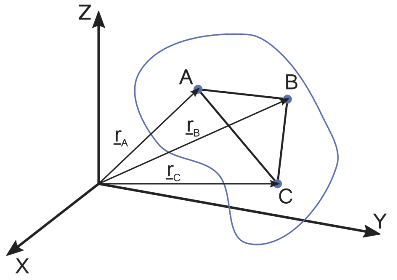
06. Principles of robotics, programming a da Vinci surgical robot in a simulated environment

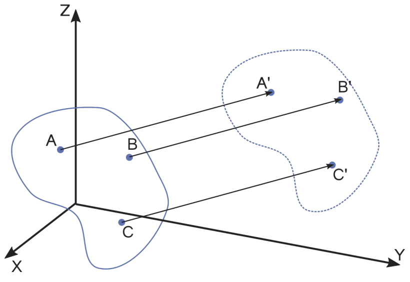
Rigid body motion



Def. Rigid body

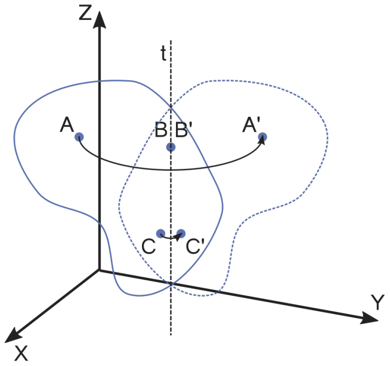
A rigid body is defined as a body on which the distance between two points remains constant in time regardless of the force applied on it.

- Shape and the volume of the rigid bodies are also constant.
- The **pose** of a rigid body can be given by the three coordinates of three of its points that do not lie on the same straight line.



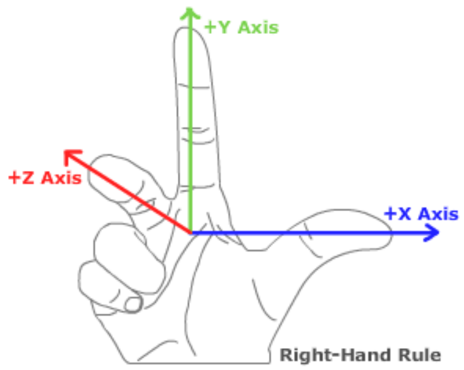
- The **pose** of a rigid body can be described in a more expressive way by the three coordinates of one of its points chosen arbitrarily **position** and the body's **orientation**.

- The **motion of rigid bodies** is composed by two elemental motions: **translation** and **rotation**.
- During **translation**, all points of the body move along straight, parallel lines.



- During **rotation**, the position of the points of the rotational axis are constant, and the other points of the body move along circles in planes perpendicular to the axis of rotation.
- The **free motion** of rigid bodies can always be expressed as the superposition of a translational motion and a rotation around a single axis.

3D transformations

- 

  Position: 3D offset vector
- **Orientation:** 3 x 3 rotation matrix
  - further orientation representations: Euler-angles, RPY, angle axis, quaternion
- **Pose**: 4 × 4 (homogenous) transformation matrix
- **Frame**: origin, 3 axes, 3 base vectors, right hand rule

- **Homogenous transformation:** rotation and translation in one transfromation
    - e.g., for the rotation $\mathbf{R}$ and translation $\mathbf{v}$:

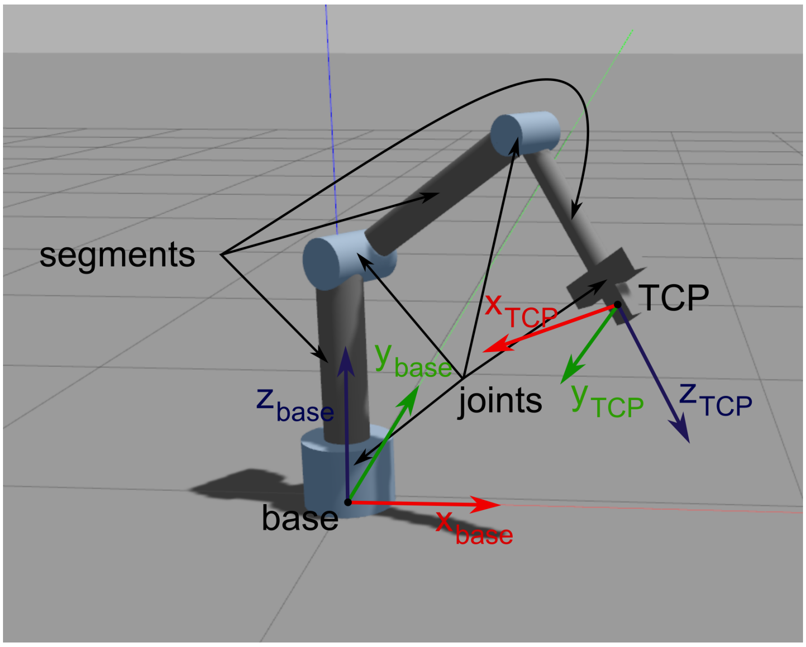
$$ \mathbf{T} = \left[\matrix{\mathbf{R} & \mathbf{v}\\\mathbf{0} & 1 }\right] = \left[\matrix{r_{1,1} & r_{1,2} & r_{1,3} & v_x\\r_{2,1} & r_{2,2} & r_{2,3} & v_y\\r_{3,1} & r_{3,2} & r_{3,3} & v_z\\ 0 & 0 & 0 & 1 }\right] $$

- **Homogenous coordinates:**
    - **Vector:** extended with 0, $\mathbf{a_H}=\left[\matrix{\mathbf{a} \\ 0}\right]=\left[\matrix{a_x \\ a_y \\ a_z \\ 0}\right]$
    - **Point:** extended by 1, $\mathbf{p_H}=\left[\matrix{\mathbf{p} \\ 1}\right]=\left[\matrix{p_x \\ p_y \\ p_z \\ 1}\right]$
    - Applying transfomrations is much easier:

$$ \mathbf{q} = \mathbf{R}\mathbf{p} + \mathbf{v} \to \left[\matrix{\mathbf{q} \\ 1}\right] = \left[\matrix{\mathbf{R} & \mathbf{v}\\\mathbf{0} & 1 }\right] \left[\matrix{\mathbf{p} \\ 1}\right] $$

- **Degrees of Freedom** (DoF): the number of independent parameters.

Principles of robotics



- Robots are built of: **segments** (or links) és **joints**
- **Task space** (or cartesian space):
    - 3D space around us, where the task, endpoint trajectories, obstacles are defined.
    - **TCP** (Tool Center Point): Frame fixed to the end effector of the robot.
    - **Base frame**, **world frame**
- **Joint space**:
    - Properties or values regarding the joints.
    - Low-level controller.
    - Joint angles, joint velocities, accelerations, torques....

Python libraries

Numpy

- Python library
- High dimension arrays and matrices
- Mathematical functions

```
import numpy as np

# Creating ndarrays
a = np.zeros(3)
a.shape
a.shape=(3,1)
a = np.ones(5)
a = np.empty(10)
l = np.linspace(5, 10, 6)
r = np.array([1,2])    # ndarray from python list
r = np.array([[1,2],[3,4]])
type(r)

# Indexing
l[0]
l[0:2]
l[-1]
r[:,0]

# Operations on ndarrays
r_sin = np.sin(r)
np.max(r)
np.min(r)
np.sum(r)
np.mean(r)
np.std(r)

l < 7
l[l < 7]
np.where(l < 7)

p = np.linspace(1, 5, 6)
q = np.linspace(10, 14, 6)

s = p + q
s = p * q
s = p * 10
s = p + 10
s = p @ q    # dot product
s = r.T
```

If not installed:

```
pip3 install numpy
```

Matplotlib

- Visualization in python
- Syntax similar to Matlab

```
import numpy as np
from matplotlib import pyplot as plt
```

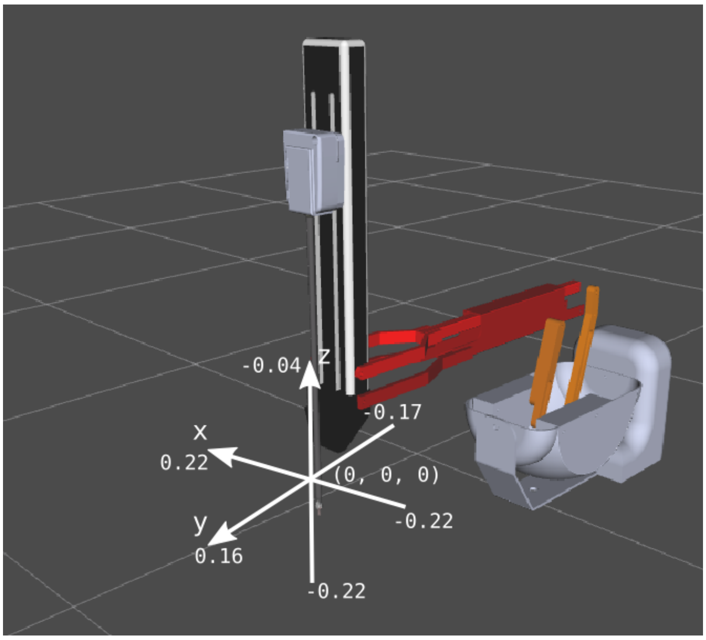
```
X = np.linspace(-np.pi, np.pi, 256)
C, S = np.cos(X), np.sin(X)

plt.plot(X, C)
plt.plot(X, S)

plt.show()
```

If not installed:

```
pip3 install matplotlib
```

Practice

1: dVRK ROS2 install



1. On Ubuntu 20.04 you will need the following packages:

```
sudo apt install python3-vcstool python3-colcon-common-extensions python3-pykdl
libxml2-dev libraw1394-dev libncurses5-dev qtcreator swig sox espeak cmake-curses-
```

```
gui cmake-qt-gui git subversion gfortran libcppunit-dev libqt5xmlpatterns5-dev
libbluetooth-dev ros-foxy-joint-state-publisher* ros-foxy-xacro
```

2. Clone the dVRK ROS2 packages with `vcs`, then build:

```
cd ~/ros2_ws/src
vcs import --input https://raw.githubusercontent.com/jhu-dvrk/dvrk_robot_ros2/main/
dvrk.vcs --recursive
cd ~/ros2_ws
colcon build --symlink-install --cmake-args -DCMAKE_BUILD_TYPE=Release
source ~/ros2_ws/install/setup.bash
```

3. Start the RViz simulation of PSM1 (Patient Side Manipulator). Do not forget to HOME on the dVRK console. Study the simulator operation using the learned prancs (`ros2 topic list`, `ros2 topic echo` `ros2 run rqt_gui rqt_gui`, etc.).

```
# dVRK main console
ros2 run dvrk_robot dvrk_console_json -j ~/ros2_ws/install/sawIntuitiveResearchKitAll/
share/sawIntuitiveResearchKit/share/console/console-PSM1_KIN_SIMULATED.json
```

```
# ROS 2 joint and robot state publishers
ros2 launch dvrk_model dvrk_state_publisher.launch.py arm:=PSM1
```

```
# RViz
ros2 run rviz2 rviz2 -d ~/ros2_ws/install/dvrk_model/share/dvrk_model/rviz/PSM1.rviz
```

```
ros2 run rqt_gui rqt_gui
```

For URDF related errors

```
locale # check for UTF-8

sudo apt update && sudo apt install locales
sudo locale-gen en_US en_US.UTF-8
sudo update-locale LC_ALL=en_US.UTF-8 LANG=en_US.UTF-8
export LANG=en_US.UTF-8

locale # verify settings
```

2: PSM subscriber

1. Create a new python source file named `psm_grasp.py` in `~/ros2_ws/src/ros2_course/ros2_course`. Specify the new entry point in `setup.py` in the usual way.

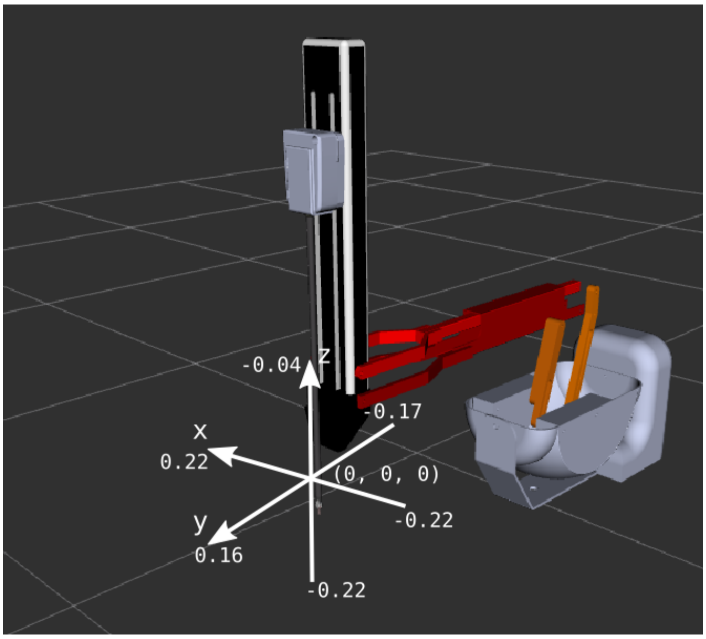
2. Subscribe to topics that publish the TCP (Tool Center Point) position of the PSM and the angle of the jaws of the tweezers.

```
/PSM1/measured_cp
/PSM1/jaw/measured_js
```

1. Build and run the node:

```
source ros_setup.sh -v 2
cd ~/ros2_ws
colcon build --symlink-install
ros2 run ros2_course psm_grasp
```

3. Moving PSM TCP along a linear trajectory

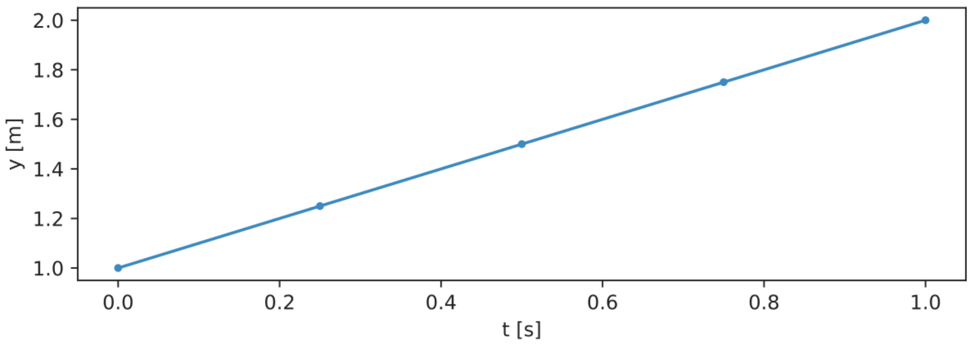


1. The PSM expects the desired TCP position and the angle closed by the jaws of the clamp in the topics below. Create publishers in `psm_grasp.py` for these topics.

```
/PSM1/servo_cp
/PSM1/jaw/servo_jp
```

2. Write a function that moves the TCP along a linear trajectory to the desired position. Send the pin to position (0.0, 0.05, -0.12), leave the orientation unchanged. The sampling time should be 0.01s. Using Matplotlib plot the planned trajectory x, y and z components of the projected trajectory as a function of time.

```
def move_tcp_to(self, target, v, dt):
```



1. Write a function to open and close the gripper, also using a linear trajectory.

```
def move_jaw_to(self, target, omega, dt):
```

4. Dummy marker

1. Create a new python source file named `dummy_marker.py`. Specify the entry point in `setup.py` in the usual way. Implement a python program that publishes a marker with position (-0.05, 0.08, -0.14) in topic `dummy_target_marker`. The value of the `frame_id` add tag should be `PSM1_psm_base_link`. Copy the following code into the file `dummy_marker.py`:

```
import rclpy
from rclpy.node import Node
from visualization_msgs.msg import Marker

class DummyMarker(Node):
    def __init__(self, position):
        super().__init__('minimal_publisher')
        self.position = position
        self.publisher_ = self.create_publisher(Marker, 'dummy_target_marker', 10)
        timer_period = 0.1  # seconds
        self.timer = self.create_timer(timer_period, self.timer_callback)
        self.i = 0
        i = 0

    def timer_callback(self):
        marker = Marker()
        marker.header.frame_id = 'PSM1_psm_base_link'
        marker.header.stamp = self.get_clock().now().to_msg()
        marker.ns = "dvrk_viz"
        marker.id = self.i
        marker.type = Marker.SPHERE
        marker.action = Marker.MODIFY
        marker.pose.position.x = self.position[0]
        marker.pose.position.y = self.position[1]
        marker.pose.position.z = self.position[2]
        marker.pose.orientation.x = 0.0
        marker.pose.orientation.y = 0.0
        marker.pose.orientation.z = 0.0
        marker.pose.orientation.w = 1.0
        marker.scale.x = 0.008
        marker.scale.y = 0.008
        marker.scale.z = 0.008
        marker.color.a = 1.0 # Don't forget to set the alpha!
        marker.color.r = 0.0
```

```python
        marker.color.g = 1.0
        marker.color.b = 0.0;

        self.publisher_.publish(marker)
        self.i += 1

def main(args=None):
    rclpy.init(args=args)
    marker_publisher = DummyMarker([-0.05, 0.08, -0.12])
    rclpy.spin(marker_publisher)

    # Destroy the node explicitly
    # (optional - otherwise it will be done automatically
    # when the garbage collector destroys the node object)
    marker_publisher.destroy_node()
    rclpy.shutdown()

if __name__ == '__main__':
    main()
```

2. Run the node and display the marker in RViz.

5. Grasping the marker

1. Subscribe to the topic sending the marker position in `psm_grasp.py`.

2. Modify `psm_grasp.py` to use the tweezers to grasp the generated marker.

!!! note The simulator used has a tendency for certain values to get "stuck", so it is a good idea to reset the lever at the beginning of the program using the following lines:

```python
#Reset the arm
psm.move_tcp_to([0.0, 0.0, -0.12], 0.01, 0.01)
psm.move_jaw_to(0.0, 0.1, 0.01)
```

Useful links

- Build dVRK2 on ROS2
- Marker examples

- Numpy vector magnitude
- Numpy linspace