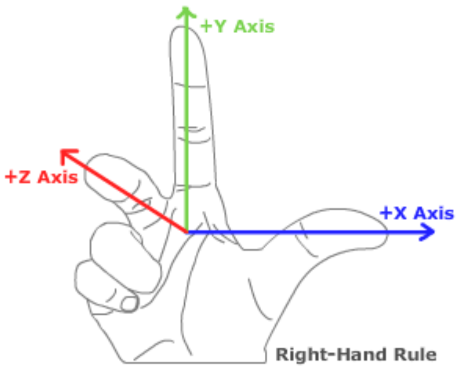
07. Kinematics, inverse kinematics, Programming of a simulated robotic arm

Repetition

3D transformations

- **Position:** 3 element offset vector



- **Orientation:** 3 x 3 rotation matrix
  - additional orientation representations: Euler angles, RPY, angle axis, quaternion
- **Pose** (pose): 4 × 4 transformation matrix
- **Coordinate system** (frame): zero point, 3 axis, 3 base vector, right-hand rule
- **Homogeneous transformations:** rotation and translation together
  - e.g. \(\mathbf{R}\) for rotation and \(\mathbf{v}\) for translation:

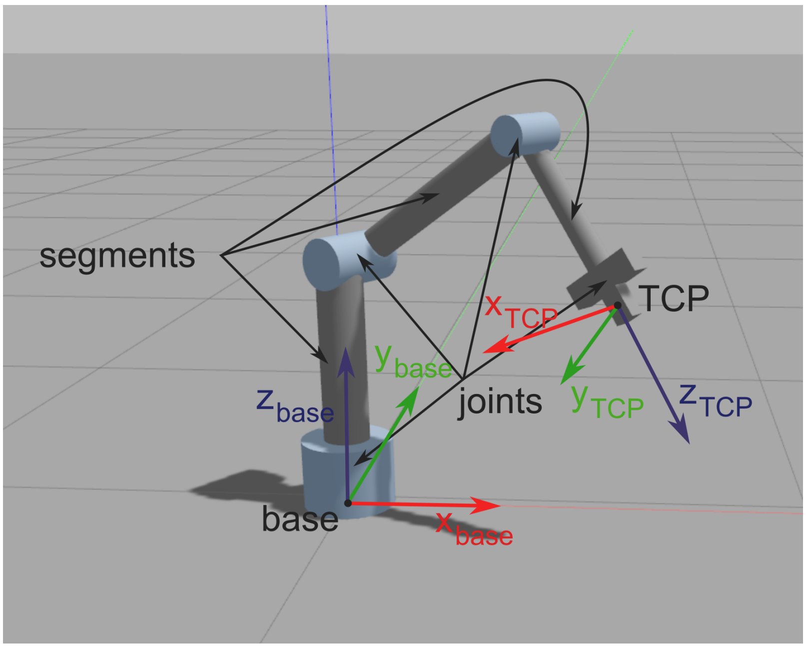
\[\mathbf{T} = \left[\matrix{\mathbf{R} & \mathbf{v}\\\mathbf{0} & 1 }\right] = \left[\matrix{r_{1,1} & r_{1,2} & r_{1,3} & v_x\\r_{2,1} & r_{2,2} & r_{2,3} & v_y\\r_{3,1} & r_{3,2} & r_{3,3} & v_z\\ 0 & 0 & 0 & 1 }\right] \]

- **Homogeneous coordinates:**
  - **Vector:** add 0, \(\mathbf{a_H}=\left[\matrix{\mathbf{a} \\ 0}\right]=\left[\matrix{a_x \\ a_y \\ a_z \\ 0}\right]\)
  - **Point:** add 1, \(\mathbf{p_H}=\left[\matrix{\mathbf{p} \\ 1}\right]=\left[\matrix{p_x \\ p_y \\ p_z \\ 1}\right]\)
  - Using transformations is simpler:

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

- **Degree of freedom** (DoF): number of independent quantities.

Robotics basics



- Robot structure: **segments** (link) and **joints**
- **Task space** (cartesian space):
  - Three-dimensional space where the task, trajectories, obstacles, etc. are defined.

    - **TCP** (Tool Center Point): coordinate frame fixed to the end effector
    - **Base/world frame**
- **Joint space**:
    - Quantities assigned to the robot's joints, which can be interpreted by the robot's low-level control system.
    - Joint coordinates, velocities, accelerations, torques...

Lecture

Kinematics, inverse kinematics

Kinematics

> **Def. Kinematics**
>
> Calculating the position of the TCP (or anything else) from the hinge coordinates.

- Kinematic model
    - Denavit--Hartenberg (DH) convention
    - URDF (Unified Robotics Description Format, XML-based)

If the coordinate systems assigned to the segments are $base, 1, 2, 3, ..., TCP$, the transfomrms between adjacent segments i and $i+1$ are $T_{i+1,i}(q_{i+1})$ (which is a function of the angle of the joint between them), the transfomrms between the base frame and TCP can be written up (for a robot with n joints):

$$T_{TCP,base}(q_1, \cdots, q_n) = T_{TCP,n-1}(q_{n}) \cdot T_{n-1,n-2}(q_{n-1}) \cdots T_{2,1}(q_2) \cdot T_{1,base}(q_1) \cdot base$$

Inverse kinematics

> **Def. Inverse kinematics**
>
> Compute joint coordinates to achieve (desired) TCP (or any other) pose.

Differential inverse kinematics

> **Def. Differential inverse kinematics**
>
> Which change in the wrist coordinates achieves the desired **small change** in the TCP pose (rotation and translation).

- **Jacobi matrix** (Jacobian): a matrix of first-order partial derivatives of a vector-valued function.

  $$ \mathbf{J} = \left[\matrix{\frac{\partial x_1}{\partial q_1} & \frac{\partial x_1}{\partial q_2} &\frac{\partial x_1}{\partial q_3} & \dots &\frac{\partial x_1}{\partial q_n} \\ \frac{\partial x_2}{\partial q_1} & \frac{\partial x_2}{\partial q_2} &\frac{\partial x_2} {\partial q_3} & \dots &\frac{\partial x_2}{\partial q_n} \\ \frac{\partial x_3}{\partial q_1} & \frac{\partial x_3}{\partial q_2} &\frac{\partial x_3}{\partial q_3} & \dots &\frac{\partial x_3}{\partial q_n} \\ \vdots &\vdots &\vdots &\ddots &\vdots \\ \frac{\partial x_m}{\partial q_1} & \frac{\partial x_m}{\partial q_2} &\frac{\partial x_m}{\partial q_3} & \dots &\frac{\partial x_m}{\partial q_n} \\}\right] $$

- **Jacobi matrix significance in robotics**: gives the relationship between joint velocities and TCP velocity.

  $$ \left[\matrix{\mathbf{v} \\ \mathbf{\omega}}\right] =\mathbf{J}(\mathbf{q})\cdot \mathbf{\dot{q}} $$

Inverse kinematics using Jacobian inverse

1. Calculate the difference between the desired and the current position: $\Delta\mathbf{r} = \mathbf{r}_{desired} - \mathbf{r}_0$
2. Calculate the difference in rotations: $\Delta\mathbf{R} = \mathbf{R}_{desired}\mathbf{R}_{0}^{T}$, then convert to axis angle representation $(\mathbf{t},\phi)$
3. Compute $\Delta\mathbf{ q}=\mathbf{J}^{-1}(\mathbf{q_0})\cdot \left[\matrix{k_1 \cdot \Delta\mathbf{r} \\ k_2 \cdot \phi \cdot \mathbf{t}}\right]$, where the inverse can be pseudo-inverse or transposed
4. $\mathbf{q}_{better} = \mathbf{q}_{0} + \Delta\mathbf{q}$

Exercise

1: Doosan2 install

Reset the `~/.bashrc` file to ROS2 default.

1. Install the dependencies.


```
sudo apt update
sudo apt-get install libpoco-dev
sudo apt-get install ros-foxy-control-msgs ros-foxy-realtime-tools ros-foxy-xacro ros-foxy-joint-state-publisher-gui
pip3 install kinpy
```

> **Tip**
>
> Also download the source of the `kinpy` package, it may be useful for understanding the API: https://pypi.org/project/kinpy/

2. Clone and build the repo.

```
mkdir -p ~/doosan2_ws/src
cd ~/doosan2_ws/src
git clone https://github.com/TamasDNagy/doosan-robot2.git
```

```
git clone https://github.com/ros-controls/ros2_control.git
git clone https://github.com/ros-controls/ros2_controllers.git
git clone https://github.com/ros-simulation/gazebo_ros2_control.git
cd ros2_control && git reset --hard 3dc62e28e3bc8cf636275825526c11d13b554bb6
&& cd ..
cd ros2_controllers && git reset --hard 83c494f460f1c8675f4fdd6fb8707b87e81cb197
&& cd ...
cd cd gazebo_ros2_control && git reset --hard
3dfe04d412d5be4540752e9c1165ccf25d7c51fb && cd ..
git clone -b ros2 --single-branch https://github.com/ros-planning/moveit_msgs
cd ~/doosan2_ws
rosdep update
rosdep install --from-paths src --ignore-src --rosdistro foxy -r -y
colcon build --cmake-args -DCMAKE_EXPORT_COMPILE_COMMANDS=ON
. install/setup.bash
rosdep update
```

Warning

Already installed on VMs, but update the repo here too:

```
cd ~/doosan2_ws/src/doosan-robot2
git pull
cd ~/doosan2_ws
colcon build --cmake-args -DCMAKE_EXPORT_COMPILE_COMMANDS=ON
```

Add the following line to the `~/.bashrc` file:

```
source ~/doosan2_ws/install/setup.bash
```

3. Test the simulator in a new window:

```
ros2 launch dsr_launcher2 single_robot_rviz_topic.launch.py model:=a0912 color:=blue
```

2: Move robot in articulated space

1. Create a new python source file named `doosan2_controller.py` in `~/ros2_ws/src/ros2_course/ros2_course` folder. Specify the new entry point in `setup.py` in the usual way. Subscribe to the topic publishing the robot's articulation angles (configuration). Create publisher for the topic that can be used to configure the wrist angles.

```
/joint_states
/joint_cmd
```

2. Move the robot to the configuration `q = [0.24, -0.3, 1.55, 0.03, 1.8, 0.5]`.

3. Kinematics

1. Import the `kinpy` package and read the urdf file describing the robot:

```
import kinpy as kp

self.chain = kp.build_serial_chain_from_urdf(open(
        "/home/<USERNAME>/doosan2_ws/src/doosan-robot2/dsr_description2/urdf/
a0912.blue.urdf").read(),
        "link6")
print(self.chain.get_joint_parameter_names())
print(self.chain)
```

2. Calculate and print the TCP position in the given configuration using the `kinpy` package.

```
tg = chain.forward_kinematics(th1)
```

4: Inverse kinematics with Jacobian inverse method

Write a method that implements the inverse kinematics problem on the robot using the Jacobian inverse method presented in the lecture. The orientation is ignored. Move the TCP to the position `(0.55, 0.05, 0.45)`. Let us diagram the TCP trajectory of TCP using Matplotlib.

1. Write a loop with a stop condition of the appropriate size of `delta_r` or `rospy.is_shutdown()`.

2. Calculate the difference between the desired and the current TCP positions (`delta_r`). Scale with the constant `k_1`.

3. Set `phi_dot_t` to `[0.0, 0.0, 0.0]` (ignore orientation).

4. Concatenate `delta_r` and `phi_dot_t`.

5. Calculate the Jacobian matrix in the given configuration using the function `kp.jacobian.calc_jacobian(...)`.

6. Calculate the pseudo-inverse of the Jacobian matrix `np.linalg.pinv(...)`.

7. Calculate `delta_q` using the above formula.

8. Increment the joint angles with the obtained values.

Bonus: Inverse kinematics with orientation

Complete the solution to the previous problem by including orientation in the inverse kinematics calculation.

Useful links

- doosan-robot2 github
- https://pypi.org/project/kinpy/
- https://en.wikipedia.org/wiki/Axis%E2%80%93angle_representation
- https://www.rosroboticslearning.com/jacobian