

Lab 2 Report

Robotics Integration Group Project I

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Abstract

This report documents the setup and experimentation undertaken in Lab 2. The primary objectives are to install and configure the Robot Operating System (*ROS*) environment on Ubuntu, establish a functioning Catkin workspace, and gain practical experience with core ROS communication mechanisms. Through a sequence of hands-on tasks, the lab introduces essential ROS concepts such as node creation, publisher-subscriber communication, topic monitoring, and system visualization using tools like `rqt_graph` and `roscore`. The experiment provides a foundational understanding of how ROS facilitates modular, distributed robotics software development.

See Resources on github.com/RamessesN/Robotics_MIT.

1 Introduction

This laboratory session focuses on the installation, configuration and initial exploration of the Robot Operating System (*ROS*), which serves as the middleware framework for subsequent robotics development. Before implementing perception, planning or control modules, it is essential to understand the *ROS* architecture and its communication mechanisms. The experiment involves setting up the *ROS* environment, creating and managing a catkin workspace, and developing simple publisher and subscriber nodes to exchange data through topics.

2 Procedure

2.1 Part I

2.1.1 Objective

To set up the *ROS* environment on the *Ubuntu 24.04* operating system, including the installation of essential packages and the configuration of a functional Catkin workspace.

2.1.2 Methodology

The initial approach for installing *ROS Noetic* was as follows:

1. Add the *ROS* package sources and install *ROS Noetic*:

```
sudo sh -c 'echo "deb http://packages.ros.org/ros/ubuntu $(lsb_release -sc)
→ main" > /etc/apt/sources.list.d/ros-latest.list'
curl -s https://raw.githubusercontent.com/ros/rosdistro/master/ros.asc | sudo
→ apt-key add -
sudo apt update
sudo apt install ros-noetic-desktop-full
```

2. Configure the *ROS* environment and install additional dependencies:

```
echo "source /opt/ros/noetic/setup.bash" >> ~/.bashrc
source ~/.bashrc
sudo apt install python3-rosdep python3-rosinstall python3-rosinstall-generator
→ \
python3-vcstool build-essential python3-catkin-tools python-is-python3
```

3. Initialize *rosdep* to enable dependency management:

```
sudo rosdep init
rosdep update
```

However, the above method is not fully compatible with *Ubuntu 24.04*. To address this, an alternative installation procedure using the *Shrike* repository was adopted, which provided a successful setup.

1. Clone the *Shrike* repository from GitHub:

```
git clone git@github.com:Minoic-Intelligence/shrike.git
```

2. Follow the instructions provided in the *Shrike* repository to complete the installation. The resulting terminal output is shown in Figure 1.

```
./scripts/install_ubuntu24.sh
./src/catkin/bin/catkin_make_isolated --install -DCMAKE_BUILD_TYPE=Release
source ./install_isolated/setup.bash
```

2.1.3 Observations

```
parallels@ubuntu-linux-2404:~/shrike$ chmod 755 ./scripts/install_ubuntu24.sh
parallels@ubuntu-linux-2404:~/shrike$ sudo ./scripts/install_ubuntu24.sh
Reading package lists... Done
Building dependency tree... Done
Reading state information... Done
Note, selecting 'libglog-1.9.0t64' instead of 'libglog-1.9.0v5'
build-essential is already the newest version (12.10ubuntu1).
cmake is already the newest version (3.28.3-1build7).
git is already the newest version (1:2.43.0-1ubuntu7.3).
python3 is already the newest version (3.12.3-0ubuntu2).
python3-pip is already the newest version (24.0+dfsg-1ubuntu1.3).
python3.12-venv is already the newest version (3.12.3-1ubuntu0.8).
curl is already the newest version (8.5.0-2ubuntu10.6).
wget is already the newest version (1.21.4-1ubuntu4.1).
pkg-config is already the newest version (1.8.1-2build1).
libboost-all-dev is already the newest version (1.83.0-1ubuntu2).
libconsole-bridge-dev is already the newest version (1.0.1+dfsg2-3build1).
liborocos-kdl1.5 is already the newest version (1.5.1-4build1).
liborocos-kdl-dev is already the newest version (1.5.1-4build1).
libpytide2-dev is already the newest version (5.15.13-1).
pyqt5-dev is already the newest version (5.15.10+dfsg-1build6).
libshiboken2-dev is already the newest version (5.15.13-1).
shiboken2 is already the newest version (5.15.13-1).
libbz2-dev is already the newest version (1.0.8-5.1build0.1).

parallels@ubuntu-linux-2404:~/shrike$ ./src/catkin/bin/catkin_make_isolated --install -DCMAKE_BUILD_TYPE=Release
Base path: /home/parallels/shrike
Build space: /home/parallels/shrike/build_isolated
Devel space: /home/parallels/shrike/devel_isolated
Install space: /home/parallels/shrike/install_isolated
Additional CMake Arguments: -DCMAKE_BUILD_TYPE=Release

-- traversing 228 packages in topological order:
-- catkin
-- genmsg
-- genpy
-- genlisp
-- genodejs
-- genpy
-- bond_core
-- cmake_modules
-- class_loader
-- common_msgs
-- common_tutorials
-- cpp_common
-- desktop
```

Figure 1: Installation of *ROS Noetic* on *Ubuntu 24.04*

2.1.4 Discussion

Installing *ROS Noetic* on *Ubuntu 24.04* presents several challenges due to incompatibilities between the standard Noetic packages and the latest system libraries. By utilizing the *Shrike* repository—which provides customized build scripts tailored for Ubuntu 24.04—the installation process was completed successfully. This outcome highlights the necessity of adapting traditional installation procedures to evolving system environments and demonstrates the value of community-maintained solutions when official support is unavailable.

2.2 Part II

2.2.1 Objective

To deepen the understanding of the *ROS* communication framework by implementing publisher and subscriber nodes, exploring topic-based message exchange, and visualizing the inter-node topology. This experiment establishes the foundation for modular, event-driven robotic behavior through:

1. Implementing *ROS* nodes that publish and subscribe to custom message types.
2. Demonstrating data flow between nodes via topics and verifying correct message delivery.
3. Utilizing diagnostic and visualization tools (such as `rqt_graph`) to examine node-topic connectivity.
4. Ensuring the workspace is properly configured to build, launch, and manage multiple nodes within a *ROS* ecosystem.

2.2.2 Methodology

- ***ROS Master***

Start the *ROS* Master using the following command. The resulting output is shown in Figure 2.

```
roscore
```

- ***ROS Nodes***

1. Launch the *turtlesim* node in a new terminal:

```
rosrun turtlesim turtlesim_node
```

2. List active nodes using:

```
rosnode list
```

3. Launch the *turtle_teleop_key* node to control the turtle with keyboard input:

```
rosrun turtlesim turtle_teleop_key
```

4. The corresponding runtime output is illustrated in Figure 3.

- ***ROS Topics***

1. Visualize the communication graph of running nodes and topics:

```
rosrun rqt_graph rqt_graph
```

2. Monitor velocity commands sent to the turtle in real time:

```
rostopic echo /turtle1/cmd_vel
```

3. Create a simple C++ example node:

```

1 #include <ros/ros.h>
2
3 int main(int argc, char** argv) {
4     ros::init(argc, argv, "example_node");
5     ros::NodeHandle n;
6
7     ros::Rate loop_rate(50);
8
9     while (ros::ok()) {
10         ros::spinOnce();
11         loop_rate.sleep();
12     }
13     return 0;
14 }
```

To compile and execute this example using *Shrike*, follow these steps:

```
cd ~/shrike/ros_ws/src
catkin_create_pkg ros_sample roscpp std_msgs
```

The resulting workspace structure is:

```
- ros_ws/
  - src/
    - ros_sample/
      - CMakeLists.txt
      - include/
      - package.xml
      - src/
        - ros_sample.cpp
```

Replace *example_node.cpp* with *ros_sample.cpp* and update the *CMakeLists.txt* file as follows:

```

cmake_minimum_required(VERSION 3.0.2)
project(ros_sample)

find_package(catkin REQUIRED COMPONENTS
  roscpp
  std_msgs
)

catkin_package()

include_directories(
  ${catkin_INCLUDE_DIRS}
)

add_executable(ros_sample_node src/ros_sample.cpp)
target_link_libraries(ros_sample_node ${catkin_LIBRARIES})
```

Build and source the workspace:

```
cd ~/shrike/ros_ws
```

```
catkin_make_isolated --install -DCMAKE_BUILD_TYPE=Release
source ~/shrike/ros_ws/devel_isolated/setup.bash
rosrun ros_sample ros_sample_node
```

Verify that the node is active using `rosnode list`. The corresponding results are shown in Figure 4.

4. **TF Tools**

- Launch the Turtle TF demo:

```
roslaunch turtle_tf turtle_tf_demo.launch
```

Note: On Ubuntu 24.04 with *Shrike*, older Noetic packages may depend on Python 2, while only Python 3 is installed. To resolve this compatibility issue, create a symbolic link:

```
sudo ln -s /usr/bin/python3 /usr/bin/python
```

- Visualize the TF tree using:

```
rosrun rqt_tf_tree rqt_tf_tree
```

The visualization shows three coordinate frames: *world* (parent), *turtle1*, and *turtle2*.

- Inspect transformations in real time:

```
rosrun tf tf_echo /turtle1 /turtle2
```

- The resulting output is illustrated in Figure 5.

5. Using *RViz*

Run the following command to launch *RViz*:

```
LIBGL_ALWAYS_SOFTWARE=1 rviz
```

Software rendering is required because *RViz* relies on OpenGL, which may not be fully supported in virtualized environments. The visualization result is shown in Figure 6.

Notice: Modify the `view_frames` script for Python 3.x compatibility:

```
try:
    vstr = subprocess.Popen(args, stdout=subprocess.PIPE,
                           stderr=subprocess.STDOUT).communicate()[0]
    vstr = vstr.decode('utf-8')
except OSError as ex:
    print("Warning: Could not execute `dot -V`. Is graphviz installed?")
    sys.exit(-1)

v = distutils.version.StrictVersion('2.16')
r = re.compile(r".*version (\d+\.\?\d*)")
print(vstr)
m = r.search(vstr)
```

2.2.3 Observations

- *ROS* Master

```

parallels@ubuntu-linux-2404:~$ roscore
... logging to /home/parallels/.ros/log/81a8cb0a-bf87-11f0-94ca-001c42d84326/roslaunch-ubuntu-linux-2404-16591.log
Checking log directory for disk usage. This may take a while.
Press Ctrl-C to interrupt
Done checking log file disk usage. Usage is <1GB.

started rosrun server http://ubuntu-linux-2404:45307/
ros_comm version 1.17.0

SUMMARY
=====

PARAMETERS
* /rosdistro: noetic
* /rosversion: 1.17.0

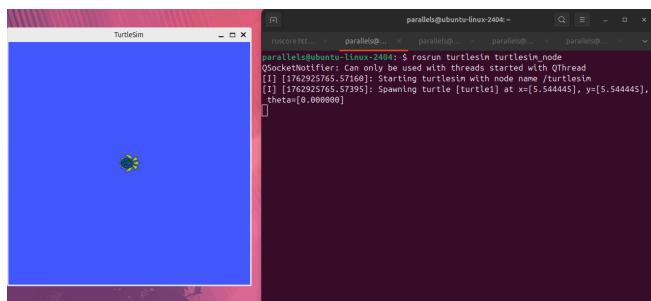
NODES

auto-starting new master
process[master]: started with pid [16602]
ROS_MASTER_URI=http://ubuntu-linux-2404:11311/

```

Figure 2: ROS Master

- *ROS Nodes*



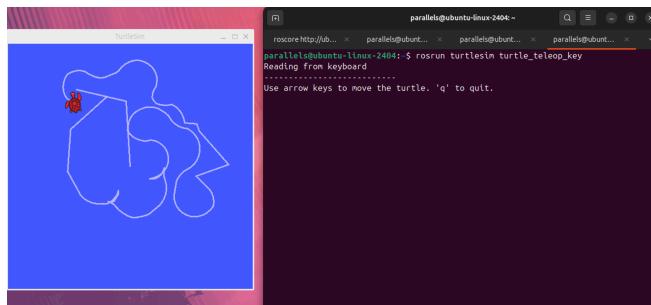
(a) Turtlesim node running

```

parallels@ubuntu-linux-2404:~$ rosnode list
/turtlesim
parallels@ubuntu-linux-2404:~$

```

(b) rosnode list output



(c) Turtle teleop node running

```

parallels@ubuntu-linux-2404:~$ rosnode list
/teleop_turtle
/turtlesim
parallels@ubuntu-linux-2404:~$

```

(d) rosnode list output

Figure 3: ROS nodes

- *ROS Topics*

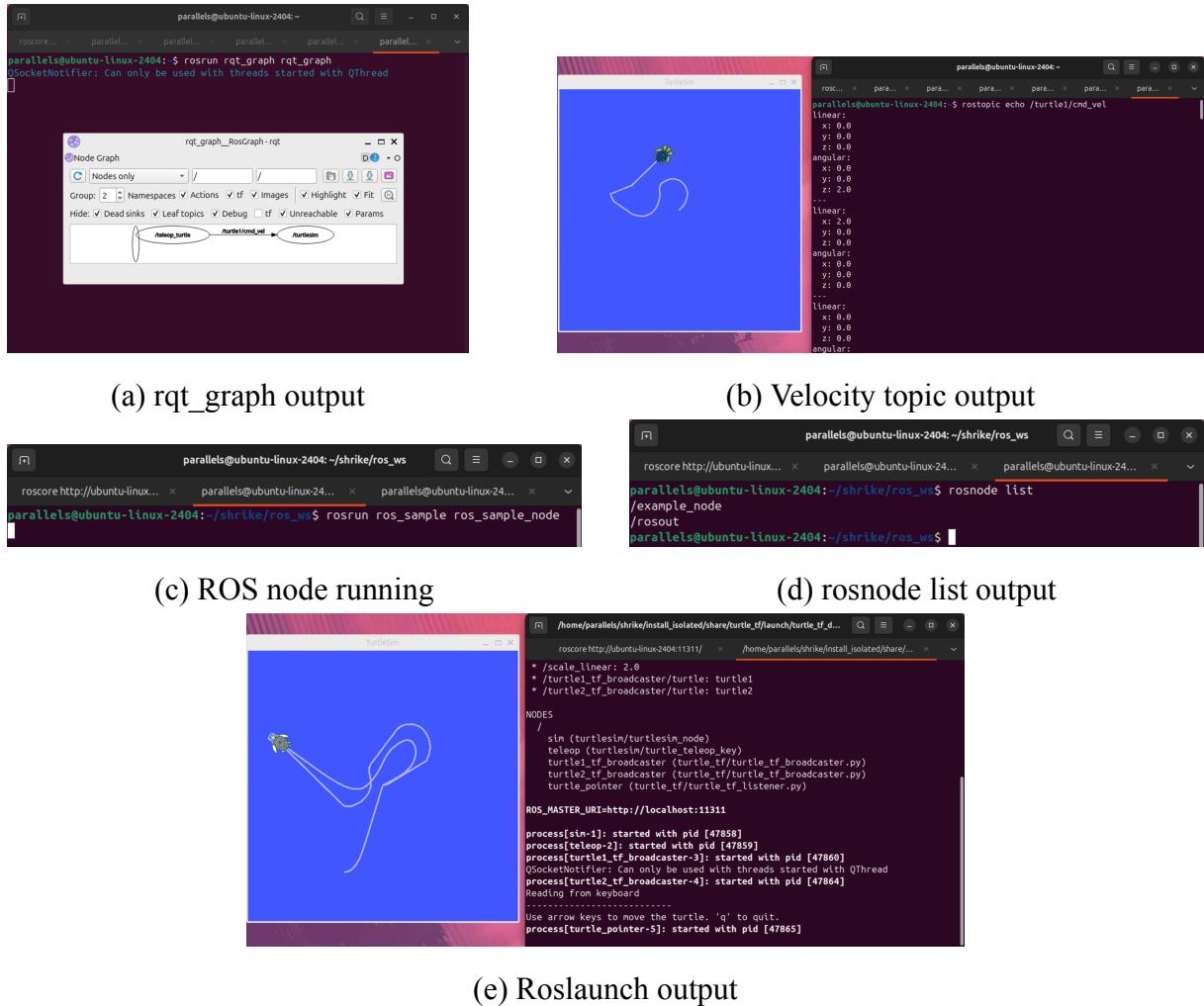


Figure 4: ROS topics

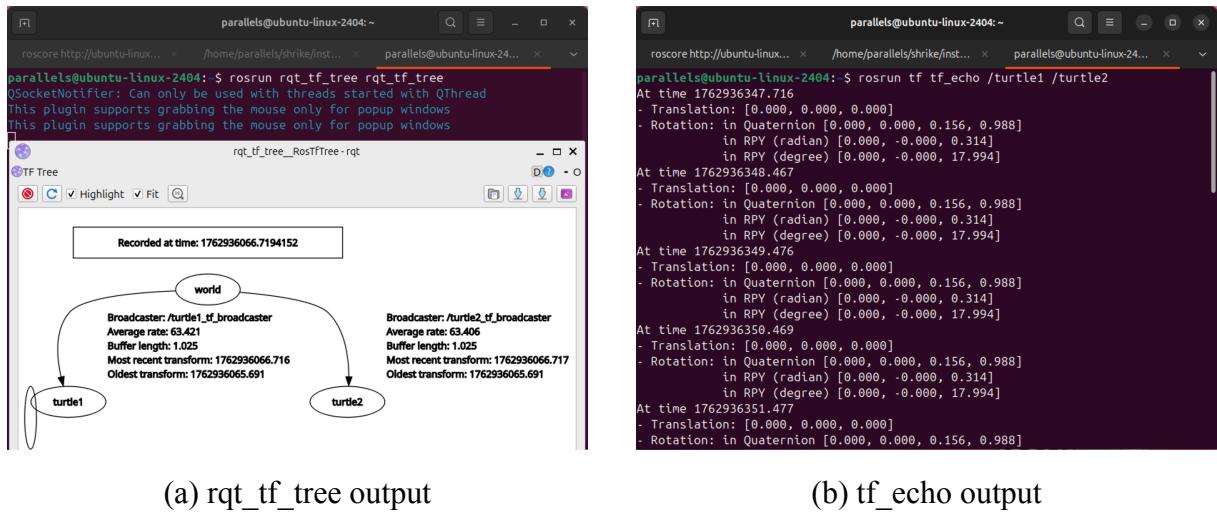


Figure 5: TF tools

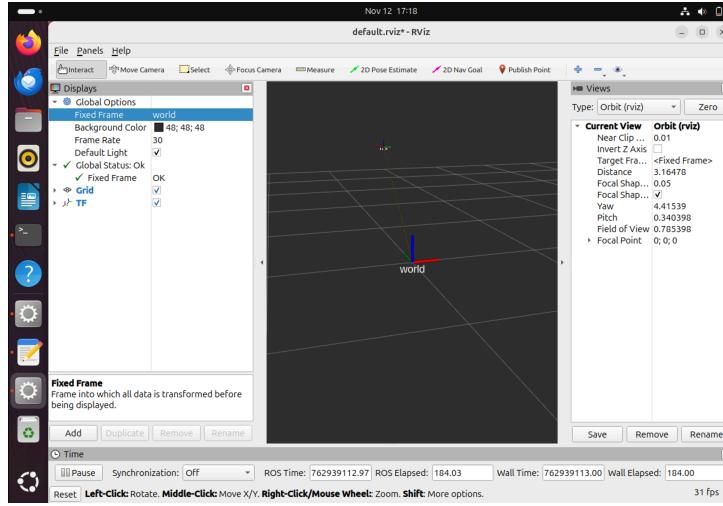


Figure 6: RViz

2.2.4 Discussion

This section demonstrates the core principles of inter-node communication and system visualization within the *ROS* framework. By implementing publisher and subscriber nodes and observing message flow using *rqt_graph* and *rostopic echo*, it becomes clear how topic-based communication enables modular and decoupled node interaction. The ability to monitor live message streams allows developers to validate correct behavior and quickly identify configuration or runtime issues.

The use of *TF* frames further illustrates the importance of coordinate transformation management in robotic systems. The hierarchical relationship among the *world*, *turtle1*, and *turtle2* frames highlights how spatial relationships are maintained and broadcast across the *ROS* network. Tools such as *rqt_tf_tree* and *tf_echo* provide intuitive means of visualizing and debugging frame hierarchies, reinforcing understanding of kinematic relationships and transformation propagation.

Running *RViz* in a virtualized environment emphasizes practical considerations for deploying visualization tools. The need to enforce software rendering with `LIBGL_ALWAYS_SOFTWARE=1` underscores how hardware acceleration and OpenGL support directly affect performance and usability.

2.3 Part III

2.3.1 Objective

To utilize the *TF* package to control the movement of drones and visualize their trajectories dynamically in *RViz*.

2.3.2 Methodology

1. Setting up the workspace

First, create a Catkin workspace named `vnav_ws` under the home directory:

```
mkdir -p ~/vnav_ws/src
cd ~/vnav_ws/
catkin init
```

The output should appear as shown in Figure 7. Next, copy the `two_drones_pkg` package into the `src` folder:

```
cp -a /source_path/two_drones_pkg ~/vnav_ws/src
```

Then, build the workspace using:

```
catkin build
```

The build output is shown in Figure 7. After the build completes, source the setup file to refresh the environment:

```
source devel/setup.bash
```

Finally, launch *ROS* to visualize the static drone scene in *RViz*:

```
roslaunch two_drones_pkg two_drones.launch static:=True
```

After adding the *TF* display, three colored axes will appear for each coordinate frame, as illustrated in Figure 8. Remember to save the *RViz* configuration once the setup is complete.

2. Basic *ROS* commands

- **Listing active nodes**

The active nodes in the static scene can be verified via `rqt_graph` and the output includes:

```
/frames_publisher_node
/plots_publisher_node
/rviz
```

- **Running without rosrun**

The static scene can also be launched manually using `rosrun`:

```
rosrun two_drones_pkg frames_publisher_node
rosrun two_drones_pkg plots_publisher_node
rosrun rviz rviz -d path/to/rviz_config.rviz
```

- **Node–topic relationships**

The topic connections between nodes are summarized below:

Node	Publishes	Subscribes	Description
<code>frames_publisher_node</code>	<code>/tf</code>	N/A	Broadcasts the coordinate transformations of AV1 and AV2
<code>plots_publisher_node</code>	<code>/visuals</code>	<code>/tf</code>	Generates trajectory <i>Markers</i> and calculates AV2's position relative to AV1
<code>rviz</code>	N/A	<code>/visuals, /tf</code>	Visualizes the drone grid and trajectories in 3D

- **Effect of omitting `static:=True`**

The `static` argument determines whether `TF` uses a static transform broadcaster. If omitted, transforms will be published dynamically at each iteration, which in dynamic scenes can increase message traffic and slightly reduce performance.

3. Dynamic scene visualization

To simulate drone movement, a `TransformBroadcaster` is instantiated to periodically send transform messages:

```
tf2_ros::TransformBroadcaster tf_broadcaster;
```

The elapsed time since startup is computed as:

```
double time = (ros::Time::now() - startup_time).toSec();
```

Each drone has an associated `TransformStamped` message:

```
geometry_msgs::TransformStamped AV1World;
geometry_msgs::TransformStamped AV2World;
AV1World.transform.rotation.w = 1.0;
AV2World.transform.rotation.w = 1.0;
```

AV1 moves along a circular path on the xy -plane centered at the world origin:

```
1 // --- AV1 ---
2 AV1World.header.frame_id = "world";
3 AV1World.child_frame_id = "av1";
4 AV1World.transform.translation.x = cos(time);
5 AV1World.transform.translation.y = sin(time);
6 AV1World.transform.translation.z = 0.0;
7
8 tf2::Quaternion q1;
9 q1.setRPY(0, 0, time);
10 AV1World.transform.rotation.x = q1.x();
11 AV1World.transform.rotation.y = q1.y();
12 AV1World.transform.rotation.z = q1.z();
13 AV1World.transform.rotation.w = q1.w();
```

AV2 follows a sinusoidal path along the $x-z$ plane:

```
1 // --- AV2 ---
2 AV2World.header.frame_id = "world";
3 AV2World.child_frame_id = "av2";
4 AV2World.transform.translation.x = sin(time);
5 AV2World.transform.translation.y = 0.0;
6 AV2World.transform.translation.z = cos(2 * time);
```

Finally, both transforms are broadcast:

```
tf_broadcaster.sendTransform(AV1World);
tf_broadcaster.sendTransform(AV2World);
```

The complete source code for `frames_publisher_node.cpp` is provided in [Source Code](#) at the end of this report.

4. Trajectory visualization

To visualize the drones' trajectories, *TF* data is queried using `lookupTransform` to retrieve each drone's position relative to the world frame:

- `tf_buffer` stores transformation history between coordinate frames.
- `lookupTransform(ref_frame, dest_frame, ros::Time(0))` retrieves the latest pose.
- `ros::Duration(0.1)` ensures synchronization by waiting briefly if needed.

Besides, with `Duration(0.1)` exists but there is no other thread to process the messages from *TF*. Therefore, the transform buffer will never be updated unless a dedicated thread or asynchronous spinner is created to handle incoming *TF* messages. In `tf2_ros`, this can be achieved by enabling the internal thread of the *TransformListener*, which continuously listens to the *TF* topic and updates the buffer in the background, as shown below:

```
tf2_ros::Buffer tf_buffer{ros::Duration(10.0), true};
tf2_ros::TransformListener tf_listener{tf_buffer};
```

Here, the second parameter `true` tells the listener to spawn a dedicated thread to process incoming *TF* data asynchronously. Without this background thread, the buffer would remain empty, and any subsequent calls to `lookupTransform()` would fail with a time extrapolation or "transform not found" error.

These steps ensure that *RViz* dynamically updates both trajectories in real time. The resulting visualization is shown in Figure 9.

5. Mathematical derivations

- In the problem formulation ,we mentioned that AV2's trajectory is an arc of parabola in the x - z plane of the world frame. Can you prove this statement?

Solution:

For AV2, its $o_2^\omega = \begin{bmatrix} \sin(t) \\ 0 \\ \cos(2t) \end{bmatrix}$.

By $\cos(2t) = 1 - 2\sin^2(t)$, we have $z = 1 - 2x^2$.

That's why the trajectory of AV2 is an arc of parabola in the x - z plane.

- Compute $o_2^1(t)$, i.e., the position of AV2 relative to AV1's body frame as a function of t .

Solution:

We have $o_2^1(t) = R_1^\omega(t)^T \cdot (o_2^\omega(t) - o_1^\omega(t))$, where $R_1^\omega(t)^T$ means the rotation matrix from AV1's body frame to the world frame, $o_2^\omega(t) - o_1^\omega(t)$ means the vector pointing from AV1 to AV2.

$$R_1^\omega(t)^T = \begin{bmatrix} x_1^\omega \\ y_1^\omega \\ z_1^\omega \end{bmatrix}.$$

$$\because z_1 \parallel z_\omega \therefore z_\omega = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}.$$

$$\because y_1 \text{ is tangent to the trajectory of AV1} \therefore \frac{d(o_1^\omega)}{dt} = \begin{bmatrix} -\sin t \\ \cos t \\ 0 \end{bmatrix}.$$

$$\therefore \sqrt{(-\sin t)^2 + (\cos t)^2} = 1 \therefore y_1^\omega = \begin{bmatrix} -\sin t \\ \cos t \\ 0 \end{bmatrix}.$$

$$\because x_1^\omega \text{ follows the right-hand rule} \therefore x_1^\omega = y_1^\omega \times z_1^\omega = \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ -\sin t & \cos t & 0 \\ 0 & 0 & 1 \end{vmatrix} = \begin{bmatrix} \cos t \\ \sin t \\ 0 \end{bmatrix}.$$

$$\therefore R_1^\omega = [x_1^\omega | x_2^\omega | x_3^\omega] = \begin{bmatrix} \cos(t) & -\sin(t) & 0 \\ \sin(t) & \cos(t) & 0 \\ 0 & 0 & 1 \end{bmatrix}.$$

$$\begin{aligned} \therefore o_2^1(t) &= R_1^\omega(t)^T \cdot (o_2^\omega(t) - o_1^\omega(t)) \\ &= \begin{bmatrix} \cos(t) & \sin(t) & 0 \\ -\sin(t) & \cos(t) & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \sin(t) - \cos(t) \\ -\sin(t) \\ \cos(2t) \end{bmatrix} \\ &= \begin{bmatrix} \sin(t) \cdot \cos(t) - 1 \\ -\sin^2(t) \\ \cos(2t) \end{bmatrix}. \end{aligned}$$

- Show that $o_2^1(t)$ describes a planar curve and find the equation of its plane Π .

Solution:

$$\text{From the previous question, we have } o_2^1(t) = \begin{bmatrix} \sin(t) \cdot \cos(t) - 1 \\ -\sin^2(t) \\ \cos(2t) \end{bmatrix}.$$

$$\because \cos(2t) = 1 - 2\sin^2(t) \therefore z_2^1 = 1 + 2y_2^1$$

$$\text{That's } \Pi : 2y - z + 1 = 0.$$

- Rewrite the above trajectory explicitly using a 2D frame of reference (x_p, y_p) on the plane found before. Try to ensure that the curve is centered at the origin of this 2D frame and that x_p, y_p are axes of symmetry for the curve.

Proof:

$$\text{Assume that there is a new coordinate } P, \text{ which center is } P^1 = \begin{bmatrix} -1 \\ -\frac{1}{2} \\ 0 \end{bmatrix}.$$

For translation matrix, we have

$$T(t) = \begin{bmatrix} \sin(t) \cdot \cos(t) - 1 \\ -\sin^2(t) \\ \cos(2t) \end{bmatrix} - \begin{bmatrix} -1 \\ -\frac{1}{2} \\ 0 \end{bmatrix} = \begin{bmatrix} \sin(t) \cdot \cos(t) \\ -\sin^2(t) + \frac{1}{2} \\ \cos(2t) \end{bmatrix}$$

For rotation matrix, we have

$$\therefore \Pi : 2y - z + 1 = 0 \therefore \text{normalline : } n = \begin{bmatrix} 0 \\ 2 \\ -1 \end{bmatrix}$$

$$\therefore z_p^1 = \frac{1}{\sqrt{5}} \begin{bmatrix} 0 \\ 2 \\ -1 \end{bmatrix}.$$

$$\begin{aligned}
& \because \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \times \begin{bmatrix} 0 \\ 2 \\ 1 \end{bmatrix} = \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ 1 & 0 & 0 \\ 0 & 2 & 1 \end{vmatrix} = 0 \\
& \therefore WLOG x_p^1 = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \\
& \therefore y_p^1 = z_p^1 \times x_p^1 = \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ 0 & \frac{2}{\sqrt{5}} & -\frac{2}{\sqrt{1}} \\ 1 & 0 & 0 \end{vmatrix} = \begin{bmatrix} 0 \\ -\frac{1}{\sqrt{5}} \\ -\frac{2}{\sqrt{5}} \end{bmatrix} \\
& \therefore R_p^1 = [x_p^1 | y_p^1 | z_p^1] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -\frac{1}{\sqrt{5}} & \frac{2}{\sqrt{5}} \\ 0 & \frac{2}{\sqrt{5}} & -\frac{1}{\sqrt{5}} \end{bmatrix} \\
& \therefore o_2^P(t) = R_1^P \cdot T(t) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -\frac{1}{\sqrt{5}} & \frac{2}{\sqrt{5}} \\ 0 & \frac{2}{\sqrt{5}} & -\frac{1}{\sqrt{5}} \end{bmatrix} \cdot \begin{bmatrix} \sin(t) \cdot \cos(t) \\ -\sin^2(t) + \frac{1}{2} \\ \cos(2t) \end{bmatrix} \\
& = \begin{bmatrix} \frac{1}{2}\sin(2t) \\ -\frac{\sqrt{5}}{2}\cos(2t) \\ 0 \end{bmatrix}.
\end{aligned}$$

That's the trajectory is under the (x_P, y_P) 2D-coordinate, which

$$\begin{cases} x_P(t) = \frac{1}{2}\sin(2t) \\ y_P(t) = -\frac{\sqrt{5}}{2}\cos(2t) \end{cases}$$

- Using the expression of $o_2^P(t)$, prove that the trajectory of AV2 relative to AV1 is an ellipse and compute the lengths of its semi-axes.

Proof:

From the previous question, we have

$$\begin{aligned}
& \begin{cases} x_p(t) = \frac{1}{2}\sin(2t) \\ y_p(t) = -\frac{\sqrt{5}}{2}\cos(2t) \end{cases} \\
& \Rightarrow \begin{cases} \sin(2t) = 2x_p(t) \\ \cos(2t) = -\frac{2}{\sqrt{5}}y_p(t) \end{cases}
\end{aligned}$$

$$\therefore 4x_p^2(t) + \frac{4}{5}y_p^2(t) = 1$$

$$\text{That's } \frac{x_p^2}{\frac{1}{4}} + \frac{y_p^2}{\frac{5}{4}} = 1$$

$$\therefore \begin{cases} x_p - \text{semiperiod} : a = \frac{1}{2} \\ y_p - \text{semiperiod} : b = \frac{\sqrt{5}}{2} \end{cases}$$

6. More properties of quaternions

Assume that there are two linear maps: $\Omega_1 : \mathbb{R}^4 \rightarrow \mathbb{R}^{4 \times 4}$ and $\Omega_2 : \mathbb{R}^4 \rightarrow \mathbb{R}^{4 \times 4}$, such that

for any $q \in \mathbb{R}^4$.

$$\Omega_1(q) = \begin{bmatrix} q_4 & -q_3 & q_2 & q_1 \\ q_3 & q_4 & -q_1 & q_2 \\ -q_2 & q_1 & q_4 & q_3 \\ -q_1 & -q_2 & -q_3 & q_4 \end{bmatrix}, \Omega_2(q) = \begin{bmatrix} q_4 & q_3 & -q_2 & q_1 \\ -q_3 & q_4 & q_1 & q_2 \\ q_2 & -q_1 & q_4 & q_3 \\ -q_1 & -q_2 & -q_3 & q_4 \end{bmatrix}.$$

The product between any two unit quaternions can be explicitly computed as:

$$q_a \otimes q_b = \Omega_1(q_a)q_b = \Omega_2(q_b)q_a$$

- For any unit quaternion q , both $\Omega_1(q)$ and $\Omega_2(q)$ are orthogonal matrices, i.e.,

$$\begin{cases} \Omega_1(q)^T \Omega_1(q) = \Omega_1(q) \Omega_1(q)^T = I_4, \\ \Omega_2(q)^T \Omega_2(q) = \Omega_2(q) \Omega_2(q)^T = I_4. \end{cases}$$

Intuitively, what is the reason that both $\Omega_1(q)$ and $\Omega_2(q)$ are orthogonal?

Proof:

Because the multiplication of unit quaternions represents a rotation operation, and rotation is a linear transformation in the vector space that preserves both length and angle. All linear transformations that preserve length correspond to orthogonal matrices.

That's if q_a is a unit quaternion, for any q_b , we have:

$$\|q_a \otimes q_b\| = \|q_a\| \cdot \|q_b\|$$

- For any unit quaternion q , both $\Omega_1(q)$ and $\Omega_2(q)$ convert q to be the unit quaternion that corresponds to the 3D identity rotation, i.e.
 $\Omega_1(q)^T q = \Omega_2(q)^T q = [0, 0, 0, 1]^T$.

Proof:

$$\Omega_1(q)^T \cdot q = \begin{bmatrix} q_4 & q_3 & -q_2 & -q_1 \\ -q_3 & q_4 & q_1 & -q_2 \\ q_2 & -q_1 & q_4 & -q_3 \\ q_1 & q_2 & q_3 & q_4 \end{bmatrix} \cdot \begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

$$\Omega_2(q)^T \cdot q = \begin{bmatrix} q_4 & -q_3 & q_2 & -q_1 \\ q_3 & q_4 & -q_1 & -q_2 \\ -q_2 & q_1 & q_4 & -q_3 \\ q_1 & q_2 & q_3 & q_4 \end{bmatrix} \cdot \begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

- For any two vectors $x, y \in \mathbb{R}^4$, show the two linear operators commute, i.e.

$$\begin{cases} \Omega_1(x) \cdot \Omega_2(y) = \Omega_2(y) \cdot \Omega_1(x), \\ \Omega_1(x) \cdot \Omega_2(y)^T = \Omega_2(y)^T \cdot \Omega_1(x). \end{cases}$$

Proof:

Though quaternion doesn't follow commutative law, it satisfies associative law.

For $\Omega_1(x) \cdot \Omega_2(y) = \Omega_2(y) \cdot \Omega_1(x)$, we have

$$\begin{cases} Left : (\Omega_1(x) \cdot \Omega_2(y)) \cdot z = (\Omega_1(x) \otimes z) \cdot \Omega_2(y) \\ Right : (\Omega_2(y) \cdot \Omega_1(x)) \cdot z = (\Omega_1(x) \otimes z) \cdot \Omega_2(y) \end{cases}$$

$\therefore Left = Right \Rightarrow \Omega_1(x) \cdot \Omega_2(y) = \Omega_2(y) \cdot \Omega_1(x)$.

For $\Omega_1(x) \cdot \Omega_2(y)^T = \Omega_2(y)^T \cdot \Omega_1(x)$, we have

$$\text{By } \Omega_2(\bar{y}) = \Omega_2(y)^T, \Omega_2(\bar{y}) = \Omega_2\left(\begin{bmatrix} -y_1 \\ -y_2 \\ -y_3 \\ -y_4 \end{bmatrix}\right) = \begin{bmatrix} y_4 & -y_3 & y_2 & -y_1 \\ y_3 & y_4 & -y_1 & -y_2 \\ -y_2 & y_1 & y_4 & -y_3 \\ y_1 & y_2 & y_3 & y_4 \end{bmatrix}.$$

Then the subsequent proof are similar to the previous one.

2.3.3 Observations

```
parallels@ubuntu-linux-2404:~/vnav_ws$ catkin init
Initializing catkin workspace in '/home/parallels/vnav_ws'.
-----
Profile: default
Extending: [env] /home/parallels/shrike/install_isolated
Workspace: /home/parallels/vnav_ws
-----
Build Space: [missing] /home/parallels/vnav_ws/build
Devel Space: [missing] /home/parallels/vnav_ws/devel
Install Space: [unused] /home/parallels/vnav_ws/install
Log Space: [missing] /home/parallels/vnav_ws/logs
Source Space: [exists] /home/parallels/vnav_ws/src
DESTDIR: [unused] None
-----
Devel Space Layout: linked
Install Space Layout: None
-----
Additional CMake Args: None
Additional Make Args: None
Additional catkin Make Args: None
Internal Make Job Server: True
Cache Job Environments: False
-----
Buildlisted Packages: None
Skiplisted Packages: None
-----
Workspace configuration appears valid.
```

```
parallels@ubuntu-linux-2404:~/vnav_ws$ catkin build
-----
Profile: default
Extending: [cached] /home/parallels/shrike/install_isolated
Workspace: /home/parallels/vnav_ws
-----
Build Space: [exists] /home/parallels/vnav_ws/build
Devel Space: [exists] /home/parallels/vnav_ws/devel
Install Space: [unused] /home/parallels/vnav_ws/install
Log Space: [exists] /home/parallels/vnav_ws/logs
Source Space: [exists] /home/parallels/vnav_ws/src
DESTDIR: [unused] None
-----
Devel Space Layout: linked
Install Space Layout: None
-----
Additional CMake Args: None
Additional Make Args: None
Additional catkin Make Args: None
Internal Make Job Server: True
Cache Job Environments: False
-----
Buildlisted Packages: None
Skiplisted Packages: None
-----
Workspace configuration appears valid.

[build] Found 1 packages in 0.0 seconds.
[build] Package table is up to date.
Starting  >>> two_drones_pkg
<<< two_drones_pkg           [ 0.1 seconds ]
[build] Summary: All 1 packages succeeded!
[build] Ignored: None.
[build] Warnings: None.
[build] Abandoned: None.
[build] Failed: None.
[build] Runtime: 0.1 seconds total.
parallels@ubuntu-linux-2404:~/vnav_ws$
```

(a) catkin init

(b) catkin build

Figure 7: Catkin workspace initialization and build

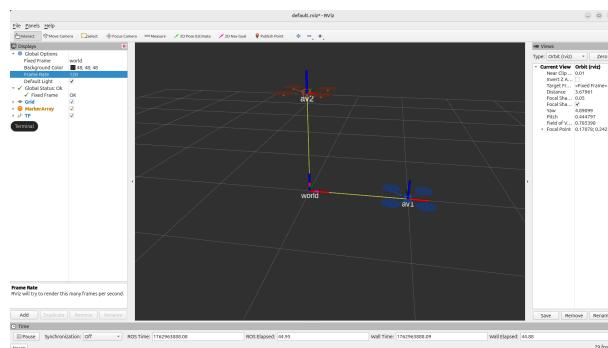


Figure 8: Static visualization of two drones in RViz

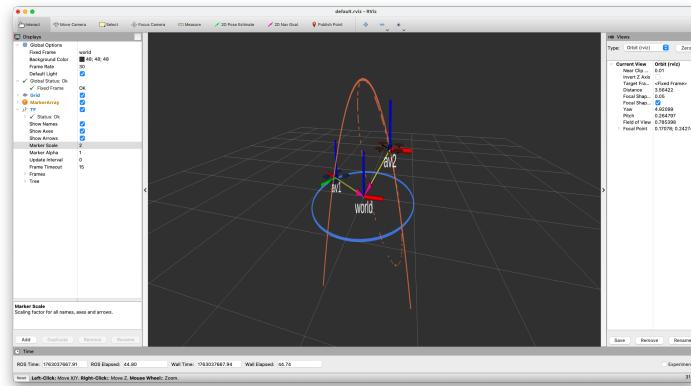


Figure 9: Dynamic trajectories of two drones in *RViz*

2.3.4 Discussion

This session successfully demonstrates how *TF* enables both static and dynamic spatial relationships to be visualized in real time. In the **static** case, each transform is broadcast only once, minimizing system overhead. In contrast, **dynamic** broadcasting continuously updates transforms according to the elapsed time, allowing for smooth motion visualization but at a higher computational and communication cost.

The design of the two distinct motion models—circular motion for AV1 and sinusoidal motion for AV2—illustrates the flexibility of *TF* in representing diverse kinematic behaviors. By combining *tf2_ros::TransformBroadcaster* with *lookupTransform*, the system maintains synchronization between frames and ensures that *RViz* accurately reflects the relative positions and orientations of both drones.

3 Reflection and Analysis

This laboratory provided a comprehensive and progressive introduction to *ROS*, beginning with environment setup and advancing toward multi-frame management, dynamic transformations, and 3D visualization. Through the installation process, I realized that *ROS*—especially *ROS 1*—remains highly sensitive to system dependencies. The challenges encountered on *Ubuntu 24.04* highlighted the importance of understanding underlying build systems and the role of community-maintained distributions such as *Shrike*, which effectively bridge compatibility gaps when official support is absent. This experience reinforces that robotics development often requires navigating practical software engineering issues beyond algorithmic implementation.

The subsequent tasks deepened my understanding of *ROS*'s computational graph. By implementing publishers, subscribers, and *TF* frames, I gained insight into how *ROS* enforces modularity: each node performs a single role, communicates through well-defined topics, and remains decoupled from system-wide execution flow. Using tools such as *rqt_graph*, *tf_echo*, and *rqt_tf_tree* provided an intuitive visualization of otherwise abstract message flow, making it easier to debug connectivity and timing issues.

Particularly in Part III, the dynamic behavior of *TF* became more apparent. Implementing

two moving drones illustrated how coordinate transformations are accumulated, queried, and rendered in real time. It became clear that *tf2* expects a continuous stream of transforms and must be supported by background threads or asynchronous spinners; otherwise, failed lookups, extrapolation errors, or empty buffers will occur. This hands-on debugging process demonstrated the practical interplay between message timing, buffer duration, and the internal mechanics of *TF* listeners.

Mathematically analyzing the drones' trajectories—deriving planar equations, performing coordinate-frame rotations, and proving that the relative motion forms an ellipse—connected theoretical kinematics with real-time visualization in *RViz*. This bridging of computation, geometry, and visualization is a core skill in robotics, and the lab provided a clear demonstration of how abstract frame transformations translate into concrete 3D animations.

4 Conclusion

Lab 2 successfully introduced the essential components of the *ROS* ecosystem, covering installation, workspace management, node communication, and *TF*-based motion visualization. By completing each part, I gained a solid understanding of how *ROS* organizes complex robotic systems into lightweight, interconnected processes that communicate through standardized mechanisms.

The experiment achieved its learning objectives:

- The *ROS* environment was correctly installed on *Ubuntu 24.04* using a community-supported framework.
- Publisher and subscriber nodes were implemented and verified through *ROS* tools.
- *TF* was used to model both static and dynamic coordinate frames.
- Two drones with distinct motion patterns were simulated and visualized in *RViz*.
- Mathematical derivation validated the geometric properties observed in the simulation.

Overall, The lab demonstrated that *ROS* is not merely a middleware but a structured ecosystem enabling scalable, modular robotics development.

5 Source Code

- *frames_publisher_node.cpp*

```
1 #include <ros/ros.h>
2 #include <tf2_ros/transform_broadcaster.h>
3 #include <tf2/LinearMath/Quaternion.h>
4
5 #include <iostream>
6
7 class FramesPublisherNode {
8     private:
9         ros::NodeHandle nh;
10        ros::Time startup_time;
11
12        ros::Timer heartbeat;
13
14        tf2_ros::TransformBroadcaster tf_broadcaster;
15
16    public:
17        FramesPublisherNode() {
18            // NOTE: This method is run once, when the node is launched.
19            startup_time = ros::Time::now();
20            heartbeat = nh.createTimer(ros::Duration(0.02),
21                &FramesPublisherNode::onPublish, this);
22            heartbeat.start();
23        }
24
25        void onPublish(const ros::TimerEvent&) {
26            double time = (ros::Time::now() - startup_time).toSec();
27
28            geometry_msgs::TransformStamped AV1World;
29            geometry_msgs::TransformStamped AV2World;
30
31            AV1World.transform.rotation.w = 1.0;
32            AV2World.transform.rotation.w = 1.0;
33
34            // --- AV1 ---
35            AV1World.header.stamp = ros::Time::now();
36            AV1World.header.frame_id = "world";
37            AV1World.child_frame_id = "av1";
38            // path: [cos(t), sin(t), 0]
39            AV1World.transform.translation.x = cos(time);
40            AV1World.transform.translation.y = sin(time);
41            AV1World.transform.translation.z = 0.0;
42            // angle: [0, 0, t]
43            tf2::Quaternion q1;
44            q1.setRPY(0, 0, time);
45            AV1World.transform.rotation.x = q1.x();
46            AV1World.transform.rotation.y = q1.y();
47            AV1World.transform.rotation.z = q1.z();
48            AV1World.transform.rotation.w = q1.w();
49
50            // --- AV2 ---
51            AV2World.header.stamp = ros::Time::now();
52            AV2World.header.frame_id = "world";
53            AV2World.child_frame_id = "av2";
54            // path: [sin(t), 0, cos(2t)]
```

```

54     AV2World.transform.translation.x = sin(time);
55     AV2World.transform.translation.y = 0.0;
56     AV2World.transform.translation.z = cos(2 * time);
57
58     // Publish the transforms
59     tf_broadcaster.sendTransform(AV1World);
60     tf_broadcaster.sendTransform(AV2World);
61 }
62 };
63
64 int main(int argc, char** argv) {
65     ros::init(argc, argv, "frames_publisher_node");
66     FramesPublisherNode node;
67     ros::spin();
68     return 0;
69 }
```

- *plots_publisher_node.cpp*

```

1 #include <geometry_msgs/Point.h>
2 #include <ros/ros.h>
3 #include <tf2_ros/transform_listener.h>
4 #include <visualization_msgs/MarkerArray.h>
5
6 #include <iostream>
7 #include <list>
8
9 class PlotsPublisherNode {
10     ros::Time startup_time;
11     ros::Timer heartbeat;
12     ros::NodeHandle nh;
13     ros::Publisher markers_pub;
14     tf2_ros::Buffer tf_buffer{ros::Duration(10.0), true};
15     tf2_ros::TransformListener tf_listener{tf_buffer};
16     int num_trails;
17
18     class TrajTrail {
19         PlotsPublisherNode* parent;
20         static int id;
21         std::list<geometry_msgs::Point> poses;
22         std::string ref_frame, dest_frame;
23         size_t buffer_size;
24
25         std::string ns;
26         float r, g, b, a;
27
28         visualization_msgs::Marker marker_out;
29
30     void update() {
31         // NOTE: you need to populate this transform
32         geometry_msgs::TransformStamped transform;
33         try {
34             transform = parent->tf_buffer.lookupTransform(
35                 ref_frame,
36                 dest_frame,
37                 ros::Time(0),
38                 ros::Duration(0.1)
39         );
40     }
```

```

41     while (poses.size() >= buffer_size) {
42         poses.pop_front();
43     }
44
45     geometry_msgs::Point tmp;
46     tmp.x = transform.transform.translation.x;
47     tmp.y = transform.transform.translation.y;
48     tmp.z = transform.transform.translation.z;
49     poses.push_back(tmp);
50 } catch (const tf2::TransformException& ex) {
51     ROS_ERROR_STREAM("transform lookup failed: " << ex.what());
52 }
53 }
54
55 public:
56 TrajTrail() : parent(nullptr){};
57
58 TrajTrail(PlotsPublisherNode* parent_,
59             const std::string& ref_frame_,
60             const std::string& dest_frame_,
61             int buffer_size_ = 160)
62 : parent(parent_),
63   ref_frame(ref_frame_),
64   dest_frame(dest_frame_),
65   buffer_size(buffer_size_) {
66     if (buffer_size <= 0) {
67         ROS_ERROR_STREAM("invalid buffer size! defaulting to 10");
68         buffer_size = 10;
69     }
70
71     marker_out.header.frame_id = ref_frame;
72     marker_out.ns = "trails";
73     marker_out.id = parent->num_trails++;
74     marker_out.type = visualization_msgs::Marker::LINE_STRIP;
75     marker_out.action = visualization_msgs::Marker::ADD;
76     marker_out.color.a = 0.8;
77     marker_out.scale.x = 0.02;
78     marker_out.lifetime = ros::Duration(1.0);
79 }
80
81 void setColor(float r_, float g_, float b_) {
82     marker_out.color.r = r_;
83     marker_out.color.g = g_;
84     marker_out.color.b = b_;
85 }
86
87 void setNamespace(const std::string& ns_) { marker_out.ns = ns_; }
88
89 void setDashed() { marker_out.type = visualization_msgs::Marker::LINE_LIST;
90   }
91
92 visualization_msgs::Marker getMarker() {
93     update();
94     marker_out.header.stamp = ros::Time::now();
95     marker_out.points.clear();
96     for (auto& p : poses) marker_out.points.push_back(p);
97
98     if (marker_out.type == visualization_msgs::Marker::LINE_LIST &&
99         poses.size() % 2)

```

```

98         marker_out.points.resize(poses.size() - 1);
99
100     return marker_out;
101 }
102 };
103
104 TrajTrail av1trail;
105 TrajTrail av2trail;
106 TrajTrail av2trail_rel;
107
108 public:
109 PlotsPublisherNode() : tf_listener(tf_buffer), num_trails(0) {
110     startup_time = ros::Time::now();
111     markers_pub = nh.advertise<visualization_msgs::MarkerArray>("visuals", 0);
112     heartbeat =
113         nh.createTimer(ros::Duration(0.02), &PlotsPublisherNode::onPublish,
114              $\hookrightarrow$  this);
115     heartbeat.start();
116     av1trail = TrajTrail(this, "world", "av1", 300);
117     av1trail.setColor(0.25, 0.52, 1.0);
118     av1trail.setNamespace("Trail av1-world");
119     av2trail = TrajTrail(this, "world", "av2", 300);
120     av2trail.setColor(0.8, 0.4, 0.26);
121     av2trail.setNamespace("Trail av2-world");
122     av2trail_rel = TrajTrail(this, "av1", "av2", 160);
123     av2trail_rel.setDashed();
124     av2trail_rel.setColor(0.8, 0.4, 0.26);
125     av2trail_rel.setNamespace("Trail av2-av1");
126
127     ROS_INFO_STREAM("Waiting for av1 and av2 transforms to be broadcast...");
128     while (ros::ok()) {
129         const bool av1_present = tf_buffer.canTransform("av1", "world",
130              $\hookrightarrow$  ros::Time(0));
131         const bool av2_present = tf_buffer.canTransform("av2", "world",
132              $\hookrightarrow$  ros::Time(0));
133         if (av1_present && av2_present) {
134             ROS_INFO_STREAM("Necessary frames are present, starting!");
135             break;
136         }
137     }
138
139     void onPublish(const ros::TimerEvent&) {
140         visualization_msgs::MarkerArray visuals;
141         visuals.markers.resize(2);
142         visualization_msgs::Marker& av1(visuals.markers[0]);
143         visualization_msgs::Marker& av2(visuals.markers[1]);
144         av1.header.frame_id = "av1";
145         av1.ns = "AVs";
146         av1.id = 0;
147         av1.header.stamp = ros::Time();
148         av1.type = visualization_msgs::Marker::MESH_RESOURCE;
149         av1.mesh_resource = "package://two_drones_pkg/mesh/quadrotor.dae";
150         av1.action = visualization_msgs::Marker::ADD;
151         av1.pose.orientation.w = 1.0;
152         av1.scale.x = av1.scale.y = av1.scale.z = av1.color.a = 1.0;
153         av1.color.r = 0.25;
154         av1.color.g = 0.52;
155         av1.color.b = 1.0;

```

```
154     av1.lifetime = ros::Duration(1.0);
155     av2 = av1;
156     av2.header.frame_id = "av2";
157     av2.ns = "AVs";
158     av2.id = 1;
159     av2.color.r = 0.8;
160     av2.color.g = 0.4;
161     av2.color.b = 0.26;
162
163     // Trails
164     visuals.markers.push_back(av1trail.getMarker());
165     visuals.markers.push_back(av2trail.getMarker());
166     visuals.markers.push_back(av2trail_rel.getMarker());
167     markers_pub.publish(visuals);
168 }
169 };
170
171 int main(int argc, char** argv) {
172     ros::init(argc, argv, "plots_publisher_node");
173     PlotsPublisherNode node;
174     ros::spin();
175     return 0;
176 }
```