Homework 4:
Forward Kinematics and DH Parameters

MEAM 520, University of Pennsylvania
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This paper-based assignment is due on **Thursday, September 26, by midnight (11:59:59 p.m.)** You should aim to turn it in during class that day. If you don't finish until later in the day, you can turn it in to Professor Kuchenbecker's office, Towne 224, in the bin or under the door. Late submissions will be accepted until Sunday, September 29, by midnight (11:59:59 p.m.), but they will be penalized by 10% for each partial or full day late, up to 30%. After the late deadline, no further assignments may be submitted.

You may talk with other students about this assignment, ask the teaching team questions, use a calculator and other tools, and consult outside sources such as the Internet. To help you actually learn the material, what you write down should be your own work, not copied from any other individual or a solution manual. Any submissions suspected of violating Penn's Code of Academic Integrity will be reported to the Office of Student Conduct. If you get stuck, post a question on Piazza or go to office hours!

These problems are adapted from the printed version of the textbook, *Robot Modeling and Control* by Spong, Hutchinson, and Vidyasagar (SHV). Please follow the extra clarifications and instructions when provided. Write in pencil, show your work clearly, $\boxed{\text{box your answers}}$, and staple together all pages of your assignment. This assignment is worth a total of 20 points.

1. Custom problem – Kinematics of Baxter *(2 points)*
   Rethink Robotics sells a two-armed manufacturing robot named Baxter. Watch YouTube videos of Baxter (e.g., http://www.youtube.com/watch?v=rjPFqkFyrOY) to learn about its kinematics. Draw a schematic of the serial kinematic chain of Baxter's left arm (the one the woman is touching in the picture below.) Use the book's conventions for how to draw revolute and prismatic joints in 3D.

2. Custom Problem – DH Convention *(2 points)*
Describing a rigid-body transformation in three dimensions generally requires six numbers. Why then are only four DH parameters (a, α, d, θ) needed to describe link i's pose relative to link $i-1$ in a serial manipulator? Be precise.

3. Custom Problem – Interpreting a Transformation Matrix *(2 points)*
Equation (3.24) on page 93 of SHV gives the SCARA manipulator's T_4^0 transformation matrix. What is the practical (geometric) meaning of each of the four columns of this matrix? Note that Figure 3.11 shows frame $o_0x_0y_0z_0$ in the wrong location; it should be translated up along the z_0 axis until x_0 lies along the horizontal line that goes toward joint 1. Keep the intuitive meaning of the elements of these matrices in your mind as you solve the remaining problems in this assignment.

Do the following steps for each of the next three problems:

- Draw a schematic of the robot in its zero configuration.
- Draw your frames on the diagram, following the DH convention.
- Use a superscript star, e.g., θ_1^*, to denote all joint variables.
- Use an arrow labeled with the joint variable name to mark the positive direction for all joint variables on the diagram.
- Use your diagram to create a table of DH parameters for the manipulator.
- Label all DH parameters that you introduce on the diagram.
- Calculate the final transformation matrix.
- Check your work by examining the final transformation matrix to determine whether it gives the answers you expect for simple situations, such as the zero configuration. Fix any problems you uncover.

4. SHV 3-4, page 112 – Forward Kinematics of a Two-Link Planar RP Arm With Offset *(4 points)*
You may choose the zero configuration.

5. SHV 3-7, page 113 – Forward Kinematics of the Three-Link Cartesian Robot *(4 points)*
Use the depicted pose as the zero configuration.

6. SHV 3-6, page 113 – Forward Kinematics of the Three-Link Articulated Robot *(6 points)*
Use the depicted pose as the zero configuration.