Configuration Space, Task Space, Workspace and Introduction to ROS

CS 6341 Robotics

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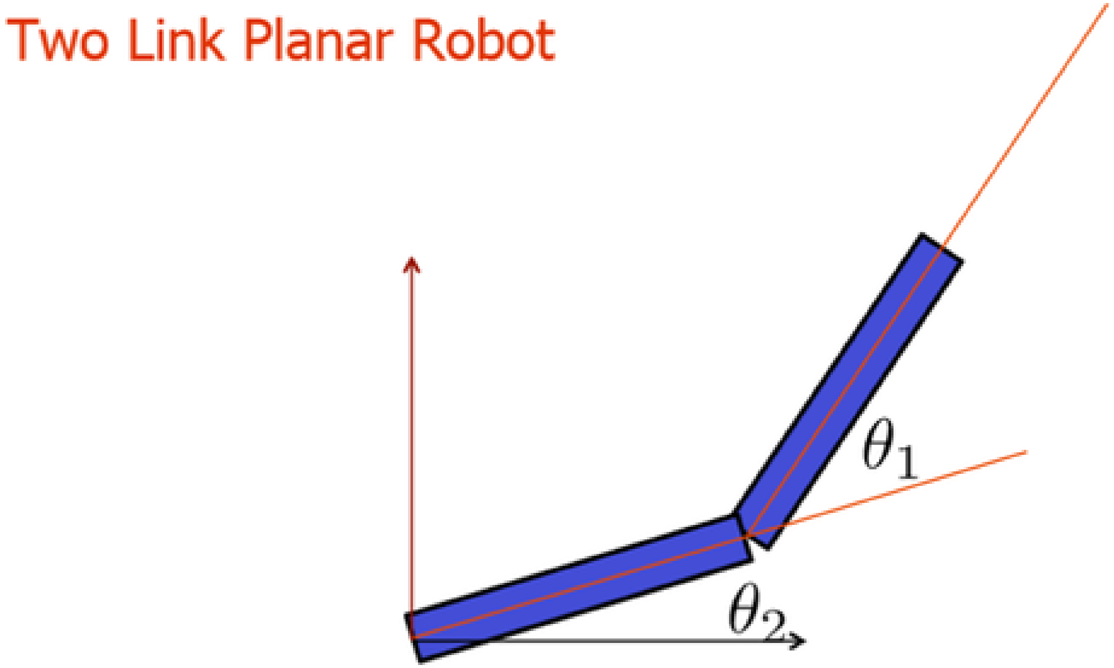
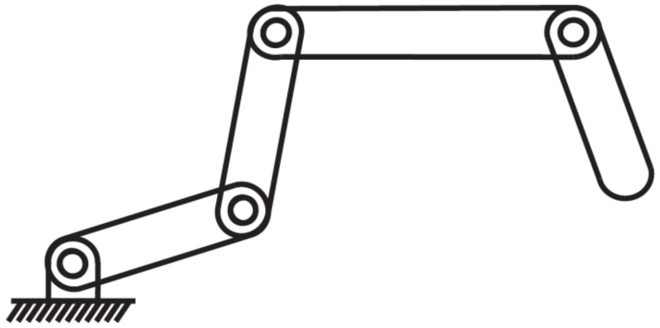
Configuration Space of a Robot





- 4 revolute joints
- 4 DOFs

Configuration Space Topology

- Configuration specifies the position of a robot
- For a robot with n joints, the configuration is a vector in $\mathbb{R}^n$
  - C-space
- Joints may have limits, upper bound and lower bound
- Topology: shape of the space
  - Consider all the feasible points in the configuration space

Configuration Space Topology

- n-dimensional Euclidean space $\mathbb{R}^n$
- n-dimensional sphere in a (n+1)-dimensional Euclidean space S^n
  - Two-dimensional surface of a sphere in three-dimensional space S^2

S^2

Task Space

- The task space is a space in which the robot's task can be naturally expressed

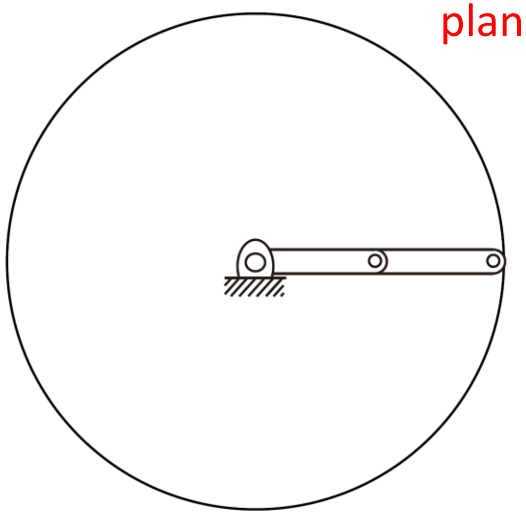
- Task examples
  - Draw on a piece of paper: $\mathbb{R}^2$
  - Manipulate a rigid body: C-space of the rigid body

- Task space is driven by the task, independently of the robot

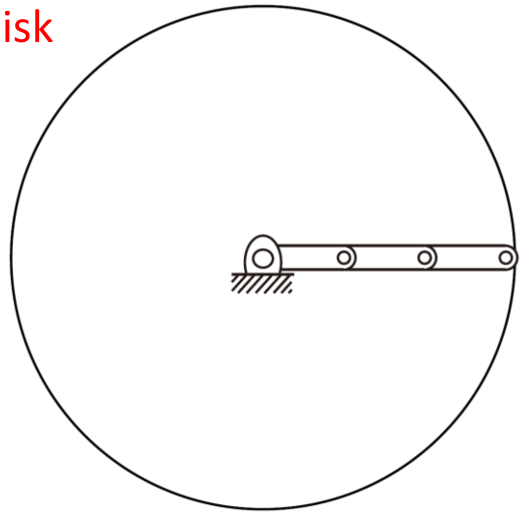
Workspace

- The workspace is a specification of the configurations that **the end-effector of the robot can reach**.
- Depends on the robot structure, independent of the task

planar disk

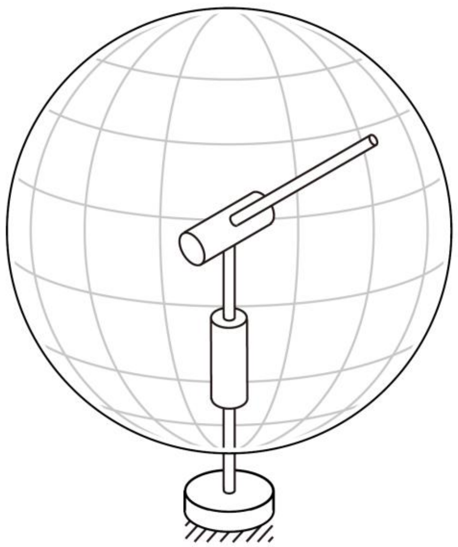


a planar 2R open chain



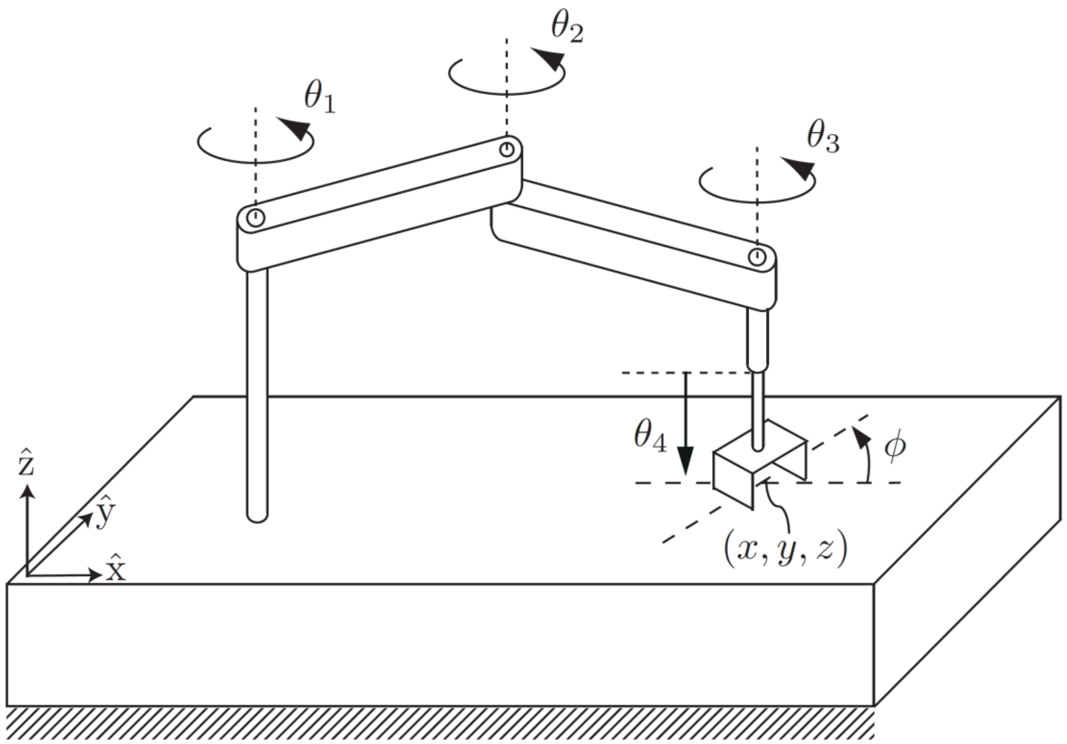
a planar 3R open chain

Surface of a sphere



a spherical 2R open chain

SCARA Robot



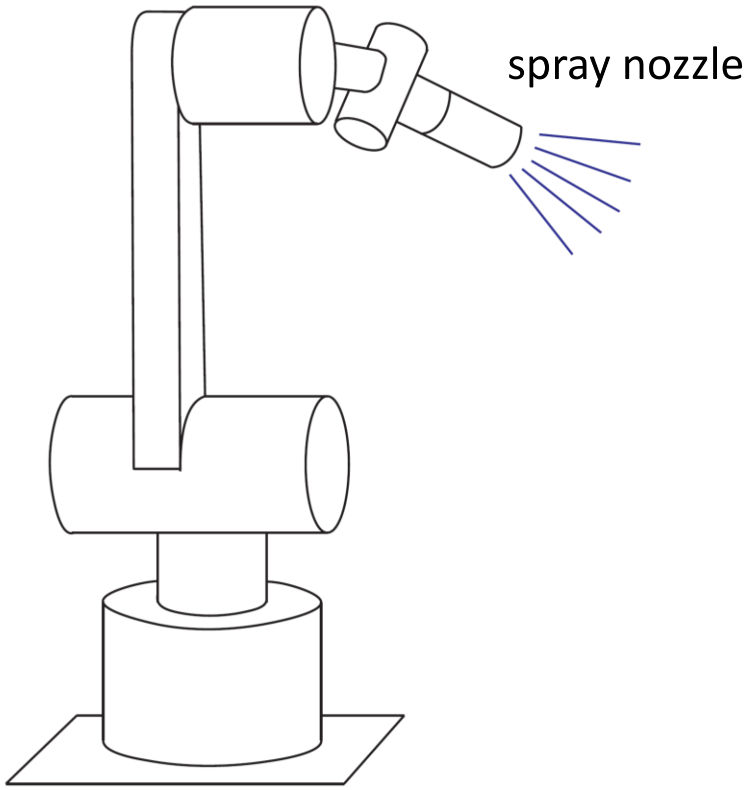
- End-effector configuration

$$(x, y, z, \phi)$$

- Task space $\mathbb{R}^3 \times S^1$

- Workspace
  - Reachable (x, y, z, ϕ)

A 6R Robot



A spray-painting robot

- End-effector configuration

$$(x, y, z) \quad (\theta, \phi)$$

Cartesian position of the nozzle

Spherical coordinates to describe the direction in which the nozzle is pointing

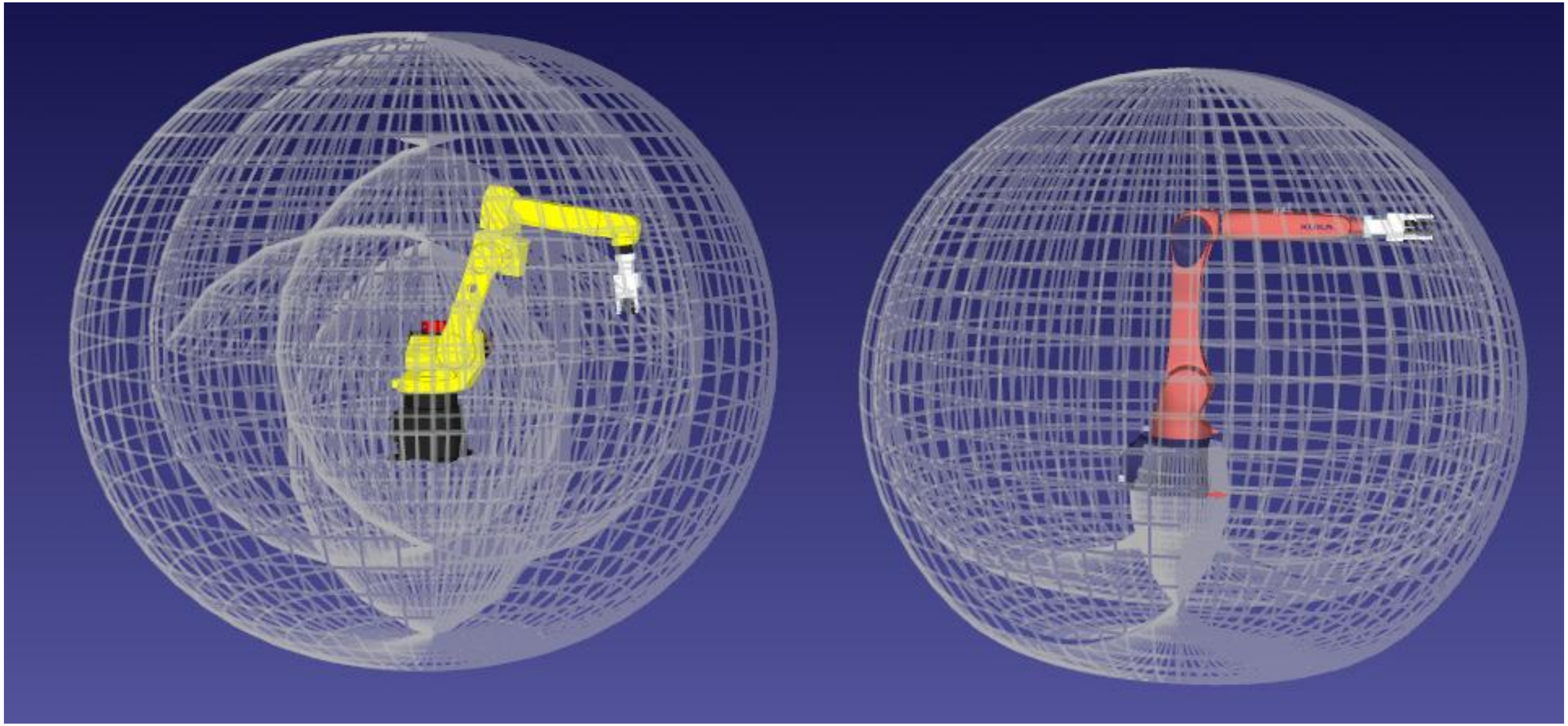
- Task space $\mathbb{R}^3 \times S^2$

- Workspace
  - Reachable

$$(x, y, z) \quad (\theta, \phi)$$

https://www.rnaautomation.com/case-study/robotic-spray-booth/

Workspace Examples



https://robodk.com/blog/robot-workspace-visualization/

Robot Operating System (ROS)

- ROS is a set of software libraries and tools that can be used to build robot applications
  - Drivers, algorithms, developer tools, etc.
- Goal of ROS: support code reuse in robotics research and development
- Operating systems: Unix-based platforms (Ubuntu)
- ROS1 (end of life) and ROS2

https://www.ros.org/
https://wiki.ros.org/

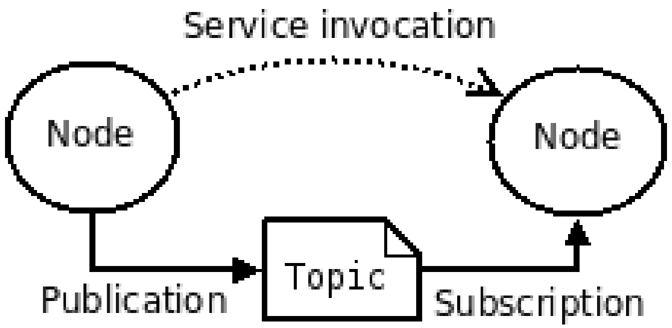
Robot Operating System (ROS)

https://www.ros.org/

ROS Computation Graph

- The computation graph is the peer-to-peer network of ROS processes that are processing data together

- Computation graph concepts
  - Nodes: processes that perform computation
  - ROS Master: provides name registration and lookup, nodes can find each other via ROS master
  - Messages: nodes communicate by passing messages, a data structure with type fields (integer, floating, arrays, etc.)



ROS Message Example

File: sensor_msgs/Image.msg

Raw Message Definition

```
# This message contains an uncompressed image
# (0, 0) is at top-left corner of image
#

Header header        # Header timestamp should be acquisition time of image
                     # Header frame_id should be optical frame of camera
                     # origin of frame should be optical center of camera
                     # +x should point to the right in the image
                     # +y should point down in the image
                     # +z should point into to plane of the image
                     # If the frame_id here and the frame_id of the CameraInfo
                     # message associated with the image conflict
                     # the behavior is undefined

uint32 height         # image height, that is, number of rows
uint32 width          # image width, that is, number of columns

# The legal values for encoding are in file src/image_encodings.cpp
# If you want to standardize a new string format, join
# ros-users@lists.sourceforge.net and send an email proposing a new encoding.

string encoding       # Encoding of pixels -- channel meaning, ordering, size
                      # taken from the list of strings in include/sensor_msgs/image_encodings.h

uint8 is_bigendian    # is this data bigendian?
uint32 step           # Full row length in bytes
uint8[] data          # actual matrix data, size is (step * rows)
```

std_msgs/Header Message

File: std_msgs/Header.msg

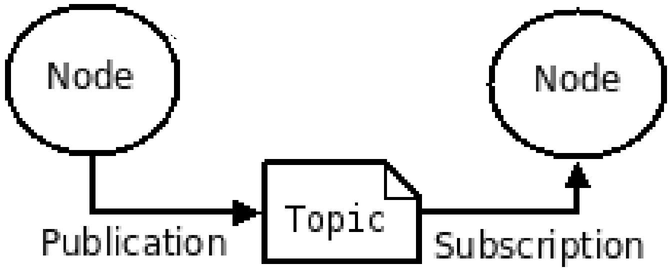
Raw Message Definition

```
# Standard metadata for higher-level stamped data types.
# This is generally used to communicate timestamped data
# in a particular coordinate frame.
#
# sequence ID: consecutively increasing ID
uint32 seq
#Two-integer timestamp that is expressed as:
# * stamp.sec: seconds (stamp_secs) since epoch (in Python the variable is called 'secs')
# * stamp.nsec: nanoseconds since stamp_secs (in Python the variable is called 'nsecs')
# time-handling sugar is provided by the client library
time stamp
#Frame this data is associated with
string frame_id
```

ROS Computation Graph

- Topics: a node publishes messages to a topic. The topic is the name to identify the content of the message

Node: Head camera



Node: Object detection

Topic: /rgb_image

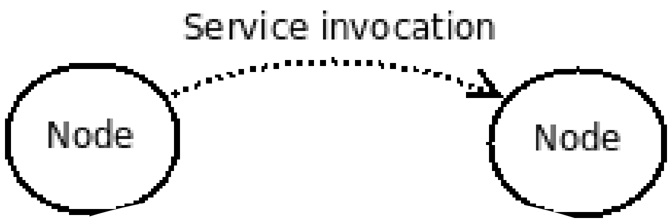
Message: sensor_msgs/Image

ROS Computation Graph

- Service: request and reply interactions

Service: FollowJointTrajectory

Node: Motion Planner



Node: Arm Controller

File: **control_msgs/FollowJointTrajectoryGoal.msg**

```
# ====== DO NOT MODIFY! AUTOGENERATED FROM AN ACTION DEFINITION ======
# The joint trajectory to follow
trajectory_msgs/JointTrajectory trajectory

# Tolerances for the trajectory.  If the measured joint values fall
# outside the tolerances the trajectory goal is aborted.  Any
# tolerances that are not specified (by being omitted or set to 0) are
# set to the defaults for the action server (often taken from the
# parameter server).

# Tolerances applied to the joints as the trajectory is executed.  If
# violated, the goal aborts with error_code set to
# PATH_TOLERANCE_VIOLATED.
JointTolerance[] path_tolerance

# To report success, the joints must be within goal_tolerance of the
# final trajectory value.  The goal must be achieved by time the
# trajectory ends plus goal_time_tolerance.  (goal_time_tolerance
# allows some leeway in time, so that the trajectory goal can still
# succeed even if the joints reach the goal some time after the
# precise end time of the trajectory).
#
# If the joints are not within goal_tolerance after "trajectory finish
# time" + goal_time_tolerance, the goal aborts with error_code set to
# GOAL_TOLERANCE_VIOLATED
JointTolerance[] goal_tolerance
duration goal_time_tolerance
```

File: **control_msgs/FollowJointTrajectoryAction.msg**

Raw Message Definition

```
# ====== DO NOT MODIFY! AUTOGENERATED FROM AN ACTION DEFINITION ======

FollowJointTrajectoryActionGoal action_goal
FollowJointTrajectoryActionResult action_result
FollowJointTrajectoryActionFeedback action_feedback
```

Compact Message Definition

```
control_msgs/FollowJointTrajectoryActionGoal action_goal
control_msgs/FollowJointTrajectoryActionResult action_result
control_msgs/FollowJointTrajectoryActionFeedback action_feedback
```

Using ROS2

- Ubuntu users
- Mac users -> Use virtual machine
- Windows users -> Use docker

Using ROS2 Jazzy with Ubuntu 24.04

- Install ROS2

  https://docs.ros.org/en/jazzy/Installation/Ubuntu-Install-Debs.html

Using ROS2 with Mac

1. Download the ubuntu-24.04.3-desktop-amd64.iso from https://ubuntu.com/download/desktop (pick arm or amd based on if you have m1 or intel mac)

2. Download UTM from https://mac.getutm.app/

3. Follow this video to install the ubuntu image in Mac https://www.youtube.com/watch?v=1WWj6qoWhJw

4. Use ROS2 as in Ubuntu

Docker: Using ROS2 with Windows

- An open platform that enables you to separate your applications from your infrastructure

- Container
  - A lightweight environment that contains everything to run an application
  - A container is a runnable instance of an image

- Image
  - A read-only template with instructions for creating a docker container

Ubuntu in Docker

- Download the ubuntu docker image https://hub.docker.com/_/ubuntu

docker pull ubuntu:24.04

Command

Docker image name

Docker image tag

Docker

docker run -i -t ubuntu:24.04

- Run an **ubuntu container**
- You need to have an **ubuntu image** locally, if not, the command will pull an ubuntu image as by docker pull ubuntu
- Docker creates a new container as though you had run docker container create
- -i, -t the container is running interactively and attached to your terminal
- When exit, the container stops but is not removed

ROS2 in Docker

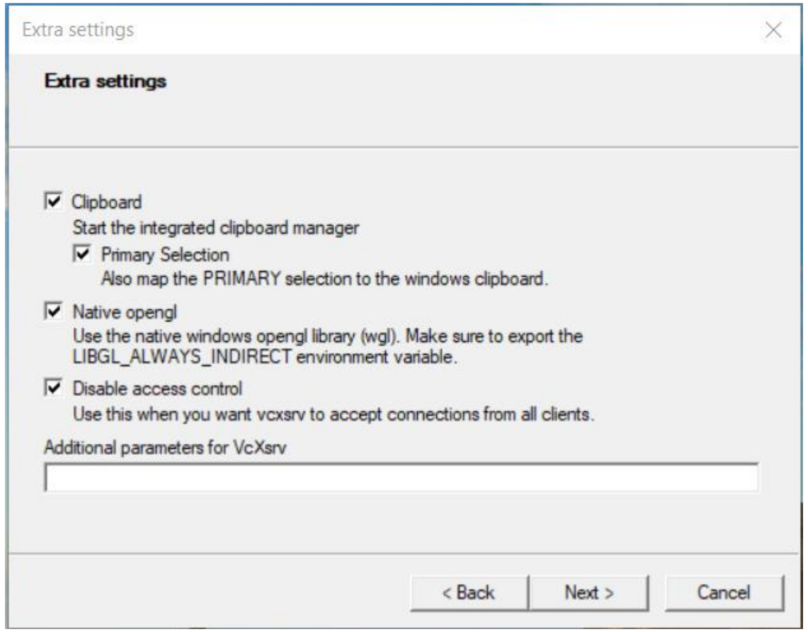
- Install Docker Desktop https://docs.docker.com/get-docker/
- Start the Docker Desktop
- Ubuntu images https://hub.docker.com/_/ubuntu
- Run command “docker run –i –t ubuntu:24.04”
- No need to use sudo in docker, do an “apt update” first
- Install ROS2 Jazzy https://docs.ros.org/en/jazzy/Installation/Ubuntu-Install-Debs.html
- Install terminator https://manpages.ubuntu.com/manpages/bionic/en/man1/terminator.1.html

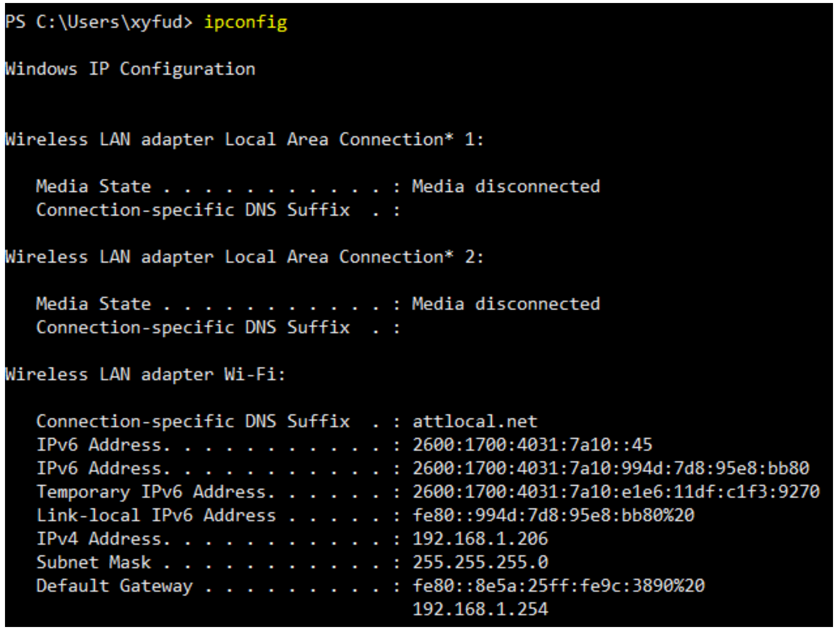
ROS in Docker

- Install X server
  - Windows: VcXsrv Windows X Server https://sourceforge.net/projects/vcxsrv/

- Start the X server
- Check IP address
- In Ubuntu terminal

Export DISPLAY=my_ip:0.0





https://medium.com/@potatowagon/how-to-use-gui-apps-in-linux-docker-container-from-windows-host-485d3e1c64a3

ROS2 in Docker

- Test ROS2 installation

- In one terminator terminal, start roscore
  - source /opt/ros/jazzy/setup.bash

- In another terminator terminal, start rviz2
  - rviz2

Commit Your Docker Image

- After you exit the docker container
- Run the command “docker container list -a” to see all the containers. Find the container ID of the latest one
- Run the command “docker container commit <CONTAINER_ID>”
- Run the command “docker image list -a” to see the latest image ID
- Run the command “docker image tag <IMAGE_ID> TAG”. Give a name to this image such as “ubuntu:ros”

Mount a Host Folder into Docker

- Use the "-v" option of the Docker run

- For example, docker run -it -v C:\data:/data ubuntu:ros

ROS2 in Docker

- After install all needed packages, exit
- docker container commit CONTAINER_ID
- docker image tag <IMAGE_ID> TAG

- Useful commands
  - docker container list –a
  - docker image list -a

- The new tagged image will have all the installed packages

Summary

- Task space
- Workspace
- ROS
- Docker

Further Reading

- Chapter 2 in Kevin M. Lynch and Frank C. Park. Modern Robotics: Mechanics, Planning, and Control. 1st Edition, 2017 http://hades.mech.northwestern.edu/images/7/7f/MR.pdf

- ROS wiki https://wiki.ros.org/

- Docker document https://docs.docker.com/get-started/overview/

- https://yuxng.github.io/Courses/CS6341Fall2025//CS_6341_Docker_Instructions.pdf