Name ______________________________

Final Exam

MEAM 520, Introduction to Robotics
University of Pennsylvania
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December 19, 2012

You must take this exam independently, without assistance from anyone else. You may bring in a calculator and four 8.5"×11" sheets of notes for reference. Aside from these pages of notes, you may not consult any outside references, such as the textbook or the Internet. Any suspected violations of Penn's Code of Academic Integrity will be reported to the Office of Student Conduct for investigation.

This exam consists of five problems. We recommend you look at all of the problems before starting to work. If you need clarification on any question, please ask a member of the teaching team. When you work out each problem, please show all steps and $\boxed{\text{box your answers}}$. On problems involving actual numbers, please keep your solution symbolic for as long as possible; this will make your work easier to follow and easier to grade. The exam is worth a total of 100 points, and partial credit will be awarded for the correct approach even when you do not arrive at the correct answer.

	Points	Score
Problem 1	20	
Problem 2	20	
Problem 3	20	
Problem 4	20	
Problem 5	20	
Total	100	

I agree to abide by the University of Pennsylvania Code of Academic Integrity during this exam. I pledge that all work is my own and has been completed without the use of unauthorized aid or materials.

Signature ______________________________

Date ______________________________

Problem 1: Short Answer *(20 points)*

a. Compared to analog angle sensors such as potentiometers, explain **one advantage** of using an **incremental optical encoder** for measuring the angle of a revolute joint. *(2 points)*

b. Compared to analog angle sensors such as potentiometers, explain **one disadvantage** of using a **incremental optical encoder** for measuring the angle of a revolute joint. *(2 points)*

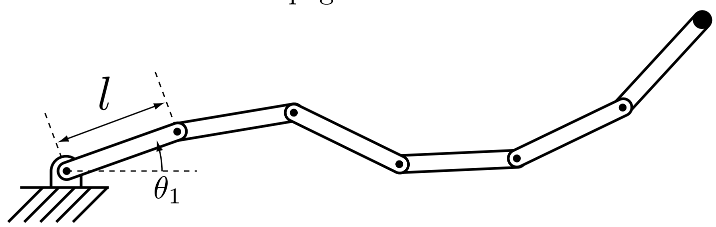
c. Why do roboticists typically use **current-drive amplifiers** instead of voltage-drive amplifiers with DC brushed motors? *(2 points)*

d. The `pumaServo.m` function imposes a **maximum joint speed** of 1 rad/s. Why did the teaching team include this speed limit? *(2 points)*

e. Ask a **good short-answer question and answer it** for yourself. Your question should pertain to this class and should be different from the actual questions on this test. *(2 points)*

Question:

Answer:



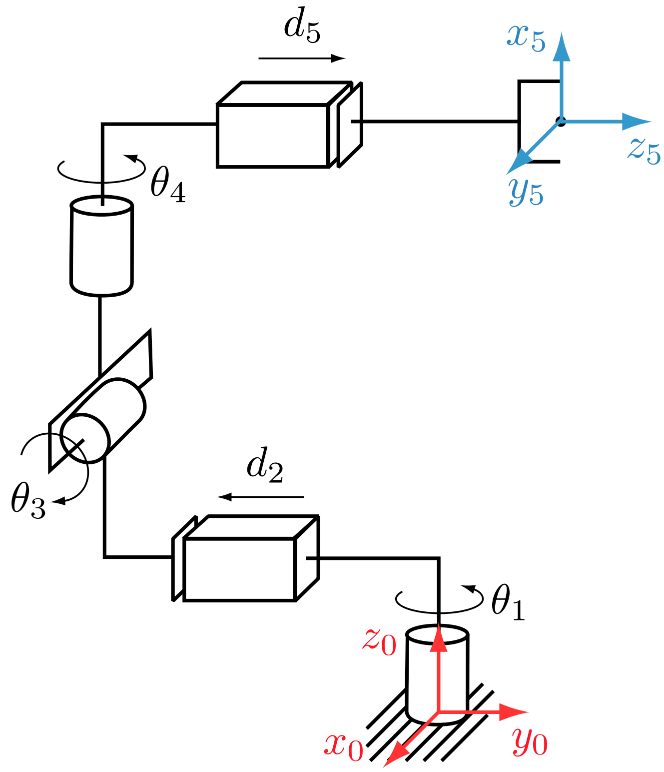
The diagram above shows a planar RRRRRR manipulator that resembles a snake. Each link has the same length l. The first angle is measured relative to horizontal, as indicated. The other angles are all measured relative to the previous link, with positive counter-clockwise.

f. How many inverse kinematics solutions exist if I specify the planar position of the snake's tip? Does the number of solutions depend on the commanded position? If so, how? *(3 points)*

g. How many inverse kinematics solutions exist if I specify both the planar position and the orientation of the snake's tip? Does the number of solutions depend on the commanded tip configuration? If so, how? *(3 points)*

h. Considering both the planar translational velocity and rotational velocity of the snake's tip, explain what singularities this robot has. Calculations should not be needed. *(4 points)*

Problem 2: Forward Kinematics ***(20 points)***



The diagram above shows an RPRRP manipulator.

- The positive direction for each joint coordinate is indicated with an arrow.
- The revolute joints are shown at $\theta = 0$.
- The prismatic joints are shown at a positive deflection.
- Frame 0's location is specified on the ground as shown.
- Frame 5's location is specified on the end-effector as shown.

a. Draw **frames 1 through 4** on the above diagram, following the DH convention. You may omit the y-axes if you want. *(4 points)*

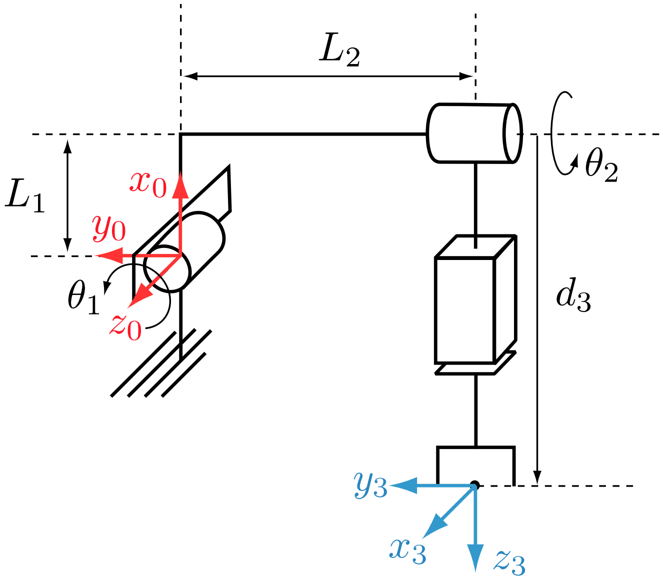
b. Fill in the table of **DH parameters** below. Use a **superscript star** to indicate joint variables, e.g., θ_1^*. **Label on the diagram** any DH parameters that you introduce. Be sure to **label the span of** d_2 **and** d_5. *(10 points)*

i	a	α	d	θ
1				
2				
3				
4				
5				

c. Is there **only one correct set** of frame locations and DH parameters for the previous question, or are there **multiple correct sets**? Explain your answer. *(3 points)*

d. Suppose you had a computer with MATLAB installed. How would you **check whether your chosen DH parameters are correct**? Carefully explain what you would do. *(3 points)*

Problem 3: Jacobians ***(20 points)***



Consider the RRP spatial manipulator shown above. The two revolute joints are shown at $\theta_1 = 0$ and $\theta_2 = 0$, and the prismatic joint is shown at a positive deflection d_3. The position of the end-effector (the origin of frame 3) in frame 0 is as follows, with s_i and c_i meaning $\sin\theta_i$ and $\cos\theta_i$ respectively:

$$p_3^0 = \begin{bmatrix} L_1 c_1 + L_2 s_1 - d_3 c_1 c_2 \\ L_1 s_1 - L_2 c_1 - d_3 s_1 c_2 \\ -d_3 s_2 \end{bmatrix}$$

a. Find the translational Jacobian J_v for this manipulator. *(4 points)*

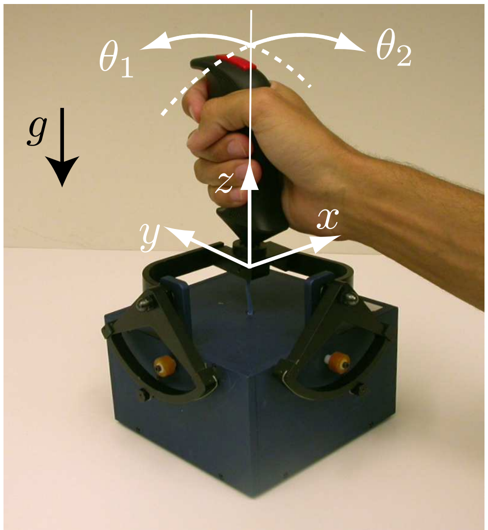
b. Find the rotational Jacobian J_ω for this manipulator. *(4 points)*

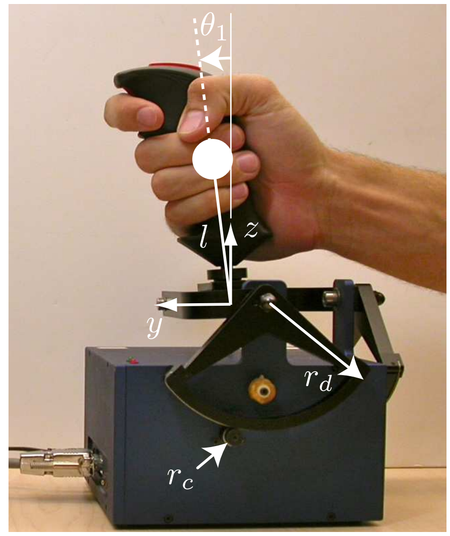
c. Suppose the manipulator is at $\theta_1 = \pi/2$, $\theta_2 = 0$, and $d_3 = 0.3$ m, with $L_1 = 0.15$ m and $L_2 = 0.2$ m. What will the **translational velocity of the end-effector** be if $\dot{\theta}_1 = 1$ rad/s, $\dot{\theta}_2 = -1$ rad/s, and $\dot{d}_3 = 1$ m/s? Express your answer in frame 0 (v_3^0). *(4 points)*

d. Can the robot's end-effector **exert forces** in all Cartesian directions at this same configuration ($\theta_1 = \pi/2$, $\theta_2 = 0$, and $d_3 = 0.3$ m, with $L_1 = 0.15$ m and $L_2 = 0.2$ m)? Explain. *(4 points)*

e. What **limitations**, if any, exist on the end-effector's **angular velocity** in this same configuration? *(4 points)*

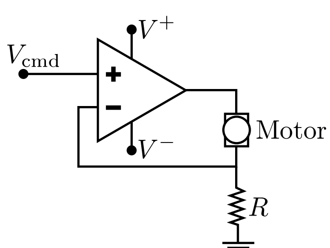
Problem 4: Input/Output Calculations *(20 points)*





The pictures above show an Immersion Impulse Engine 2000 joystick. It has two degrees of freedom: the user can move the handle forward/backward and left/right.

- Each of the joystick's joints is controlled by a Maxon RE025-055-35 118752 DC brushed motor that is located inside the base. This motor's rated voltage is 24 V, its maximum continuous current is 1.23 A, its torque constant is 0.0232 Nm/A, its terminal resistance is 2.32 Ω, its terminal inductance is 0.24 mH, and it does not have a gearhead.
- Attached to the back end of each motor shaft is an Agilent HEDS 5500 A02 incremental optical encoder with a resolution of 500 cycles per revolution (500 slits in the rotating disk).
- The output of each encoder is processed through a quadrature encoder counting circuit.
- There is a cylindrical capstan attached to the output shaft of each motor. Its radius is $r_c = 0.5$ cm.
- Thin stranded cables couple the rotation of each capstan to the rotation of its drum.
- The drum radius is $r_d = 7.0$ cm.
- The joystick's handle is rigidly attached to both drums through simple linkages.
- The distance from the point where the two joint axes intersect to the center of the hand is $l = 9.0$ cm.
- A copy of this device is available for you to inspect in the exam room. One side of the base has been removed so you may look inside to see the motors and circuitry.
- Each motor is driven via the circuit shown below, with $V^+ = 30$ V, $V^- = -30$ V, and $R = 2\ \Omega$. V_{cmd} is the voltage your software commands.



a. Your servo loop reads the present quadrature encoder counts, Q_1 and Q_2, at each time step. You notice that Q_1 increases when you move the handle *forward*, and Q_2 increases when you move the handle *left*. When you hold the handle straight up, $Q_1 = 1040$ counts and $Q_2 = -1762$ counts. The manufacturer does not provide a command for zeroing the quadrature encoder counts directly. Write **formulas for θ_1 and θ_2** such that both joint angles are zero when the handle is straight up, both are measured in radians, and both increase when the handle is moved *forward* and *right*. *(6 points)*

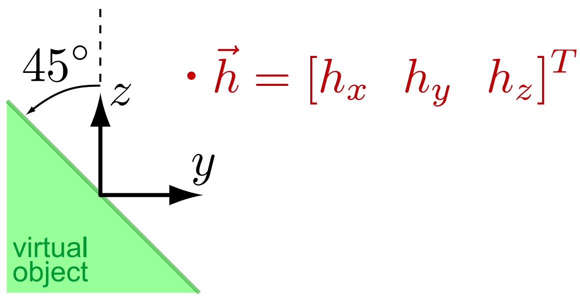
b. Imagine you hold θ_2 perfectly at zero. Write **formulas for the x, y, and z coordinates** of the center of the hand (the white circle in the diagram) as a function of θ_1 and any necessary system parameters. Use the depicted coordinate frame. *(4 points)*

c. The joystick was designed to have low friction and be lightweight. For your application, though, you added a new handle that is quite heavy. Unfortunately, this new handle tends to fall toward the extremes of its workspace when moved away from vertical. What are **two distinct approaches you could use to prevent this falling behavior**? *(4 points)*

d. Imagine your code has already calculated the two **joint torques** $\tau_1 = -0.1$ **Nm and** $\tau_2 = 0.8$ **Nm** that you want to output with this joystick. Both of these are in newton-meters (Nm) and are defined to be positive in the same directions as θ_1 and θ_2. During testing, you noticed that a positive command voltage makes each motor rotate its joint in the positive direction. What **command voltages** $V_{\mathrm{cmd},1}$ and $V_{\mathrm{cmd},2}$ should you output to each of the drive circuits? *(6 points)*

Problem 5: Haptic Rendering and Teleoperation *(20 points)*

a. Imagine you are using a PHANToM Premium 1.0 to create the three-dimensional haptic virtual environment shown below. The x-axis (not shown) is positive out of the page.



Your goal is to let the user feel an infinite frictionless flat plane that intersects the origin and is tilted 45° around the x-axis to face up and to the right. At each time step, you know the position of the haptic interface's tip ($\vec{h} = [h_x \quad h_y \quad h_z]^T$). Write pseudocode that specifies appropriate values for the **force vector components** F_x, F_y, and F_z to give the user the illusion they are touching the depicted plane. The force components are defined to be positive in the same directions as their associated axes. *(6 points)*

b. When Professor Kuchenbecker tested all of the haptic damping programs submitted for project 2, she found that most felt very smooth, like moving a spoon in honey. But a few submissions generated **a small vibration at about 33 Hz** that she could feel. The vibration was strongest when she moved fast, and it was not detectable when holding still. What do you think caused these vibrations? Be specific. *(6 points)*

c. Imagine we replaced the PUMA's tri-color LED end-effector with a small paintbrush, and we attached a cup of paint and a large piece of paper to the table within the PUMA's workspace. Carefully describe a **controller** that would enable you **to teleoperate the 6-DOF PUMA with the 3-DOF PHANToM Premium 1.0** and paint a picture. Be thorough. *(8 points)*