# EECS C106A: Remote Lab 3 - Forward Kinematics/Coordinate Transformations*

Fall 2020

---

## Goals

By the end of this lab you should be able to:

- Compute the forward kinematics map for a robotic manipulator
- Compare your own forward kinematics implementation to the functionality provided by ROS
- Make Baxter/Sawyer move to simple joint position goals
- View the sensor and state data published by Baxter using RViz

---

If you get stuck at any point in the lab you may submit a help request during your lab section at https://tinyurl.com/106alabs20. You can check your position on the queue at https://tinyurl.com/106Fall20LabQueue.

**Note:** For all labs this semester you may collaborate with a lab partner but we expect everyone to do every part of the labs themselves. You should work closely with your partner to overcome obstacles in the labs but each member of the team must do the lab themselves.

*Relevant Tutorials and Documentation:*

- `Baxter SDK`: https://github.com/RethinkRobotics/sdk-docs/wiki/API-Reference
- `Sawyer SDK`: http://sdk.rethinkrobotics.com/intera/API_Reference
- `Baxter Joint Position Control Examples` : https://github.com/RethinkRobotics/sdk-docs/wiki/Joint-Position-Example
- `Sawyer Joint Position Control Examples` : http://sdk.rethinkrobotics.com/intera/Joint_Position_Example

## Contents




*Developed by Aaron Bestick, Austin Buchan, Fall 2014. Modified by Victor Shia and Jaime Fisac, Fall 2015; Dexter Scobee and Oladapo Afolabi, Fall 2016; David Fridovich-Keil and Laura Hallock, Fall 2017. Ravi Pandya, Nandita Iyer, Phillip Wu, and Valmik Prabhu, Fall 2018. Converted to remote by Amay Saxena and Tiffany Cappellari, Fall 2020 (the year of the plague).

# Introduction

Coordinate transformations are one of the fundamental mathematical tools of robotics. One of the most common applications of coordinate transformations is the forward kinematics problem. Given a robotic manipulator, forward kinematics answers the following question: Given a specified angle for each joint in the manipulator, can we compute the orientation of a selected link of the manipulator relative to a fixed world coordinate frame or a frame attached to another point on the robot?

This lab will explore this question in two parts, which need not be done in order. In Part 1, you'll use the code you wrote as part of the prelab to write the forward kinematics map for one of Baxter's arms, then you'll compare your results against some of ROS's built-in tools. In Part 2, you'll explore Baxter/Sawyer's basic joint position control functions, and take a quick look at how ROS helps you manage the coordinate transformations associated with all of Baxter/Sawyer's moving parts.

# 1 Getting started with Git

Our starter code is on Git for you to clone and so that you can easily access any updates we make to the starter code. It can be found at https://github.com/ucb-ee106/lab3_starter.git. First, create a new ROS workspace called `lab3`.

```
mkdir -p ~/ros_workspaces/lab3/src
cd ~/ros_workspaces/lab3/src
catkin_init_workspace

cd ~/ros_workspaces/lab3
catkin_make
```

Next clone our starter code by running

```
git clone https://github.com/ucb-ee106/lab3_starter.git
```

wherever you would like and then you are free to move the files into your lab's workspace into the appropriate subdirectories. We highly recommend you make a **private** GitHub repository for each of your labs just in case.

# 2 Forward kinematics

As discussed in lecture, the forward kinematics problem involves finding the configuration of a specified link in a robotic manipulator relative to some other reference frame, given the angles of each of the joints in the manipulator. In this exercise, you'll write your own code to compute the forward kinematics map for one of the Baxter robot's arms.

## 2.1 Kinematic functions

You should have already completed the relevant kinematic functions in `kin_func_skeleton.py` as part of your pre-lab. Take a look at it to refresh your memory as you will need to use this file for this lab.

## 2.2 Writing the forward kinematics map

Writing the forward kinematics map for a serial chain manipulator involves the following steps:

1. Define a reference "zero" configuration for the manipulator at which we'll say $\theta = 0$, where $\theta = [\theta_1, \ldots, \theta_n]$ is the vector of joint angles for an $n$-degree-of-freedom manipulator
2. Choose where on the robot to attach the fixed base frame and the moving tool frame

3. Write the coordinate transformation from the base to the tool frame when the manipulator is in the zero configuration ($g_{st}(0)$)

4. Find the axis of rotation ($\omega_i$) for each joint as well as a single point $q_i$ on each axis of rotation (all in the base frame)

5. Write the twist $\xi_i$ for each joint in the manipulator

6. Write the product of exponentials map for the complete manipulator

7. Multiply the map by the original base-to-tool coordinate transformation to get the new transformation between the base and tool frames ($g_{st}(\theta)$, now as a function of the joint angles)

**Task 1:** Using the code from the pre-lab and referring to the textbook if necessary, write a Python function that computes the coordinate transformation between the base and tool frames for the Baxter arm pictured below (steps 3-7 above). Your function should take an array of 7 joint angles as its only argument and return the 4x4 homogeneous transformation matrix $g_{st}(\theta)$. Refer to Figure 1 for the parameters of the Baxter arm. The only other parameter you should need is the rotation matrix

$$R = \begin{bmatrix} 0.0076 & -0.7040 & 0.7102 \\ 0.0001 & 0.7102 & 0.7040 \\ -1.0000 & -0.0053 & 0.0055 \end{bmatrix}$$

where

$$g_{st}(0) = \begin{bmatrix} R & q \\ 0 & 1 \end{bmatrix}$$

for the appropriate value of $q$.

Note: Copying the information into Python from the diagram below can take a while, so we have done it for you in `lab3_skeleton.py`.

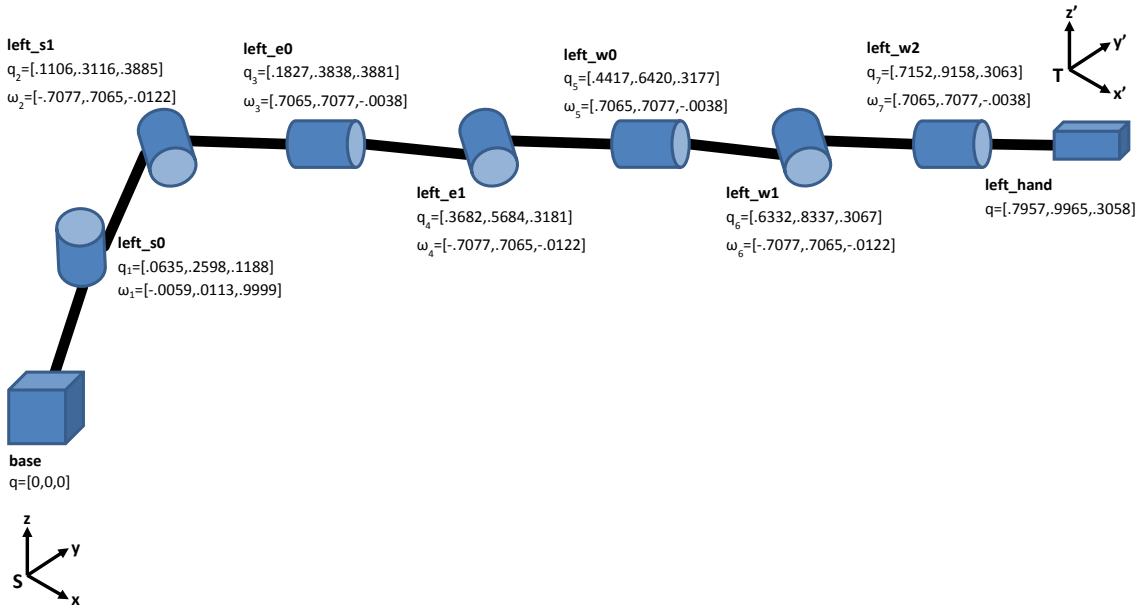


Figure 1: Baxter arm parameters.

## 2.3 Compare with built-in ROS functionality

Once you think you have your forward kinematics map finished, you'll compare with with some built-in functions offered by ROS.

To do this, we'll use a new tool called `rosbag`, which allows you to record and play back all the messages published on a set of topics, in order to test pieces of your software. I recorded a set of data from Baxter while I moved its left arm around. Find the `baxter.bag` file (from `lab3_starter`), start `roscore`, and play the file with

```
rosbag play baxter.bag
```

Notice how you can pause playback with the space bar and view the published messages with the usual tools like `rostopic list` and `rostopic echo`.

Try `rostopic echo`-ing the `robot/joint_states` topic, which gives the current joint angles of all joints in Baxter's left and right arms, as well as those of the head and torso. Using knowledge from `rostopic echo`, you can figure out what joint angles correspond to Baxter's left arm. (Hint: names starting with 'left_' correspond to the left arm.)

Next, try running the command

```
rosrun tf tf_echo base left_hand
```

while the bag file is playing. Any ideas about the data that's displayed?

**Task 2:** Write a subscriber node `forward_kinematics.py` that receives the messages from the `robot/joint_states` topic, plugs the appropriate joint angles from each message into your forward kinematics map from the last task, and displays the resulting transformation matrix on the terminal. Display this in another window alongside the `tf` data discussed above. Do you notice any differences? What do you think the "RPY" portion of the tf message is?

---

## Checkpoint 1

Submit a checkoff request at https://tinyurl.com/106alabs20. At this point you should be able to:

- Explain how you constructed your functions in your pre-lab
- Explain the functionality of your `forward_kinematics` node and demonstrate how it works
- Demonstrate that your `forward_kinematics` node and `tf` produce similar outputs (What's different? Are the values actually different? Could you translate one to the other?)

---

# 3 Make Baxter/Sawyer move

In this section, you'll explore some of Baxter/Sawyer's basic position control functionality. Close all running ROS nodes and terminals from the previous part, including the one running `roscore`, before you begin.

To set up your environment, make a shortcut (symbolic link) to the Baxter environment script `~/rethink_ws/baxter.sh` using the command

```
ln -s ~/rethink_ws/baxter.sh ~/ros_workspaces/lab3/baxter.sh
```

from the root of your workspace. Use one of the following lines to ssh into either the Baxter or Sawyer (intera) robot environment respectively:

```
./baxter.sh sim
./intera.sh sim
```

then run `source devel/setup.bash` so your new workspace is on the `$ROS_PACKAGE_PATH`.

Baxter and Sawyer have different interface packages (`baxter_interface` and `intera_interface`, respectively), but they are virtually identical. Don't forget to check that you have the correct package imported! The main difference is the obvious one: Sawyer only has one arm! This means that whenever you try to move an arm on Sawyer, it must be the **right** one. On Baxter, you may use either arm.

Before beginning to run anything on the robot, ssh into the environment and run

```
roslaunch baxter_gazebo baxter_world.launch
```

if you are using the Baxter model or

```
roslaunch sawyer_gazebo sawyer_world.launch
```

if you are using the Sawyer model. This will start a Gazebo window in which you should be able to see a model of your robot.

Then enable the robot by running

```
rosrun baxter_tools enable_robot.py -e
```

or

```
rosrun intera_interface enable_robot.py -e
```

in a new terminal window.

Now open up a new terminal and then open the `baxter_examples` package inside the `baxter_ws` workspace and examine the `scripts/joint_position_ keyboard.py` file, which allows you to move the Baxter's limbs using the keyboard. If you are using a Baxter, run the program and test its commands. If you are on a Sawyer, run the corresponding example in the `intera_sdk/intera_examples` package. Note that you don't need to start `roscore` — launch files already start a roscore for you!

Instead of publishing directly to a topic to control Baxter/Sawyer's arms (as with turtlesim), the respective SDKs provide a library of functions that take care of the publishing and subscribing for you.

**Task 3:** Create and open a new package called `joint_ctrl` in your `lab3` workspace. What dependencies will be needed? (Hint: Include `baxter_examples/intera_examples` as a dependency.) Make a copy of the `joint_position_keyboard.py` file (from the appropriate package, depending on which type of robot you are using) inside the `joint_ctrl` package, giving it a new name. Edit your copy so that instead of capturing keypresses, it prompts the user for a list of seven joint angles, then moves to the specified position. (Hint: You might have to call `limb.set_joint_positions()` repeatedly at some interval, say, 10ms, while the robot is in the process of moving to the new position.) The `set_joint_positions()` function takes a single argument, which should be a Python dictionary object mapping the names of each joint to the desired joint angles (e.g., `{'left_s0': 0.0, 'left_s1': 0.53, ..., 'left_w2':1.20}`). Dictionaries are used as follows:

```
# Create an empty dictionary
test_dict = {}

# Add values to the dictionary
test_dict['key1'] = 'value1'
test_dict['a_number'] = 1.024

# Read values from the dictionary
print(test_dict['key1'])
print(test_dict['a_number'])

# Output:
# value1
# 1.024

# You can also create a dictionary with a literal expression
test_dict2 = {'key1': 'value1', 'a_number': 1.024}
```

Test your code with several different combinations of joint angles and observe the results. Once you get your code to work, run the command

```
rosrun tf tf_echo base left_hand
```

or

```
rosrun tf tf_echo base right_hand
```

as appropriate and observe the output as you move the robot around. Any ideas what the data represents?

Finally, run

```
rosrun rviz rviz
```

Once RViz loads, ensure that `Displays > Global Options > Fixed Frame` is set to `world`. Next, click the Add button and add a RobotModel object to the window so you can see the robot move. Any thoughts as to where RViz gets the data on the robot's position?

Next, add two copies of the Axes object to the display. In the Displays pane of the left side of the screen, set the Reference Frame of one Axes object to `/base` and the other to `/right_hand`. You should see both sets of axes displayed on Baxter. What do you think the axes represent?

Finally, remove both Axes objects and add a single TF object to the display. What happens?

---

## Checkpoint 2

Submit a checkoff request at https://tinyurl.com/106alabs20. At this point you should be able to:

- Demonstrate the code you wrote to set Baxter/Sawyer's joint positions
- Use RViz to display the different state and sensor data topics published by Baxter/Sawyer
- Explain what the Axes and TF displays in RViz represent

---