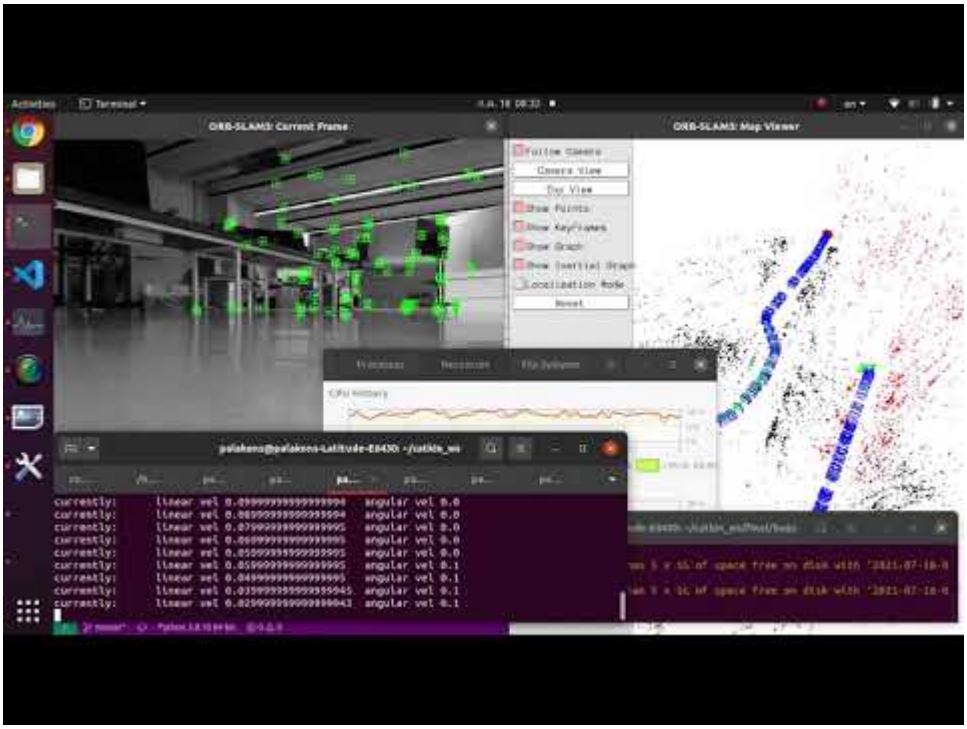
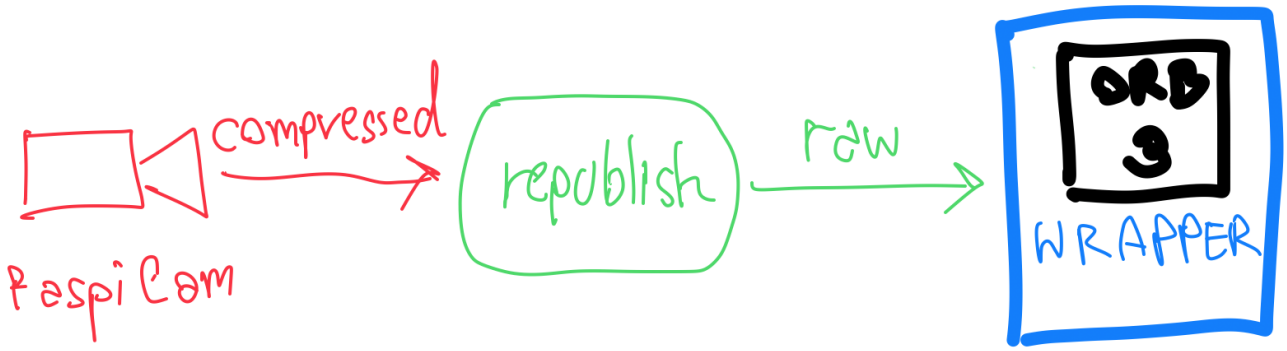
Monocular ORB-SLAM3 on TurtleBot3: Waffle Pi

Description: This tutorial demonstrates SLAM with the newly-released ORB_SLAM3 on a TurtleBot3 Waffle and ROS1. With the bag file provided, we should get the results below:



The system overview for the essential part is below:



From the compressed video stream from TurtleBot3, a node republishes and un-compresses the stream. The wrapper node will then take the video stream and feed it into the actual ORB_SLAM3 node to perform the SLAM.

Environment: ROS1 Noetic / Ubuntu 20.04.2 LTS / TurtleBot3: Waffle Pi (Raspberry Pi Camera Module v2)

`.bashrc`: MASTER: PC

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1. Installing Prerequisites

1.1. The Basics

Install OpenGL, Glew, CMake:

```
sudo apt install libgl1-mesa-dev
sudo apt install libglew-dev
sudo apt install cmake
```

Extra dependency:

```
sudo apt install libpython2.7-dev
sudo apt install python3-pip
sudo apt install pkg-config
sudo apt install libegl1-mesa-dev libwayland-dev libxkbcommon-dev wayland-
protocols
sudo pip3 install numpy pyopengl Pillow pybind11
```

1.2. Pangolin

Install Pangolin

```
cd ~
git clone https://github.com/stevenlovegrove/Pangolin.git
cd Pangolin
mkdir build
cd build
cmake ..
cmake --build .
```

1.3. OpenCV4

Install OpenCV4 (this will take the whole night)

1.3.1. Download the packages:

```
cd ~
# Install minimal prerequisites (Ubuntu 18.04 as reference)
sudo apt update && sudo apt install -y cmake g++ wget unzip
# Download and unpack sources
mkdir -p opencv  && cd opencv
wget -O opencv.zip https://github.com/opencv/opencv/archive/master.zip
wget -O opencv_contrib.zip
https://github.com/opencv/opencv_contrib/archive/master.zip
unzip opencv.zip
unzip opencv_contrib.zip
rm *.zip
```

1.3.2. Build OpenCV4 (Skip if you have v. 3.3 or later)

1.3.2.1. Check previous installations

Check below location if/what version we have OpenCV installed:

```
ls /usr/local/lib | grep libopencv_core
ls /usr/lib | grep libopencv_core
```

This can be one of the three cases:

- If you already have OpenCV v. 3.3 or later, skip this OpenCV installation.
- If you do not have any OpenCV installed, do proceed with this installation
- If you have OpenCV v. earlier than 3.3, your OpenCV is too old.
    - First, remove the current OpenCV by running:

      ```
      sudo rm /usr/local/{bin,lib}/*opencv*
      ```

    - Then, proceed with the OpenCV installation

```
cd ~/opencv
# Create build directory and switch into it
mkdir -p build && cd build
# Configure
cmake -DOPENCV_EXTRA_MODULES_PATH=../opencv_contrib-master/modules ../opencv-
master
NPROC=$(nproc)
make -j$NPROC
# Build
cmake --build .
sudo make install
```

1.3.3. Check OpenCV4

```
ls /usr/local/lib | grep libopencv_core
ls /usr/lib | grep libopencv_core
```

Should see this

```
pkg-config --cflags opencv4
```

Should see this

```
-I/usr/include/opencv4/opencv -I/usr/include/opencv4
```

1.4. Eigen

Install Eigen

```
cd ~
wget https://gitlab.com/libeigen/eigen/-/archive/3.3.9/eigen-3.3.9.tar.gz
tar zxvf eigen-3.3.9.tar.gz
rm eigen-3.3.9.tar.gz
cd eigen-3.3.9
mkdir build
cd build
cmake ..
sudo make install
```

2. Setup our SLAM System

There are two steps:

2.1. Build ORB_SLAM3

Install ORB_SLAM3 (which automatically installs DBoW2 and g2o)

```
cd ~/catkin_ws/src
git clone https://github.com/UZ-SLAMLab/ORB_SLAM3.git ORB_SLAM3
cd ORB_SLAM3
chmod +x build.sh
```

Then build:

```
./build.sh
./build_ros.sh
```

If there is an error, check 6. Troubleshooting.

2.2. Build ROS wrapper for ORB-SLAM3

```
cd ~/catkin_ws/src/
git clone https://github.com/thien94/orb_slam3_ros_wrapper.git
```

With your favorite editor, open `~/catkin_ws/src/orb_slam3_ros_wrapper/CMakeLists.txt`

```
# Change this to the installation of ORB-SLAM3.
set(ORB_SLAM3_DIR
   $ENV{HOME}/catkin_ws/src/ORB_SLAM3
)
```

Then build the packages:

```
cd ~/catkin_ws/
catkin_make
```

2.3. yaml for waffle

Create a new file `~/catkin_ws/src/ORB_SLAM3/Examples/Monocular-Inertial/waffle.yaml`. Copy-paste content below to it:

```
%YAML:1.0

#--------------------------------------------------------------------------------------------
# Camera Parameters. Adjust them!
#--------------------------------------------------------------------------------------------
Camera.type: "PinHole"

# Camera calibration and distortion parameters (OpenCV)
#     [fx  0 cx]
# K = [ 0 fy cy]
#     [ 0  0  1]
Camera.fx: 511.14379665531055
Camera.fy: 509.0205888729015
Camera.cx: 311.77052174481076
Camera.cy: 247.45247029125034

# D
Camera.k1: 0.19890011251605139
Camera.k2: -0.31768240010469145
Camera.p1: 0.00225190429372325
Camera.p2: -0.0016667252501190678

# Camera resolution
Camera.width: 640
Camera.height: 480

# Camera frames per second
Camera.fps: 15.0

# Color order of the images (0: BGR, 1: RGB, ignored if images are grayscale)
Camera.RGB: 1

# Transformation from camera to body-frame (imu)
Tbc: !!opencv-matrix
   rows: 4
   cols: 4
   dt: f
```

```
   data: [1., 0.0, 0.0, -0.076,
          0., 1.0, 0.0, -0.000,
         -0., 0.0, 1.0, -0.025,
         0.0, 0.0, 0.0,  1.0]

# IMU noise
IMU.NoiseGyro: 1.7e-4 #1.6968e-04
IMU.NoiseAcc: 2.0000e-3 #2.0e-3
IMU.GyroWalk: 1.9393e-05
IMU.AccWalk: 3.0000e-03 # 3e-03
IMU.Frequency: 120

#--------------------------------------------------------------------------------
-----------
# ORB Parameters
#--------------------------------------------------------------------------------
-----------

# ORB Extractor: Number of features per image
ORBextractor.nFeatures: 1000 # 1000

# ORB Extractor: Scale factor between levels in the scale pyramid
ORBextractor.scaleFactor: 1.2

# ORB Extractor: Number of levels in the scale pyramid
ORBextractor.nLevels: 8

# ORB Extractor: Fast threshold
# Image is divided in a grid. At each cell FAST are extracted imposing a minimum
response.
# Firstly we impose iniThFAST. If no corners are detected we impose a lower value
minThFAST
# You can lower these values if your images have low contrast
ORBextractor.iniThFAST: 20
ORBextractor.minThFAST: 7

#--------------------------------------------------------------------------------
-----------
# Viewer Parameters
#--------------------------------------------------------------------------------
-----------
Viewer.KeyFrameSize: 0.05
Viewer.KeyFrameLineWidth: 1
Viewer.GraphLineWidth: 0.9
Viewer.PointSize:2
Viewer.CameraSize: 0.08
Viewer.CameraLineWidth: 3
Viewer.ViewpointX: 0
Viewer.ViewpointY: -0.7
Viewer.ViewpointZ: -3.5 # -1.8
Viewer.ViewpointF: 500
```

2.3.1. In case not using a Camera from TurtleBot3: Waffle Pi

When working with the camera from other than this system, to update the yaml file above, follow the section 3.3. Calibrate the camera, and shell commands below:

Camera fps to update `Camera.fps:`:

```
rostopic hz /raspicam_node/image/compressed
```

Transformation from the camera to the IMU using `tf` package to update `Tbc: !!opencv-matrix`:

```
rosrun rqt_tf_tree rqt_tf_tree
rosrun tf tf_echo camera_rgb_frame imu_link
```

2.4. Create `launchfile`

Create the `launchfile` at `~/catkin_ws/orb_slam3_mono_waffle_pi.launch` with content below:

```
<launch>
    <node name="rqt_image_view" pkg="rqt_image_view" type="rqt_image_view"
output="screen" >
    </node>
    <node name="rqt_graph_node" pkg="rqt_graph" type="rqt_graph" output="screen" >
    </node>

    <node name="image_to_raw" pkg="image_transport" type="republish"
output="screen" args="compressed in:=/raspicam_node/image/ raw
out:=/camera/image_raw">
    </node>
    <!-- ORB-SLAM3 -->
    <node name="orb_slam3_mono_node" pkg="orb_slam3_ros_wrapper"
type="orb_slam3_ros_wrapper_mono" output="screen">

        <!-- Parameters for original ORB-SLAM3 -->
        <param name="voc_file"      type="string"   value="$(find
ORB_SLAM3)/../../../Vocabulary/ORBvoc.txt" />
        <param name="settings_file" type="string"   value="$(find
ORB_SLAM3)/../../Monocular-Inertial/waffle.yaml" />

        <param name="do_equalize"   type="bool"     value="false" />

        <!-- Parameters for ROS -->
        <param name="map_frame_id"  type="string"   value="world" />
        <param name="pose_frame_id" type="string"   value="camera" />
    </node>
</launch>
```

2.4.1. Line-by-line explanation

```
<node name="rqt_image_view" pkg="rqt_image_view" type="rqt_image_view"
output="screen" >
</node>
<node name="rqt_graph_node" pkg="rqt_graph" type="rqt_graph" output="screen" >
</node>
```

These are the two nodes to view the videos stream from the TurtleBot3 and ROS's node graph.

```
<node name="image_to_raw" pkg="image_transport" type="republish" output="screen"
args="compressed in:=/raspicam_node/image/ raw out:=/camera/image_raw">
</node>
```

The `rpicam` hardware compresses the video stream by default for the good reasons. The SLAM node cannot digest the compressed stream directly. The `image_to_raw` node is for converting such `compressed` streams back to `raw` stream. `/camera/image_raw` is the topic that our SLAM node is subscribing to.

```
<!-- ORB-SLAM3 -->
<node name="orb_slam3_mono_node" pkg="orb_slam3_ros_wrapper"
type="orb_slam3_ros_wrapper_mono" output="screen">
    <!-- Parameters for original ORB-SLAM3 -->
    <param name="voc_file"      type="string"   value="$(find
ORB_SLAM3)/../../../Vocabulary/ORBvoc.txt" />
    <param name="settings_file" type="string"   value="$(find
ORB_SLAM3)/../../Monocular-Inertial/waffle.yaml" />

    <param name="do_equalize"   type="bool"     value="false" />

    <!-- Parameters for ROS -->
    <param name="map_frame_id"  type="string"   value="world" />
    <param name="pose_frame_id" type="string"   value="camera" />
</node>
```

Above is the parameters for the ORB_SLAM3 algorithms. We can see that the node will take our `waffle.yaml` as the `settings_file` argument.

3. Setup Camera (skip for in-class demo)

3.1. Confirm RPI Camera

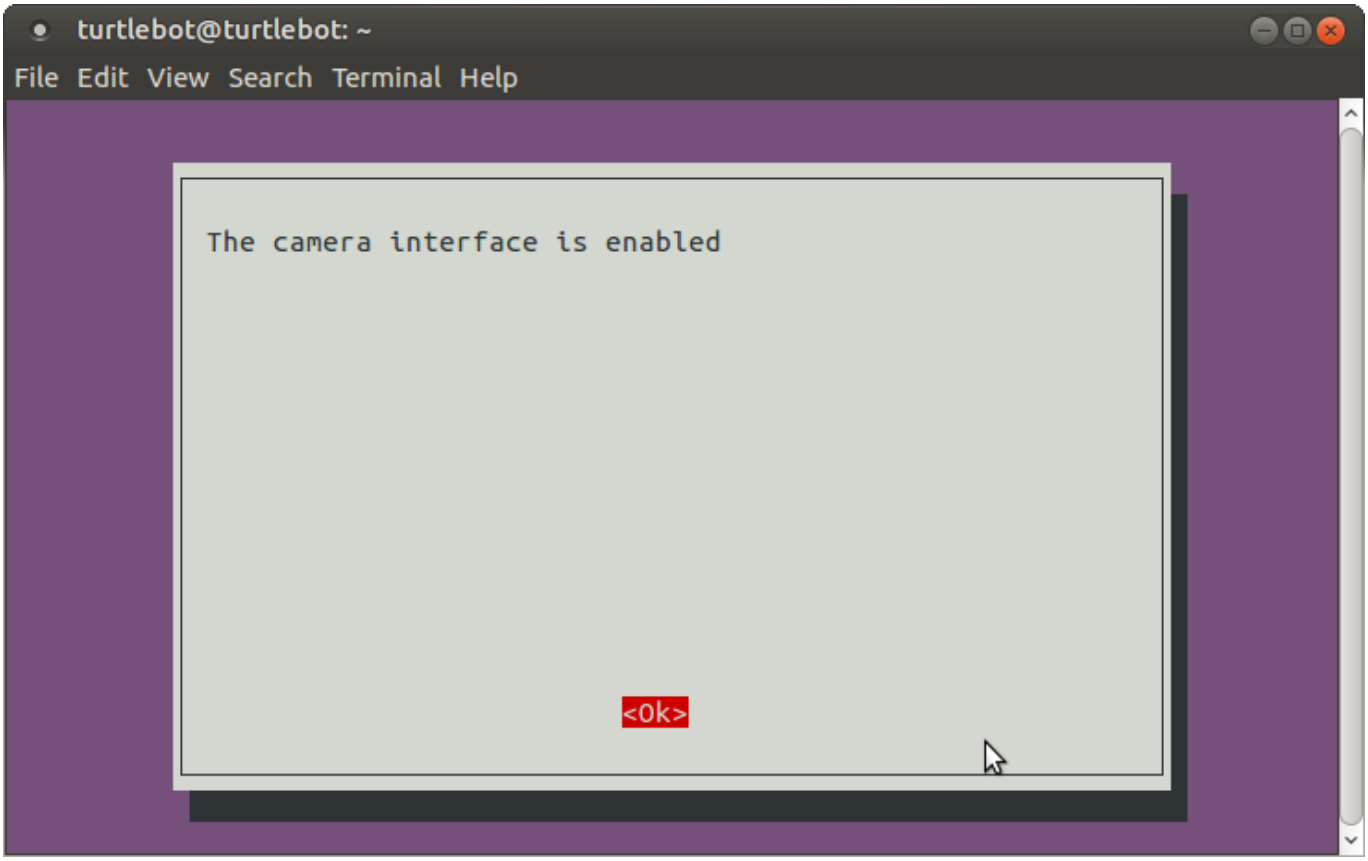
We follow the official Raspberry Pi Camera tutorial.

```
ssh pi@<turtlebot's IP Address>
```

First, edit the camera configuration:

```
sudo raspi-config
```

Select `Interfacing Options`, and `Camera`. After enabling the camera, you should see the screen below with the message 'The camera interface is enabled' below.



Then select `ok`, `Finish`, and reboot the TurtleBot3.

```
sudo reboot
```

Access the TurtleBot3 again:

```
ssh pi@<turtlebot's IP Address>
```

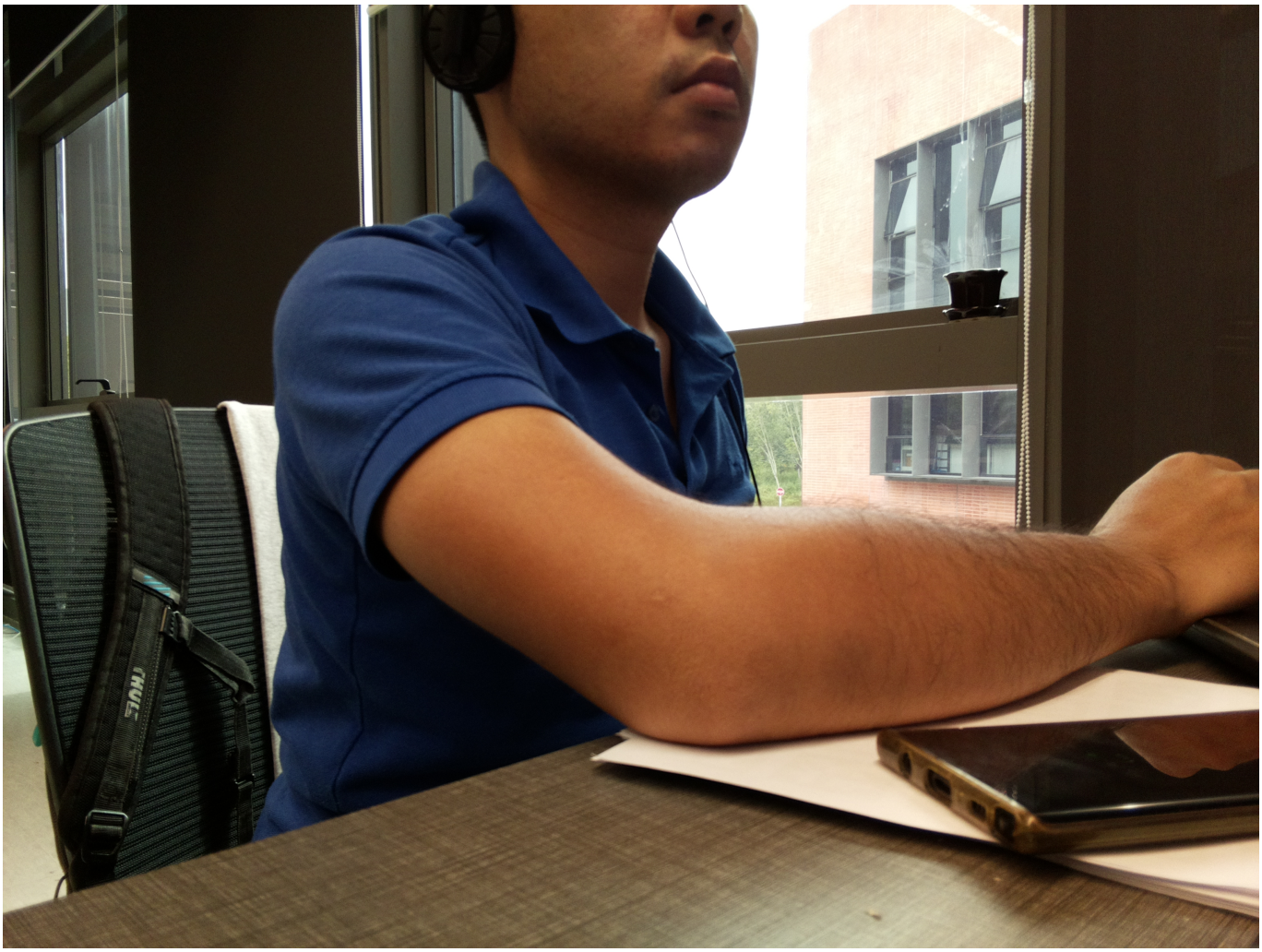
Take a photo: (say cheese!)

```
raspistill -v -o test.jpg
```

From the PC (not the TurtleBot3's) terminal, copy the newly taken photo to your PC.

```
cd ~/catkin_ws
scp pi@<turtlebot's IP Address>:~/test.jpg .
```

Now see your photo!



You can see the quality and resolution of the camera!

3.2. Install camera packages on the TurtleBot3

On TurtleBot3:

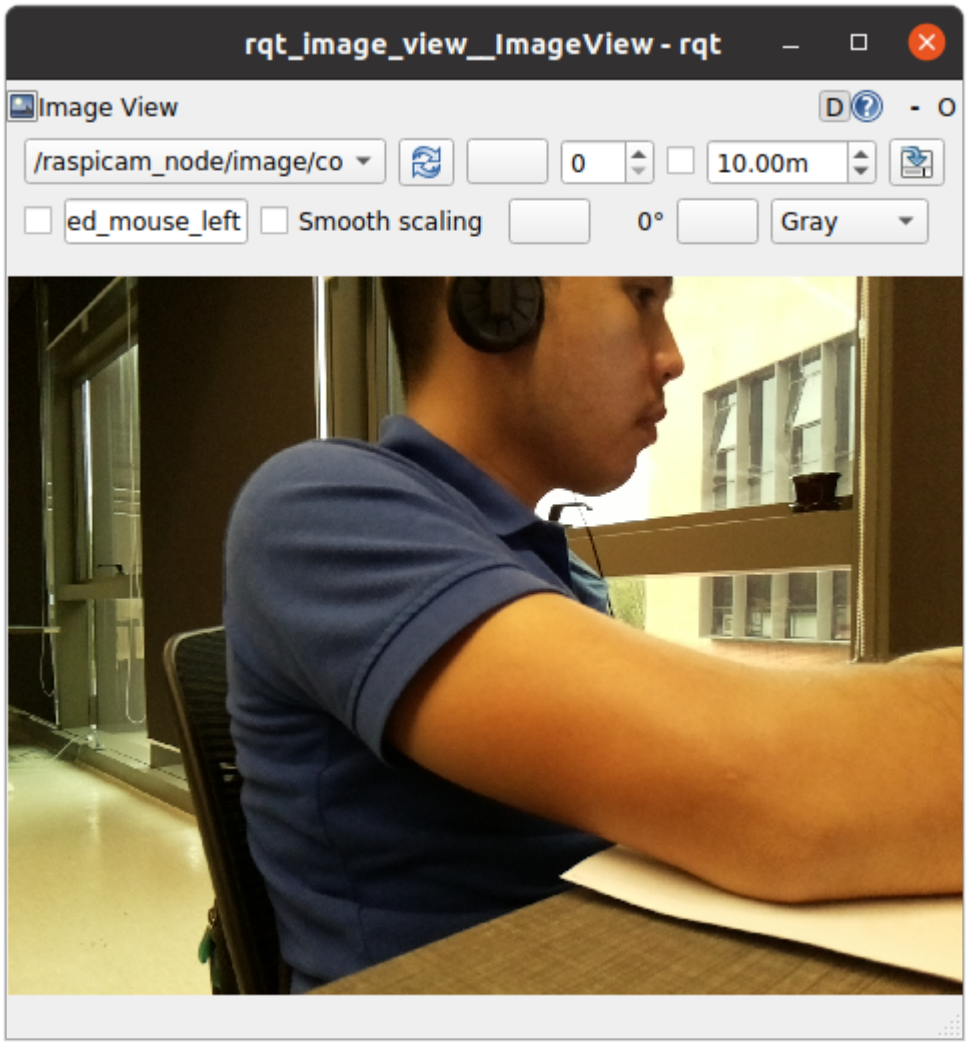
```
cd ~/catkin_ws/src
git clone https://github.com/UbiquityRobotics/raspicam_node.git
sudo apt-get install ros-kinetic-compressed-image-transport ros-kinetic-camera-info-manager
cd ~/catkin_ws && catkin_make
```

Then, try asking the TurtleBot3 to publish the image:

```
roslaunch turtlebot3_bringup turtlebot3_rpicamera.launch
```

On PC (with the configured MASTER IP Addresses), use `rqt_image_view` to show the image.

```
rqt_image_view
```



3.3. Calibrate the camera

There are ways on obtaining the camera *intrinsic parameters*, one of them is below:

3.3.1. Prepare the Calibration Pattern

- Print out on paper the Checkerboard Pattern. This particular pattern size is a `9x7` or `7x9` pattern (counting the *internal corners*). You can make it durable and your friend will borrow it to calibrate their cameras for years to come.
- Attach the paper to a moveable, flat surface (corrugated board, future board, or a laptop, etc.) because we need to move the pattern around in front of the camera. Or you could attach the pattern to a wall and move the camera; possible, but less convenient.
- Measure the width of *one* square. It could be 0.02 m as the file mentioned, or a different size if you print it on, for example, an A3 paper.

I used a different calibration pattern (a *loan for use* from a friend so I do not have to go through the steps above). The specifications are below:

Calibration Pattern	My friend's	This tutorial's
Size	9x6	9x7
Square's width	0.02373 m	0.02 m ??

3.3.2. Start the node system

Bring up TurtleBot3's camera

- On TurtleBot3,

```
rosrun raspicam_node raspicam_node
```

- On PC,
  - Terminal#1: To provide an uncompressed the video stream

```
rosrun image_transport republish compressed in:=/raspicam_node/image/
raw out:=/camera/image_raw
```

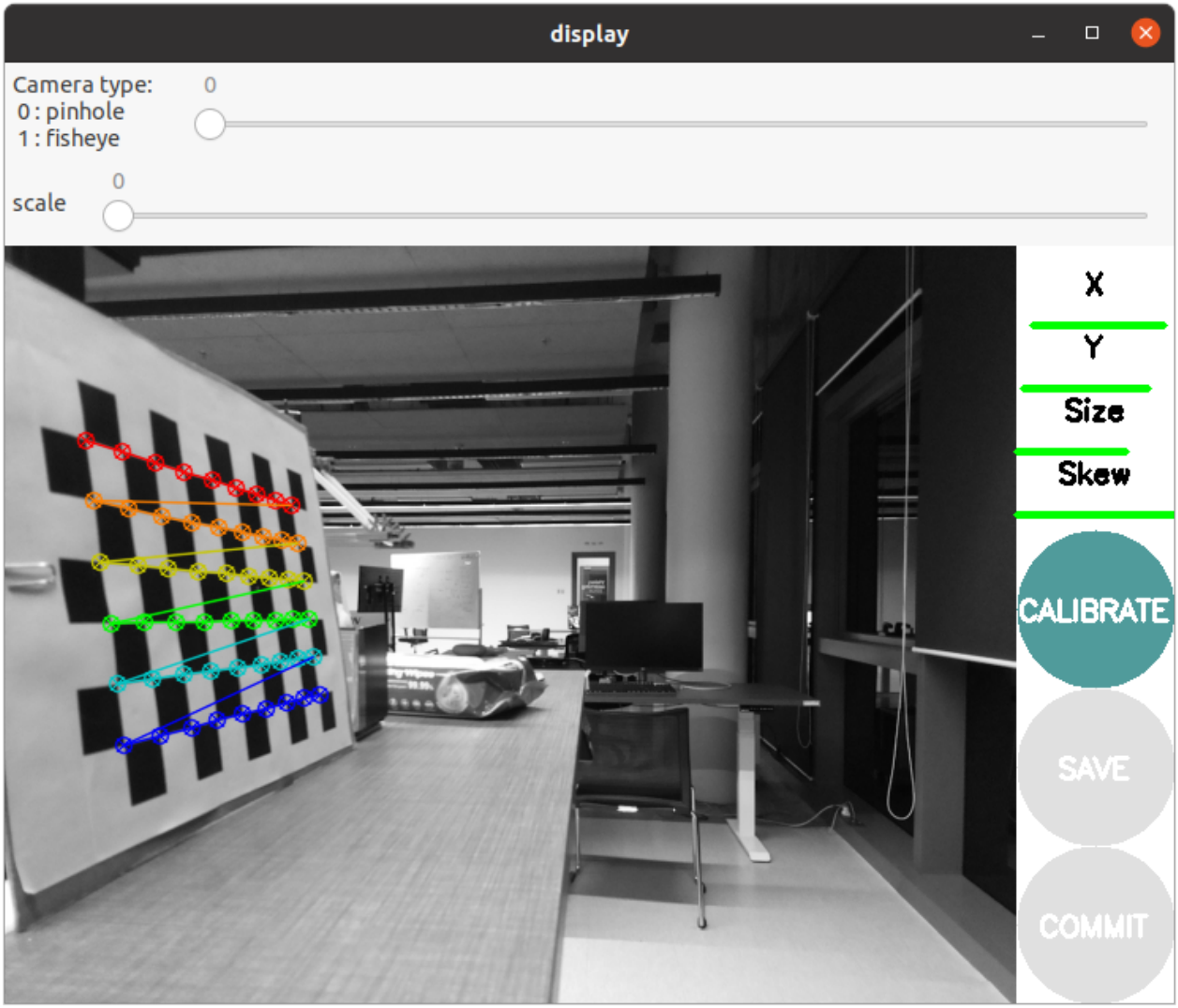
  - Terminal#2: To start the calibration node

    Use your `--size` and `--square` parameters as per 3.3.1. Prepare the Calibration Pattern; it could look similar to below:

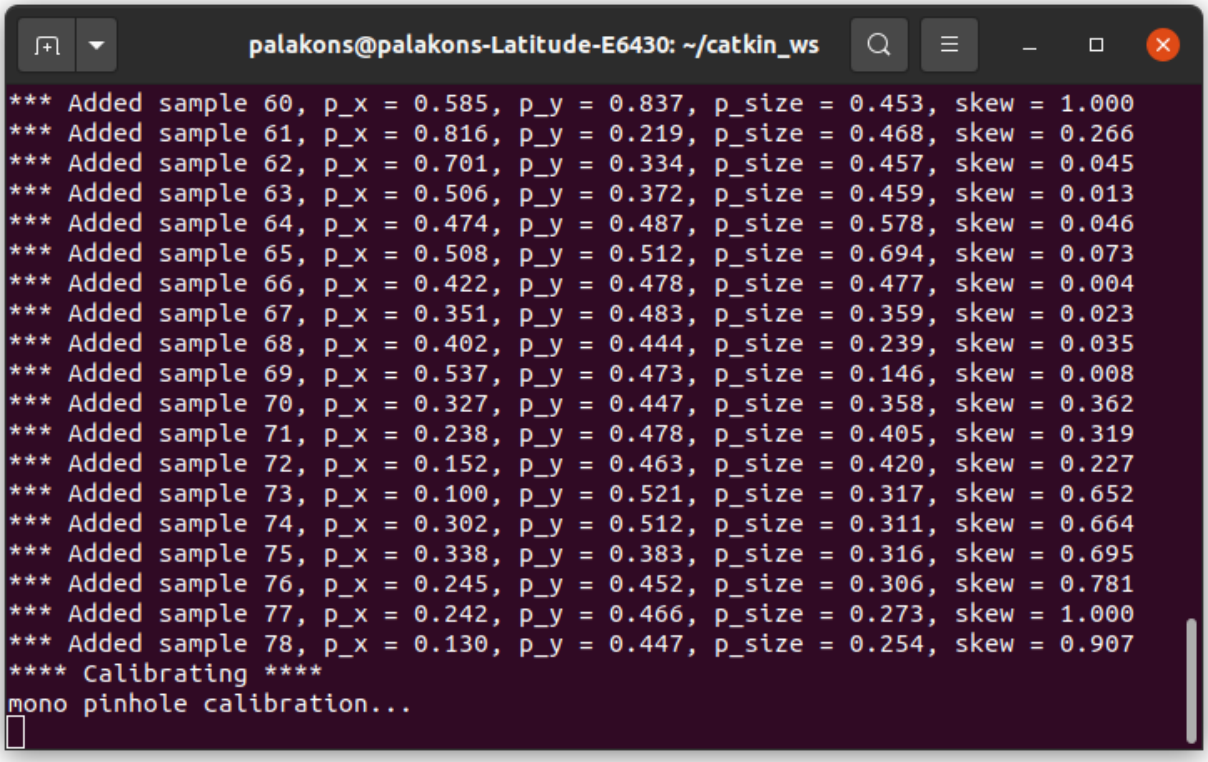
```
rosrun camera_calibration cameracalibrator.py --size 9x7 --square 0.02
image:=/camera/image_raw camera:=/raspicam_node
```

3.3.3. Perform the calibration

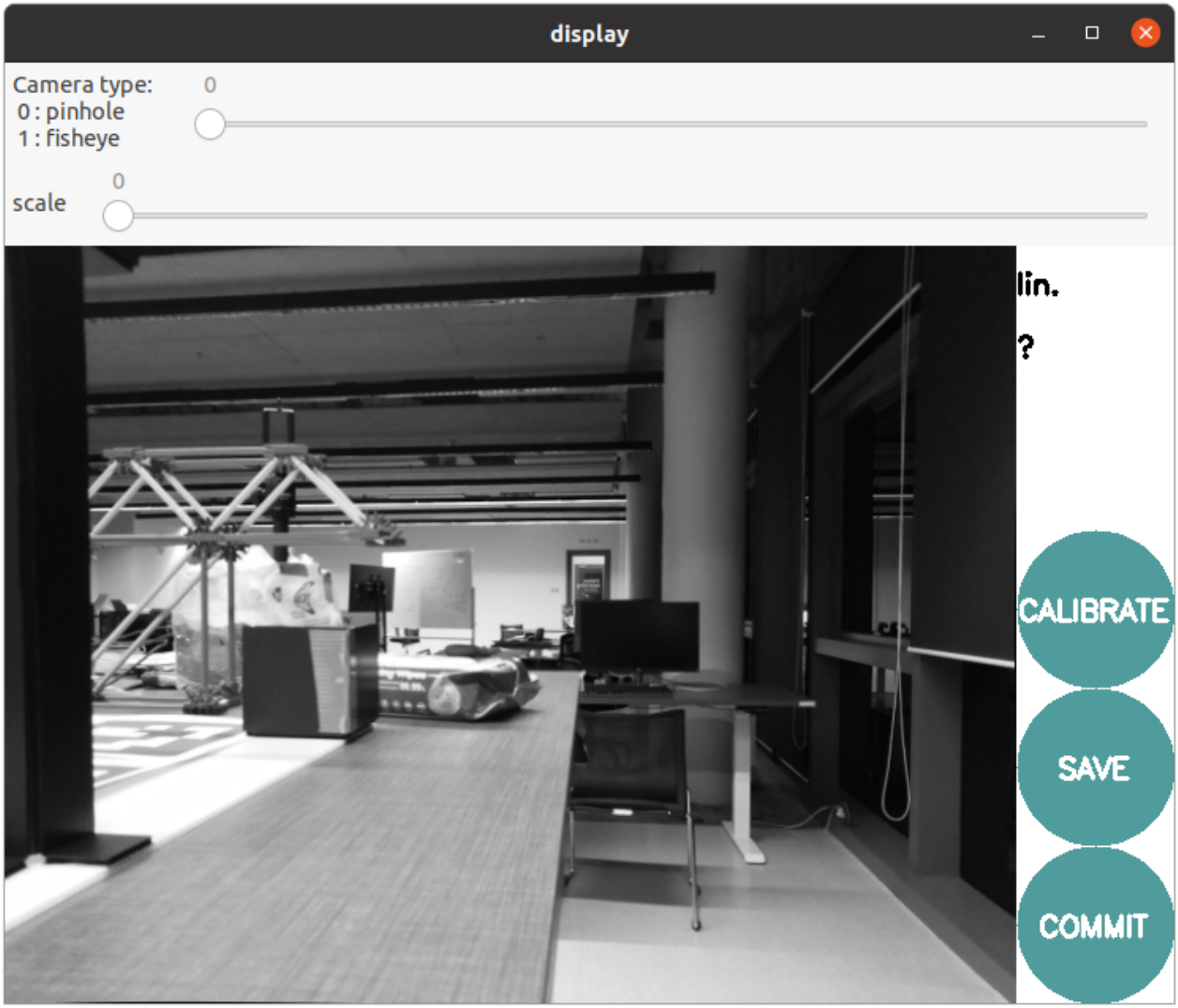
- Move, and skew the pattern around to cover the camera field of view.
- In each image frame, when the calibration node detects the pattern, it draws lines connecting the corners.
- When the system detects enough frames, the `CALIBRATE` button is enabled.



- Click `CALIBRATE`



- Wait for the calibration process



- Click `SAVE`, and `COMMIT`. According to the Package Summary, *When the user presses the `CALIBRATE` button, the node computes the camera calibration parameters. When the user clicks `COMMIT`, the node uploads these new calibration parameters to the camera driver using a service call.*

3.3.4. See the calibration results

We can see the same calibration results inside the terminal, in yaml, and in text files.

- From the Terminal

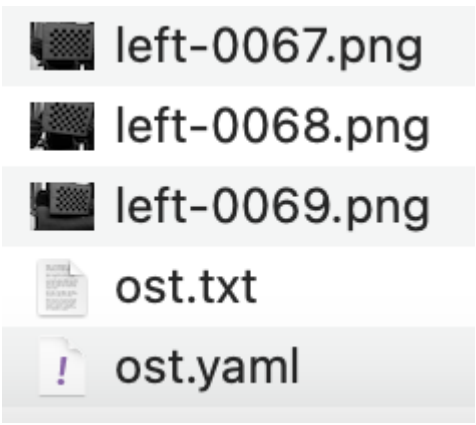
```
mono pinhole calibration...
D = [0.19890011251605139, -0.31768240010469145, 0.00225190429372325,
-0.0016667252501190678, 0.0]
K = [511.14379665531055, 0.0, 311.77052174481076, 0.0, 509.0205888729015,
247.45247029125034, 0.0, 0.0, 1.0]
R = [1.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0, 0.0, 1.0]
P = [525.563232421875, 0.0, 310.04905644909013, 0.0, 0.0, 524.0479125976562,
247.7008932694298, 0.0, 0.0, 0.0, 1.0, 0.0]
None
# oST version 5.0 parameters
```

```
[image]

width
640

height
480

[narrow_stereo]

camera matrix
511.143797 0.000000 311.770522
0.000000 509.020589 247.452470
0.000000 0.000000 1.000000

distortion
0.198900 -0.317682 0.002252 -0.001667 0.000000

rectification
1.000000 0.000000 0.000000
0.000000 1.000000 0.000000
0.000000 0.000000 1.000000

projection
525.563232 0.000000 310.049056 0.000000
0.000000 524.047913 247.700893 0.000000
0.000000 0.000000 1.000000 0.000000

('Wrote calibration data to', '/tmp/calibrationdata.tar.gz')
```

- From the output files:

  Let's copy it to `~/catkin_ws` for later references: calibration results along with the image frames:

```
cp /tmp/calibrationdata.tar.gz ~/catkin_ws
```



- ost.txt

```
# oST version 5.0 parameters


[image]

width
640

height
480

[narrow_stereo]

camera matrix
511.143797 0.000000 311.770522
0.000000 509.020589 247.452470
0.000000 0.000000 1.000000

distortion
0.198900 -0.317682 0.002252 -0.001667 0.000000

rectification
1.000000 0.000000 0.000000
0.000000 1.000000 0.000000
0.000000 0.000000 1.000000

projection
507.718292 0.000000 307.882255 0.000000
0.000000 504.573120 249.457519 0.000000
0.000000 0.000000 1.000000 0.000000
```

- YAML file:

```
image_width: 640
image_height: 480
camera_name: narrow_stereo
camera_matrix:
  rows: 3
  cols: 3
  data: [511.1438 ,   0.     , 311.77052,
          1.     , 509.02059, 247.45247,
          2.     ,   0.     ,   1.     ]
distortion_model: plumb_bob
distortion_coefficients:
  rows: 1
  cols: 5
  data: [0.198900, -0.317682, 0.002252, -0.001667, 0.000000]
rectification_matrix:
```

```
  rows: 3
  cols: 3
  data: [1., 0., 0.,
        0., 1., 0.,
        0., 0., 1.]
projection_matrix:
  rows: 3
  cols: 4
  data: [507.71829,   0.     , 307.88226,   0.     ,
          1.     , 504.57312, 249.45752,   0.     ,
          2.     ,   0.     ,   1.     ,   0.     ]
```

4. Start SLAM

There are two ways we can try in this tutorial: BAG file, and video stream from the TurtleBot3

4.1. SLAM from BAG file data

On MASTER/PC

Starting from all terminal closed...

- Terminal #1: Make sure the `roscore` is up below any other node

```
roscore
```

- Terminal #2: Launch the `launchfile`

```
roslaunch ~/catkin_ws/orb_slam3_mono_waffle_pi.launch
```

- Terminal #3: Play the BAG file
  - Download BAG file (~1.5GB) and move it to `~/catkin_ws`.
  - Run BAG file

```
cd ~/catkin_ws
rosbag play ORB_SLAM3_Monocular_2021-07-18-08-27-30.bag
```

4.2. SLAM from the Real TurtleBot3 (if in-class time allow)

To run on real TurtleBot3, instead of playing the BAG file above, we will bring up the TurtleBot3.

Starting from all terminal closed...

- On MASTER/PC

- Terminal #1: Make sure the `roscore` is up below any other node

```
roscore
```

- On TurtleBot3
  - Terminal #1: Bring up TurtleBot3

```
roslaunch turtlebot3_bringup turtlebot3_robot.launch
```

  - Terminal #2: Start RPI Camera

```
roslaunch turtlebot3_bringup turtlebot3_rpicamera.launch
```

- On MASTER/PC
  - Terminal #2: Launch the `launchfile`

```
roslaunch ~/catkin_ws/orb_slam3_mono_waffle_pi.launch
```

  - Terminal #3: Teleop node

```
roslaunch turtlebot3_teleop turtlebot3_teleop_key.launch
```

5. Bonus activities (skip for in-class demo)

For advanced users, you are encouraged to try additional tasks below:

Tasks	**Level**
Check what messages are published from `orb_slam3_mono_node` node	One shell cmd
Visualize the published data in `rviz`	One shell cmd and correct `rviz settings`
With the published data, perform 3D SLAM using RTAB-Map	Install RTAB-Map package and bride data/parameters correctly
Instead of the BAG file or the TurtleBot3, run the SLAM on Gazebo	One shell cmd and ensure correct topic names
ORB_SLAM3 on Monocular camera and the IMU	Update setting/calibration in the yaml file

6. Troubleshooting

6.1. operator/

If we see below error during building the ORB-SLAM3:

```
.../catkin_ws/src/ORB_SLAM3/src/LocalMapping.cc:628:49: error: no match for
‘operator/’ (operand types are ‘cv::Matx<float, 3, 1>’ and ‘float’)
  628 |                 x3D = x3D_h.get_minor<3,1>(0,0) / x3D_h(3);
      |                       ~~~~~~~~~~~~~~~~~~~~~~~~~ ^ ~~~~~~~~
      |                                           |           |
      |                                           |           float
      |                                          cv::Matx<float, 3, 1>

.../catkin_ws/src/ORB_SLAM3/src/CameraModels/KannalaBrandt8.cpp:534:41: error: no
match for ‘operator/’ (operand types are ‘cv::Matx<float, 3, 1>’ and ‘float’)
  534 |         x3D = x3D_h.get_minor<3,1>(0,0) / x3D_h(3);
      |               ~~~~~~~~~~~~~~~~~~~~~~~~~ ^ ~~~~~~~~
      |                                   |           |
      |                                   |           float
      |                                  cv::Matx<float, 3, 1>
```

We will follow this link to replace

```
x3D = x3D_h.get_minor<3,1>(0,0) / x3D_h(3);
```

with

```
x3D = cv::Matx31f(x3D_h.get_minor<3,1>(0,0)(0) / x3D_h(3), x3D_h.get_minor<3,1>
(0,0)(1) / x3D_h(3), x3D_h.get_minor<3,1>(0,0)(2) / x3D_h(3));
```

on both source files `~/catkin_ws/src/ORB_SLAM3/src/CameraModels/KannalaBrandt8.cpp` and `~/catkin_ws/src/ORB_SLAM3/src/LocalMapping.cc`

6.2. CMakelists.txt error for opencv not found

Edit `~/catkin_ws/src/ORB_SLAM3/CMakeLists.txt` at line 37:

Replace with

```
# find_package(OpenCV 4.0)
find_package(OpenCV 4.0 REQUIRED PATHS "/usr/include/opencv4" )
```

Edit `~/catkin_ws/src/ORB_SLAM3/Examples/ROS/ORB_SLAM3/CMakeLists.txt` at line 37:

Replace with

```
# find_package(OpenCV 3.0 QUIET)
find_package(OpenCV 4.0 REQUIRED PATHS "/usr/include/opencv4" )
```

The `"/usr/include/opencv4"` was obtained from 1.3.3. Check OpenCV4

6.3. Resource not found: turtlebot_bringup

```
Resource not found: turtlebot_bringup
```

Edit the launch file to seek `turtlebot3_bringup` instead.

6.4. Bad (python) interpreter

When seeing the error messages similar to below:

```
/opt/ros/noetic/bin/rosrun:
/opt/ros/noetic/lib/camera_calibration/cameracalibrator.py: /usr/bin/python: bad
interpreter: No such file or directory
/opt/ros/noetic/bin/rosrun: line 150:
/opt/ros/noetic/lib/camera_calibration/cameracalibrator.py: Success
```

it means that the shell is looking for the python interpreter at the path `/usr/bin/python` which is not existed.

In most cases we do have the python interpreter, but at a different path; we will have to run a shell command to create a symbolic link.

```
cd /usr/bin
sudo ln -fs /usr/bin/python3 python
```

6.5. CMake: `MESSAGE` called with incorrect number of arguments

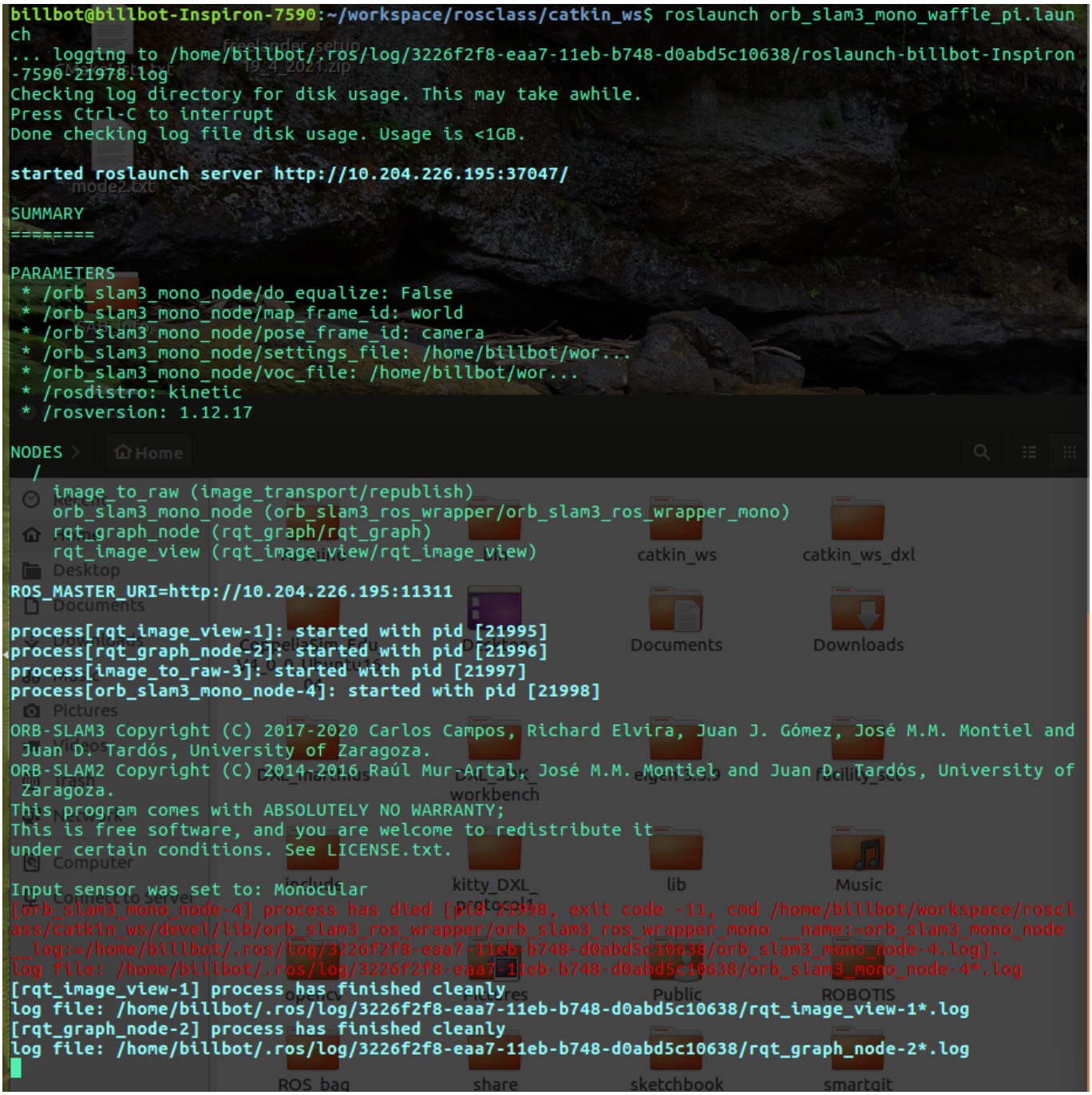
To solve, commenting out the line 45 of `~/catkin_ws/src/ORB_SLAM3/CMakeLists.txt`:

```
...
endif()

MESSAGE("OPENCV VERSION:")
#MESSAGE(${OpenCV_VERSION})
```

```
  find_package(Eigen3 3.1.0 REQUIRED)
  ...
```

6.6. [orb_slam3_mono_node-x] process has died

When seeing the error messages similar to below:

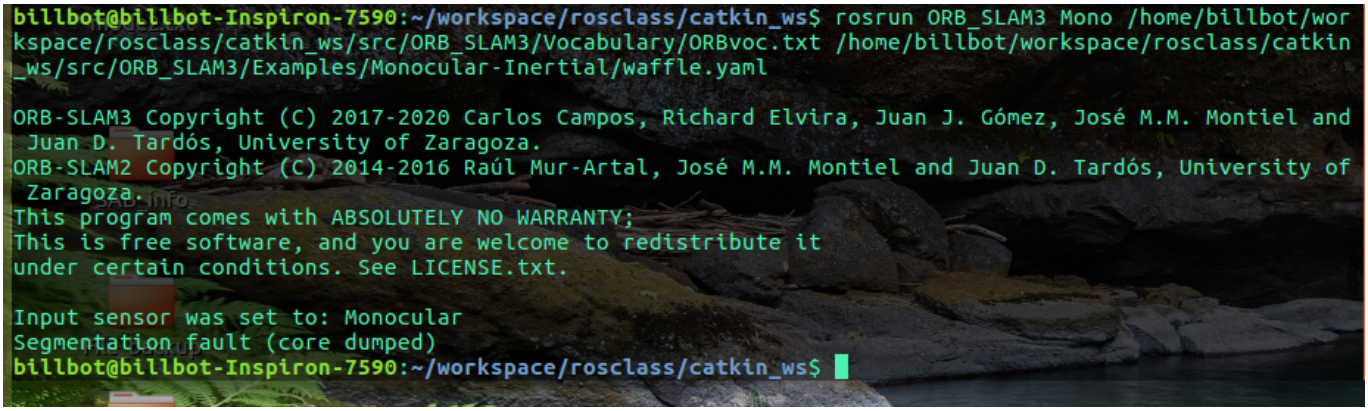


We could investigate further by running:

```
  rosrun ORB_SLAM3 Mono ~/catkin_ws/ORB_SLAM3/Vocabulary/ORBvoc.txt
  ~/catkin_ws/src/ORB_SLAM3/Examples/Monocular-Inertial/waffle.yaml
```

Observe the output from the terminal, they can be one of the two cases below:

6.6.1. Segmentation fault (core dumped)



(cr. Joe Chu)

If this happens, do try on a machine with the recommended OS and ROS version.

7. Additional Resources

For additional resources please visit below:

- ORM_SLAM3
- ROS communities
- Raspberry Pi Camera
- ROS wrapper for ORB-SLAM3
- /camera_info
- RTAB-Map
- Pangolin