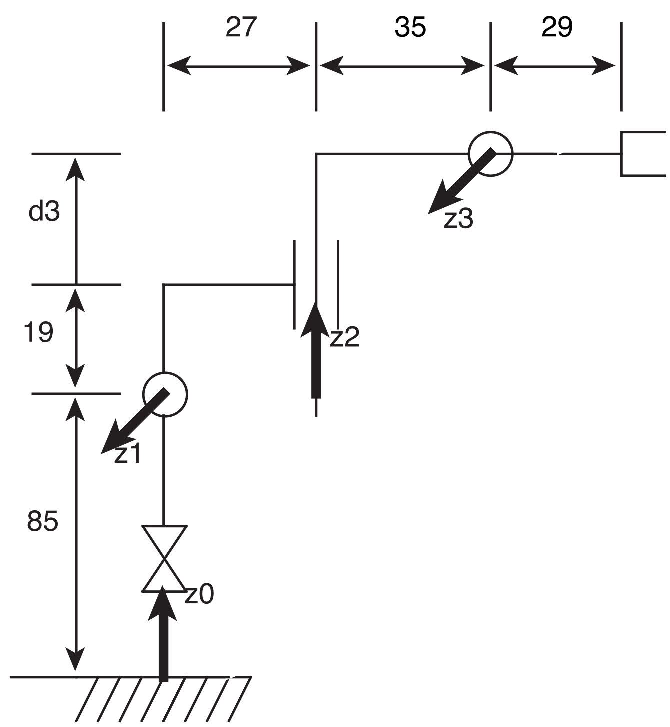
Fall 2019—16-642 Manipulation, Estimation and Control
Problem Set 4

Due: 25 November 2019

- **Submit write up:** You must *neatly* write up (preferably type up) your solutions and submit it electronically via canvas.
- **Collaboration Policy** You are encouraged to work with other students in the class, however you must turn in your own *unique* solution. If you work with others, you must list their names on your submission.
- **Time and late Policy**: Submit via canvas by the start of the lecture on the due date. If you do not turn your problem set in on time, you can turn it in up to 48 hours later but you will lose half of the points. After 48 hours, you will receive a zero.

1. (25 points) For the manipulator drawn below, draw the location of the DH frames and create a table of DH parameters. The positive direction of each joint is depicted by the z axis associated for that joint, which has conveniently been included for you. For each frame, explain whether the frame was uniquely defined by the DH convention. If it was not, describe the choices you made in defining it. (and don't forget to include the last frame!)

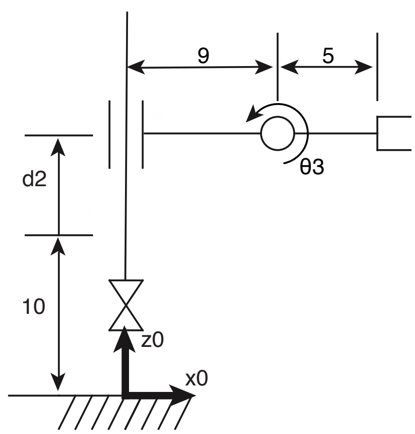


2. (20 points) Given the DH parameters in the table below, draw the manipulator that they describe. Assume that frame 0 is oriented with the z-axis pointing up, x-axis pointing right, and y-axis pointing into the page.

i	θ_i	d_i	a_i	α_i
1	θ_1	5	7	90^o
2	θ_2	0	2	-90^o
3	0	ℓ_3	0	90^o
4	θ_4	0	3	0

hint: First use the parameters to determine where all of the frames should be, then determine where the joints should go, then draw in the links connecting them.

3. Consider the manipulator drawn below in a configuration where $\theta_1 = \theta_3 = 0$ and the task space is assumed to be the position only of the end effector (i.e., $\mathbb{X} = \mathbb{R}^3$). The positive direction of the first joint is given by the z_0 axis.



- (10 points) Find the Jacobian $J(\Theta)$ using the direct differentiation method.
- (10 points) Find the Jacobian $J(\Theta)$ using the column-by-column building method. Make sure to explain your answer.
- (10 points) Are there any singular configurations? If so list them. You can use whatever method you want to find them, but make sure to explain your answer.

4. **tee-ball robot:** (25 points) Consider using a 3 link RRR planar manipulator to hit a baseball off of a tee. The third link of the robot will be used as the bat. The ball is placed at the position $(x, y) = (2, 0)$. In order to get a perfect hit, the manipulator should strike the ball with the center of the third link, the third link should be aligned with the x axis, and the point that strikes the ball should be moving with a velocity of 10 m/s in the y direction and 0 m/s in the x direction. Each link is 1 m long, and you can assume that the width of the link and the radius of the ball are both negligible.

   Note: this problems assumes that the 2D coordinate frame is placed with its origin at the center of the first joint, with the x-axis pointing to the right and the y-axis pointing up.