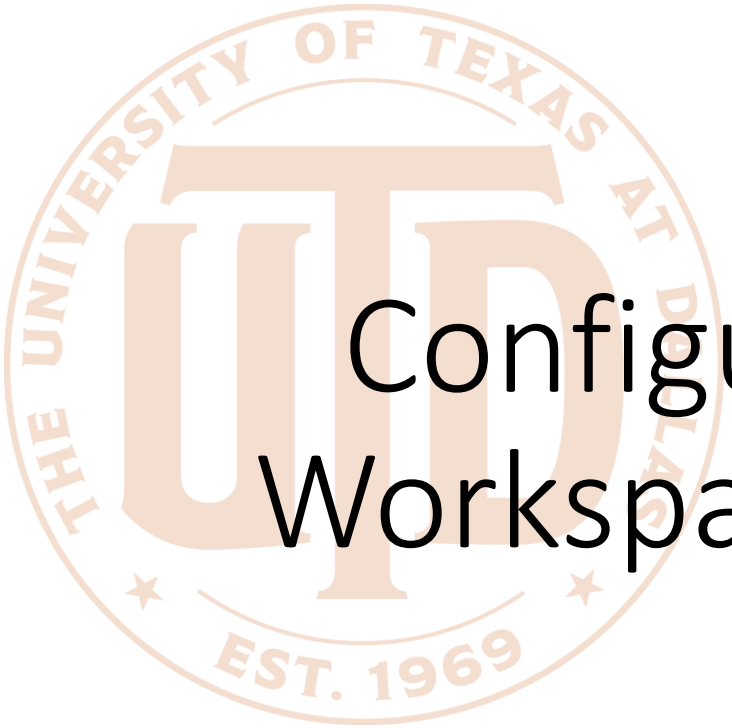

Configuration Space, Task Space, Workspace and Introduction to ROS

CS 6301 Special Topics: Introduction to Robot Manipulation and Navigation

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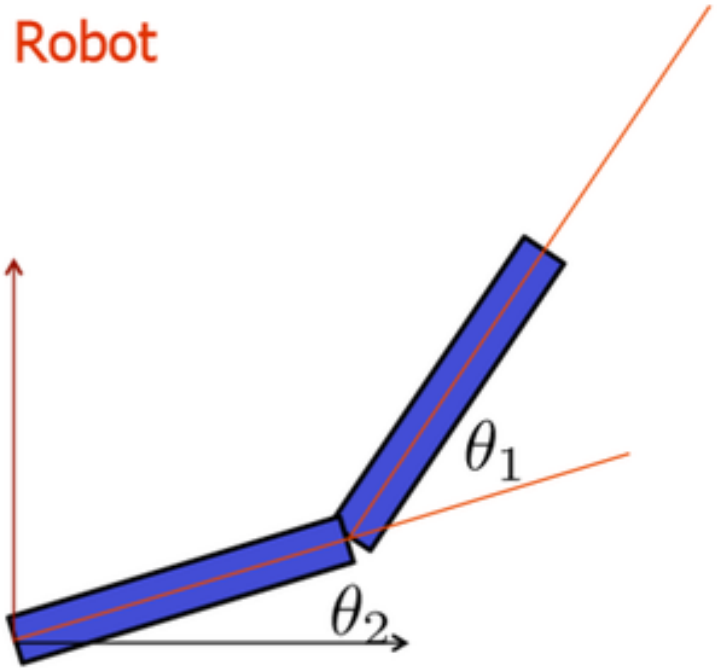
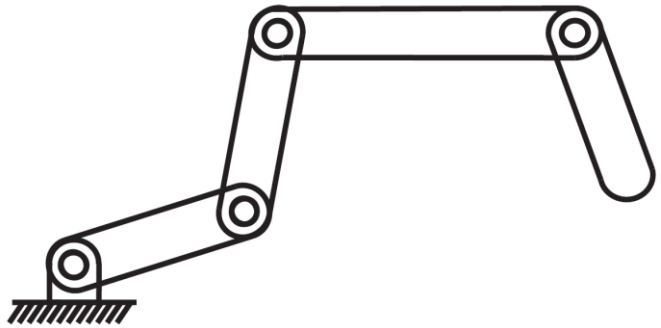
The University of Texas at Dallas

Configuration Space of a Robot

Two Link Planar 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

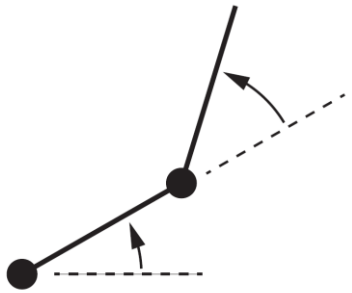
- n-dimensional Euclidean space $\mathbb{R}^n$
- n-dimensional sphere in a (n+1)-dimensional Euclidean space S^n
  - Two-dimensional surface of a sphere in three-dimensional space S^2

S^2

- The C-space can have different representations, but its shape is the same
  - A point on a unit circle can have two representations
  - angle θ, or coordinates (x, y) $x^2 + y^2 = 1$

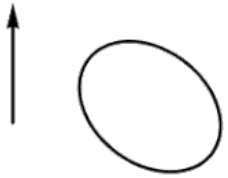
Configuration Space Topology

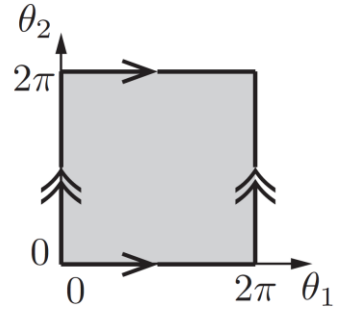
- C-space as Cartesian product (all ordered pairs)
  - A rigid body in the plane $\mathbb{R}^2 \times S^1$
  - A PR robot (Prismatic-Revolute) $\mathbb{R}^1 \times S^1$
    - Ignore joint limits
  - A 2R robot $S^1 \times S^1 = T^2$ n-dimensional surface of a torus in an (n+1)-dimensional space



2R robot arm

$T^2 = S^1 \times S^1$





$[0, 2\pi) \times [0, 2\pi)$

sample representation

Configuration Space Topology

- C-space of a planar rigid body (chassis of a mobile robot) with a 2R robot arm

$$\mathbb{R}^2 \times S^1 \times T^2 = \mathbb{R}^2 \times T^3$$

- C-space of a rigid body in 3D space
  - 3D translation
  - 3D rotation

$$\mathbb{R}^3 \times S^2 \times S^1$$

Task Space

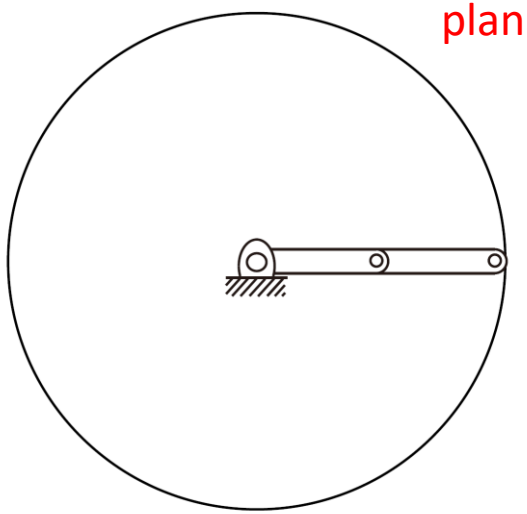
- The task space is a space in which the robot's task can be naturally expressed

- 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

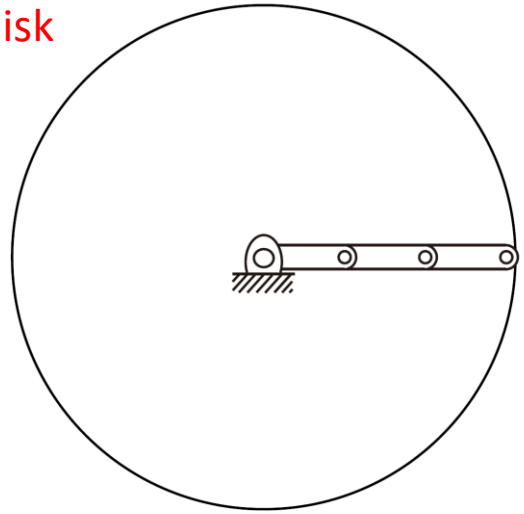
Workspace

- 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

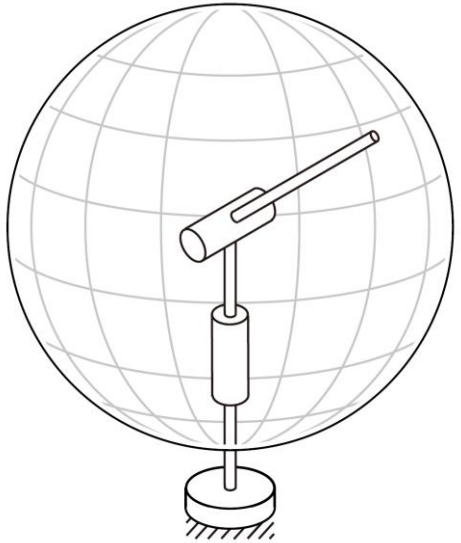


a planar 2R open chain

planar disk



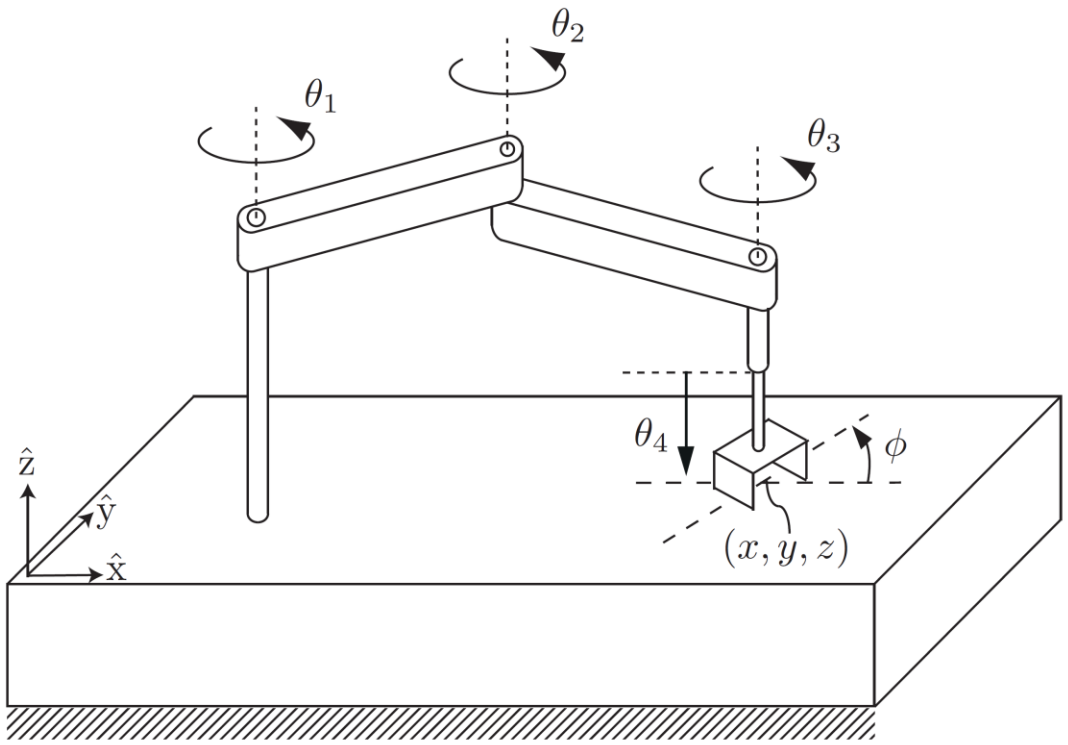
a planar 3R open chain



Surface of a sphere

a spherical 2R open chain

SCARA Robot



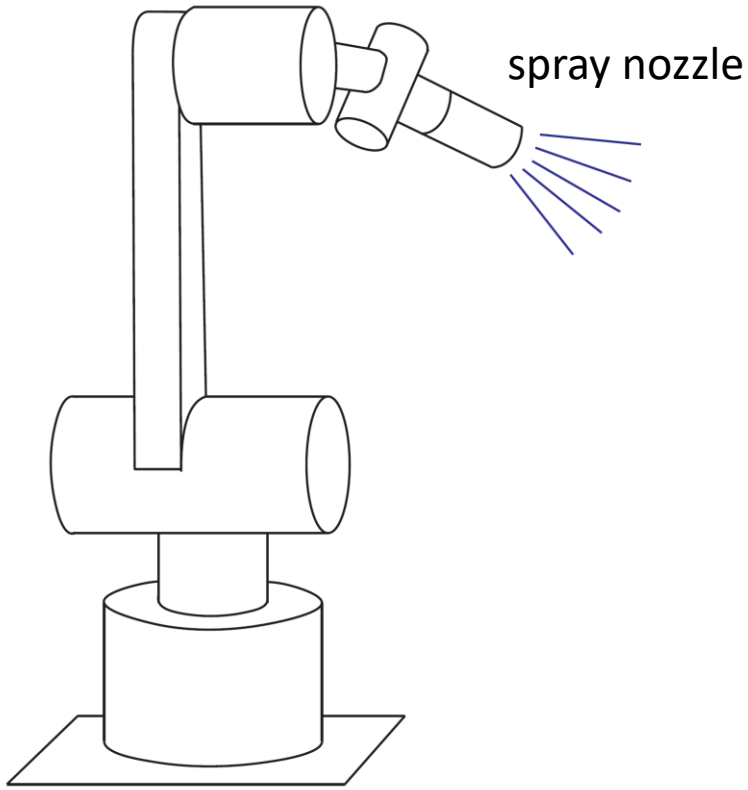
- End-effector configuration

  (x, y, z, ϕ)

- 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

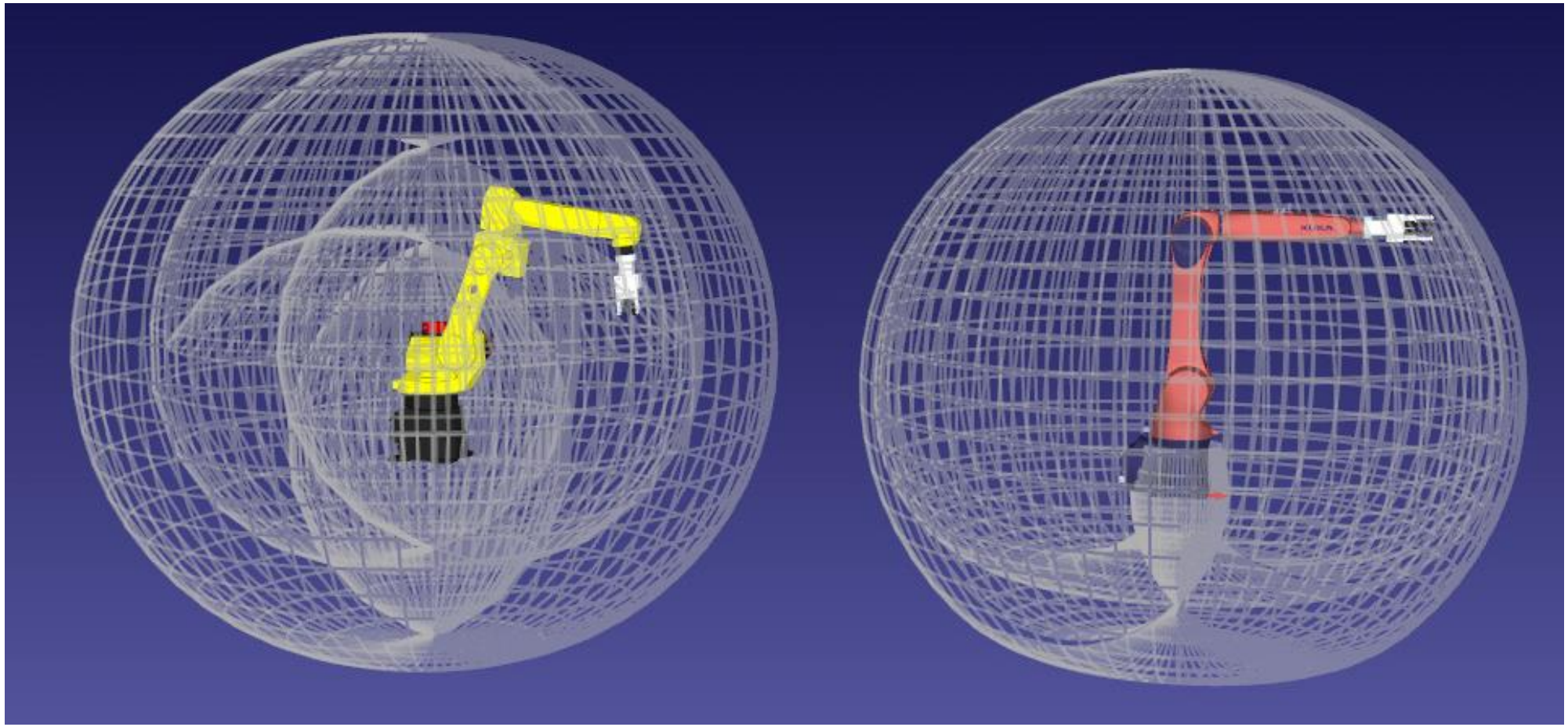
Spherical coordinates to describe the direction in which the nozzle is pointing

- 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 Programming

- Sensing
  - How to receive data from sensors on the robot?
  - RGB image, depth image, lidar scan, odometry, joint state
- Computation
  - Use the sensor data for computation
  - Object recognition, motion planning, compute control command, etc.
- Control
  - How to send the control command to the robot?

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)

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

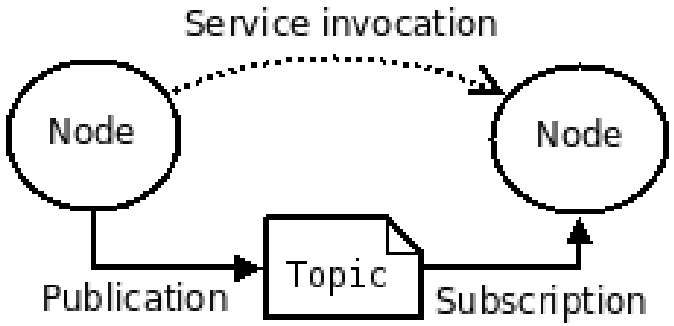
Robot Operating System (ROS)

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

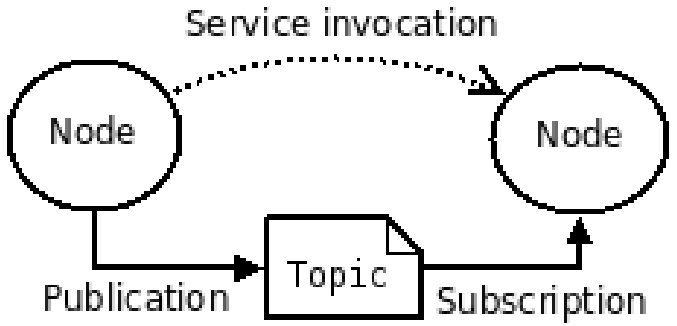
File: std_msgs/Header.msg

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

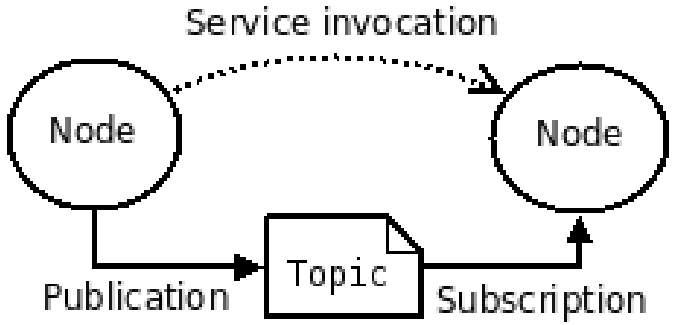
Node: Object detection

Topic: /rgb_image

Message: sensor_msgs/Image

ROS Computation Graph

- Service: request and reply interactions



Service: `FollowJointTrajectory`

Node: Motion Planner

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
```

Node: Arm Controller

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
```

ROS Computation Graph

- ROS bags
  - A format for saving and playing back ROS message data
  - We can save sensor data into a ros bag, and use it for development

```
rosbag record --duration=30 --output-name=/tmp/mybagfile.bag \
    /topic1 /topic2 /topic3
```

Using ROS

- Ubuntu users
- Mac users
- Windows users

Using ROS with Ubuntu

- Install ROS http://wiki.ros.org/noetic/Installation/Ubuntu

1.1 Configure your Ubuntu repositories

Configure your Ubuntu repositories to allow "restricted," "universe," and "multiverse." You can follow the Ubuntu guide for instructions on doing this.

1.2 Setup your sources.list

Setup your computer to accept software from packages.ros.org.

```
sudo sh -c 'echo "deb http://packages.ros.org/ros/ubuntu $(lsb_release -sc) main" > /etc/apt/sources.list.d/ros-latest.list'
```

Mirrors Source Debs are also available

1.3 Set up your keys

```
sudo apt install curl # if you haven't already installed curl
curl -s https://raw.githubusercontent.com/ros/rosdistro/master/ros.asc | sudo apt-key add -
```

1.4 Installation

First, make sure your Debian package index is up-to-date:

```
sudo apt update
```

Using ROS with Mac

1. Download the Ubuntu 20.04 .iso from https://cdimage.ubuntu.com/releases/focal/release/ (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 ROS as in Ubuntu

Docker: Using ROS 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

docker run -i -t ubuntu:20.04 /bin/bash

- 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
- Docker starts the container and execute /bin/bash
- -i, -t the container is running interactively and attached to your terminal
- When exit, the container stops but is not removed

ROS in Docker

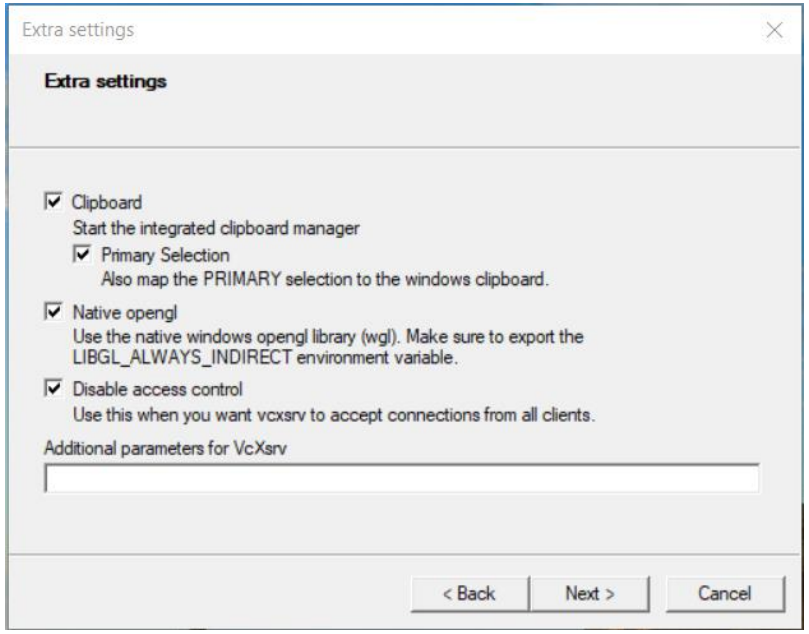
- Install Docker Desktop https://docs.docker.com/get-docker/
- Start the Docker Desktop
- Ubuntu images https://hub.docker.com/_/ubuntu
- Run command “docker run –i –t ubuntu:20.04 /bin/bash”
- No need to use sudo in docker, do an “apt update” first
- Install ROS http://wiki.ros.org/noetic/Installation/Ubuntu
- Install terminator https://manpages.ubuntu.com/manpages/bionic/en/man1/terminator.1.html

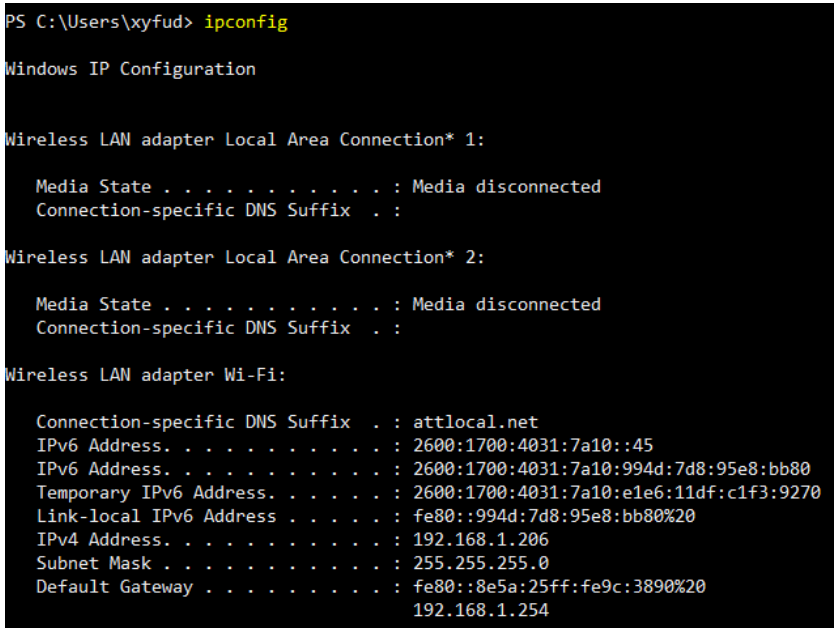
ROS in Docker

- Install X server
  - Windows: VcXsrv Windows X Server https://sourceforge.net/projects/vcxsrv/
  - Mac: Xquartz https://www.xquartz.org/

- 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

ROS in Docker

- Test ROS installation

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

- In another terminator terminal, start rviz
  - source /opt/ros/noetic/setup.bash
  - rosrun rviz rviz

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

ROS 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/