

MAE 204 Lab Assignment 2

Forward Kinematics

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1. Objectives

This lab is designed to test out forward kinematics with the UR3e robot arm.

- 1) **Pre-lab:** we will write a MATLAB script that computes forward kinematics. Please use the given script templates.
- 2) **During the lab:** we will verify your script by measuring the robot's position at select positions

2. Forward Kinematics

Forward kinematics lets you calculate the position and orientation of the end effector from the joint angles. Recall the formulation from the Modern Robotics Textbook:

$$T(\theta) = e^{[S_1]\theta_1} e^{[S_2]\theta_2} \dots e^{[S_{n-1}]\theta_{n-1}} e^{[S_n]\theta_n} M$$

For UR3e robot arm, $n = 6$ since the arm has six revolute joints. $T(\theta)$ is the end effector homogeneous transformation matrix, while $S_1 \dots S_6$ denote the six screw axes and M signifies the end effector zero configuration transformation matrix (when all joint angles, $\theta_1 \dots \theta_6 = 0$).

3. Safety

The robot has the built-in force/torque limits as well as a protective stop, where it will stop operating when it detects a collision. Still, please be aware that the robot may collide with surrounding objects (including you!) or itself during operation.

3.1. Speed of robot

While we will not be using the teach pendant to program the robot, the slider bar on the bottom part of the teach pendant will still adjust the speed of the robot. **If you are moving the robot in a new trajectory, first try at slower speeds.**

3.2. During operation

For safety reasons, while the robot is operating please stay at a safe distance.

When the robot is moving, **be ready to press the emergency stop button** in case the robot does something unexpected.



Emergency stop button on the teaching pendant

4. Pre-lab

We recommend that you finish this section before coming to the lab.

4.1. Establishing screw axes, end effector zero config.

In order to compute forward kinematics, we first need to establish the six screw axes, $S_1 \dots S_6$, as well as the end effector zero configuration transformation matrix M .

Refer to *figure 1* below for the zero configuration (all joint angles are 0) of UR3e. Note that since we're not using the gripper for this lab, we have replaced the \$5,000 gripper with a \$7 dowel rod.

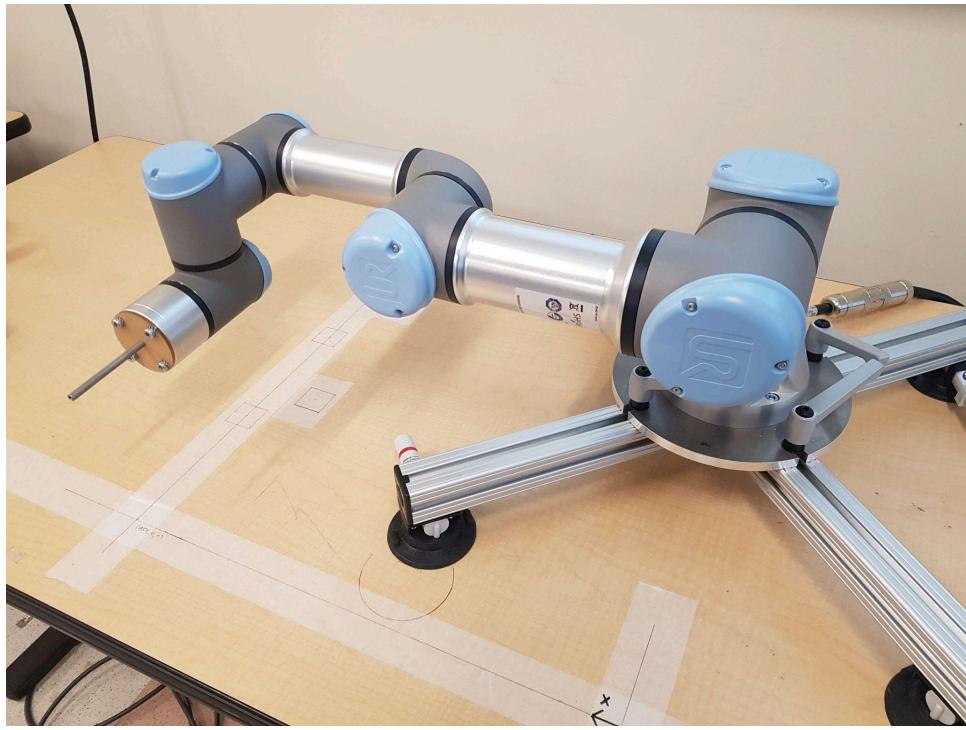


Figure 1. Zero configuration of UR3e, with a dowel rod as the end-effector

The rotational axes of the joints at zero configuration, as well as the origin and axes of the space frame are shown below. **Note that the origin is *not* on the base of the robot.** In fact, the base of the robot is at coordinates (0, - 300, 88), in mm.

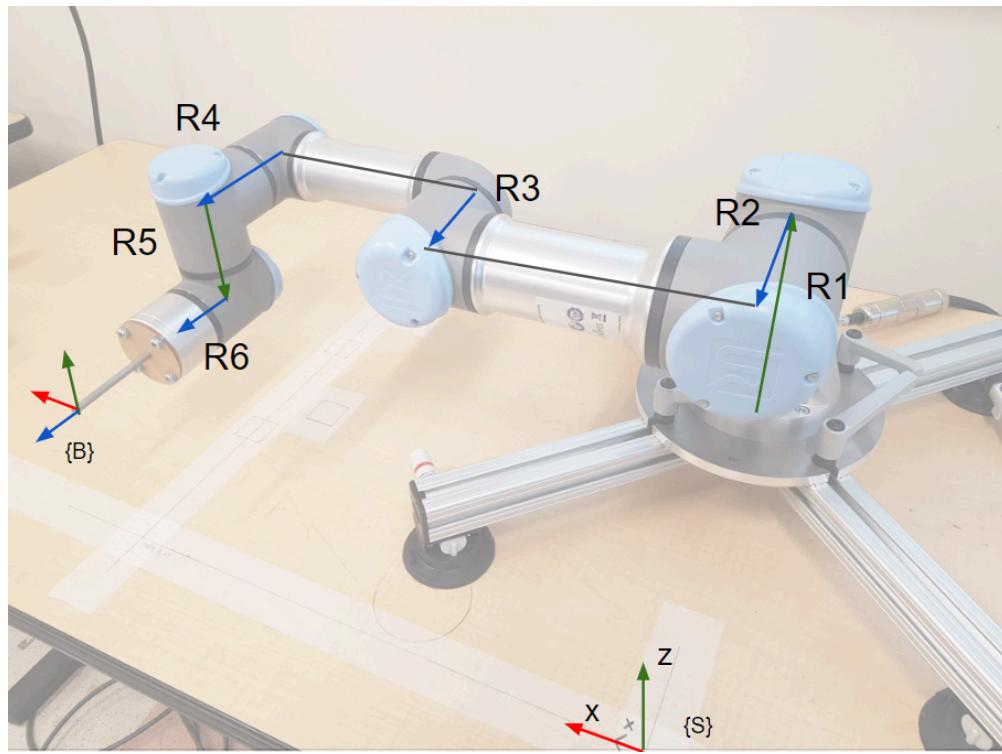


Figure 2. Rotational axes of the joints, origin and axes of the space frame. All angles between the limbs are right angles.

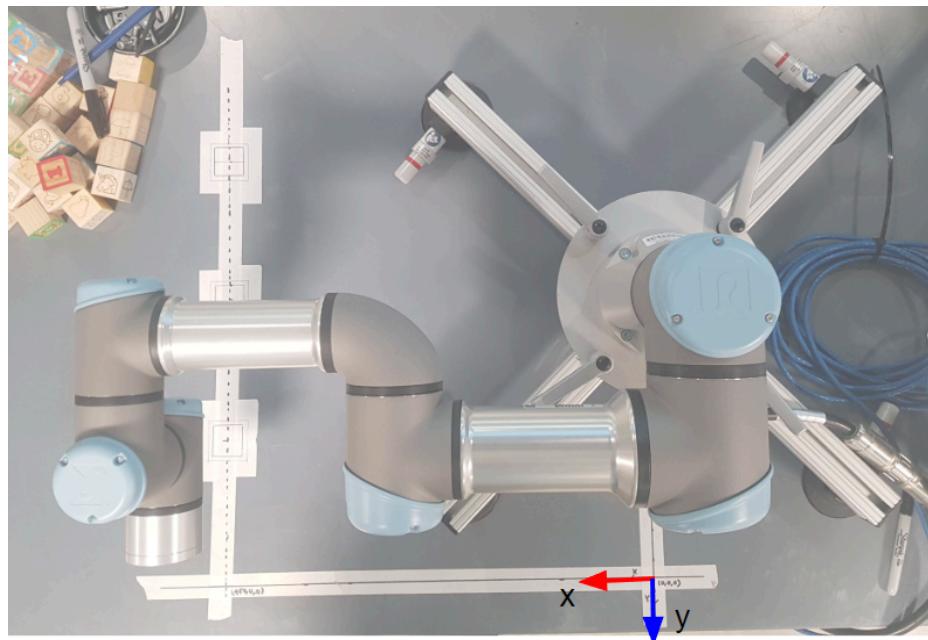


Figure 3. Origin and axes of the space frame, from above

Since the base of the robot is at coordinates (0, -300, 88) mm, the first screw axis (using mm as unit) is:

$$S_1 = [0, 0, 1, -300, 0, 0]$$

In order to calculate the rest of the screw axes and the M matrix, you will need the following dimensions of the robot arm:

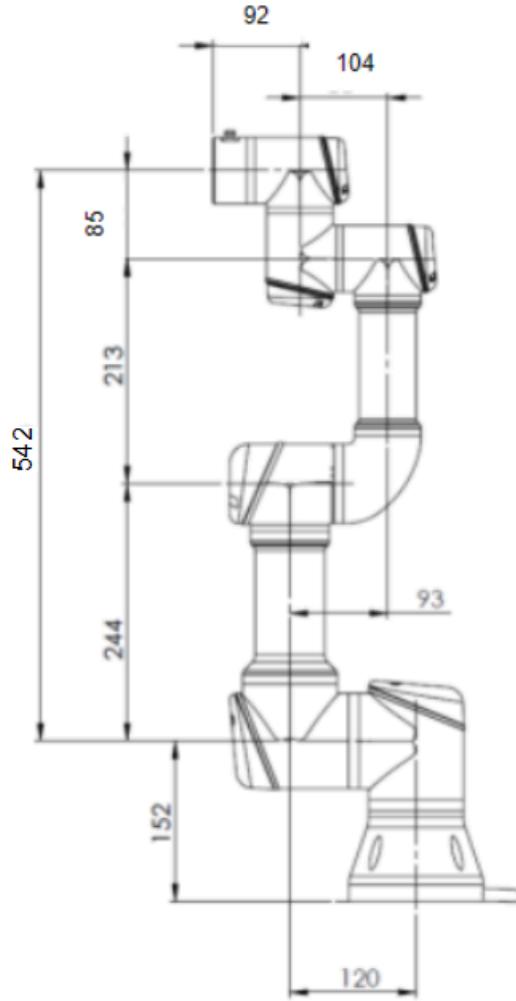


Figure 4. Dimensions of UR3e robot arm (in mm)

For this lab, the end effector position is defined as the end of the dowel rod. The dowel rod assembly is 78 mm long (refer to Figure 2 above).

Please modify the **S** and **M** variables in the provided **lab2.m** template with correct values for S and M . Note that we have already filled out S_1 as an example.

4.2 Forward kinematics script

Modify **lab2.m** to compute forward kinematics of the UR3e robot (*please write your own script*). Your function should take in the joint angles $\theta_1 \dots \theta_6$ and calculate the end effector transformation matrix T . Again, recall the formulation:

$$T(\theta) = e^{[S_1]\theta_1} e^{[S_2]\theta_2} \dots e^{[S_{n-1}]\theta_{n-1}} e^{[S_n]\theta_n} M$$

Note: Feel free to use the provided support function **VecTose3.m**. It takes in a screw axis S (1x6 vector), and returns the corresponding $se(3)$ matrix, the matrix representation of twist (4x4).

When finished, running lab2.m should compute forward kinematics according to your functions, and print out both the end effector transformation matrix T as well as its position components. For instance, inputting [0, 0, 0, 0, 0, 0] as the six joint angles should print your M matrix.

5. During the lab

During the lab, we will verify your script by moving the UR3e robot to certain joint angle positions, and comparing:

- 1) Physical measurements of the end-effector position
- 2) Forward kinematics results of your script.

5.1 Driving the robot, recording end effector position

We will move the robot to the following joint angle positions:

- 1) $[-20^\circ, -40^\circ, 60^\circ, 10^\circ, 30^\circ, 0^\circ]$
- 2) $[5^\circ, 10^\circ, -30^\circ, 230^\circ, -50^\circ, 150^\circ]$
- 3) A joint angle set of your choice! **Please move your robot slowly and watch out for any collision.**

To move the robot, simply use the teach pendant (use the “Move” function found on the top bar, then input joint angles on the bottom right).

Once the robot has stopped moving, use the provided rulers to measure the x, y, and z coordinates of the end-effector.

5.2. Verify your script

Compare your measurements with the results from your forward kinematics script. Are the measurements consistent with your calculations? Please calculate the root mean squared error between the calculated and measured position values:

$$e = \sqrt{\frac{1}{3} ((x_{prediction} - x_{measurement})^2 + (y_{prediction} - y_{measurement})^2 + (z_{prediction} - z_{measurement})^2)}$$

for each position and include them in your report.

6. Location

Same as lab 1 (**EBU2, Room 335**)

7. Time slot

As in lab 1, please sign up here (in **Lab 2 sheet**):

https://docs.google.com/spreadsheets/d/1PD8n946e983pw7utsF9b5pJI249mkIEAlc55G_W9fKI/edit?usp=sharing

Please notify your TA if you have conflict with ***all*** of the remaining time slots.

8. Deliverables

Each group should submit a single report, in PDF format, through Gradescope. It should include:

- 1) Overview / summary of lab activities
- 2) Results section, including:
 - The **six screw axes** S you calculated, as well as the **end effector zero configuration transformation matrix** M .
 - The three sets of joint angles you used (including the two that we provided), the end effector positions calculated by your script, and the end effector positions physically measured in the lab.
 - Report the **error** between the calculated position and the measured position (refer to Section 5.2 above)
- 3) Briefly discuss the results and analyze the possible sources of error.
- 4) Please publish your **lab2.m** and append it to the PDF (Appendix section).

As with lab 1, there is no template or length limit for your report.

Please submit your report by: 2/16 at midnight

9. Acknowledgements

This lab was originally developed by Prof. Michael Tolley and his TAs. We would also like to thank the instructors and TAs of the ECE470 course at the University of Illinois, and the ENME480 course at the University of Maryland for their advice and technical assistance.