docker container.

```
$ docker run --rm -it --name stella_vslam-socket stella_vslam-socket
root@hostname:/stella_vslam/build#
```

See *Tutorial* to run SLAM examples in the container.
Please don't forget to append `SocketPublisher.server_uri` entry to the `config.yaml` if you use the downloaded datasets in the tutorial.

If you need to access to any files and directories on a host machine from the container, *bind directories* between the host and the container.

4.3 Bind of Directories

If you need to access to any files and directories on a host machine from the container, bind directories between the host and the container using `--volume` or `--mount` option. (See the docker documentataion.)

For example:

```
# launch a container of stella_vslam-desktop with --volume option
$ docker run -it --rm --runtime=nvidia -e DISPLAY=$DISPLAY -v /tmp/.X11-unix/:/tmp/.X11-
↪unix:ro \
    --volume /path/to/dataset/dir/:/dataset:ro \
    --volume /path/to/vocab/dir:/vocab:ro \
    stella_vslam-desktop
# dataset/ and vocab/ are found at the root directory in the container
root@0c0c9f115d74:/# ls /
...   dataset/   vocab/   ...
```

```
# launch a container of stella_vslam-socket with --volume option
$ docker run --rm -it --name stella_vslam-socket --net=host \
    --volume /path/to/dataset/dir/:/dataset:ro \
    --volume /path/to/vocab/dir:/vocab:ro \
    stella_vslam-socket
# dataset/ and vocab/ are found at the root directory in the container
root@0c0c9f115d74:/# ls /
...   dataset/   vocab/   ...
```

CHAPTER

FIVE

RUNNING ON ROS

We provide ROS and ROS2 package examples to help you run stella_vslam on ROS framework.

5.1 ROS Package

5.1.1 Installation

Requirements

- ROS : `noetic` is recommended. (If you have built OpenCV (3.3.1 or later) manually, you can use `melodic` or later.)
- *stella_vslam*
- image_transport : Required by this ROS package examples.
- cv_bridge : Please build it with the same version of OpenCV used in stella_vslam.

Prerequisites

Tested for **Ubuntu 18.04**.

Please install the following dependencies.

- ROS : Please follow Installation of ROS.
- stella_vslam : Please follow *Installation of stella_vslam*.

Note: Please build stella_vslam with PangolinViewer or SocketViewer if you plan on using it for the examples.

Install the dependencies via `apt`.

```
apt update -y
apt install ros-${ROS_DISTRO}-image-transport
```

Download the source of `cv_bridge`.

```
mkdir -p ~/catkin_ws/src
git clone --branch ${ROS_DISTRO} --depth 1 https://github.com/ros-perception/vision_
↪opencv.git
```

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```
cp -r vision_opencv/cv_bridge ~/catkin_ws/src
rm -rf vision_opencv
```

Build Instructions

When building with support for PangolinViewer, please specify the following cmake options: `-DUSE_PANGOLIN_VIEWER=ON` and `-DUSE_SOCKET_PUBLISHER=OFF` as described in *build of stella_vslam*. stella_vslam and stella_vslam_ros need to be built with the same options.

```
cd ~/catkin_ws/src
git clone --recursive --branch ros --depth 1 https://github.com/stella-cv/stella_vslam_
↪ros.git
cd ~/catkin_ws
catkin_make -DUSE_PANGOLIN_VIEWER=ON -DUSE_SOCKET_PUBLISHER=OFF
```

5.1.2 Examples

Run the core program required for ROS-based system in advance.

```
roscore
```

Note: Please leave the **roscore** run.

Publisher

Publish Images by a video

```
rosrun image_publisher image_publisher ./aist_living_lab_1/video.mp4 /image_raw:=/camera/
↪image_raw
```

Publish Images of a USB Camera

For using a standard USB camera for visual SLAM or localization.

```
apt install ros-${ROS_DISTRO}-usb-cam
```

```
rosparam set usb_cam/pixel_format yuyv
rosrun usb_cam usb_cam_node
```

Republish the ROS topic to `/camera/image_raw`.

```
rosrun image_transport republish \
    raw in:=/usb_cam/image_raw raw out:=/camera/image_raw
```

Subscriber

Subscribers continually receive images. Please execute one of the following command snippets in the new terminal.

Note: Option arguments are the same as *the examples of stella_vslam*.

Tracking and Mapping

We provide an example snippet for visual SLAM. The source code is placed at `stella_vslam_ros/src/run_slam.cc`.

```
source ~/catkin_ws/devel/setup.bash
rosrun stella_vslam_ros run_slam \
    -v /path/to/orb_vocab.fbow \
    -c /path/to/config.yaml \
    --map-db-out /path/to/map.msg
```

Localization

We provide an example snippet for localization based on a prebuilt map. The source code is placed at `stella_vslam_ros/src/run_slam.cc`.

```
source ~/catkin_ws/devel/setup.bash
rosrun stella_vslam_ros run_slam \
    --disable-mapping \
    -v /path/to/orb_vocab.fbow \
    -c /path/to/config.yaml \
    --map-db-in /path/to/map.msg
```

5.2 ROS2 Package

5.2.1 Installation

Requirements

- ROS2 : `foxy` or later.
- *stella_vslam*
- image_common : Required by this ROS package examples.
- vision_opencv : Please build it with the same version of OpenCV used in stella_vslam.
- image_tools : An optional requirement to use USB cameras.

Prerequisites

Tested for **Ubuntu 20.04**.

Please install the following dependencies.

- ROS2 : Please follow Installation of ROS2.
- stella_vslam : Please follow *Installation of stella_vslam*.

Note: Please build stella_vslam with PangolinViewer or SocketViewer if you plan on using it for the examples.

Download repositories of `image_common` and `vision_opencv`.

```
mkdir -p ~/ros2_ws/src
cd ~/ros2_ws/src
git clone -b ${ROS_DISTRO} --single-branch https://github.com/ros-perception/image_
↪common.git
git clone -b ros2 --single-branch https://github.com/ros-perception/vision_opencv.git
```

For using USB cam as a image source, donload a repository of `demos` and pick `image_tools` module.

```
cd ~/ros2_ws
git clone https://github.com/ros2/demos.git
cp -r demos/image_tools src/
rm -rf demos
```

Build Instructions

When building with support for PangolinViewer, please specify the following cmake options: `-DUSE_PANGOLIN_VIEWER=ON` and `-DUSE_SOCKET_PUBLISHER=OFF` as described in *build of stella_vslam*. stella_vslam and stella_vslam_ros need to be built with the same options.

```
cd ~/ros2_ws/src
git clone --recursive --branch ros2 --depth 1 https://github.com/stella-cv/stella_vslam_
↪ros.git
cd ~/ros2_ws
colcon build --symlink-install --cmake-args -DUSE_PANGOLIN_VIEWER=ON -DUSE_SOCKET_
↪PUBLISHER=OFF
```

5.2.2 Examples

Publisher

Publish Images by a video

```
ros2 run image_publisher image_publisher_node ./aist_living_lab_1/video.mp4 --ros-args --
↪remap /image_raw:=/camera/image_raw
```

Publish Images Captured by a USB Camera

For using a standard USB camera for visual SLAM or localization.

```
ros2 run image_tools cam2image
```

Republish the ROS topic to `/camera/image_raw`.

```
ros2 run image_transport republish \
    raw in:=image raw out:=/camera/image_raw
```

Subscriber

Subscribers continually receive images. Please execute one of the following command snippets in the new terminal.

Note: Option arguments are the same as *the examples of stella_vslam*.

Tracking and Mapping

We provide an example snippet for visual SLAM. The source code is placed at `stella_vslam_ros/src/run_slam.cc`.

```
source ~/ros2_ws/install/setup.bash
ros2 run stella_vslam_ros run_slam \
    -v /path/to/orb_vocab.fbow \
    -c /path/to/config.yaml \
    --map-db-out /path/to/map.msg
```

Localization

We provide an example snippet for localization based on a prebuilt map. The source code is placed at `stella_vslam_ros/src/run_slam.cc`.

```
source ~/ros2_ws/install/setup.bash
ros2 run stella_vslam_ros run_slam \
    --disable-mapping \
    -v /path/to/orb_vocab.fbow \
    -c /path/to/config.yaml \
    --map-db-in /path/to/map.msg
```

CHAPTER

SIX

EXAMPLE

We provided example code snippets for running stella_vslam with variety of datasets.

6.1 SLAM with Video Files

We provide an example snippet for using video files (e.g. `.mp4`) for visual SLAM. The source code is placed at `./example/run_video_slam.cc`.

The camera that captures the video file must be calibrated. Create a config file (`.yaml`) according to the camera parameters.
We provided a vocabulary file for FBoW at here.

You can create a map database file by running one of the `run_****_slam` executables with `--map-db-out map_file_name.msg` option.

6.2 SLAM with Image Sequences

We provided an example snippet for using image sequences for visual SLAM. The source code is placed at `./example/run_image_slam.cc`.

The camera that captures the video file must be calibrated. Create a config file (`.yaml`) according to the camera parameters.
We provided a vocabulary file for FBoW at here.

You can create a map database file by running one of the `run_****_slam` executables with `--map-db-out map_file_name.msg` option.

6.3 SLAM with Standard Datasets

6.3.1 KITTI Odometry dataset

KITTI Odometry dataset is a benchmarking dataset for monocular and stereo visual odometry and lidar odometry that is captured from car-mounted devices. We provided an example source code for running monocular and stereo visual SLAM with this dataset. The source code is placed at `./example/run_kitti_slam.cc`.

Start by downloading the dataset from here. Download the grayscale set (`data_odometry_gray.zip`).

After downloading and uncompressing it, you will find several sequences under the `sequences/` directory.

```
$ ls sequences/
00  01  02  03  04  05  06  07  08  09  10  11  12  13  14  15  16  17  18  19  20  21
```

In addition, download a vocabulary file for FBoW from here.

A configuration file for each sequence is contained under `./example/kitti/`.

If you built examples with Pangolin Viewer support, a map viewer and frame viewer will be launced right after executing the following command.

```
# at the build directory of stella_vslam
# monocular SLAM with sequence 00
$ ./run_kitti_slam \
    -v /path/to/orb_vocab/orb_vocab.fbow \
    -d /path/to/KITTI/Odometry/sequences/00/ \
    -c ../example/kitti/KITTI_mono_00-02.yaml
# stereo SLAM with sequence 05
$ ./run_kitti_slam \
    -v /path/to/orb_vocab/orb_vocab.fbow \
    -d /path/to/KITTI/Odometry/sequences/05/ \
    -c ../example/kitti/KITTI_stereo_04-12.yaml
```

6.3.2 EuRoC MAV dataset

EuRoC MAV dataset is a benchmarking dataset for monocular and stereo visual odometry that is captured from drone-mounted devices. We provide an example source code for running monocular and stereo visual SLAM with this dataset. The source code is placed at `./example/run_euroc_slam.cc`.

Start by downloading the dataset from here. Download the `.zip` file of a dataset you plan on using.

After downloading and uncompressing it, you will find several directories under the `mav0/` directory.

```
$ ls mav0/
body.yaml  cam0  cam1  imu0  leica0  state_groundtruth_estimate0
```

In addition, download a vocabulary file for FBoW from here.

We provided the two config files for EuRoC, `./example/euroc/EuRoC_mono.yaml` for monocular and `./example/euroc/EuRoC_stereo.yaml` for stereo.

If you have built examples with Pangolin Viewer support, a map viewer and frame viewer will be launched right after executing the following command.

```
# at the build directory of stella_vslam
# monocular SLAM with any EuRoC sequence
$ ./run_euroc_slam \
    -v /path/to/orb_vocab/orb_vocab.fbow \
    -d /path/to/EuRoC/MAV/mav0/ \
    -c ../example/euroc/EuRoC_mono.yaml
# stereo SLAM with any EuRoC sequence
$ ./run_euroc_slam \
    -v /path/to/orb_vocab/orb_vocab.fbow \
    -d /path/to/EuRoC/MAV/mav0/ \
    -c ../example/euroc/EuRoC_stereo.yaml
```

6.3.3 TUM RGBD dataset

TUM RGBD dataset is a benchmarking dataset fcontaining RGB-D data and ground-truth data with the goal to establish a novel benchmark for the evaluation of visual odometry and visual SLAM systems. The source code is placed at `./example/run_tum_rgbd_slam.cc`.

Start by downloading the various dataset from here. One of many example datasets can be found from here. Download the `.tgz` file of a dataset you plan on using.

After downloading and uncompressing it, you will find two directories and few text files under the `rgbd_dataset_freiburg3_calibration_rgb_depth/` directory.

```
$ ls rgbd_dataset_freiburg3_calibration_rgb_depth
accelerometer.txt  depth  depth.txt  groundtruth.txt  rgb  rgb.txt
```

If you would like to preprocess dataset then you can usee tool from here.

In addition, download a vocabulary file for FBoW from here.

We provided the config files for RGBD dataset at, `./example/tum_rgbd`.

For above specific example we shall use two config files, `./example/tum_rgbd/TUM_RGBD_mono_3.yaml` for monocular and `./example/tum_rgbd/TUM_RGBD_rgbd_3.yaml` for RGBD.

6.3.4 Tracking and Mapping

```
# at the build directory of stella_vslam
# monocular SLAM with rgbd_dataset_freiburg3_calibration_rgb_depth
$ ./run_tum_rgbd_slam \
    -v /path/to/orb_vocab/orb_vocab.fbow \
    -d /path/to/rgbd_dataset_freiburg3_calibration_rgb_depth/ \
    -c ../example/tum_rgbd/TUM_RGBD_mono_3.yaml \
    --no-sleep \
    --auto-term \
    --map-db-out fr3_slam_mono.msg

# RGBD SLAM with rgbd_dataset_freiburg3_calibration_rgb_depth
$ ./run_tum_rgbd_slam \
    -v /path/to/orb_vocab/orb_vocab.fbow \
    -d /path/to/rgbd_dataset_freiburg3_calibration_rgb_depth/ \
    -c ../example/tum_rgbd/TUM_RGBD_rgbd_3.yaml \
```

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```
    --no-sleep \
    --auto-term \
    --map-db-out fr3_slam_rgbd.msg
```

6.3.5 Localization

```
# at the build directory of stella_vslam
# monocular localization with rgbd_dataset_freiburg3_calibration_rgb_depth
$ ./run_tum_rgbd_slam --disable-mapping \
    -v /path/to/orb_vocab/orb_vocab.fbow \
    -d /path/to/rgbd_dataset_freiburg3_calibration_rgb_depth/ \
    -c ../example/tum_rgbd/TUM_RGBD_mono_3.yaml \
    --no-sleep \
    --auto-term \
    --map-db-in fr3_slam_mono.msg

# RGBD SLAM with rgbd_dataset_freiburg3_calibration_rgb_depth
$ ./run_tum_rgbd_slam --disable-mapping \
    -v /path/to/orb_vocab/orb_vocab.fbow \
    -d /path/to/rgbd_dataset_freiburg3_calibration_rgb_depth/ \
    -c ../example/tum_rgbd/TUM_RGBD_rgbd_3.yaml \
    --no-sleep \
    --auto-term \
    --map-db-in fr3_slam_rgbd.msg
```

6.4 SLAM with UVC camera

6.4.1 Tracking and Mapping

We provided an example snippet for using a UVC camera, which is often called a webcam, for visual SLAM. The source code is placed at `./example/run_camera_slam.cc`.

Please specify the camera number you want to use by `-n` option.
The camera must be calibrated. Create a config file (`.yaml`) according to the camera parameters.
You can scale input images to the performance of your machine by `-s` option. Please modify the config accordingly.
We provided a vocabulary file for FBoW at here.

CHAPTER

SEVEN

PARAMETERS

7.1 System

Name	Description
map_format	msgpack or sqlite3
min_num_shared_lms	minimum number of shared landmarks for covisibility graph connection. Keyframes that exceed the threshold are considered to share a sufficient number of landmarks and are used for local BA, loop detection and graph optimization.

7.2 Camera

Name	Description
name	It is used by the camera database to identify the camera.
setup	monocular, stereo, RGBD
model	perspective, fisheye, equirectangular, radial_division (note: If you want to use stereo_rectifier, you need to specify perspective.)
fx, fy	Focal length (pixel)
cx, cy	Principal point (pixel)
k1, k2, p1, p2, k3	Distortion parameters for perspective camera. When using StereoRectifier, there is no distortion after stereo rectification.
k1, k2, k3, k4	Distortion parameters for fisheye camera
distortion	Distortion parameters for radial_division camera
fps	Framerate of input images
cols, rows	Resolution (pixel)
color_order	Gray, RGB, RGBA, BGR, BGRA
focal_x_baseline	For stereo cameras, it is the value of the baseline between the left and right cameras multiplied by the focal length fx. For RGBD cameras, if the measurement method is stereo, set it based on its baseline. If the measurement method is other than that, set the appropriate value based on the relationship between depth accuracy and baseline.
depth_threshold	The ratio used to determine the depth threshold.

7.3 Feature

Name	Description
name	name of ORB feature extraction model (id for saving)
scale_factor	Scale of the image pyramid
num_levels	Number of levels of in the image pyramid
ini_fast_threshold	FAST threshold for try first
min_fast_threshold	FAST threshold for try second time

7.4 Preprocessing

Name	Description
min_size	Size of node occupied by one feature point. The larger this value, the fewer feature points are extracted.
depthmap_factor	The ratio used to convert depth image pixel values to distance.

7.5 Tracking

Name	Description
reloc_distance_threshold	Maximum distance threshold (in meters) where close keyframes could be found when doing a relocalization by pose.
reloc_angle_threshold	Maximum angle threshold (in radians) between given pose and close keyframes when doing a relocalization by pose.
enable_auto_relocalization	If true, automatically try to relocalize when lost.
use_robust_matcher_for_relocalization_request	If true, use robust matcher for relocalization request.
max_num_local_keyframs	Max number of local keyframes for tracking.
backend	g2o or gtsam

7.6 Mapping

Name	Description
baseline_dist_thr_ratio	For two frames of baseline below the threshold, no triangulation will be performed. In the monocular case, the scale is indefinite, so relative values are recommended. Either baseline_dist_thr or this one should be specified. If not specified, baseline_dist_thr_ratio will be used.
baseline_dist_thr	For two frames of baseline below the threshold, no triangulation will be performed.
redundant_obs_ratio_thr	
observed_ratio_thr	
num_reliable_keyfrms	
enable_interruption_of_landmark_generation	If true, enable interruption of landmark generation
enable_interruption_before_local_BA	If true, enable interruption before local BA
backend	g2o or gtsam

7.7 StereoRectifier

Name	Description
model	camera model type before rectification. The option is perspective or fisheye. (note: If you want to use fisheye model for stereo_rectifier, you need to specify Camera::model to perspective.)
K_left, K_right	Intrinsic parameters. The 3x3 matrix are written in row-major order.
D_left, D_right	Distortion parameters. The 5 parameters are k1, k2, p1, p2, k3.
R_left, R_right	Stereo-recitification parameters. The 3x3 matrix are written in row-major order.

7.8 Initializer

Name	Description
num_ransac_iterations	max number of iterations of RANSAC (only for monocular initializer)
min_num_valid_pts	min number of valid pts (It should be greater than or equal to **min_num_triangulated_**)
min_num_triangulated_pts	Minimum number of triangulated points
parallax_deg_threshold	min parallax (only for monocular initializer)
reprojection_error_threshold	reprojection error threshold (only for monocular initializer)
num_ba_iterations	max number of iterations of BA (only for monocular initializer)
scaling_factor	initial scaling factor (only for monocular initializer)
use_fixed_seed	Use fixed random seed for RANSAC if true

7.9 Relocalizer

Name	Description
bow_match_lowe_ratio	
proj_match_lowe_ratio	
min_num_bow_matches	
min_num_valid_obs	

7.10 KeyframeInserter

Name	Description
max_interval	max interval to insert keyframe
min_interval	
max_distance	
enough_lms_thr	
lms_ratio_thr_almost_all_lms_are_tracked	Threshold at which we consider that we are tracking almost all landmarks. Ratio-threshold of "the number of 3D points observed in the current frame" / "that of 3D points observed in the last keyframe"
lms_ratio_thr_view_changed	Threshold at which we consider the view to have changed. Ratio-threshold of "the number of 3D points observed in the current frame" / "that of 3D points observed in the last keyframe"

7.11 PangolinViewer

Name	Description
keyframe_size	
keyframe_line_width	
graph_line_width	
point_size	
camera_size	
camera_line_width	
menu_width	
viewpoint_x, viewpoint_y, viewpoint_z, viewpoint_f	

7.12 SocketPublisher

Name	Description
emitting_interval	
image_quality	
server_uri	
max_num_keyframes	Limit the number of keyframes transferred at one time. This avoids disconnections when loading large maps.
max_num_landmarks	Limit the number of landmarks transferred at one time. This avoids disconnections when loading large maps.
publish_points	If true, pointcloud transfer is enabled. The default is true. Pointcloud transfer is slow, so disabling pointcloud transfer may be useful to improve performance of SocketViewer.

7.13 LoopDetector

Name	Description
enabled	flag which indicates the loop detector is enabled or not
num_final_matches_threshold	the threshold of the number of mutual matches after the Sim3 estimation
min_continuity	the threshold of the continuity of continuously detected keyframe set
reject_by_graph_distance	If true, reject by distance on essential graph
loop_min_distance_on_graph	Minimum distance to allow for loop candidates
top_n_covisibilities_to_search	Top n covisibilities to search (0 means disabled)
num_matches_thr	Minimum number of matches to allow for loop candidates
num_matches_thr_brute_force	Minimum number of matches to allow for loop candidates after brute force matching. (0 means disabled)
num_optimized_inliers_thr	Minimum number of matches to allow for loop candidates after optimization by transform_optimizer
backend	g2o or gtsam

7.14 MarkerModel

Name	Description
type	Only “aruco” is a valid value
width	Physical size of marker
marker_size	4, 5, 6, 7. See https://docs.opencv.org/4.x/d5/dae/tutorial_aruco_detection.html.
max_markers	50, 100, 250, 1000. See https://docs.opencv.org/4.x/d5/dae/tutorial_aruco_detection.html.

CHAPTER

EIGHT

RELOCALIZATION

8.1 What is Relocalization? Why it is needed?

In Visual SLAM, the robot/camera explores its environment while

1. estimates its location using the map and the last location as prior information (Tracking), and simultaneously
2. update the map (the database that records landmarks) of environment (Mapping).

Relocalization module can estimate the location without using any prior information other than the map (with the high cost of computation). This is useful when the previous location cannot be used as prior information, for example when tracking fails.

8.2 Steps in Relocalization

1. Acquire relocalization candidate keyframes (Used as a reference keyframe for relocalization)
2. Compute matching points for each candidate by using BoW tree matcher
3. Discard the candidate if the number of 2D-3D matches is less than the threshold
4. Setup an PnP solver with the current 2D-3D matches
5. Estimate the camera pose using EPnP (+ RANSAC)
6. Apply pose optimizer
7. Apply projection match to increase 2D-3D matches
8. Re-apply the pose optimizer
9. Apply projection match again if the number of the observations is less than the threshold
10. Apply projection match again, then set the 2D-3D matches
11. Discard if the number of the observations is less than the threshold and do the pose estimation again
12. If the number of observation is greater than threshold succeed in relocalization

See the details on how to run the relocalization at here.

CHAPTER

NINE

TROUBLE SHOOTING

9.1 For building

1. stella_vslam terminates abnormaly soon after **launching** or **optimization with g2o**.

   Please configure and rebuild g2o and stella_vslam with `-DBUILD_WITH_MARCH_NATIVE=OFF` option for `cmake`.

9.2 For SLAM

CHAPTER

TEN

CITATION OF ORIGINAL VERSION OF OPENVSLAM (XDSPACELAB/OPENVSLAM)

```
@inproceedings{openvslam2019,
  author = {Sumikura, Shinya and Shibuya, Mikiya and Sakurada, Ken},
  title = {{OpenVSLAM: A Versatile Visual SLAM Framework}},
  booktitle = {Proceedings of the 27th ACM International Conference on Multimedia},
  series = {MM '19},
  year = {2019},
  isbn = {978-1-4503-6889-6},
  location = {Nice, France},
  pages = {2292--2295},
  numpages = {4},
  url = {http://doi.acm.org/10.1145/3343031.3350539},
  doi = {10.1145/3343031.3350539},
  acmid = {3350539},
  publisher = {ACM},
  address = {New York, NY, USA}
}
```