Penn Engineering | GRASP Laboratory

General Robotics, Automation, Sensing & Perception Lab

GRASP Seminar Series

Wu & Chen

Fridays 11am – 12pm

Sep 14	GRASP Research Overview
Sep 21	Raquel Urtasun (Uber)
Sep 28	Deepak Pathak (UC Berkeley)
Oct 5	Lex Fridman (MIT)
Oct 12	Naomi Leonard (Princeton)
Oct 19	Yaser Sheikh (CMU/Oculus-Facebook)
Oct 26	Serge Belongie (Cornell)
Nov 2	Mark Cutkosky (Stanford)
Nov 9	Kevin Lynch (Northwestern)
Nov 16	Elliot Hawkes (UC Santa Barbara)
Nov 30	Kristen Graumen (UT Austin)

Tentative schedule. Check GRASP website for updates.

MEAM 520
Lecture 6: DH Parameters

Cynthia Sung, Ph.D.
Mechanical Engineering & Applied Mechanics
University of Pennsylvania

Last Time

The **Denavit-Hartenberg transform** results from successive rotations and translations via the four DH parameters

a parameterization for homogeneous transformations

The transform from i to i-1 is

$$A_i = \begin{bmatrix} c_{\theta_i} & -s_{\theta_i}c_{\alpha_i} & s_{\theta_i}s_{\alpha_i} & a_i c_{\theta_i} \\ s_{\theta_i} & c_{\theta_i}c_{\alpha_i} & -c_{\theta_i}s_{\alpha_i} & a_i s_{\theta_i} \\ 0 & s_{\alpha_i} & c_{\alpha_i} & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

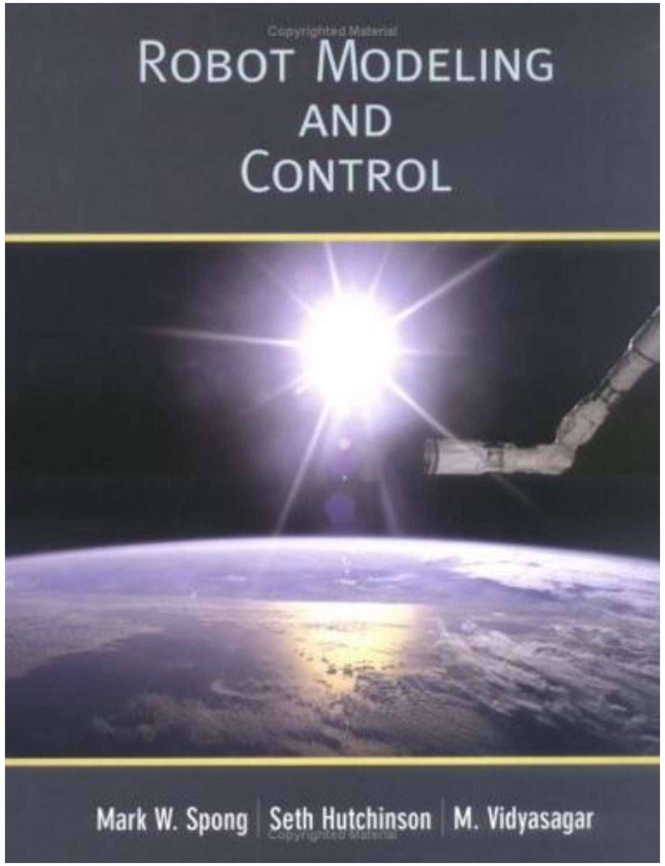
Three DH parameters will be **constant** for each joint's transformation, and one will **vary**.

Plug DH parameters into the above formula to find each joint's transformation matrix.

The final transformation matrix from tip to base is

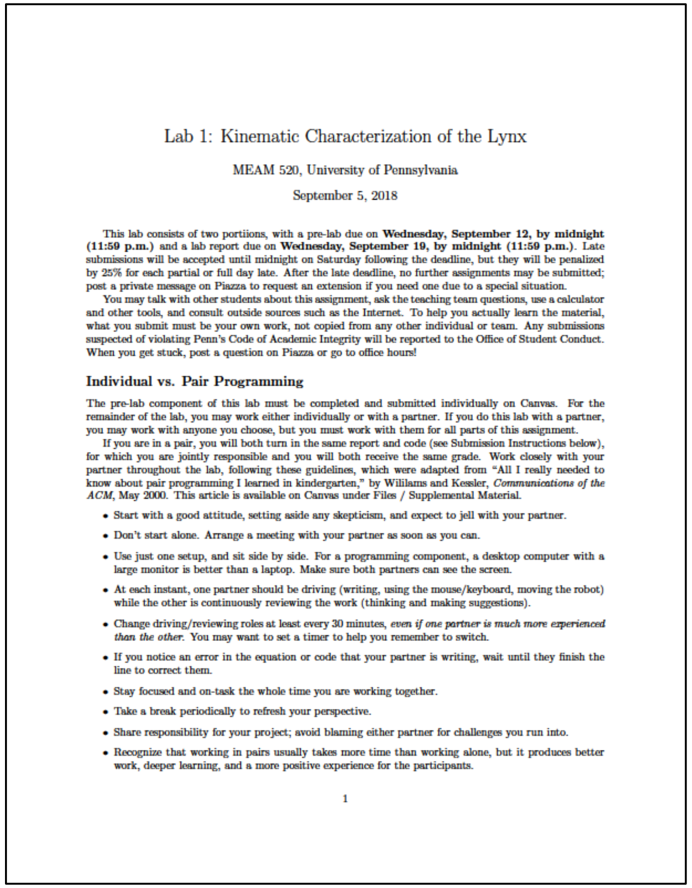
$$\mathbf{T}_n^0 = A_1(q_1) \cdots A_n(q_n)$$

Today: More DH Parameters



Chapter 3: Forward and Inverse Kinematics

- Read Sec. 3.2



Lab 1: Kinematic Characterization of the Lynx

MEAM 520, University of Pennsylvania

September 5, 2018

This lab consists of two portiions, with a pre-lab due on **Wednesday, September 12, by midnight (11:59 p.m.)** and a lab report due on **Wednesday, September 19, by midnight (11:59 p.m.)**. Late submissions will be accepted until midnight on Saturday following the deadline, but they will be penalized by 25% for each partial or full day late. After the late deadline, no further assignments may be submitted; post a private message on Piazza to request an extension if you need one due to a special situation.

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 submit must be your own work, not copied from any other individual or team. Any submissions suspected of violating Penn's Code of Academic Integrity will be reported to the Office of Student Conduct. When you get stuck, post a question on Piazza or go to office hours!

Individual vs. Pair Programming

The pre-lab component of this lab must be completed and submitted individually on Canvas. For the remainder of the lab, you may work either individually or with a partner. If you do this lab with a partner, you may work with anyone you choose, but you must work with them for all parts of this assignment.

If you are in a pair, you will both turn in the same report and code (see Submission Instructions below), for which you are jointly responsible and you will both receive the same grade. Work closely with your partner throughout the lab, following these guidelines, which were adapted from "All I really needed to know about pair programming I learned in kindergarten," by Wililams and Kessler, *Communications of the ACM*, May 2000. This article is available on Canvas under Files / Supplemental Material.

- Start with a good attitude, setting aside any skepticism, and expect to jell with your partner.
- Don't start alone. Arrange a meeting with your partner as soon as you can.
- Use just one setup, and sit side by side. For a programming component, a desktop computer with a large monitor is better than a laptop. Make sure both partners can see the screen.
- At each instant, one partner should be driving (writing, using the mouse/keyboard, moving the robot) while the other is continuously reviewing the work (thinking and making suggestions).
- Change driving/reviewing roles at least every 30 minutes, *even if one partner is much more experienced than the other*. You may want to set a timer to help you remember to switch.
- If you notice an error in the equation or code that your partner is writing, wait until they finish the line to correct them.
- Stay focused and on-task the whole time you are working together.
- Take a break periodically to refresh your perspective.
- Share responsibility for your project; avoid blaming either partner for challenges you run into.
- Recognize that working in pairs usually takes more time than working alone, but it produces better work, deeper learning, and a more positive experience for the participants.

1

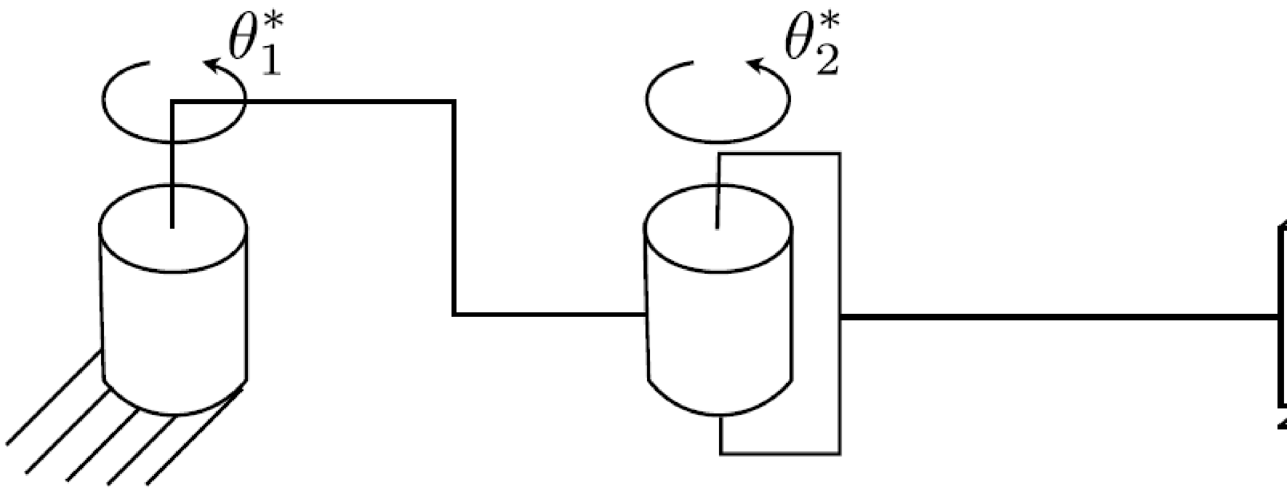
Lab 1 due 9/19, 11:59 p.m.

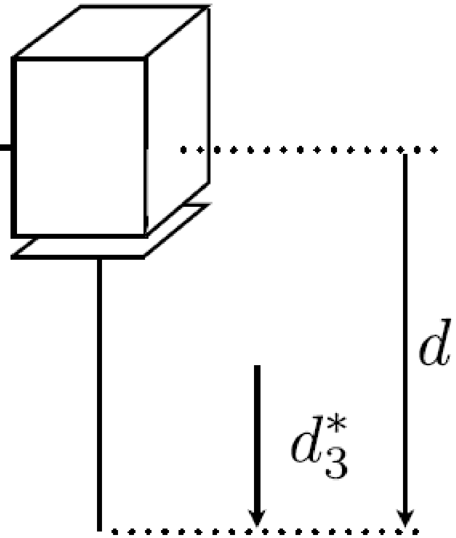
Today: More DH Parameters

- Do one example
- Check one example
- You do an example

SCARA

Shown at $\theta_1^* = 0, \theta_2^* = 0,$ and $d_3^* = d$



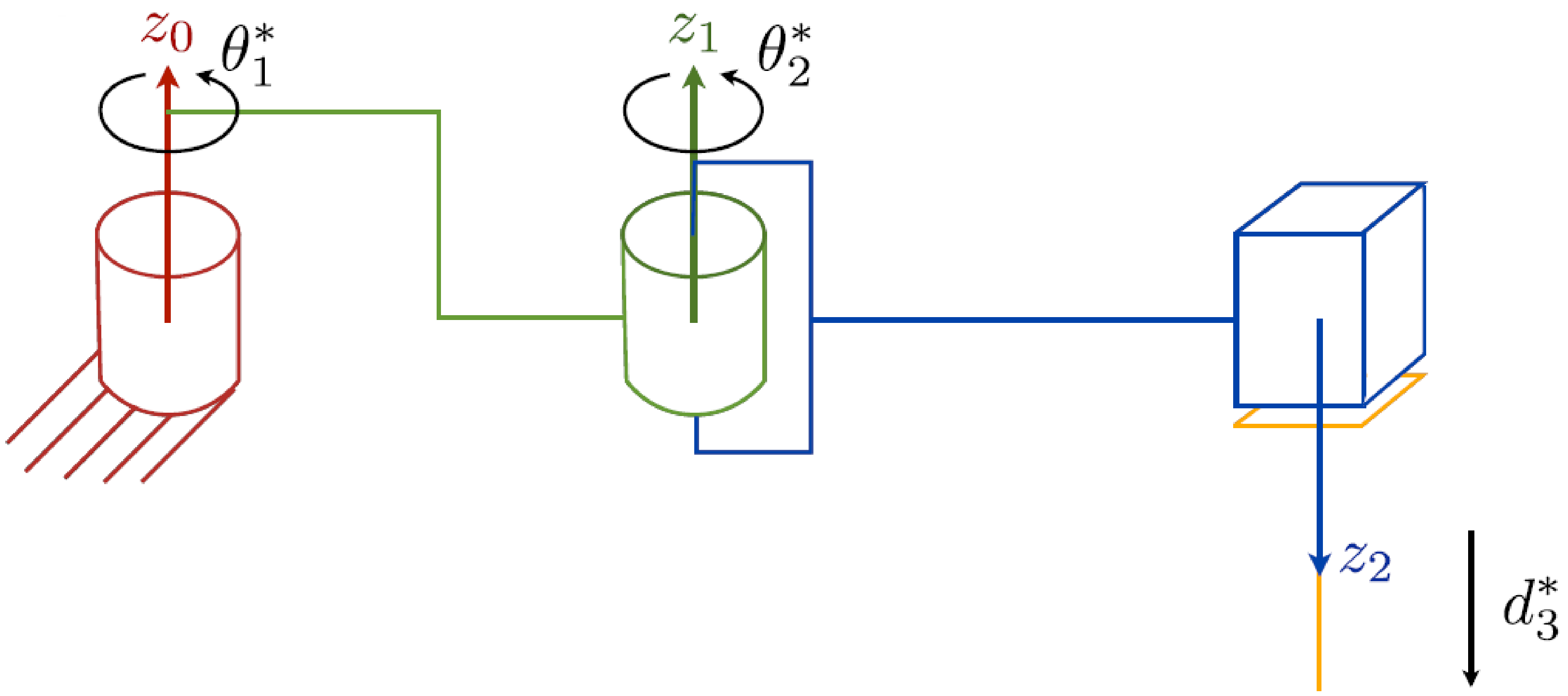


The diagram should show revolute joints at zero.

Prismatic joints are usually shown at a positive displacement instead of zero.

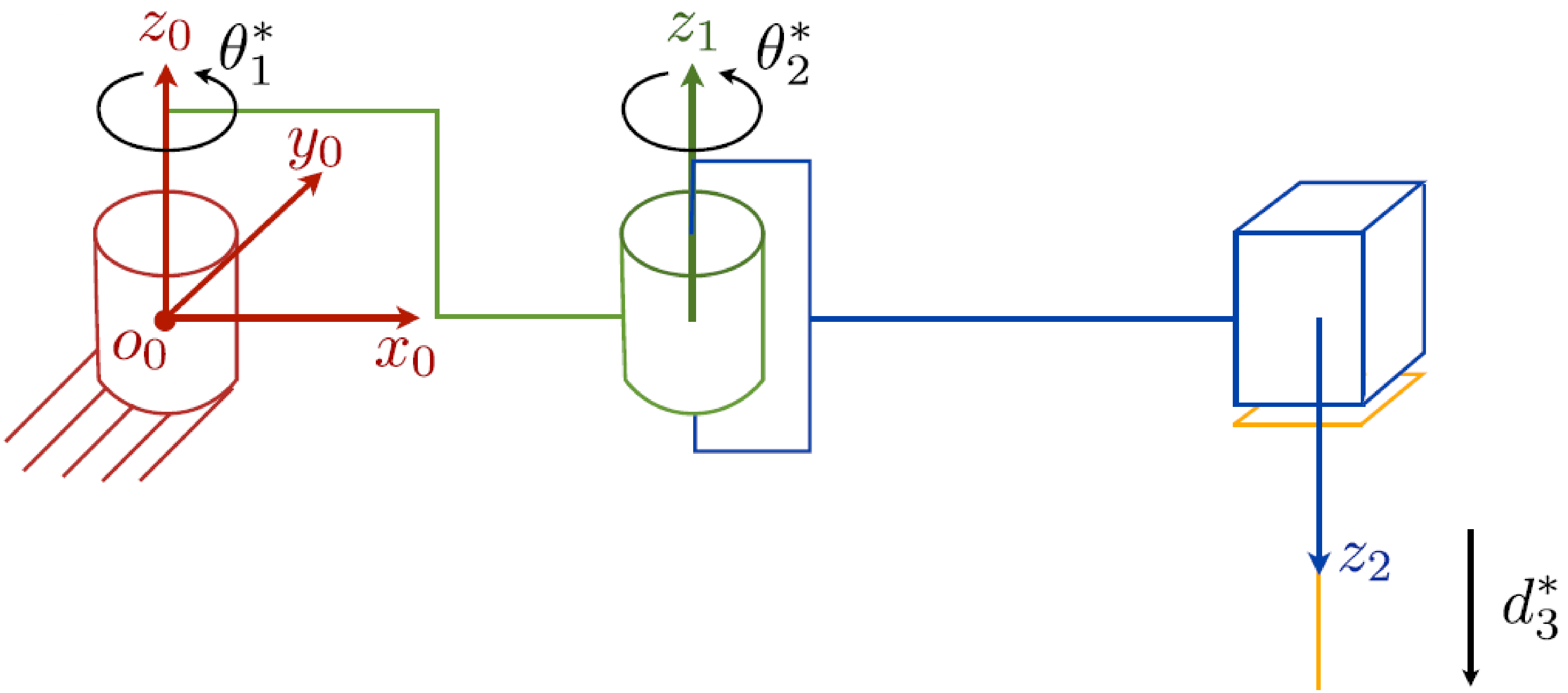
Step 1: Locate and label the joint axes $z_0, \ldots, z_{n-1}$.


SCARA



SCARA

Step 2: Establish the base frame. Set the origin anywhere on the z_0-axis. The x_0 and y_0 axes are chosen conveniently to form a right-handed frame.



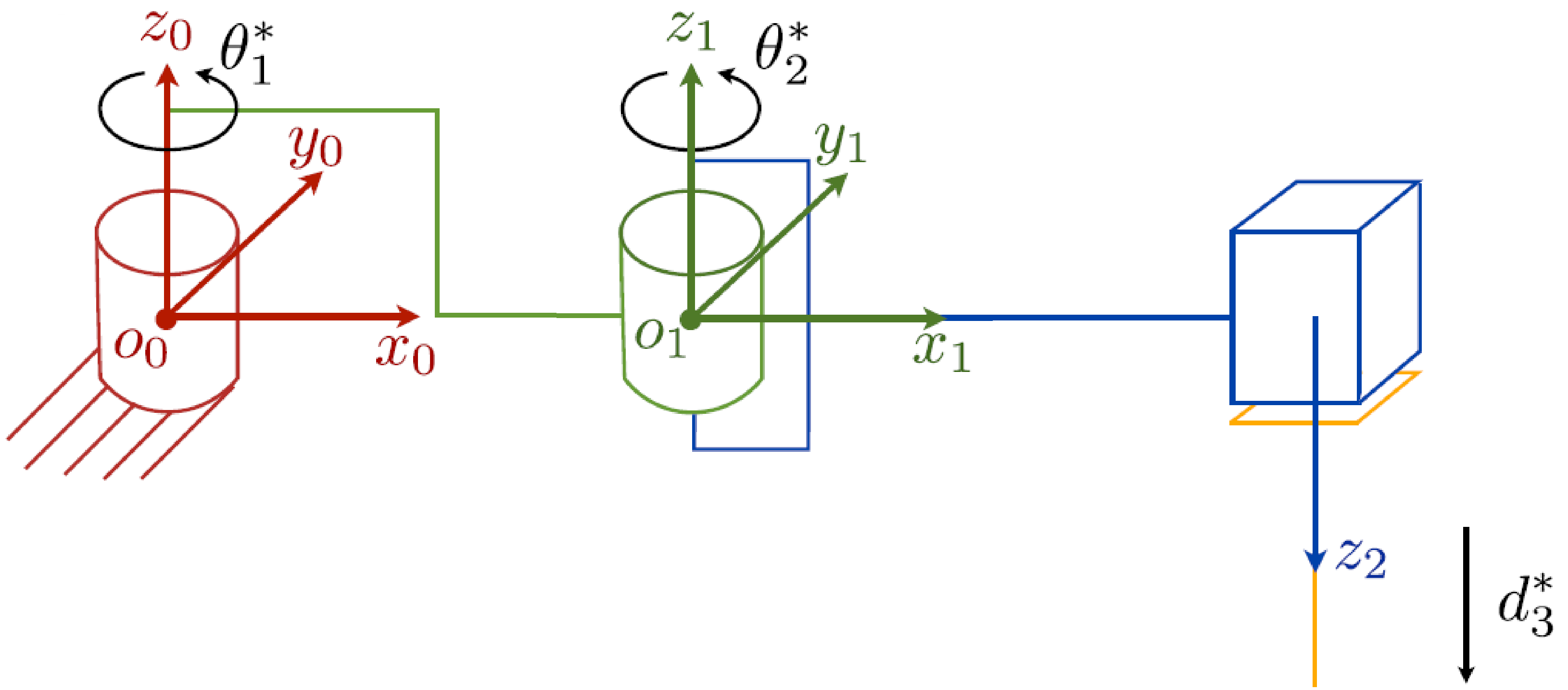
SCARA

For $i = 1, \ldots n-1$,

Step 3: Locate the origin o_i where the common normal to z_i and z_{i-1} intersects z_i. If z_i intersects z_{i-1} locate o_i at this intersection. If z_i and z_{i-1} are parallel, locate o_i in any convenient position along z_i.

Step 4: Establish x_i along the common normal between z_{i-1} and z_i through o_i, or in the direction normal to the $z_{i-1} - z_i$ plane if z_{i-1} and z_i intersect.

Step 5: Establish y_i to complete a right-handed frame.



SCARA

For *i* = 1, … *n* – 1,

Step 3: Locate the origin o_i where the common normal to z_i and z_{i-1} intersects z_i. If z_i intersects z_{i-1} locate o_i at this intersection. If z_i and z_{i-1} are parallel, locate o_i in any convenient position along z_i.

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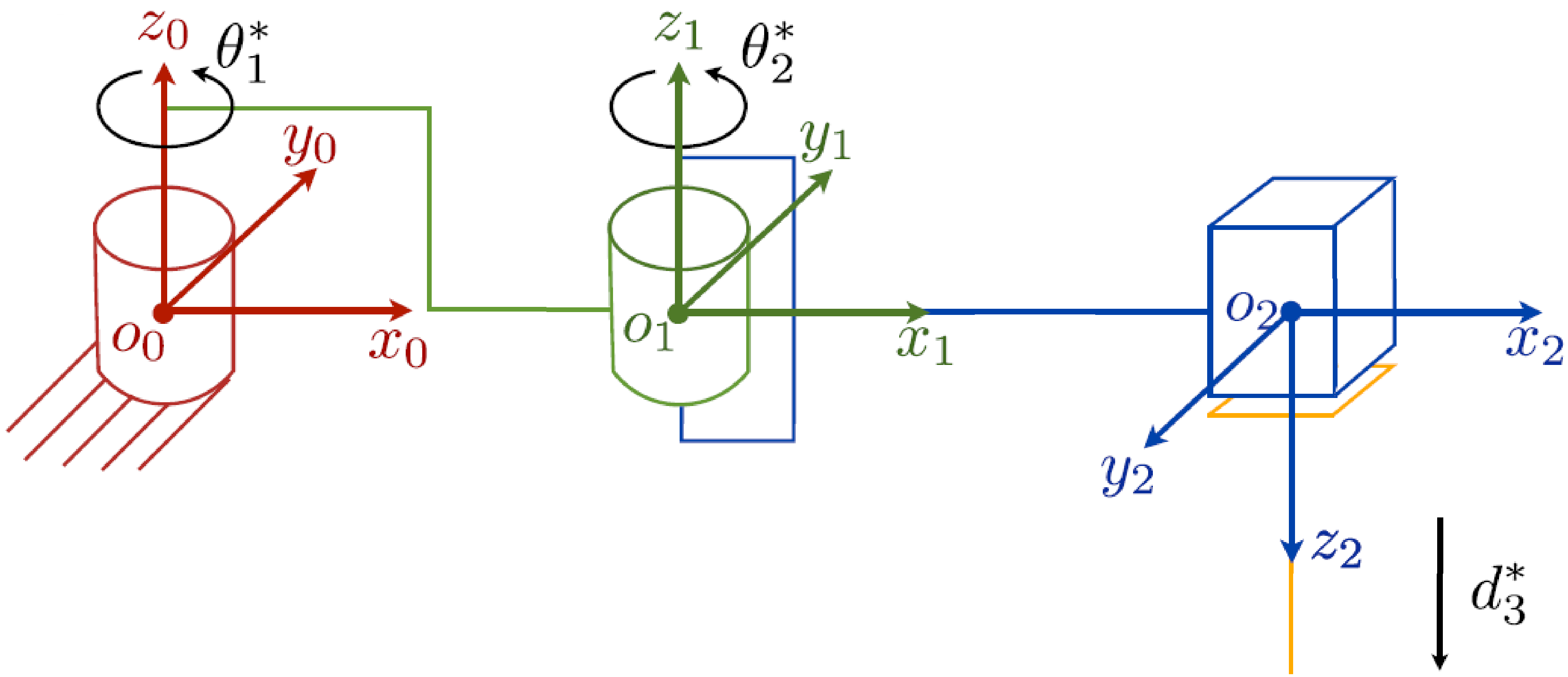
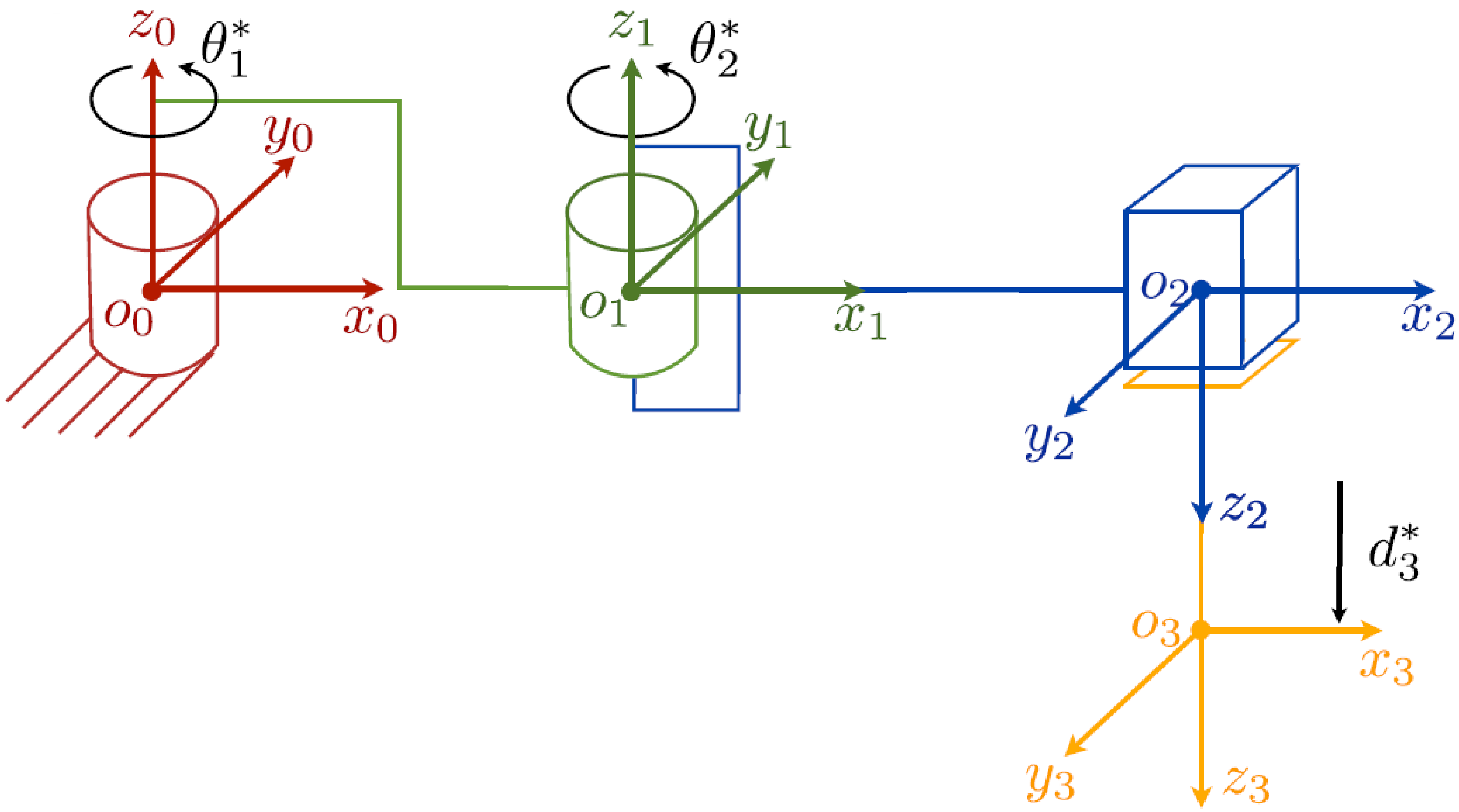


SCARA

Step 6: Establish the end-effector frame $o_n x_n y_n z_n$. Assuming the n-th joint is revolute, set $z_n = a$ along the direction z_{n-1}. Establish the origin o_n conveniently along z_n, preferably at the center of the gripper or at the tip of any tool that the manipulator may be carrying. Set $y_n = s$ in the direction of the gripper closure and set $x_n = n$ as $s \times a$. If the tool is not a simple gripper set x_n and y_n conveniently to form a right-handed frame.



SCARA

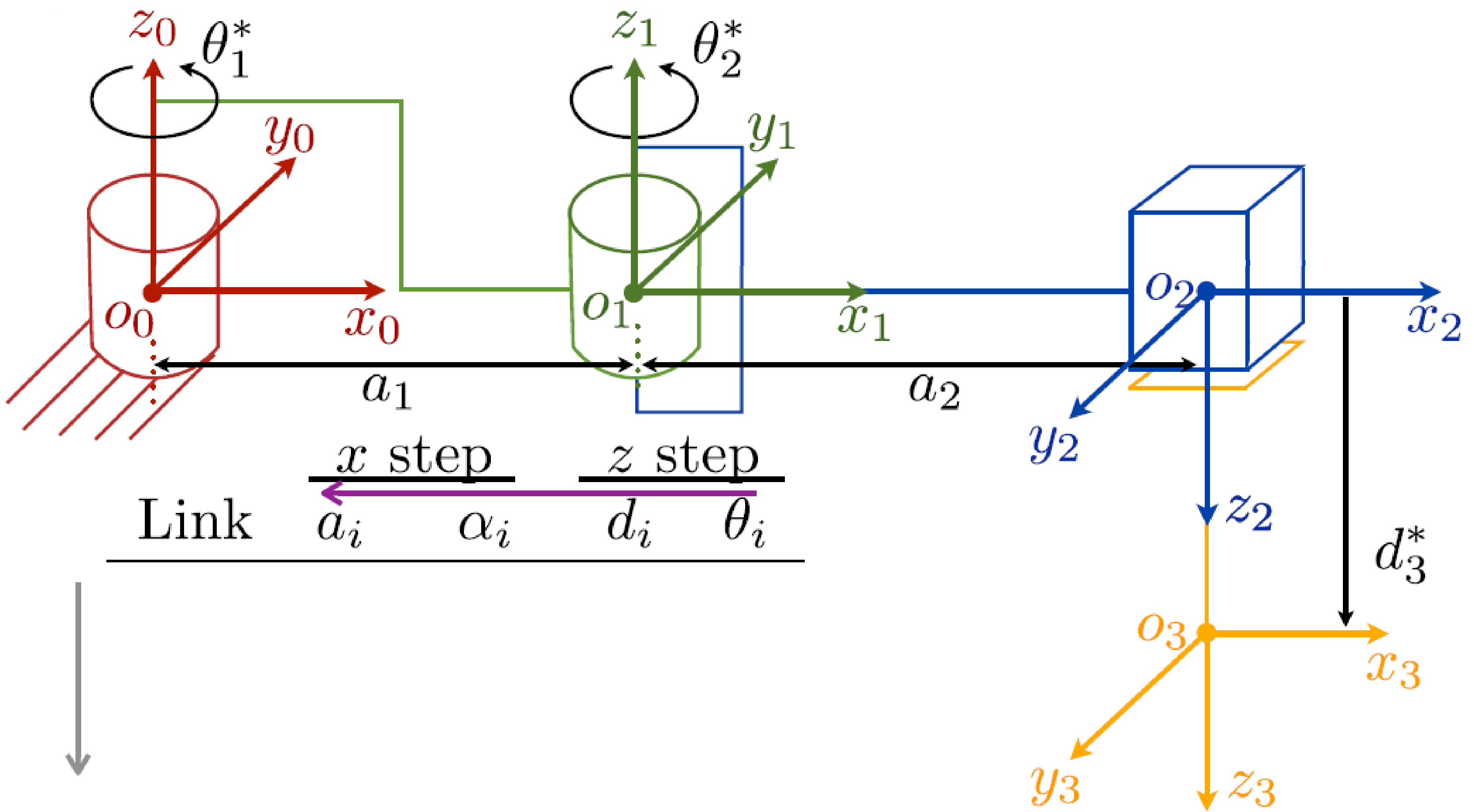
Step 7: Create a table of link parameters a_i, d_i, α_i, θ_i.

$a_i =$ distance along x_i from the intersection of the x_i and z_{i-1} axes to o_i.

$d_i =$ distance along z_{i-1} from o_{i-1} to the intersection of the x_i and z_{i-1} axes. d_i is variable if joint i is prismatic.

$\alpha_i =$ the angle between z_{i-1} and z_i measured about x_i.

$\theta_i =$ the angle between x_{i-1} and x_i measured about z_{i-1}. θ_i is variable if joint i is revolute.



SCARA

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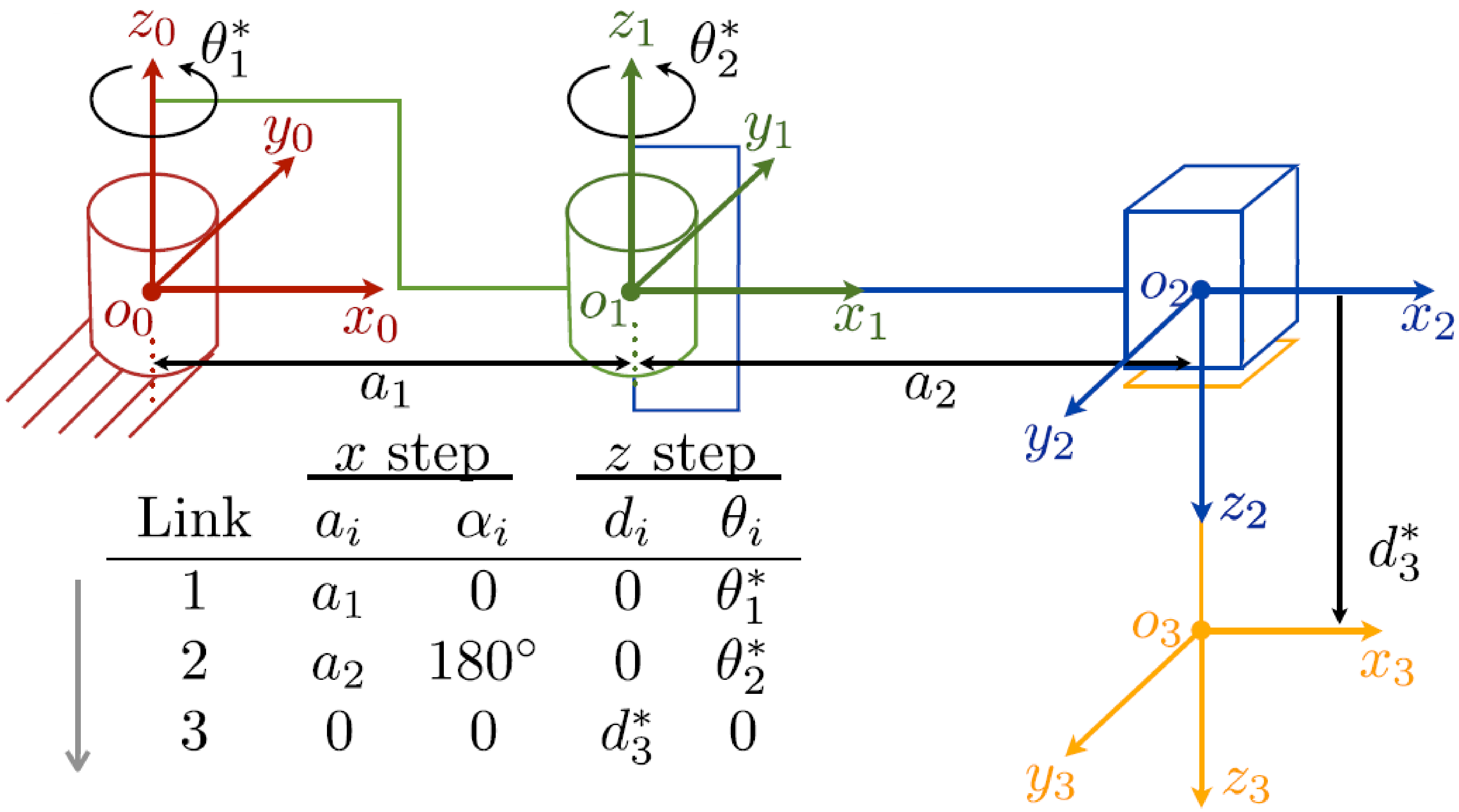


	x step		z step	
Link	a_i	α_i	d_i	θ_i
1	a_1	0	0	θ_1^*
2	a_2	180°	0	θ_2^*
3	0	0	d_3^*	0

Step 8: Form the homogeneous transformation matrices A_i by substituting the above parameters into (3.10).

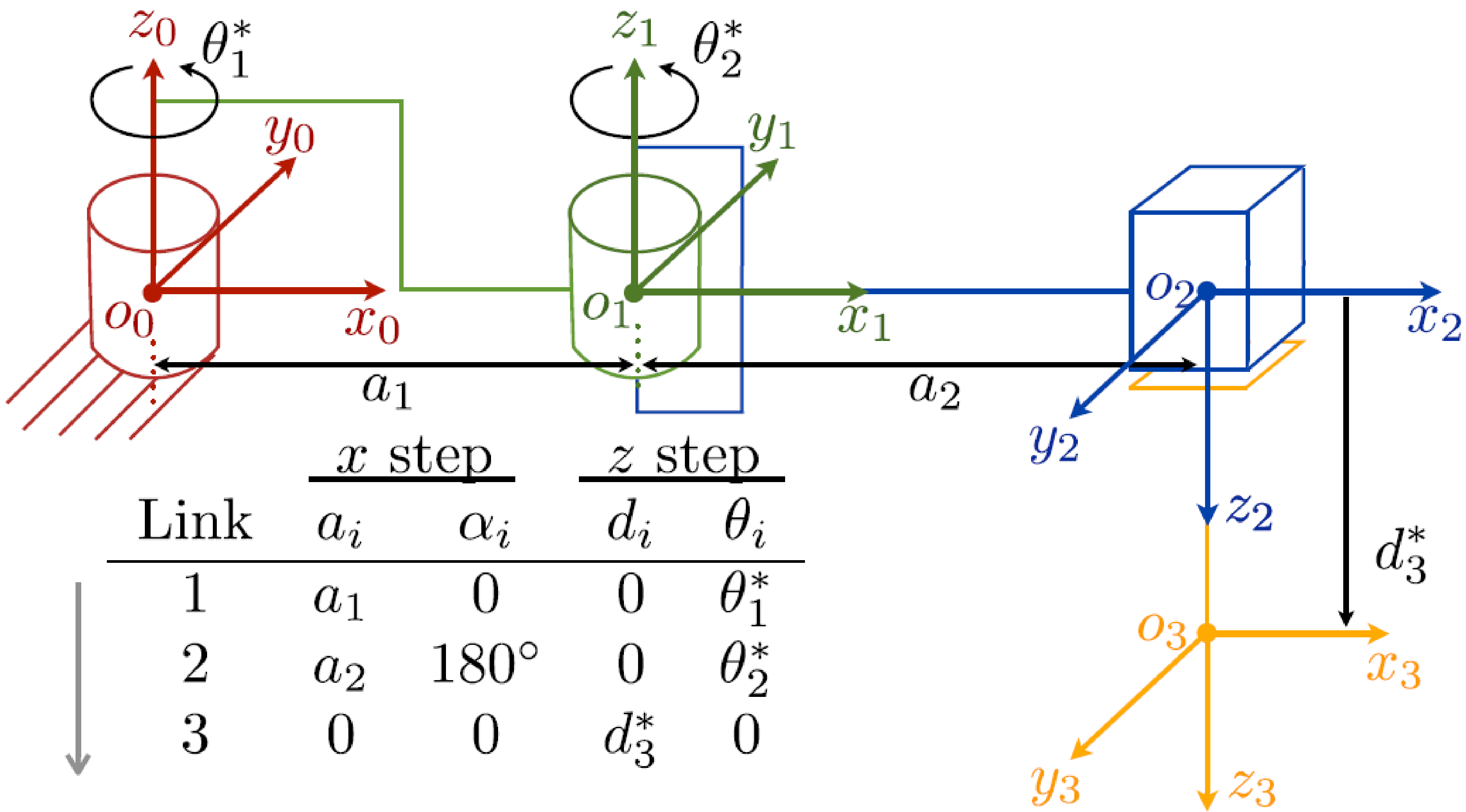
$$A_i = \begin{bmatrix} c_{\theta_i} & -s_{\theta_i}c_{\alpha_i} & s_{\theta_i}s_{\alpha_i} & a_i c_{\theta_i} \\ s_{\theta_i} & c_{\theta_i}c_{\alpha_i} & -c_{\theta_i}s_{\alpha_i} & a_i s_{\theta_i} \\ 0 & s_{\alpha_i} & c_{\alpha_i} & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

SCARA

$$A_1 = \begin{bmatrix} c_1 & -s_1 & 0 & a_1c_1 \\ s_1 & c_1 & 0 & a_1s_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_2 = \begin{bmatrix} c_2 & s_2 & 0 & a_2c_2 \\ s_2 & -c_2 & 0 & a_2s_2 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_3 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$



	x step		z step	
Link	a_i	α_i	d_i	θ_i
1	a_1	0	0	θ_1^*
2	a_2	180°	0	θ_2^*
3	0	0	d_3^*	0

Step 9: Form $T_n^0 = A_1 \cdots A_n$. This then gives the position and orientation of the tool frame expressed in base coordinates.

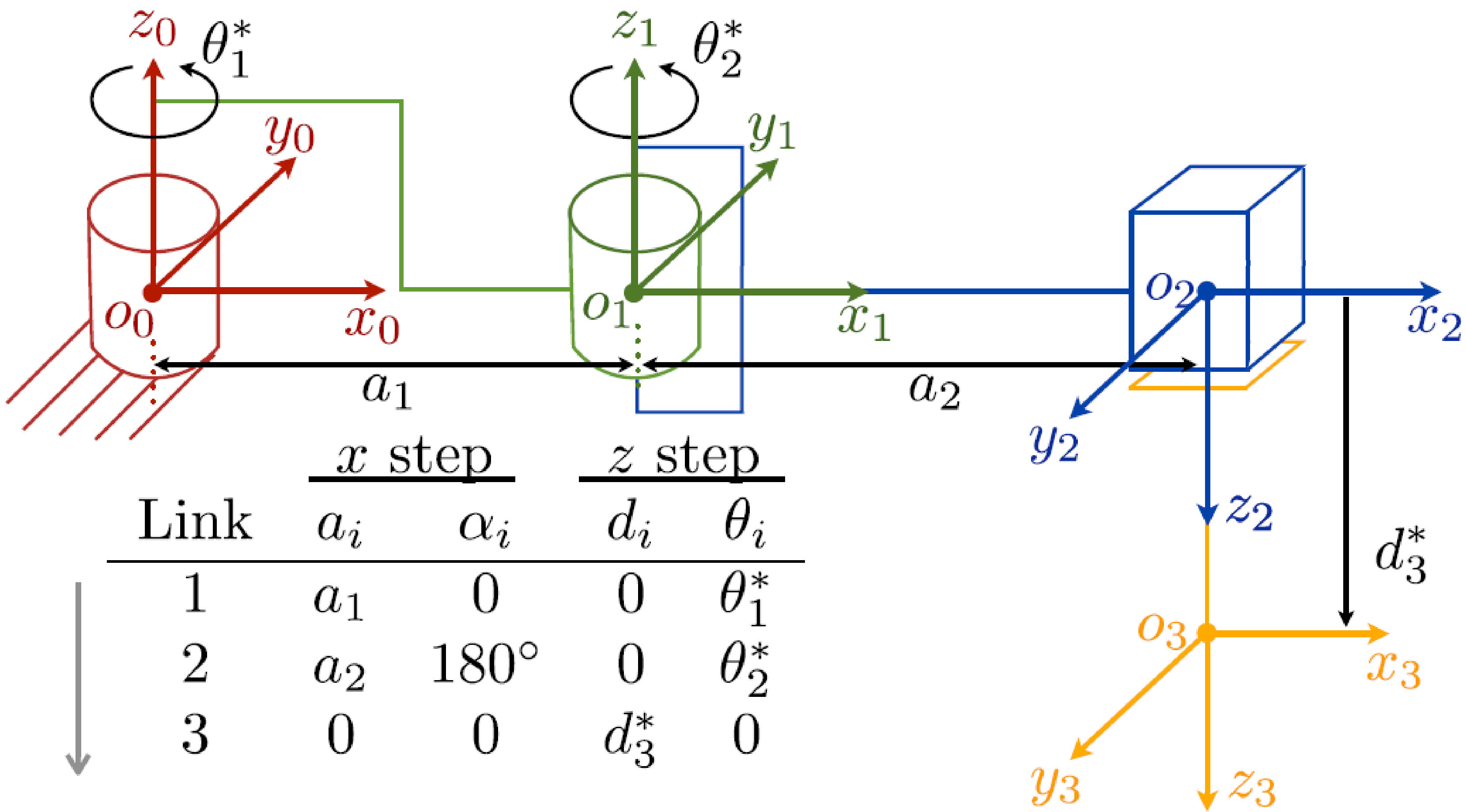
$$T_3^0 = A_1 A_2 A_3 = \begin{bmatrix} c_{12}^* & s_{12}^* & 0 & a_1 c_1^* + a_2 c_{12}^* \\ s_{12}^* & -c_{12}^* & 0 & a_1 s_1^* + a_2 s_{12}^* \\ 0 & 0 & -1 & -d_3^* \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

SCARA

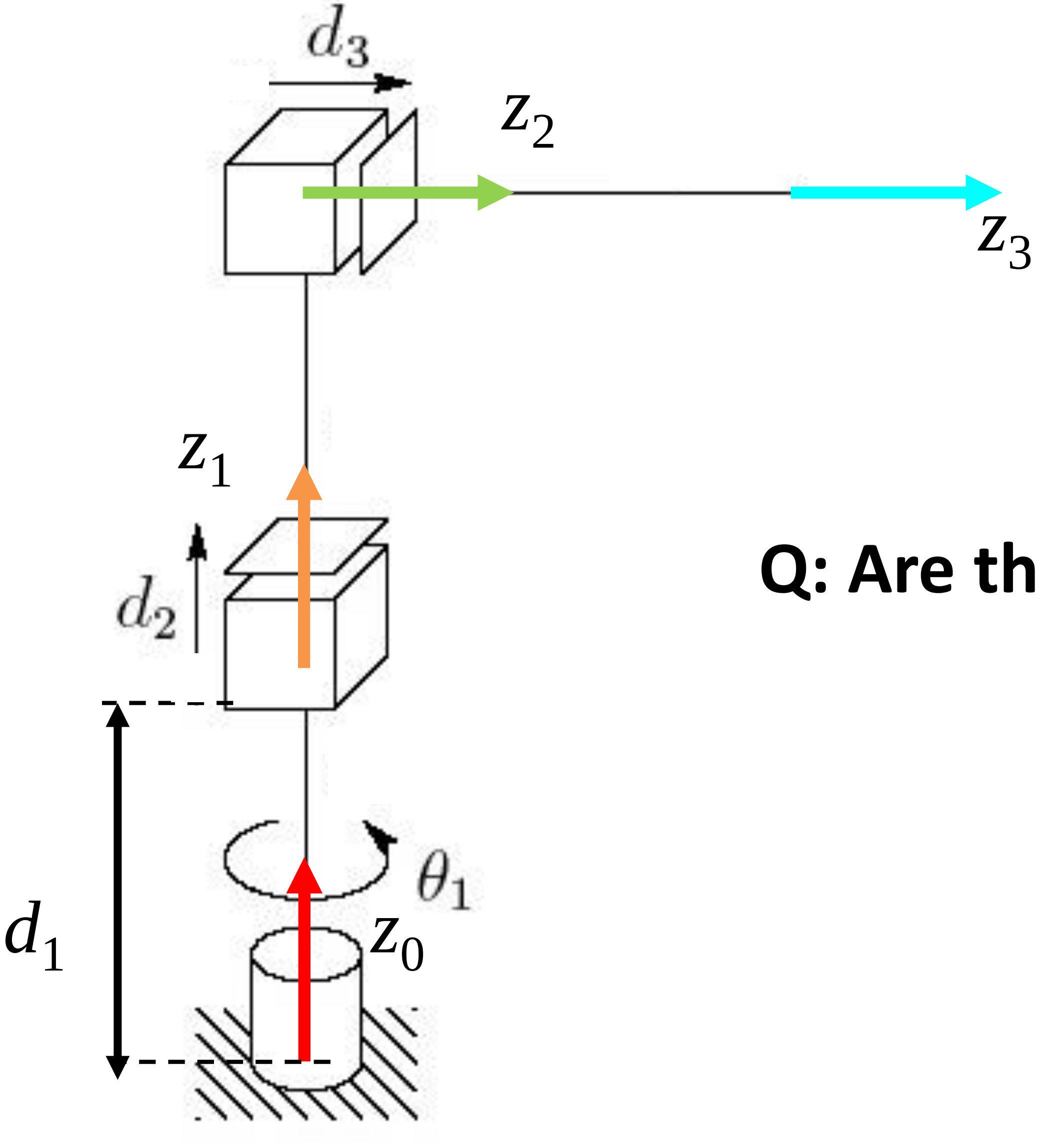
$$A_1 = \begin{bmatrix} c_1 & -s_1 & 0 & a_1 c_1 \\ s_1 & c_1 & 0 & a_1 s_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_2 = \begin{bmatrix} c_2 & s_2 & 0 & a_2 c_2 \\ s_2 & -c_2 & 0 & a_2 s_2 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_3 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

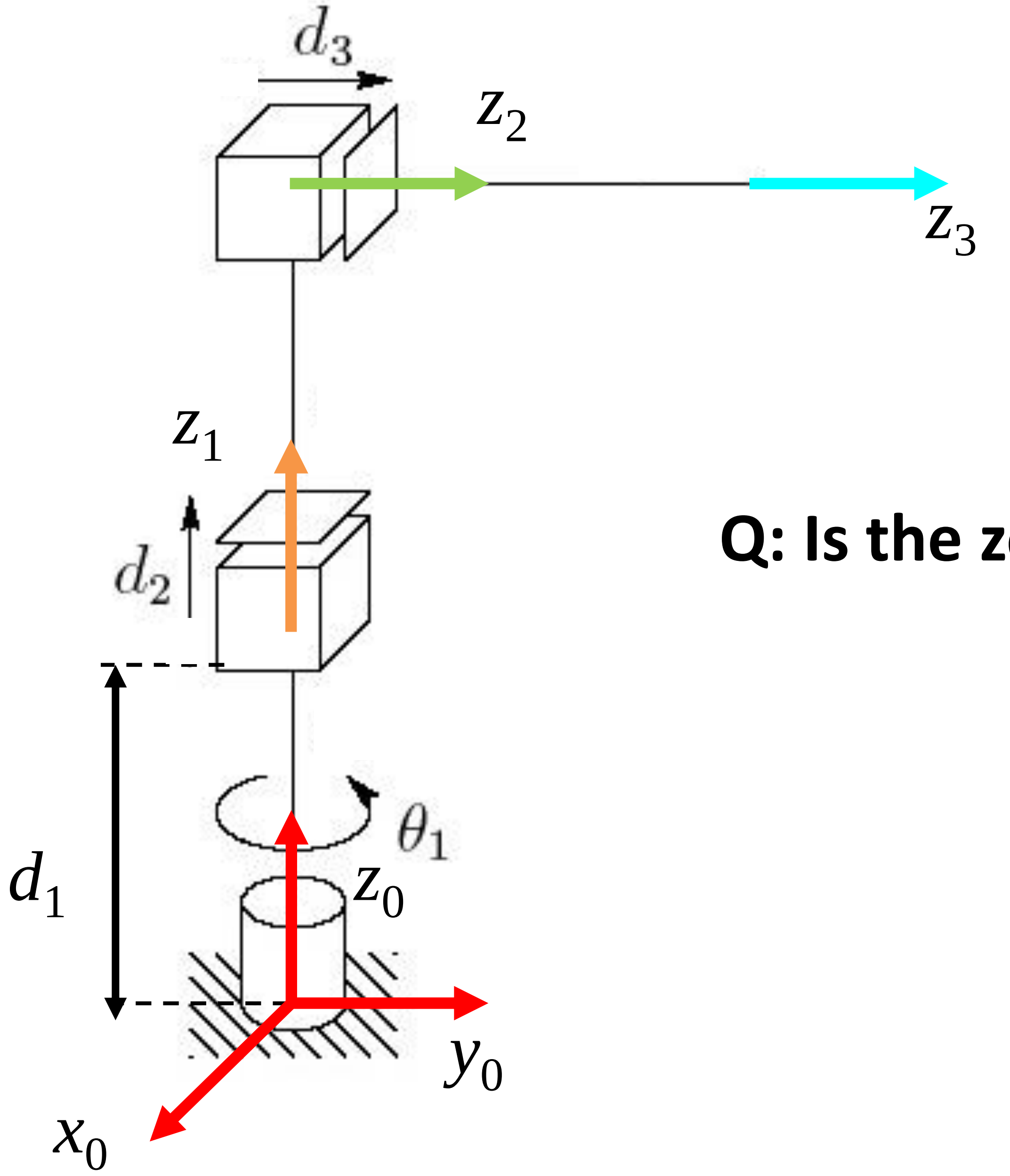


	x step		z step	
Link	a_i	α_i	d_i	θ_i
1	a_1	0	0	θ_1^*
2	a_2	180°	0	θ_2^*
3	0	0	d_3^*	0



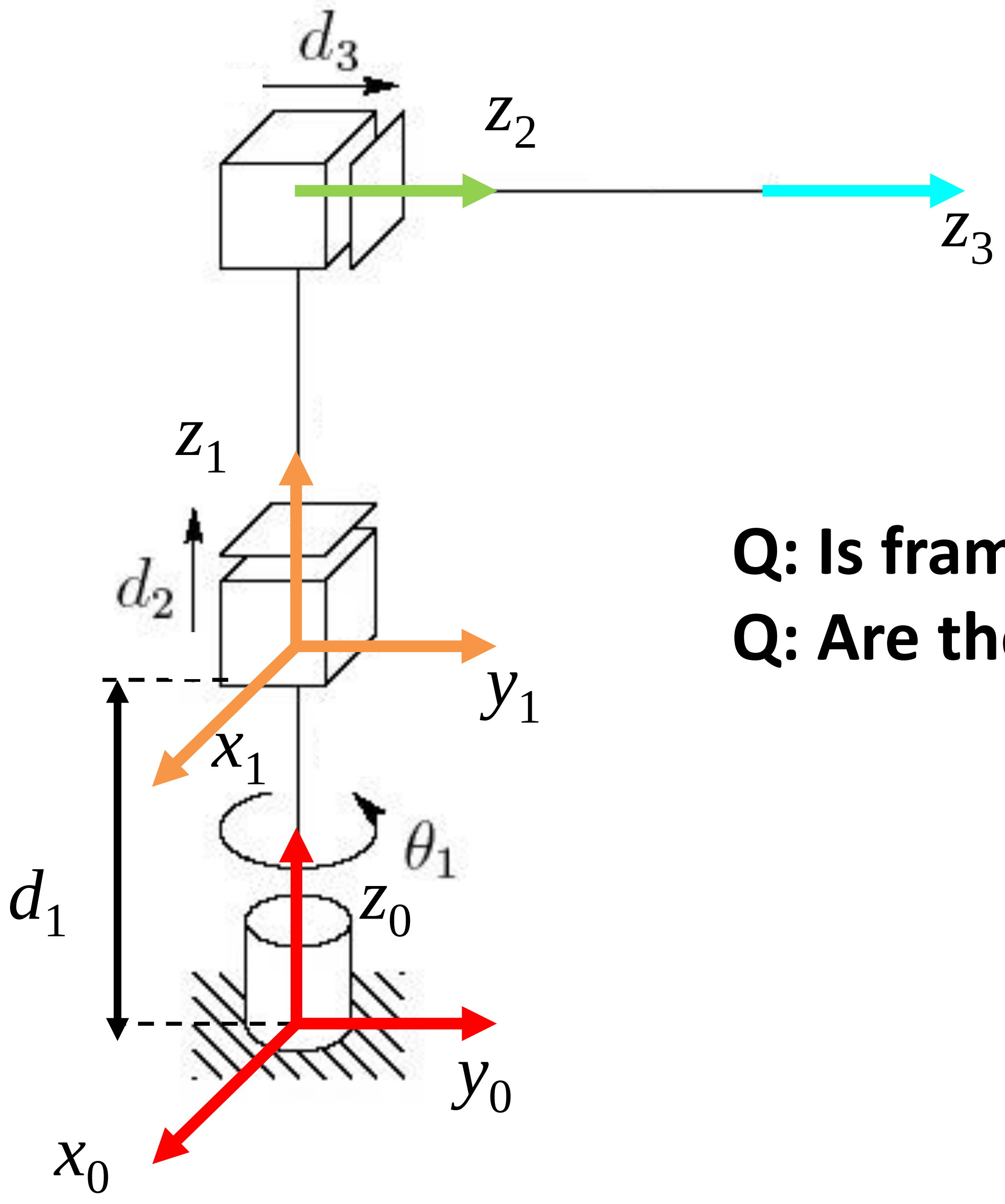
cylindrical

Q: Are these z-axis locations correct?



Q: Is the zero frame correct?

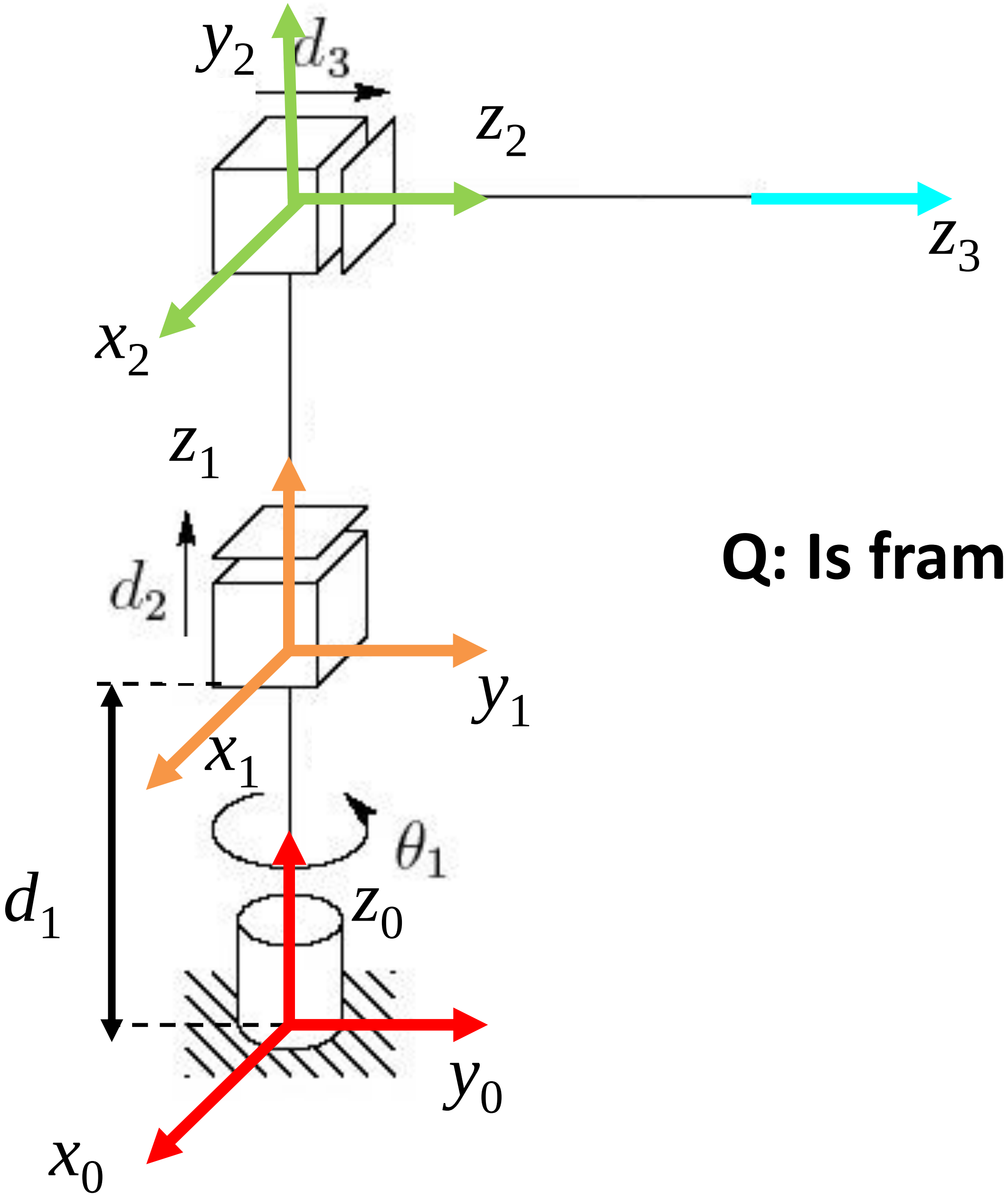
cylindrical



cylindrical

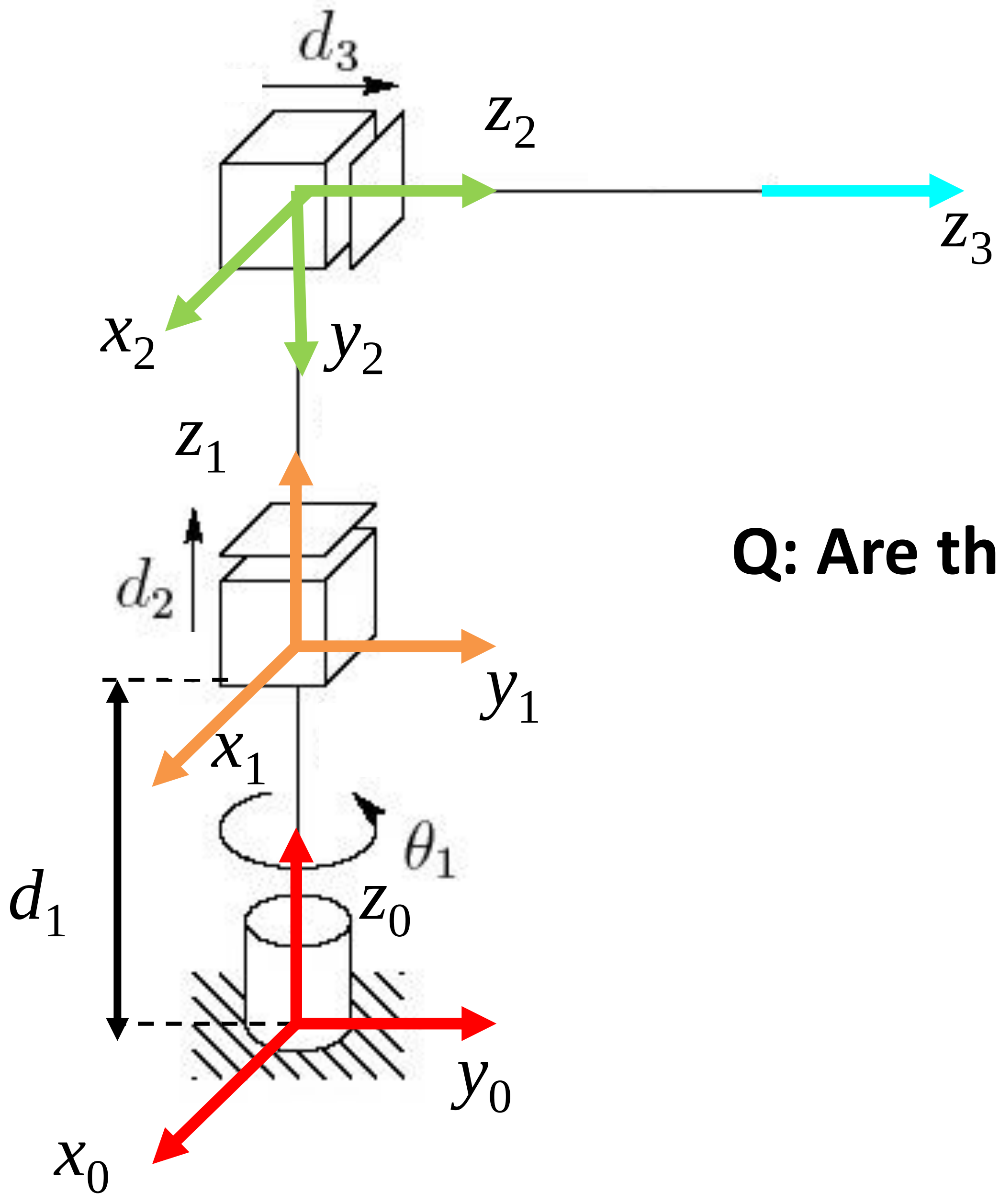
Q: Is frame 1 correct?

Q: Are there other options?



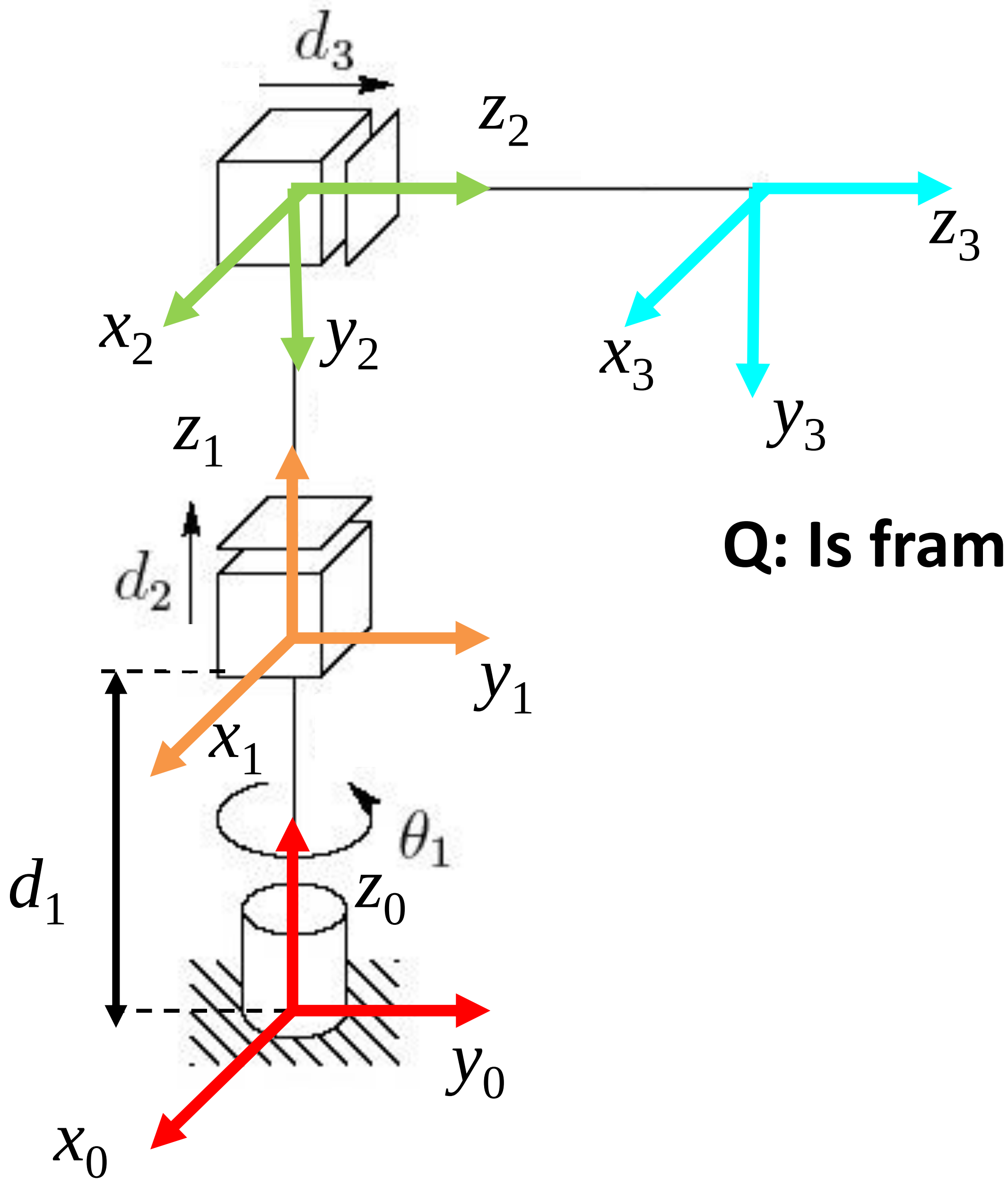
Q: Is frame 2 correct?

cylindrical



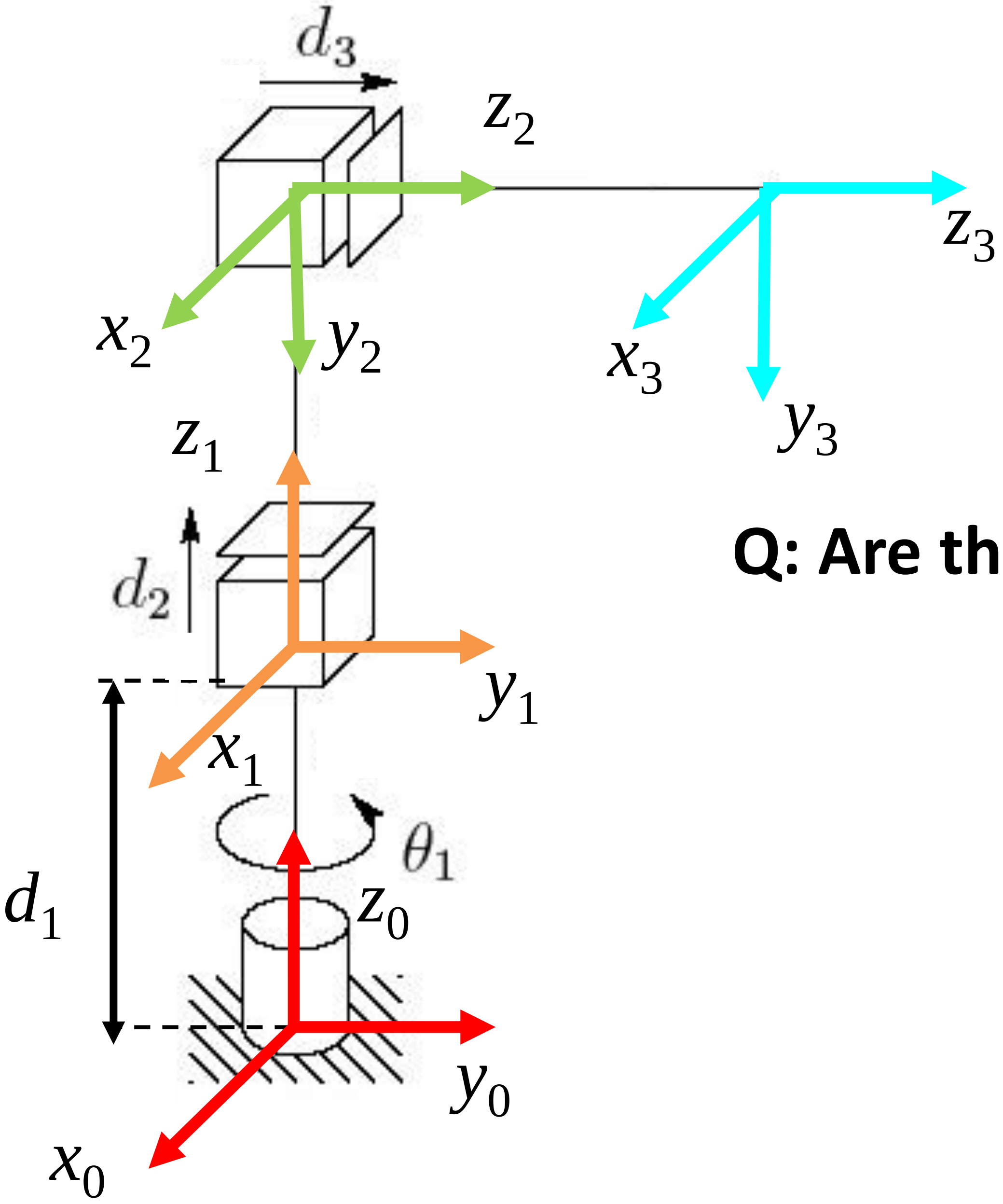
Q: Are there other options?

cylindrical



Q: Is frame 3 correct?

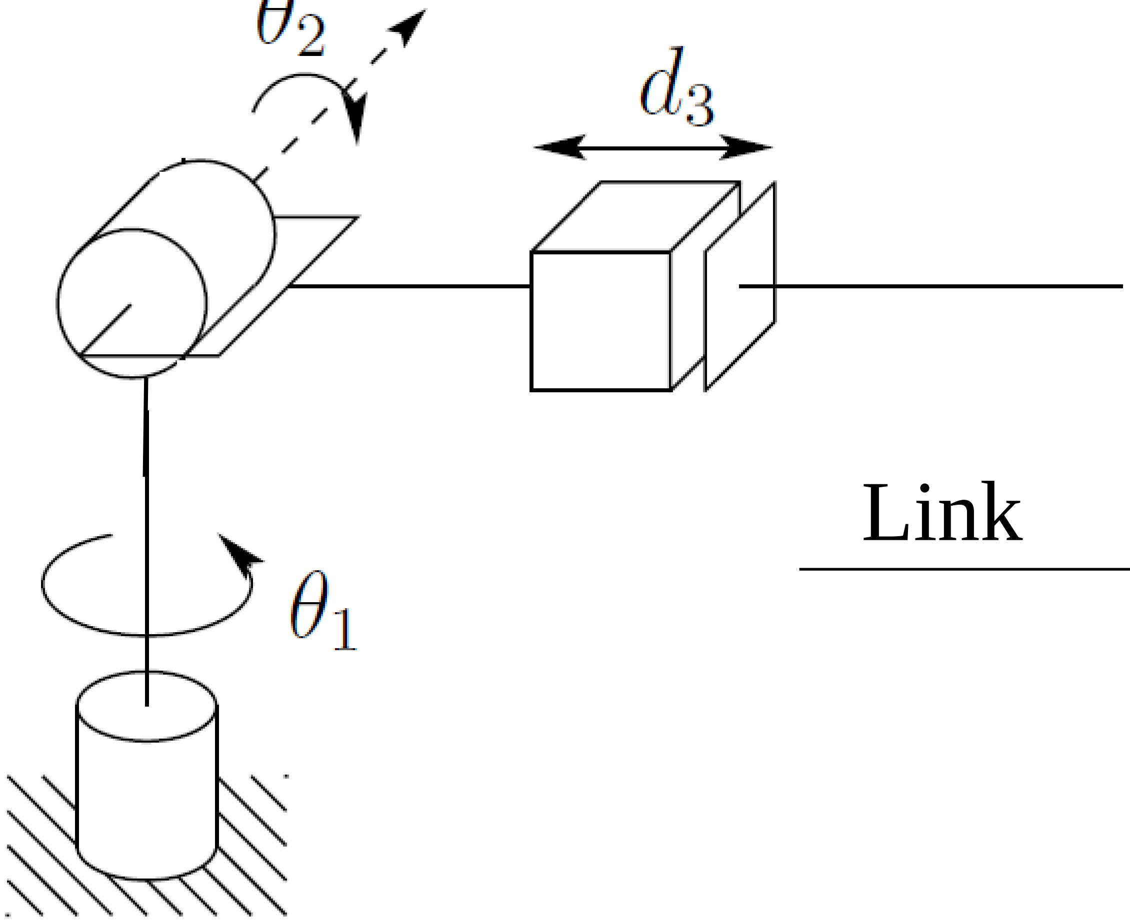
cylindrical



Q: Are there other options?

cylindrical

Your coordinate frame may not lie on the robot?!?!



Link	a_i	α_i	d_i	θ_I

You Practice

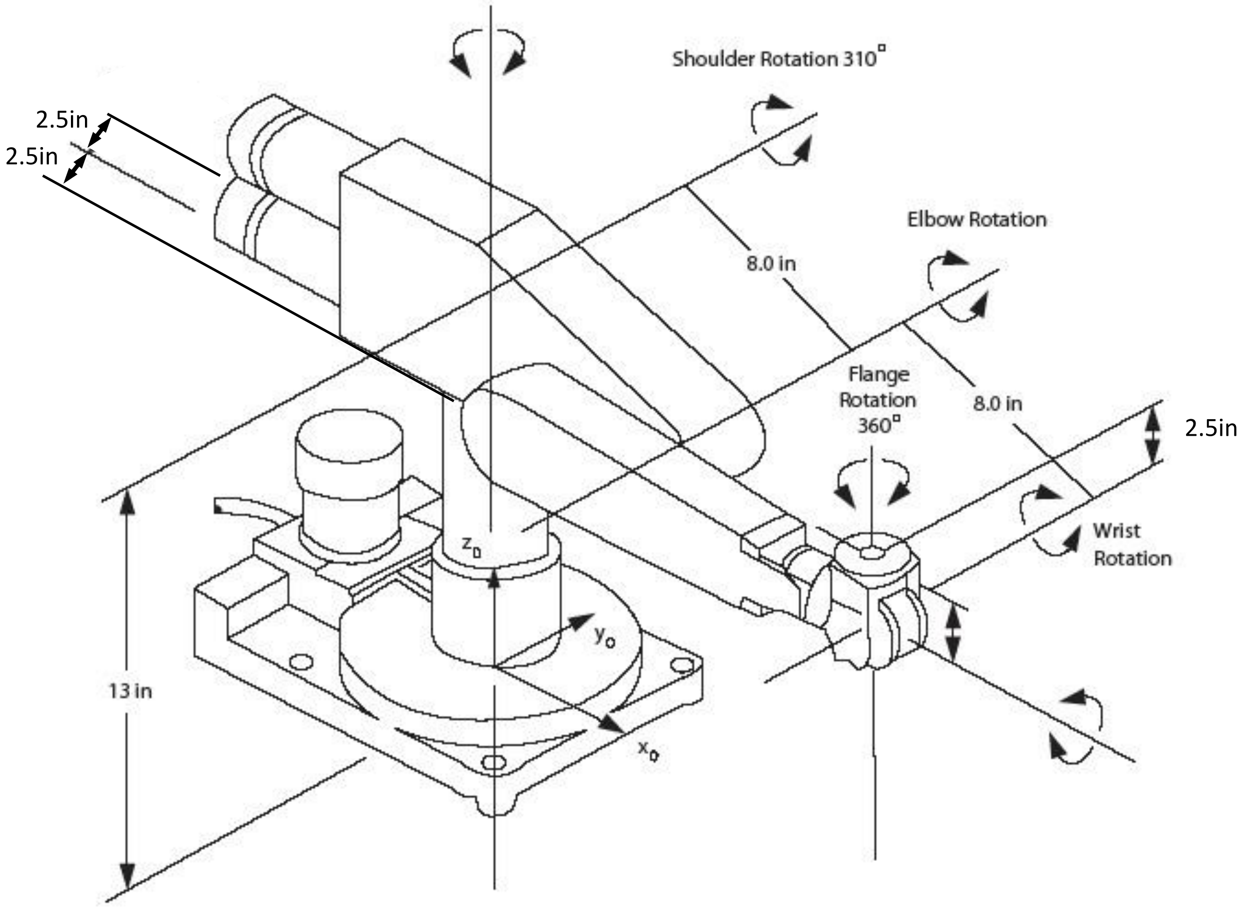
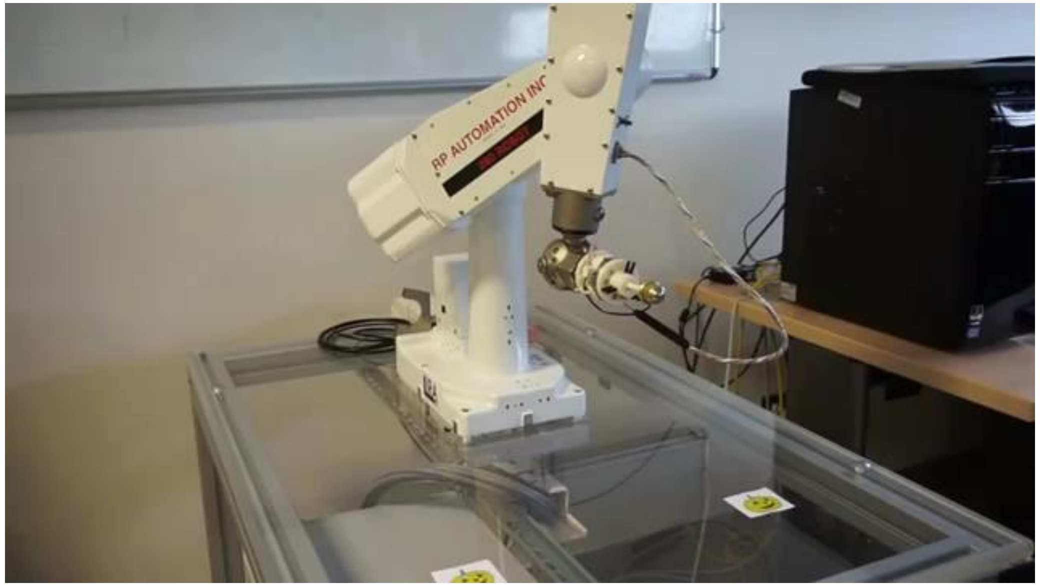


Figure 3.31: PUMA 260 manipulator.



https://www.youtube.com/watch?v=3zhTopWv2oI

Next time: Inverse Position Kinematics

Chapter 3: Forward and Inverse Kinematics

- Read 3.3 – 3.4