ME 449 Robotic Manipulation
Fall 2015
Problem Set 4
Due Tuesday November 24 at beginning of class (turn in on Canvas).
**Note: There will be no office hours on November 16, November 23, or November 24! Please bring your questions to office hours on Tuesday November 17 or the added office hour Thursday November 19 3-4 PM!**

**1.** Exercise 1 from Chapter 9.

**2.** Exercise 2 from Chapter 9.

**3.** Exercise 5 from Chapter 9.

**4.** Write the following functions for your robotics library. These functions build on the functions written for previous assignments.

(i) `CubicTimeScaling`: Takes a total travel time $T$ and the current time $t$ satisfying $0 \leq t \leq T$ and returns the path parameter $s$ corresponding to a motion that begins and ends at zero velocity.

(ii) `QuinticTimeScaling`: Takes a total travel time $T$ and the current time $t$ satisfying $0 \leq t \leq T$ and returns the path parameter $s$ corresponding to a motion that begins and ends at zero velocity and zero acceleration.

(iii) `JointTrajectory`: Takes initial joint variables $\theta_{\text{start}} \in \mathbb{R}^n$, final joint variables $\theta_{\text{end}}$, the time of the motion $T$ in seconds, the number of points $N \geq 2$ in the discrete representation of the trajectory, and the time-scaling method (cubic time scaling or quintic time scaling; these can be represented by the numbers 3 and 5, or you can pass the name of the function to use); and returns a trajectory as a matrix with $N$ rows, where each row is an $n$-vector of joint angles at an instant in time. The first row is $\theta_{\text{start}}$ and the $N$th row is $\theta_{\text{end}}$. The elapsed time between each row is $T/(N-1)$. The trajectory is a straight-line motion in joint space.

(iv) `ScrewTrajectory`: Similar to `JointTrajectory`, except that it takes the initial end-effector configuration $X_{\text{start}} \in SE(3)$, the final configuration $X_{\text{end}}$, and returns the trajectory as a list of $N$ matrices in $SE(3)$ separated in time by $T/(N-1)$. This represents a discretized trajectory of the screw motion from $X_{\text{start}}$ to $X_{\text{end}}$.

(v) `CartesianTrajectory`: Similar to `ScrewTrajectory`, except the origin of the end-effector frame follows a straight line, decoupled from the rotational motion.

**5.** For the UR5 robot from the previous assignment, let $\theta_{\text{start}}$ consist of all joint angles equal to 0.1 rad, and $\theta_{\text{end}}$ consist of all joint angles equal to $\pi/2$.

(i) Use `JointTrajectory` to help plot the position of one joint as a function of time (i.e., $\theta_1(s(t))$) for $T = 2$ s and a cubic time scaling. Use 101 plot points (20 ms between points). (No need to plot more than one joint, since all are the same.)

(ii) Use `JointTrajectory` to help plot the position of one joint as a function of time for $T = 2$ s and a quintic time scaling. Use 101 plot points (20 ms between points).

(iii) Animate the quintic `JointTrajectory` using MATLAB or rviz. Include five screen shots: the first, 26th, 51st, 76th, and last points (separated in time by 500 ms).

**6.** For the UR5 robot, let $X_{\text{start}} = X(\theta_{\text{start}})$ and $X_{\text{end}} = X(\theta_{\text{end}})$ for $\theta_{\text{start}}$ and $\theta_{\text{end}}$ from the previous problem.

(i) Give $X_{\text{start}}$ and $X_{\text{end}}$.

(ii) Use `CartesianTrajectory` to find $X(s(t))$ for $T = 2$ s and 101 points (20 ms between points) and a quintic time scaling. Use your numerical inverse kinematics routine to convert these 101 points $X(s)$ to 101 sets of joint angles $\theta(s)$. You already know the solution for the first point, since $\theta_{\text{start}}$ is known, and you can use this as the initial guess for your second point; your solution for the second point as the initial guess for the third point; etc. You can use 0.5 mm and $0.1°$ as your stopping criteria for numerical inverse kinematics. Plot all six joint angles as a function of time.

(iii) Animate your solution to the previous problem using MATLAB or rviz. Include five screen shots: the first, 26th, 51st, 76th, and last points (separated in time by 500 ms).