MEAM 520

DH Parameter Examples

Katherine J. Kuchenbecker, Ph.D.
General Robotics, Automation, Sensing, and Perception Lab (GRASP)
MEAM Department, SEAS, University of Pennsylvania

GRASP
LABORATORY

Lecture 8: September 24, 2013

Homework 2:
Rotation Matrices and Homogeneous Transformations

MEAM 520, University of Pennsylvania
Katherine J. Kuchenbecker, Ph.D.

September 10, 2013

This paper-based assignment is due on Tuesday, September 17, 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 Thursday, September 19, by noon (11:59:59 a.m.), but they will be penalized by 10% for each partial or full day late, up to 20%. After the late deadline, no further assignments may be submitted.

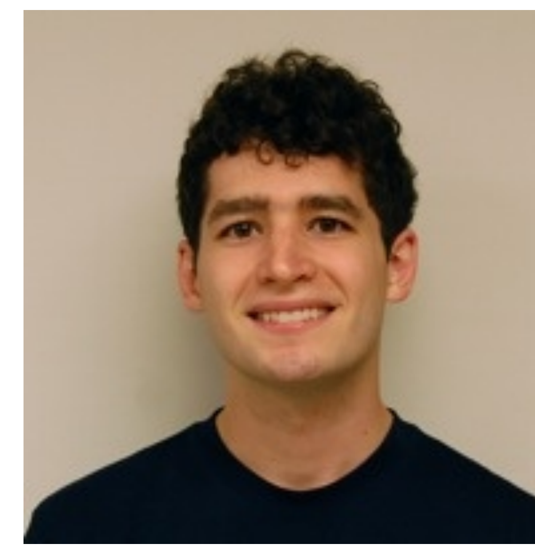
You may talk with other students about this assignment, ask the teaching team questions, use a calculator and other tools, and consult outside sources such as the Internet. To help you actually learn the material, what you write down should be your own work, not copied from any other individual or a 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 from 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. SHV 2-6, page 65 – Verifying Three Properties of $R_{z,\theta}$ *(2 points)*
2. SHV 2-10, page 66 – Sequence of Rotations *(2 points)*
   Please specify each element of each matrix in symbolic form and show the order in which the matrices should be multiplied; as stated in the problem, you do not need to perform the matrix multiplication.
3. SHV 2-14, page 67 – Rotating a Coordinate Frame *(4 points)*
   Sketch the initial, intermediate, and final frames by reading the text in the problem. Make your drawings big, and remember the right-hand rule. Then find R in two ways: by inspection of your sketch and by calculation. Check your solutions against one another.
4. SHV 2-23, page 68 – Axis/Angle Representation *(4 points)*
   Be careful with the sketch, and remember the right-hand rule.
5. SHV 2-39, page 70 – Homogeneous Transformations *(4 points)*
   Treat frame $o_2x_2y_2z_2$ as being located at the center of the cube's bottom surface (as drawn in Figure 2.14), not at the center of the cube (as stated in the problem). Be careful with notation; you are looking for H_1^0, H_2^0, H_3^0, and H_3^2.
6. SHV 2-43, page 71-72 – Commutativity of Homogeneous Transformations *(4 points)*

Pick up your graded Homework 2 from Naomi and Tyler before or after class.


Naomi Fitter


Tyler Barkin

Extra handouts also available at back.

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MEAM 520, University of Pennsylvania
Katherine J. Kuchenbecker, Ph.D.

September 10, 2013

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6. SHV 2-43, page 71-72 – Commutativity of Homogeneous Transformations *(4 points)*

Homework 2 is graded. Scores are on Canvas.

Common mistakes:

- Doing the wrong first problem.
- Not specifying matrix elements when requested.
- Not sketching k-vector in the axis-angle problem.
- Mixing up positive and negative signs in translation part of H.
- Last problem.

Solutions to Homework 2
Rotation Matrices and Homogeneous Transformations

MEAM 520
Introduction to Robotics
University of Pennsylvania
Professor Kuchenbecker
Fall 2013

Homework 2 Solutions are on reserve in the Engineering Library.

Go look at them, post on Piazza, or come to office hours if you have any confusions.

Many thanks to the two students who shared their LaTeX source code for use in the solutions.

Homework 3: Flying Box Version 2
(Updated to Improve Clarity)

MEAM 520, University of Pennsylvania
Katherine J. Kuchenbecker, Ph.D.

September 17, 2013

This assignment is due on **Friday, September 20, by midnight (11:59:59 p.m.)** Your code should be submitted via email according to the instructions at the end of this document. Late submissions will be accepted until Sunday, September 22, by midnight (11:59:59 p.m.), but they will be penalized by 10% for each partial or full day late, up to 20%. 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 team. 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!

Individual vs. Pair Programming

You may do this assignment either individually or with a partner, according to your personal preference. Read the assignment to decide which option is right for you. If you do this homework with a partner, you may work with anyone you choose, even someone with substantial MATLAB experience. If you are looking for a partner, consider using the "Search for Teammates!" tool on Piazza.

If you are in a pair, you should work closely with your partner throughout this assignment, following the paradigm of pair programming. You will turn in one MATLAB script for which you are both jointly responsible, and you will both receive the same grade. Please follow these pair programming guidelines, which were adapted from "All I really need to know about pair programming I learned in kindergarten," by Williams and Kessler, *Communications of the ACM*, May 2000:

- Start with a good attitude, setting aside any skepticism and expecting to jell with your partner.
- Don't start writing code alone. Arrange a meeting with your partner as soon as you can.
- Use just one computer, and sit side by side; a desktop computer with a large monitor is better for this than a laptop. Make sure both partners can see the screen.
- At each instant, one partner should be driving (using the mouse and keyboard or recording design ideas) while the other is continuously reviewing the work (thinking and making suggestions).
- Change driving/reviewing roles at least every thirty 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 a bug in the code your partner is typing, wait until they finish the line to correct them.
- Stay focused and on-task the whole time you are working together.
- Recognize that pair programming usually takes more effort than programming alone, but it produces better code, deeper learning, and a more positive experience for the participants.
- Take a break periodically to refresh your perspective.
- Share responsibility for your project; avoid blaming either partner for challenges you run into.

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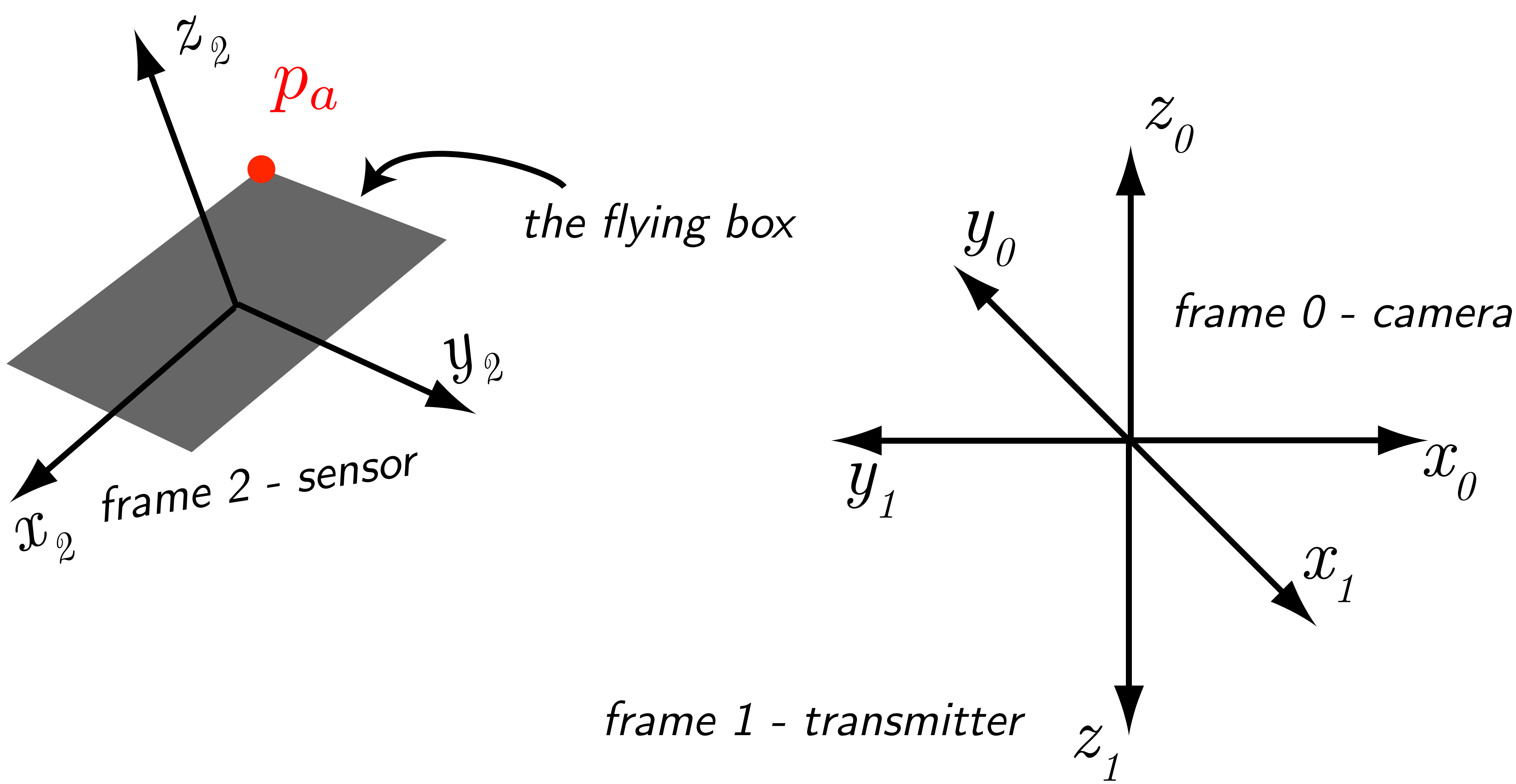
Homework 3 is now being graded. Scores will be on Canvas soon.

Common mistakes:

- Submitting late.
- Incorrect rotation matrices around each axis.
- Incorrect order when multiplying the matrices.
- Not transforming positions from frame 1 to frame 0.



$$p_a^0 = H_1^0 H_2^1 p_a^2$$

Subscript and superscript cancel

Editor – /Users/kuchenbe/Documents/teaching/meam 520/assignments/03 box/matlab/flying_box_kuchenbe.m

EDITOR PUBLISH VIEW

flying_box_kuchenbe.m

```matlab
%% flying_box_kuchenbe.m
%
% This Matlab script provides the solution for the flying box
% problem on Homework 1 in MEAM 520 at the University of Pennsylvania.
% The original was written by Professor Katherine J. Kuchenbecker
% (kuchenbe@seas.upenn.edu). Students will modify this code to create
% their own script.
%
% Change the name of this file to replace "starter" with your PennKey.  For
% example, Professor Kuchenbecker's script would be flying_box_kuchenbe.m

%% SETUP

% Delete all variables from our workspace.
clear

% Set student names.
studentNames = 'KJK (Solution)';

% Load the TrakStar data recorded during the movie.
% This MATLAB data file includes time histories of the x, y, and z
% coordinates in inches, as well as time histories of the azimuth,
% elevation, and roll angles in degrees.
load flying_box;


%% DEFINITIONS

% We need to keep track of three frames in this code.
%
% Frame 0 is the frame of the camera's view, with x positive to the right,
% y positive straight back, and z positive up.  The is the base frame, and
% it's what we plot in.  Its origin coincides with the origin of frame 1.
%
% Frame 1 is the frame of the TrakStar transmitter, which sits on the desk.
% It has x positive straight out, y positive to the left, and z positive
% down.  This is the frame in which the sensor positions and orientations
% are expressed.  Its origin is near the center of the transmitter's beige
```

script | Ln 13 Col 1

flying_box_kuchenbe.m

Table of Contents

This Matlab script provides the solution for the flying box problem on Homework 1 in MEAM 520 at the University of Pennsylvania. The original was written by Professor Katherine J. Kuchenbecker (kuchenbe@seas.upenn.edu). Students will modify this code to create their own script.

Change the name of this file to replace "starter" with your PennKey. For example, Professor Kuchenbecker's script would be flying_box_kuchenbe.m

SETUP

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DEFINITIONS

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% Frame 0 is the frame of the camera's view, with x positive to the right,
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%
% Frame 1 is the frame of the TrakStar transmitter, which sits on the desk.
% It has x positive straight out, y positive to the left, and z positive
% down.  This is the frame in which the sensor positions and orientations
% are expressed.  Its origin is near the center of the transmitter's beige
% cube, which can be seen in the video.
%
% Frame 2 is the frame of the TrakStar sensor, which is being moved around.
% Its x-axis is straight out horizontal through the front of the box, in
% the direction the hand is facing.  Its y-axis is mostly horizontal during
% the video, and its z-axis is mostly vertical.

% Define the locations of the box's four corners (ignoring thickness) in
% the sensor's frame (frame 2).  The length is in the direction of the
```

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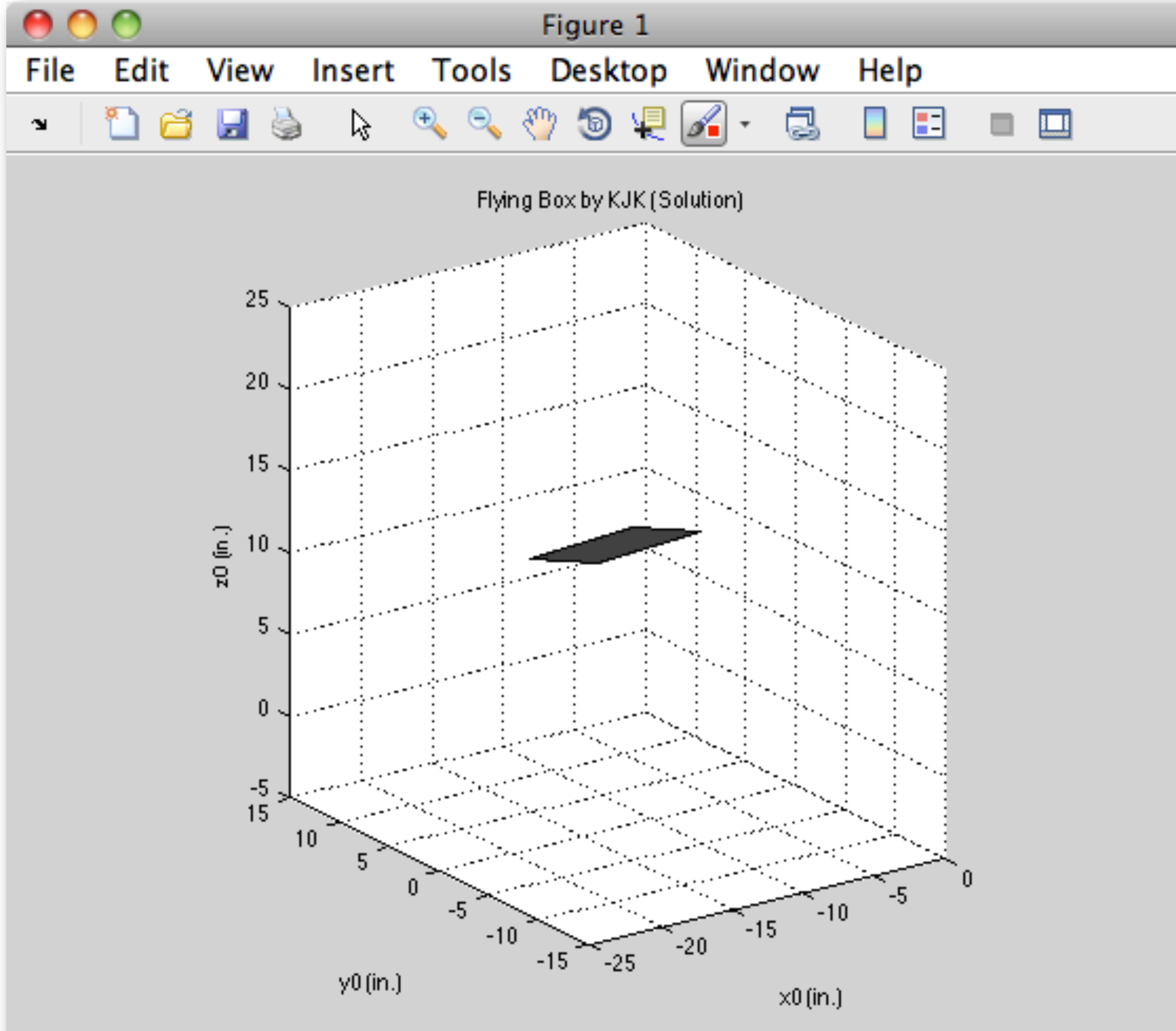

How did I make the flying box move over time?

Homework 4:
Forward Kinematics and DH Parameters

MEAM 520, University of Pennsylvania
Katherine J. Kuchenbecker, Ph.D.

September 19, 2013

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.

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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.

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Homework 4

Due Thursday 9/26 by midnight.

Late deadline is Sunday 9/29 at midnight.

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.

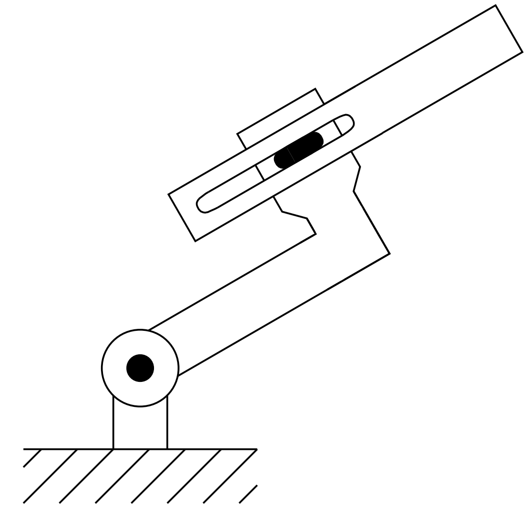
Do the following steps for each of the next three problems:

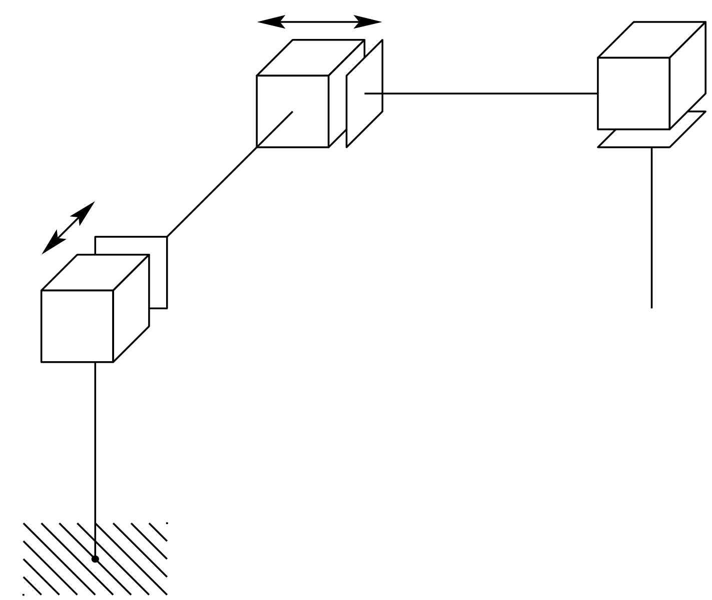
- Draw a schematic of the robot in its zero configuration.
- Draw your frames on the diagram, following the DH convention.
- Use a superscript star, e.g., θ_1^*, to denote all joint variables.
- Use an arrow labeled with the joint variable name to mark the positive direction for all joint variables on 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.

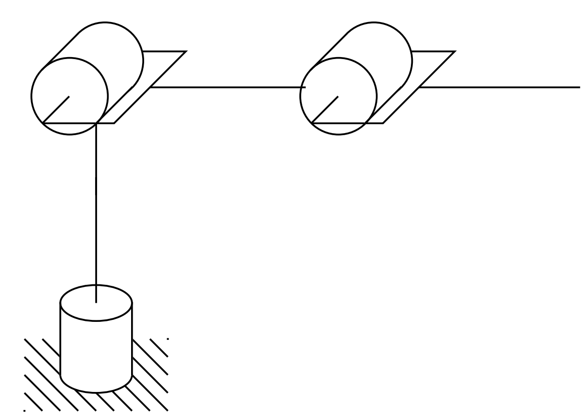
4. SHV 3-4, page 112 – Forward Kinematics of a Two-Link Planar RP Arm With Offset *(4 points)*
   You may choose the zero configuration.

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.



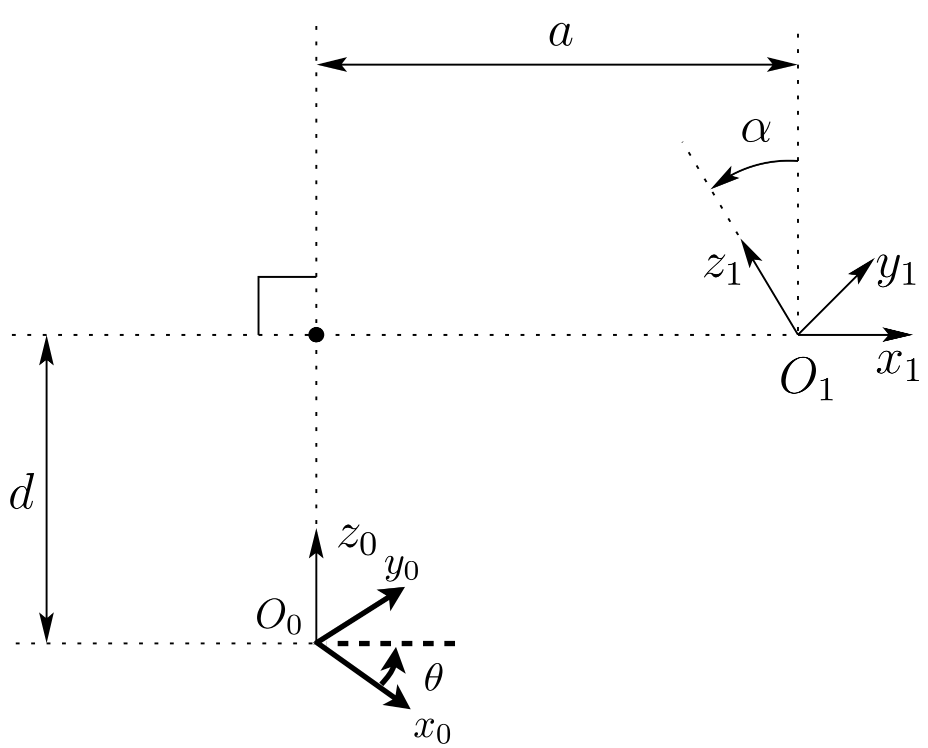




The Denavit-Hartenberg (DH) Convention for Manipulator Forward Kinematics

Given the design of my robot and the current values for its joint variables, where is the end-effector, and how is it oriented?

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



$$A_i = \mathrm{Rot}_{z,\theta_i}\ \mathrm{Trans}_{z,d_i}\ \mathrm{Trans}_{x,a_i}\ \mathrm{Rot}_{x,\alpha_i}$$

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

Link	a_i	α_i	d_i	θ_i

DH Coordinate Frame Assumptions

(DH1) The axis x_1 is perpendicular to the axis z_0.

(DH2) The axis x_1 intersects the axis z_0.

Great List of DH Steps on page 110-111 in SHV

Procedure for Deriving the Forward Kinematics of a Manipulator
Following the Denavit-Hartenberg (DH) Convention
From "Robot Modeling and Control" by Spong, Hutchinson, and Vidyasagar

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

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.

For $i = 1, \ldots, n-1$, perform Steps 3 to 5.

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.

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.

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

(fixed!)

$a_i =$ 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.

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

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.

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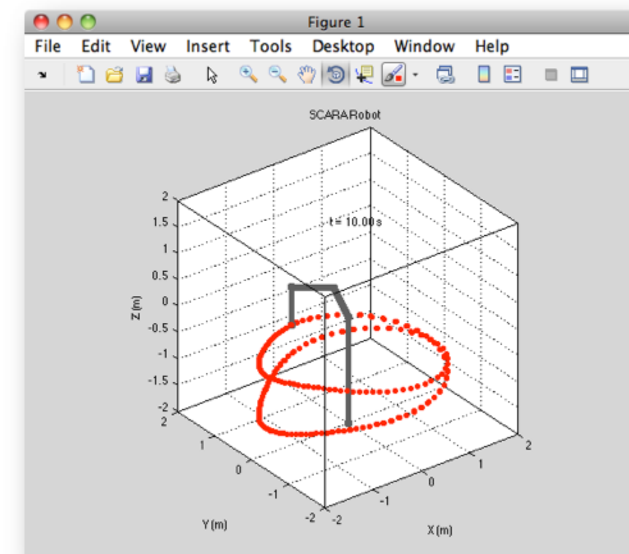
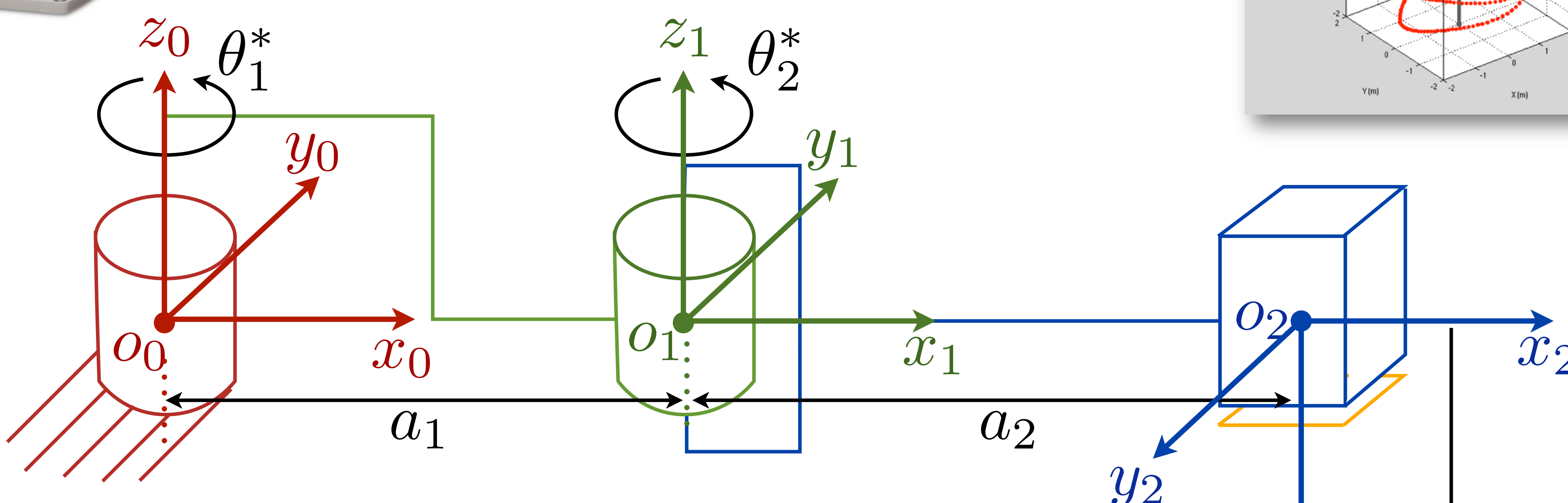
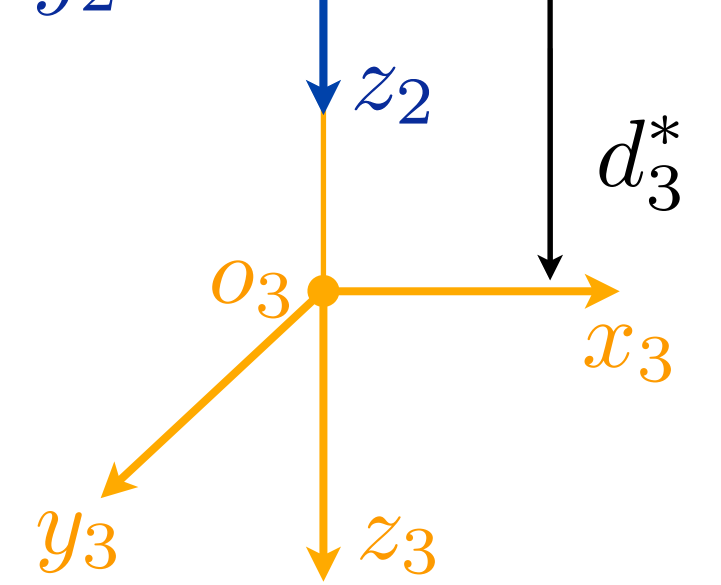
$$T_3^0 = A_1\ A_2\ A_3$$

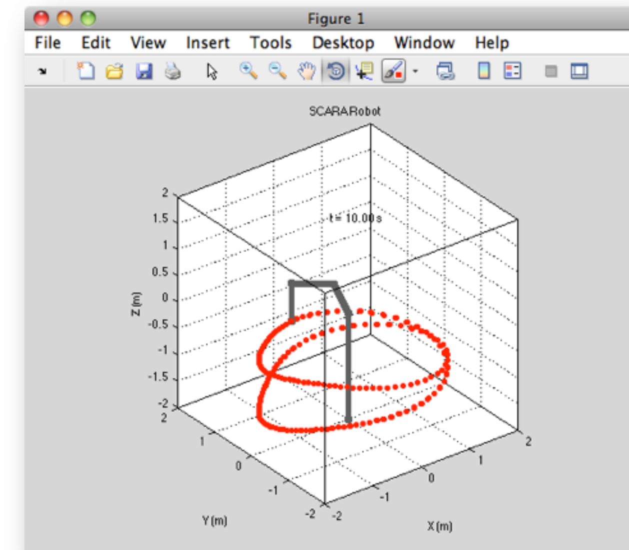


The slides on the SCARA robot example were updated to color the link to match the frame that moves with it.





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



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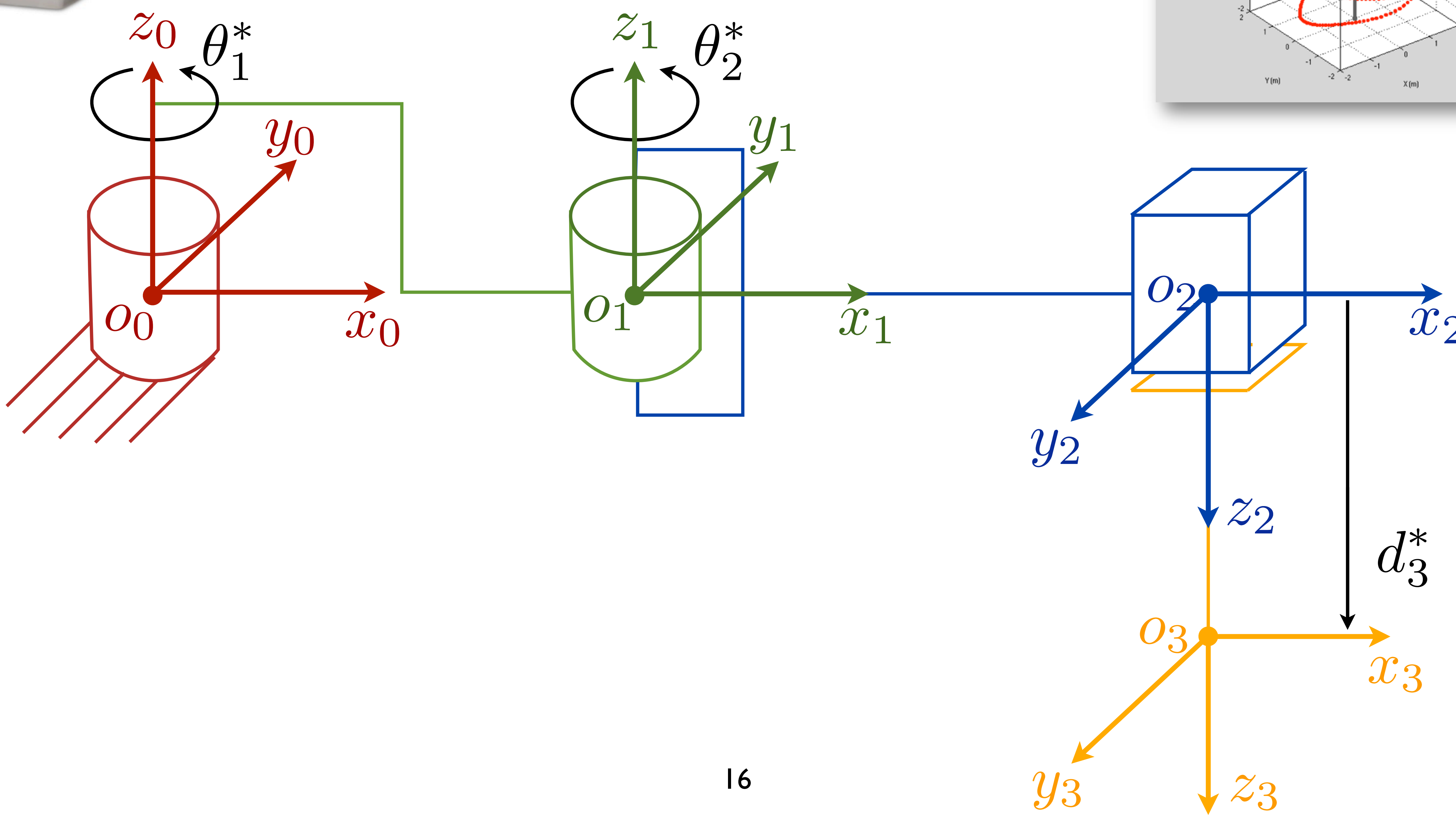
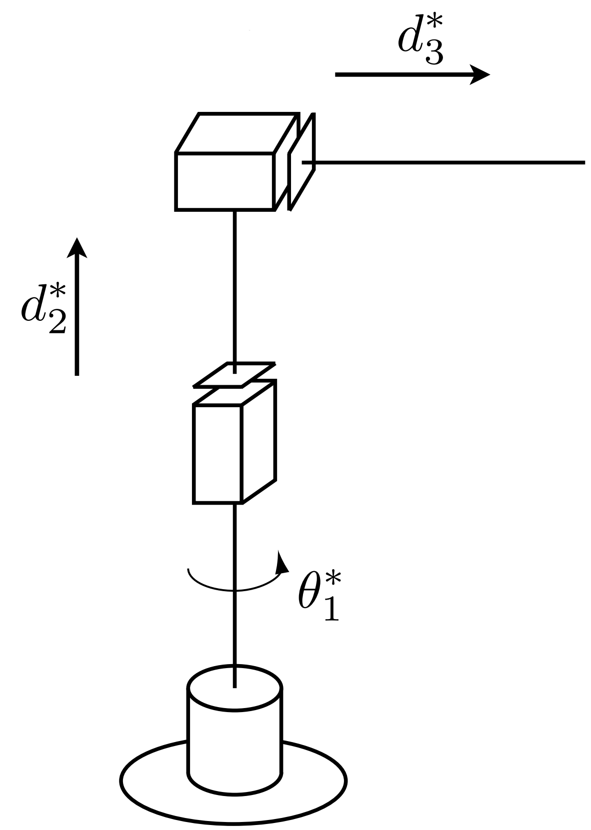


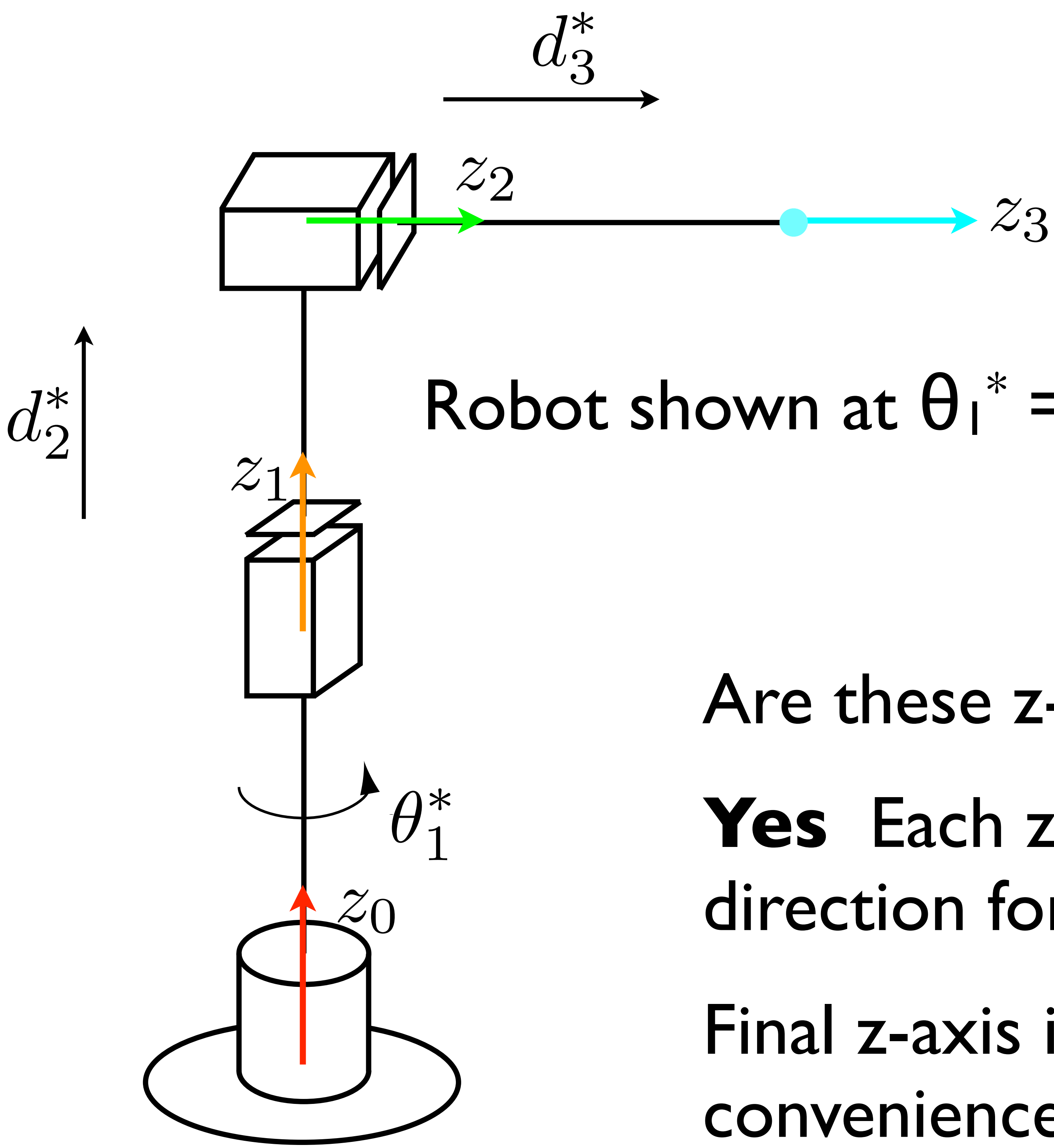
DH Example #1
Cylindrical Robot

DH Parameters for the Cylindrical Robot



Link	a_i	α_i	d_i	θ_i

The RPP Cylindrical Robot



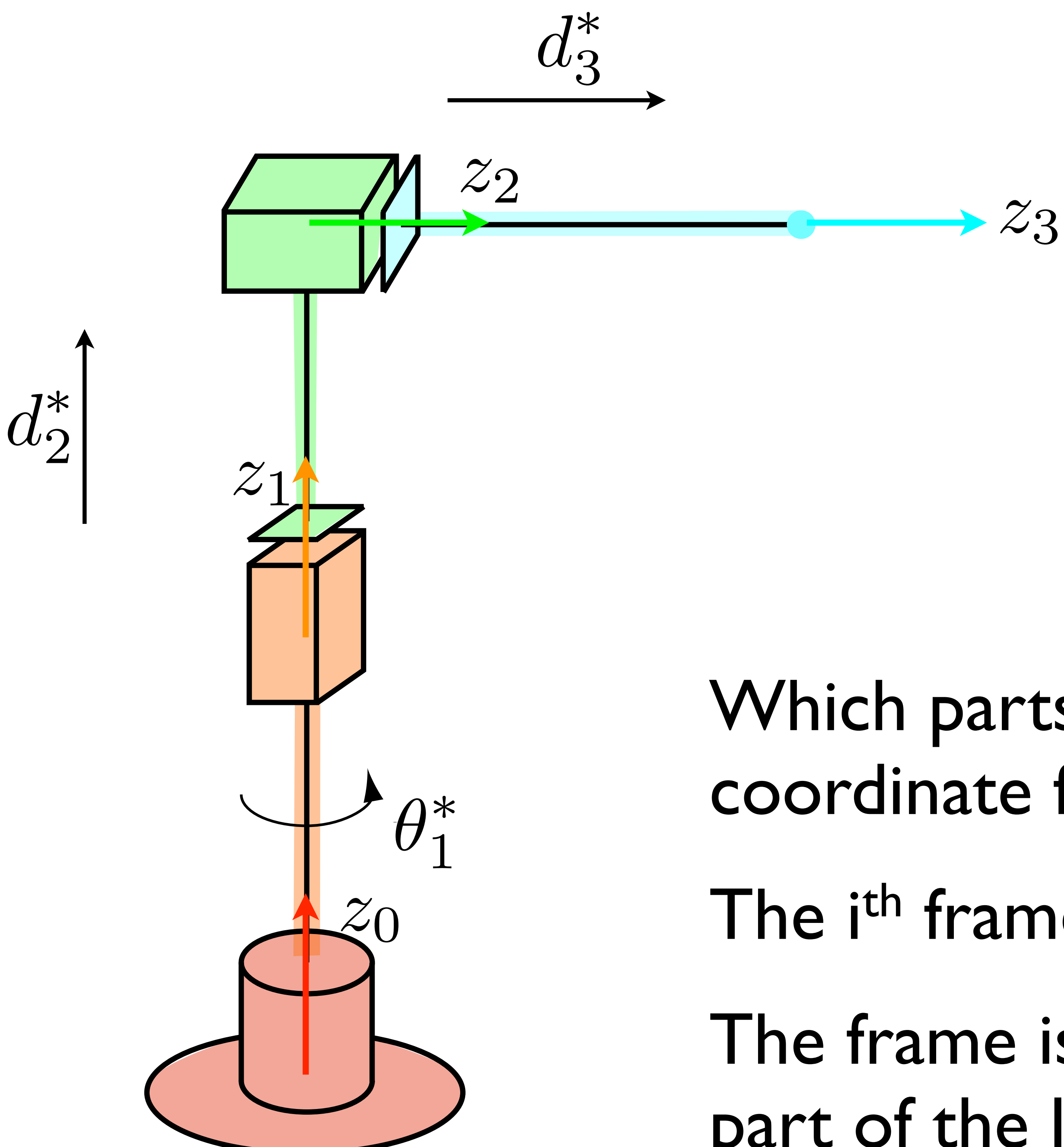
Robot shown at $\theta_1^* = 0$, $d_2^* > 0$ $d_3^* > 0$

Are these z-axis locations correct?

Yes Each z-axis defines the positive axial direction for the following joint variable.

Final z-axis is parallel to previous one for convenience. Could have chosen other.

The RPP Cylindrical Robot

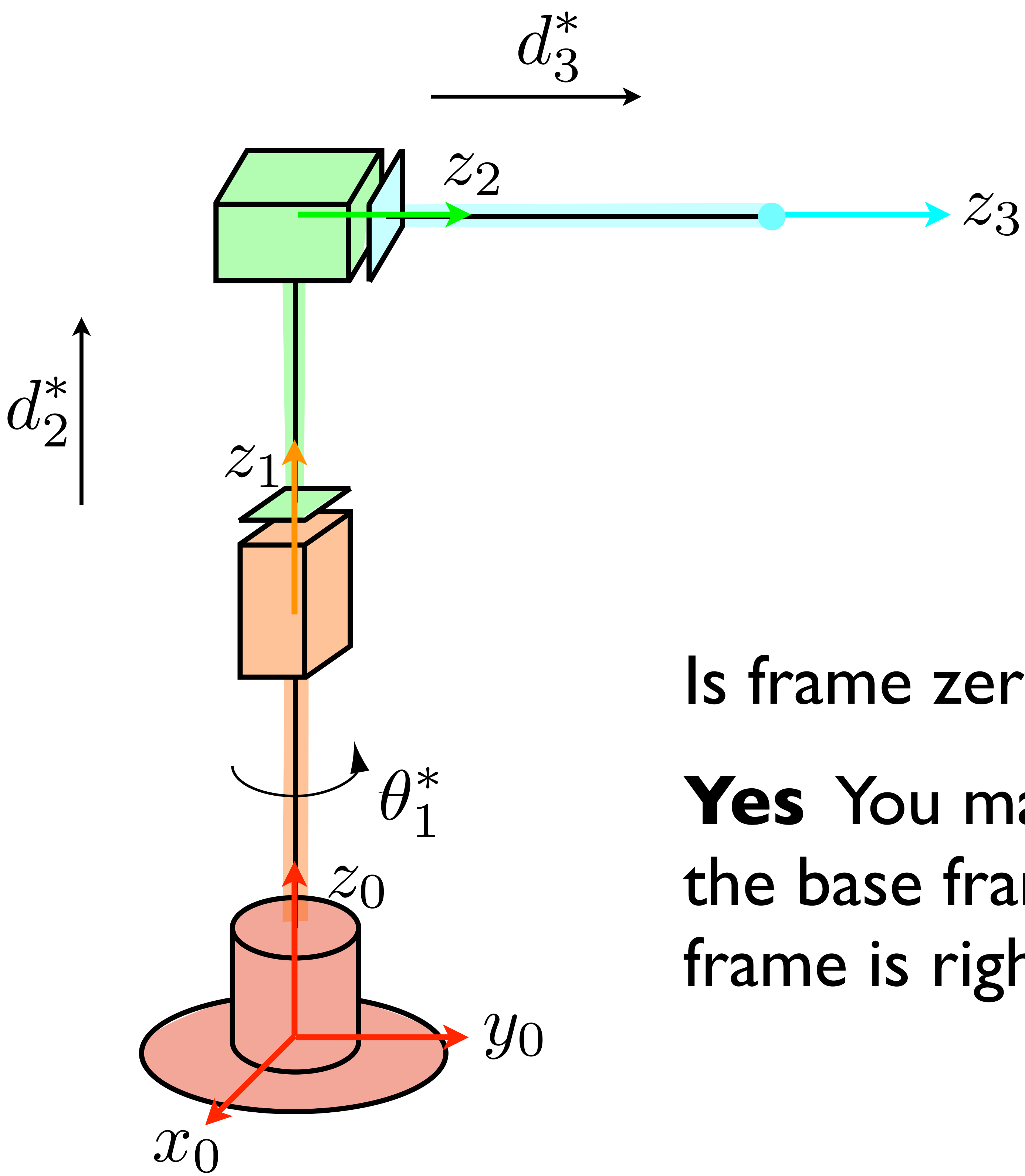


Which parts of the robot move with each coordinate frame?

The i[th] frame moves with the i[th] link.

The frame is typically on the most distant part of the link, defining the next axis.

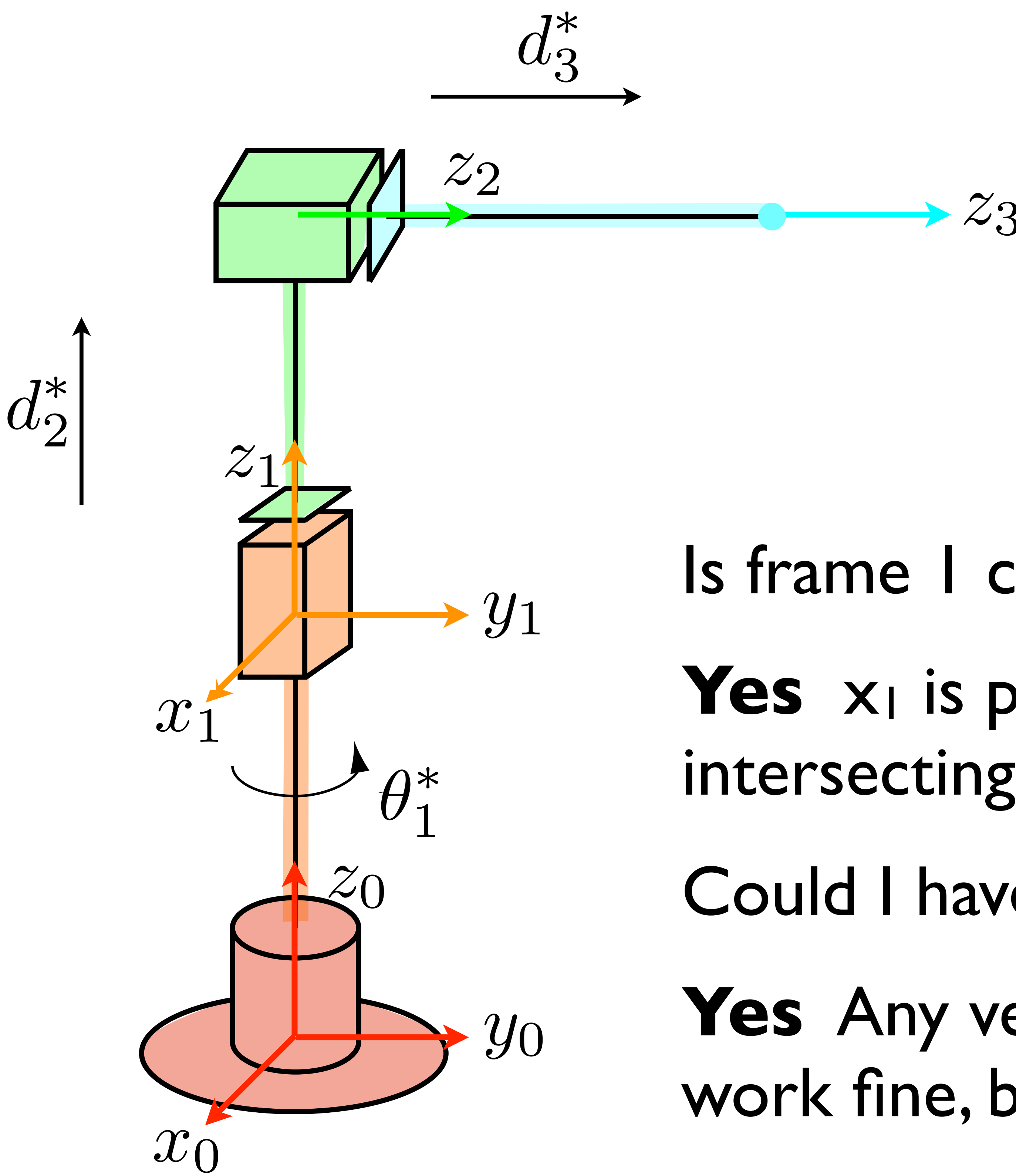
The RPP Cylindrical Robot



Is frame zero correct?

Yes You may pick any x- and y-axes for the base frame as long as the resulting frame is right-handed.

The RPP Cylindrical Robot



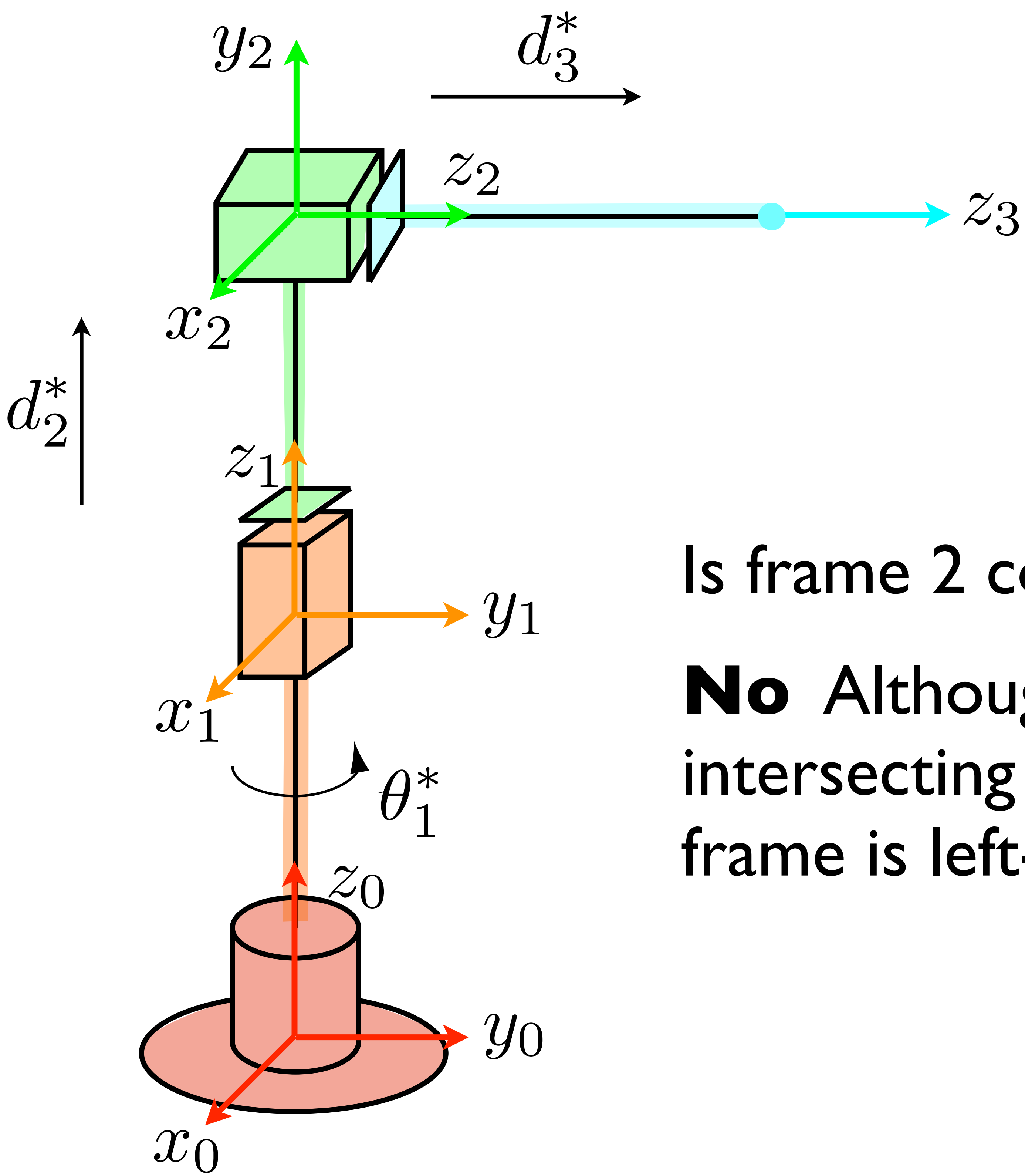
Is frame 1 correct?

Yes x_1 is perpendicular to and intersecting both z_0 and z_1.

Could I have chosen any other x_1?

Yes Any vector perpendicular to z_1 would work fine, but the parameters would differ.

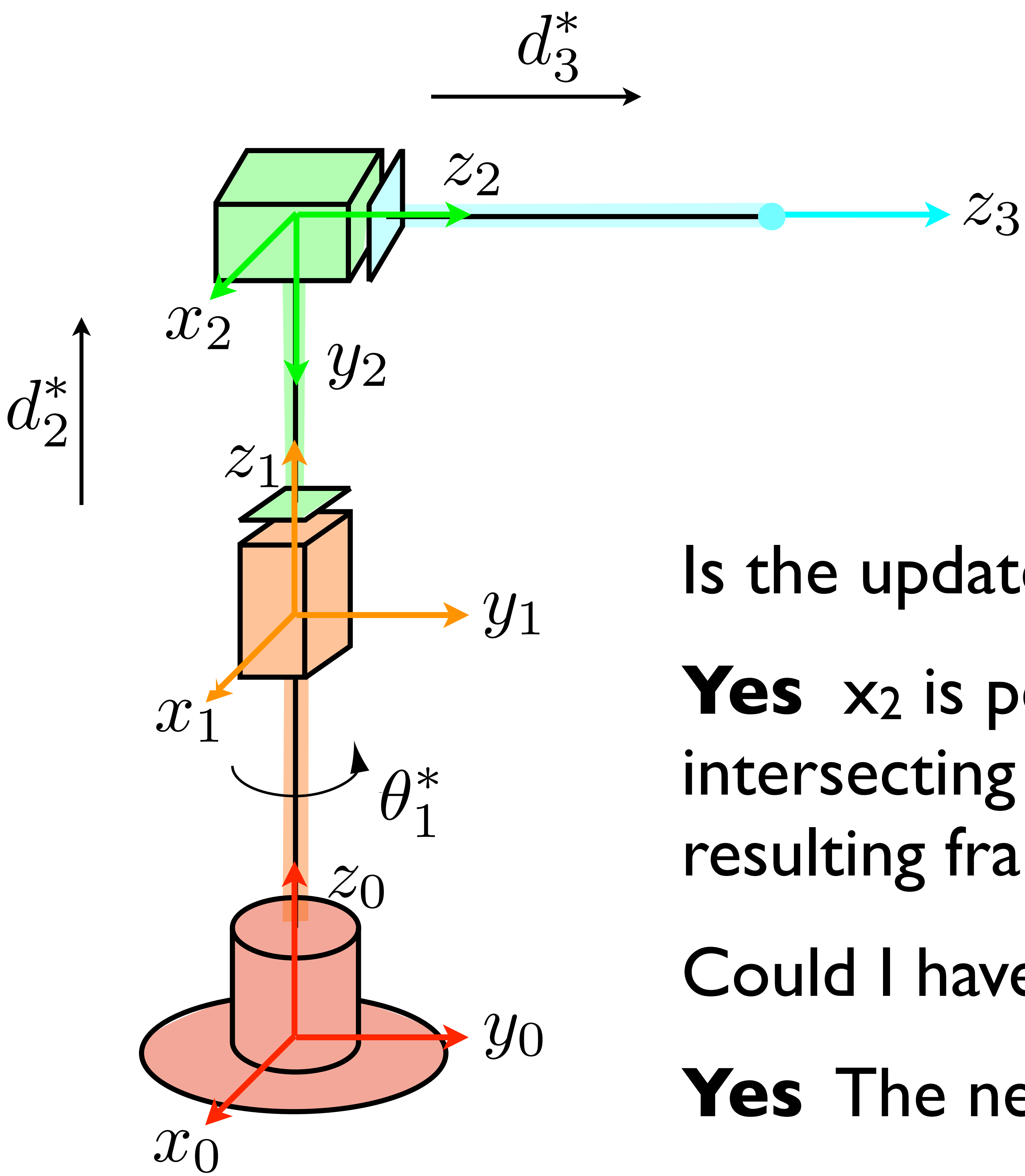
The RPP Cylindrical Robot



Is frame 2 correct?

No Although x_2 is perpendicular to and intersecting both z_1 and z_2, the resulting frame is left-handed. Must be corrected.

The RPP Cylindrical Robot



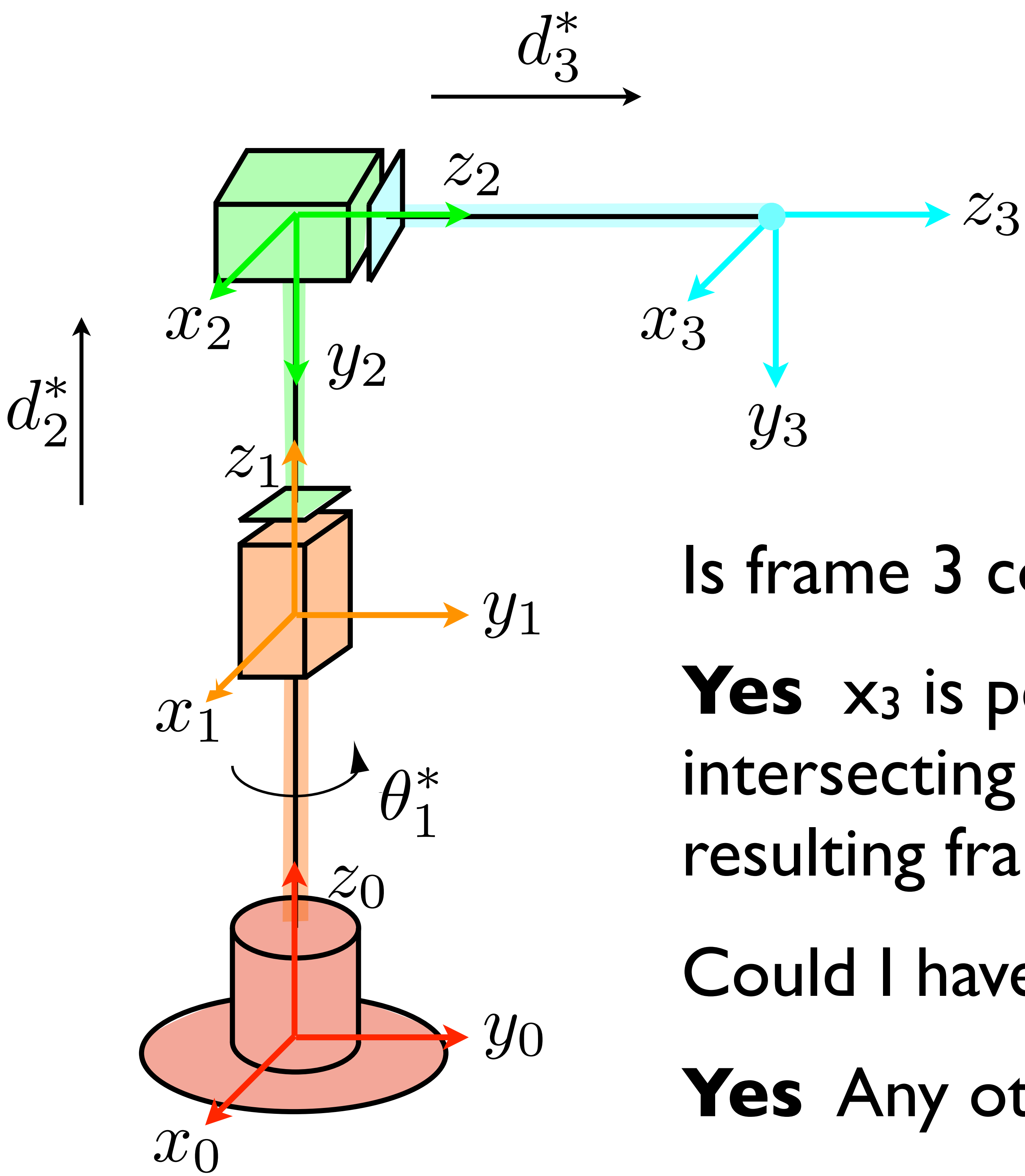
Is the updated frame 2 correct?

Yes x_2 is perpendicular to and intersecting both z_1 and z_2, and the resulting frame is right-handed.

Could I have chosen any other x_2?

Yes The negative of what is shown would also be correct.

The RPP Cylindrical Robot



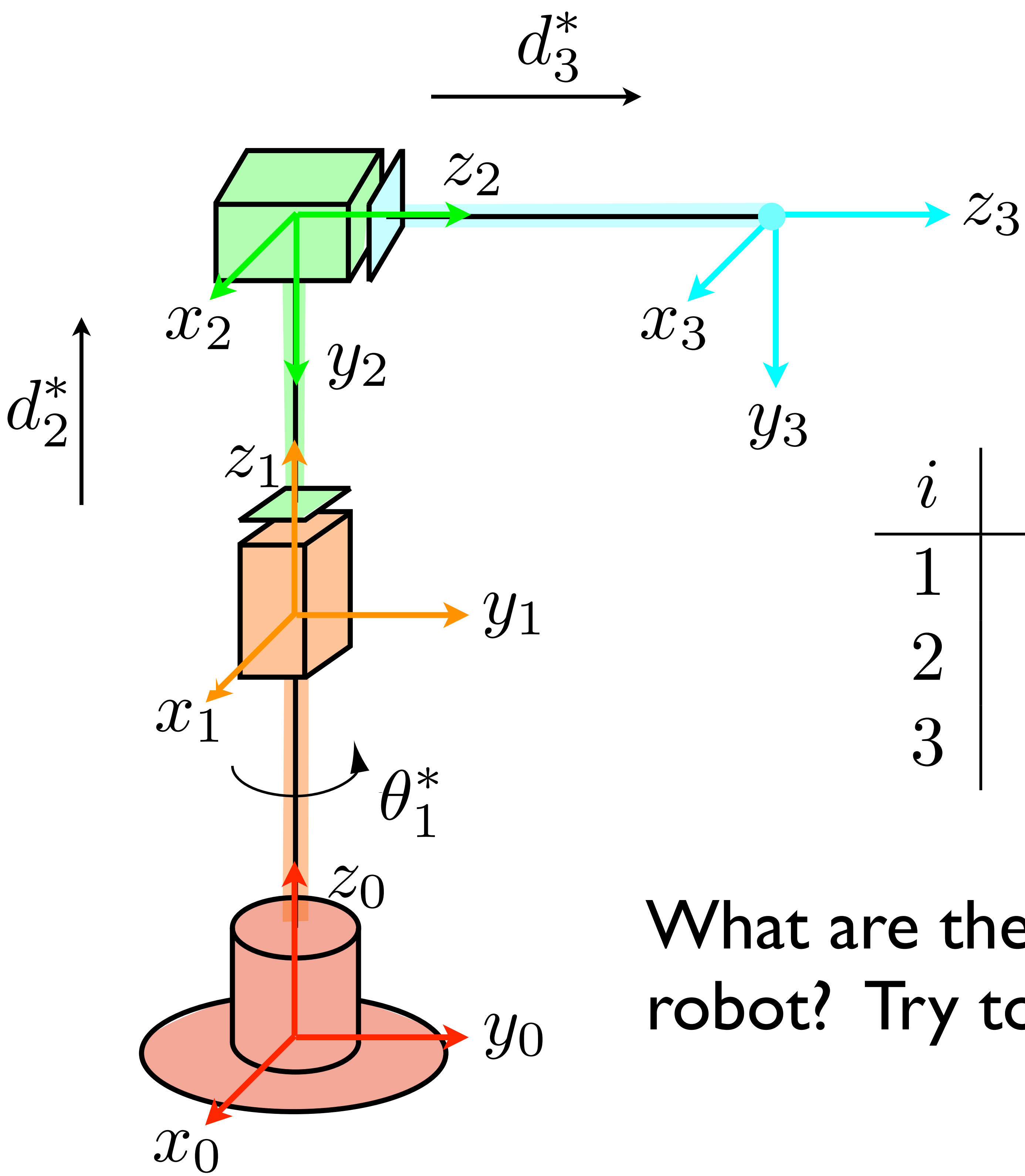
Is frame 3 correct?

Yes x_3 is perpendicular to and intersecting both z_2 and z_3, and the resulting frame is right-handed.

Could I have picked any other x_3 and y_3?

Yes Any other right-handed option is fine.

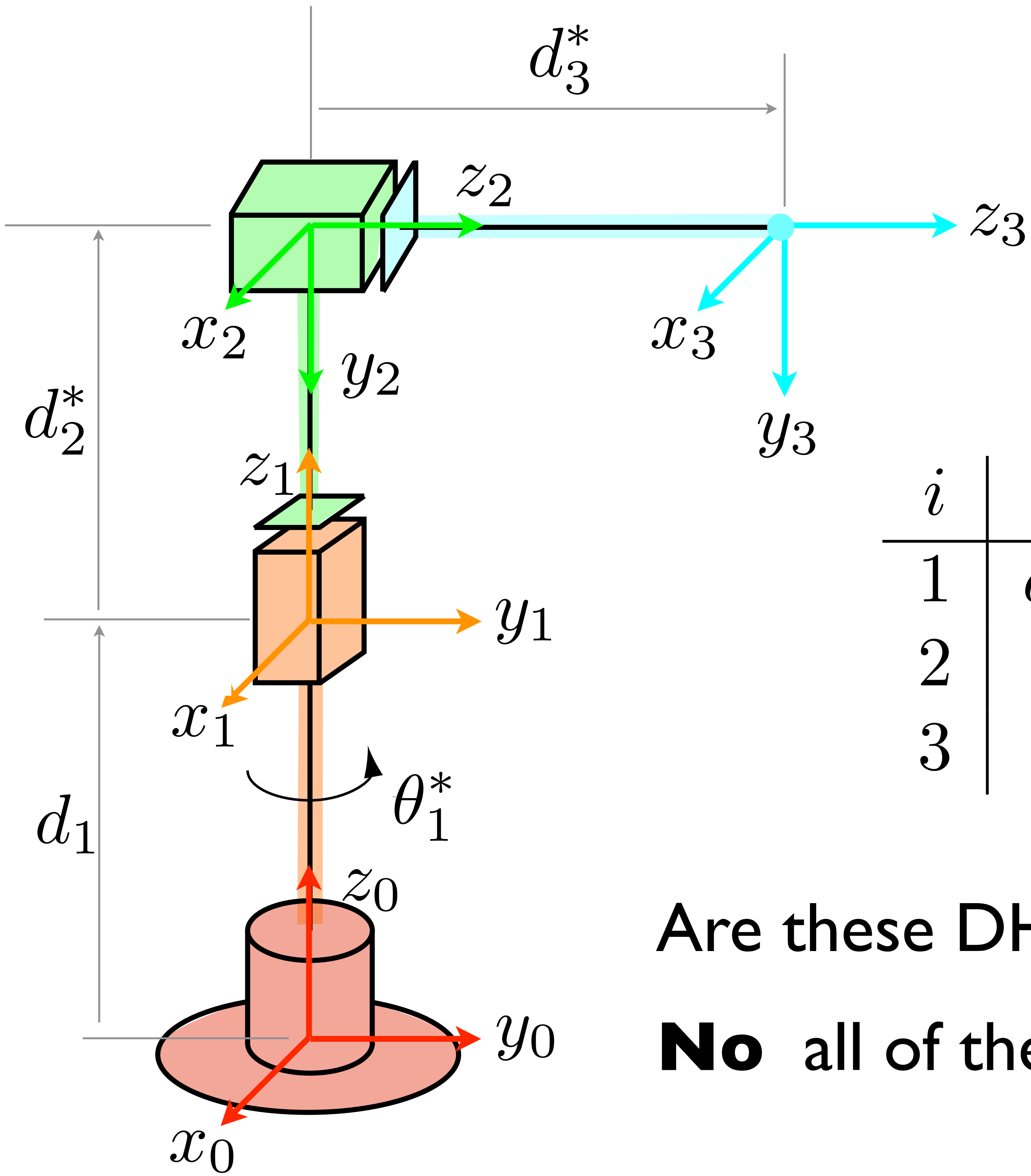
The RPP Cylindrical Robot



	x-step		z-step	
i	a	α	d	θ
1				
2				
3				

What are the DH parameters for this robot? Try to write them down yourself.

The RPP Cylindrical Robot

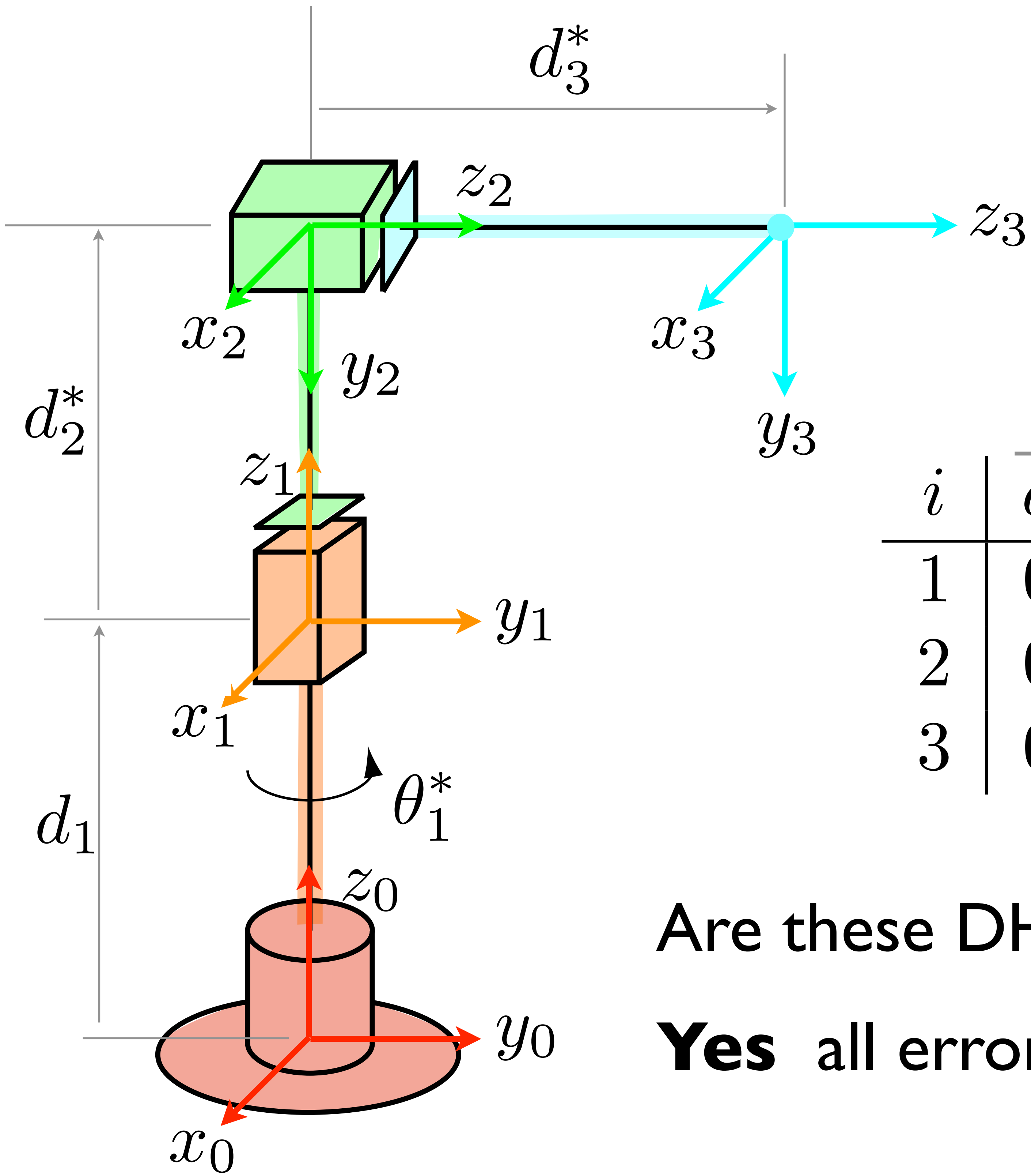


i	a (x-step)	α (x-step)	d (z-step)	θ (z-step)
1	a_1	$0°$	d_1	θ_1^*
2	0	$+90°$	d_2^*	$0°$
3	0	$0°$	d_3^*	$90°$

Are these DH parameters correct?

No all of the rows have errors.

The RPP Cylindrical Robot

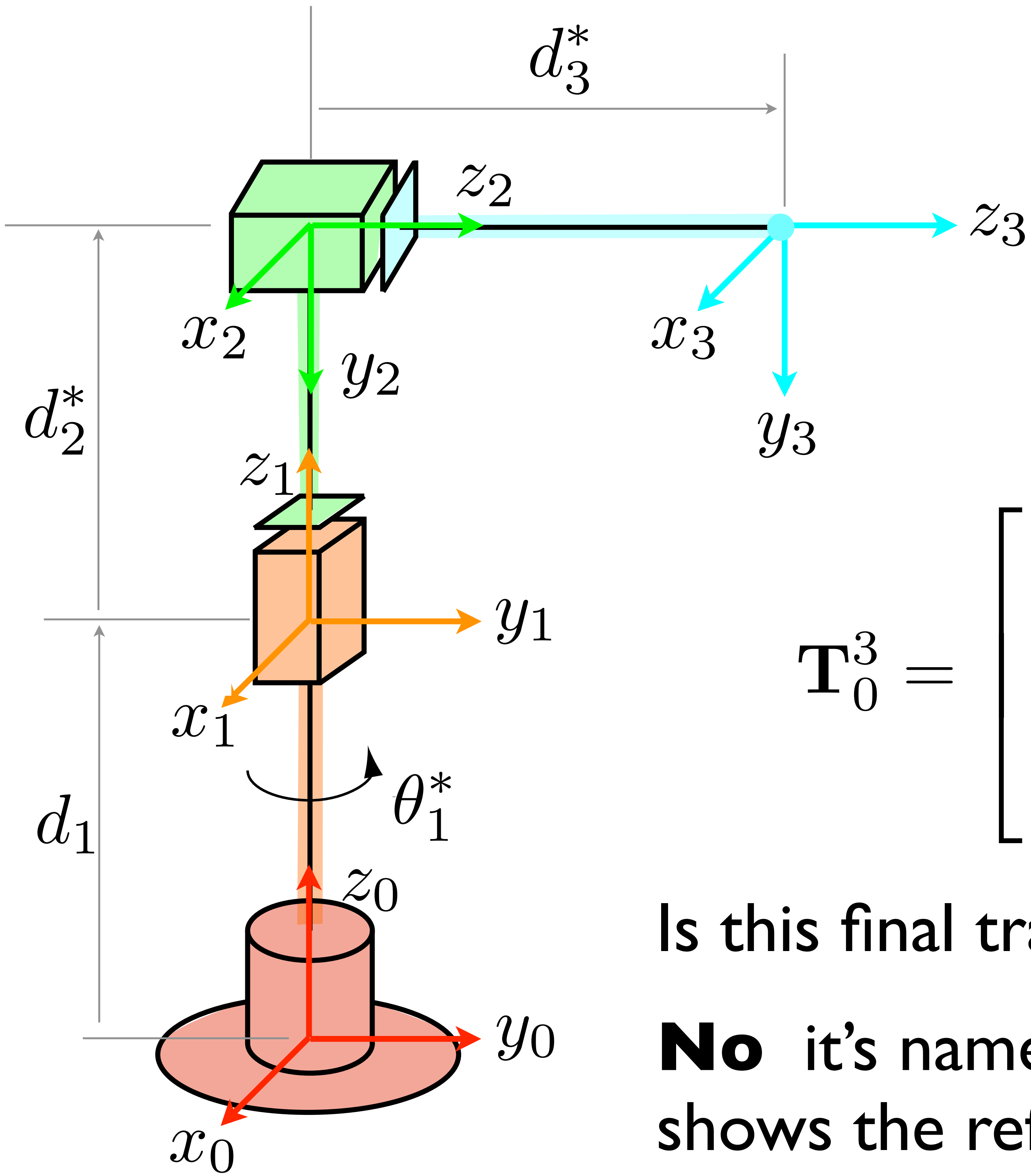


	x-step		z-step	
i	a	α	d	θ
1	0	$0°$	d_1	θ_1^*
2	0	$-90°$	d_2^*	$0°$
3	0	$0°$	d_3^*	$0°$

Are these DH parameters correct?

Yes all errors are corrected.

The RPP Cylindrical Robot

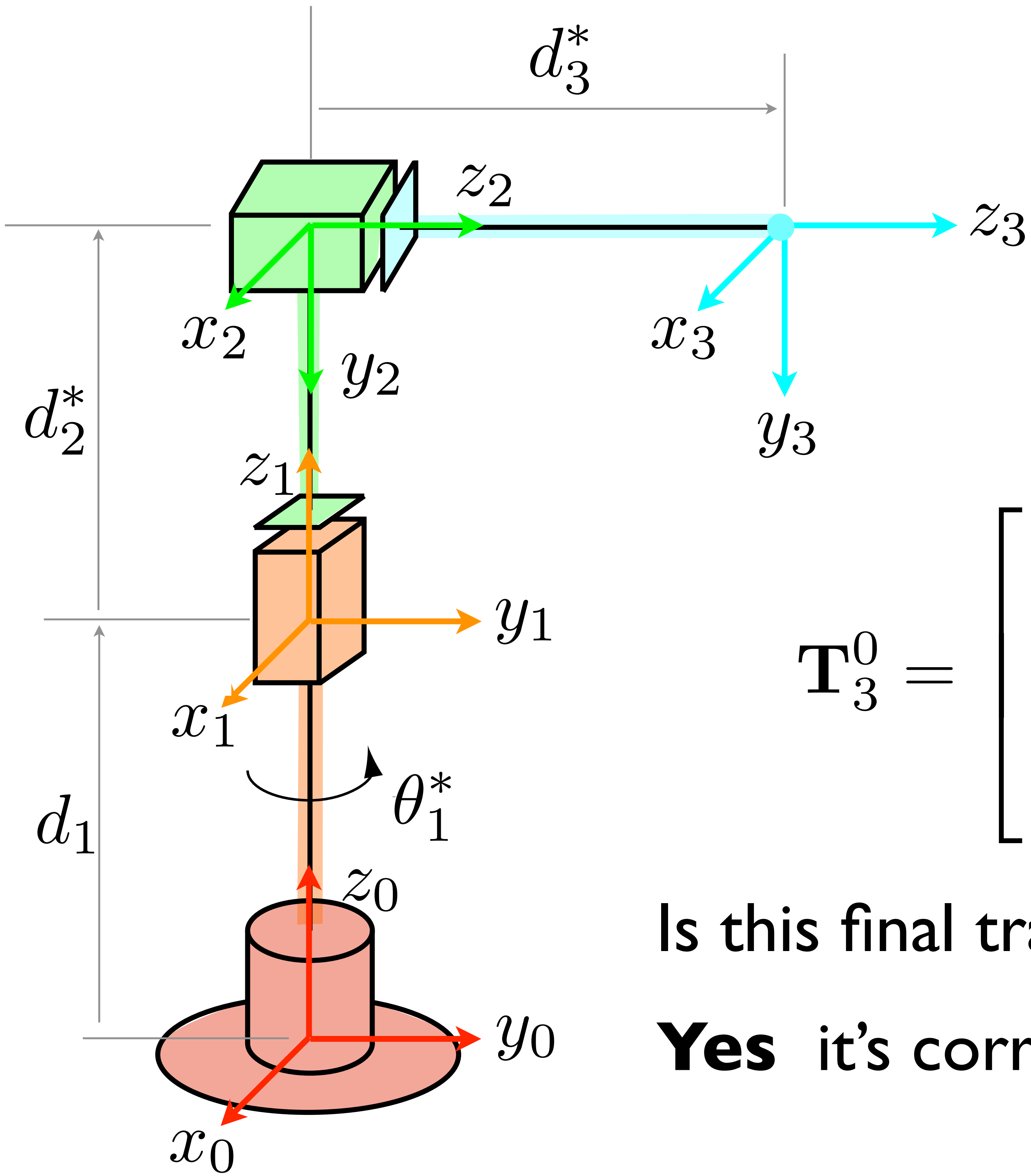


$$\mathbf{T}_0^3 = \begin{bmatrix} c_1^* & 0 & -s_1^* & -d_3^* s_1^* \\ s_1^* & 0 & c_1^* & d_3^* c_1^* \\ 0 & -1 & 0 & d_1 + d_2^* \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Is this final transformation correct?

No it's named incorrectly. Superscript shows the reference frame.

The RPP Cylindrical Robot

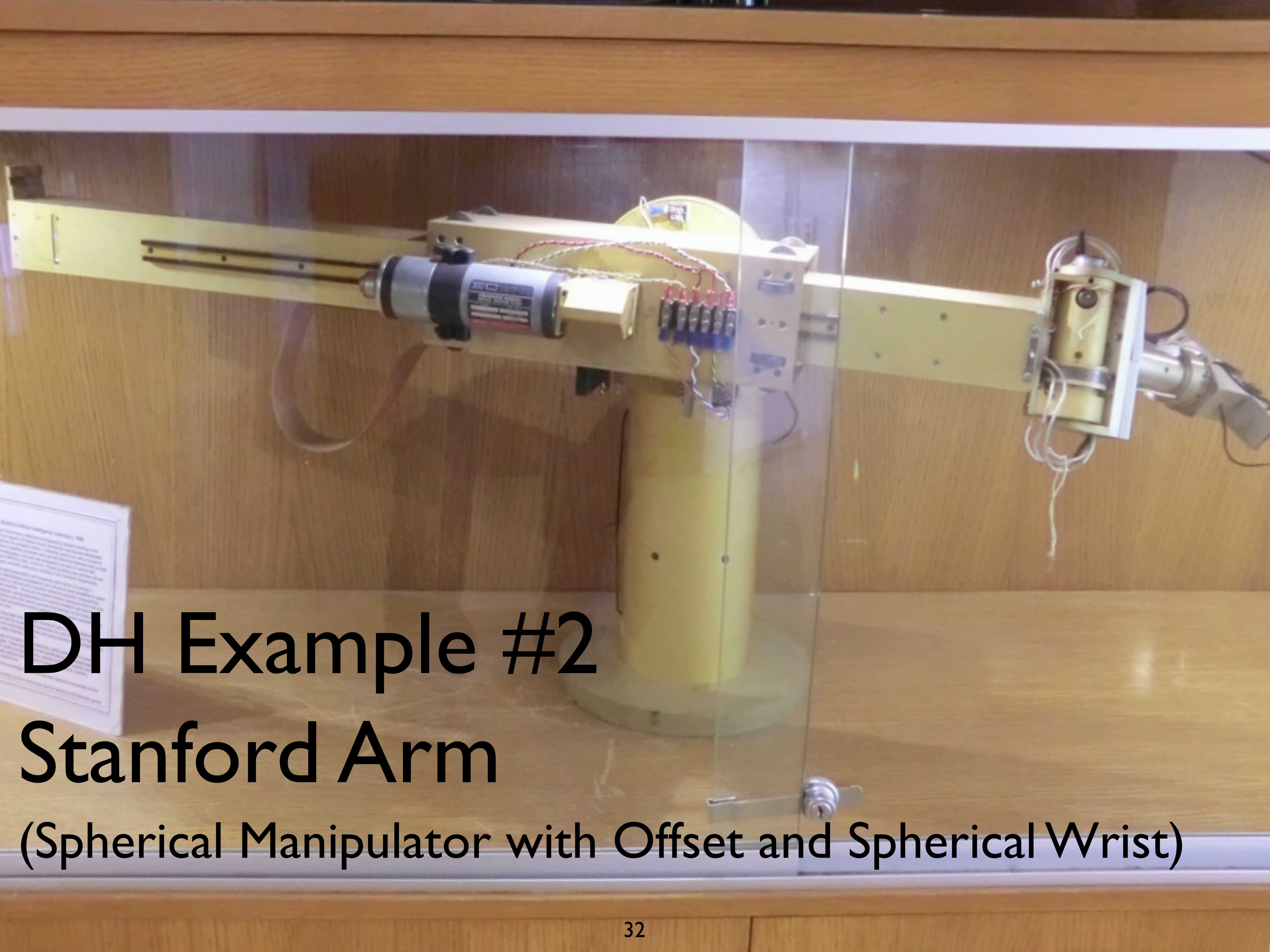


$$\mathbf{T}_3^0 = \begin{bmatrix} c_1^* & 0 & -s_1^* & -d_3^* s_1^* \\ s_1^* & 0 & c_1^* & d_3^* c_1^* \\ 0 & -1 & 0 & d_1 + d_2^* \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Is this final transformation correct?

Yes it's correct!

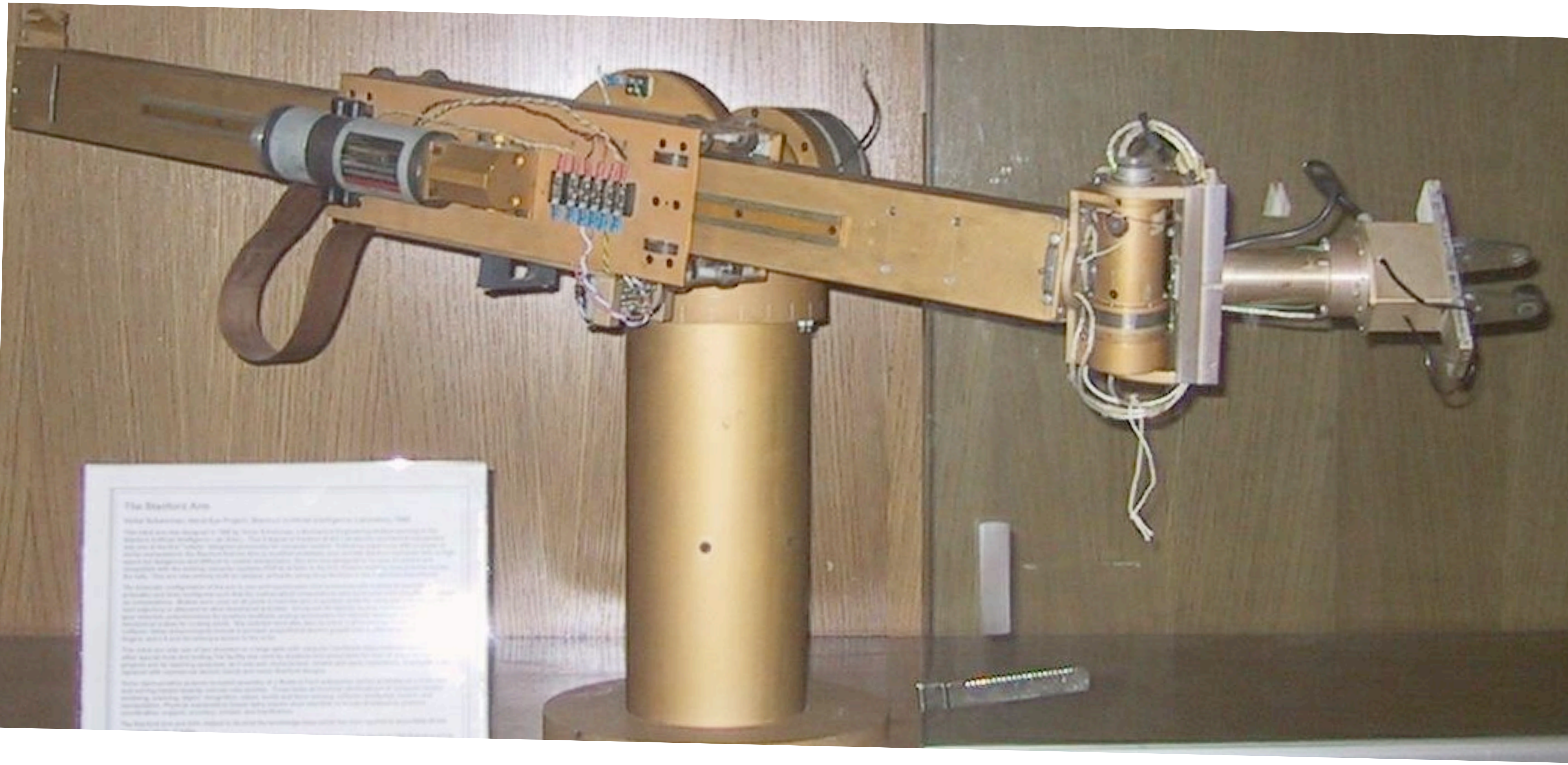
What questions do you have ?



DH Example #2
Stanford Arm

(Spherical Manipulator with Offset and Spherical Wrist)

Stanford Arm: RRPRRR Manipulator

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http://www.youtube.com/watch?v=O1oJzUSITeY
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Over the last decades, computer vision systems have become increasingly capable of controlling robotic movement. One example of early research and development of computer vision and robotic systems was recorded at the
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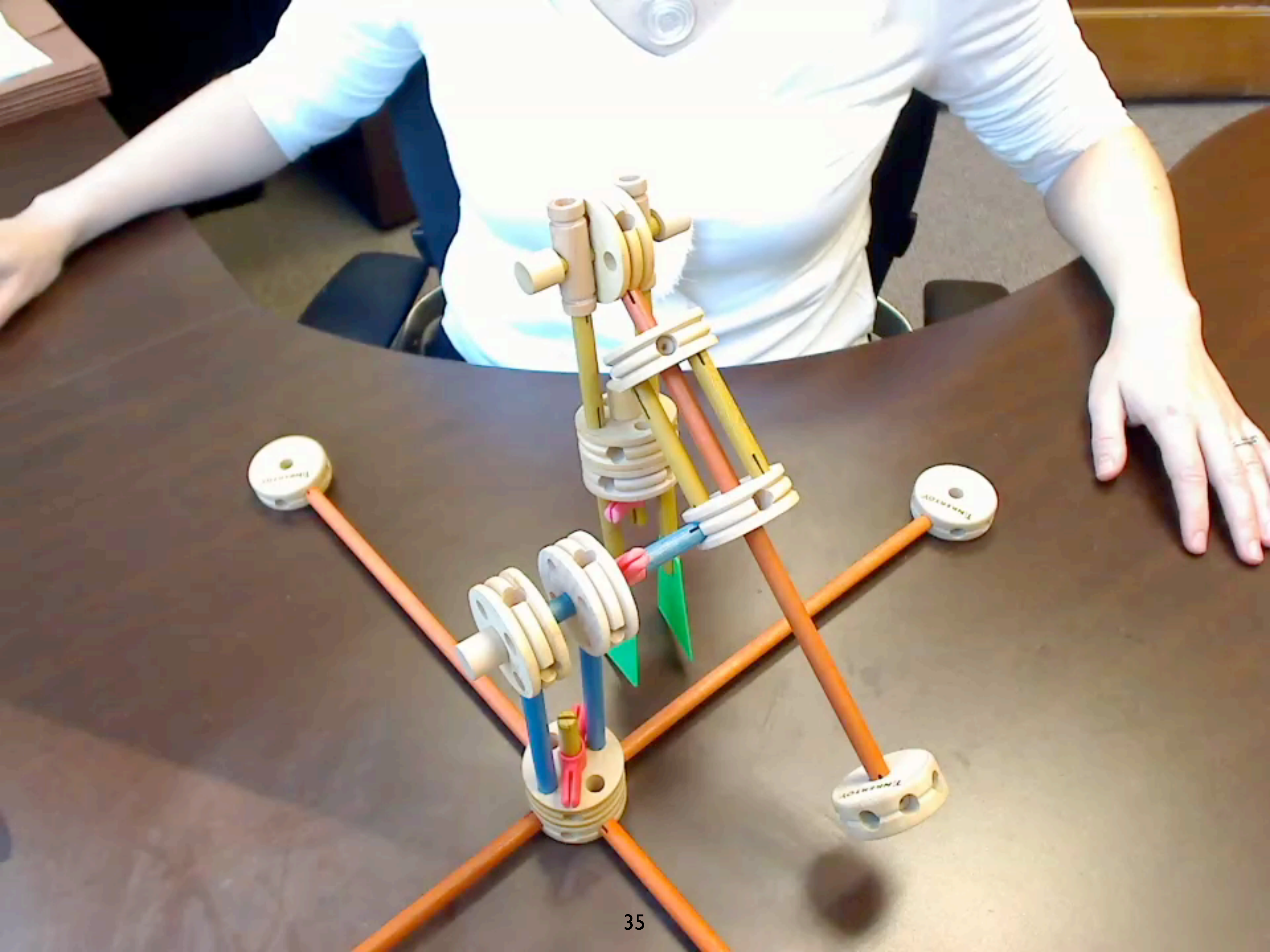
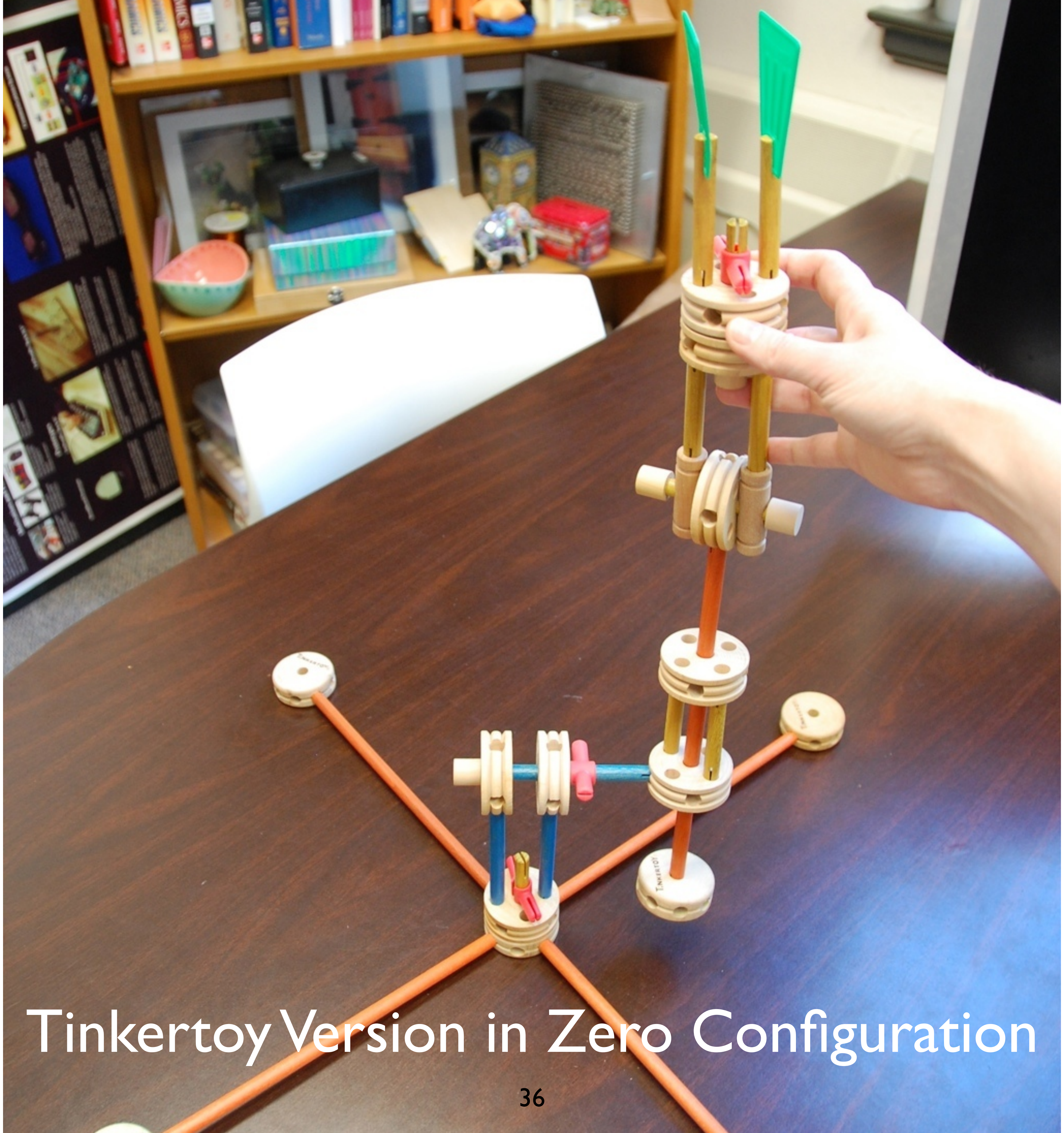
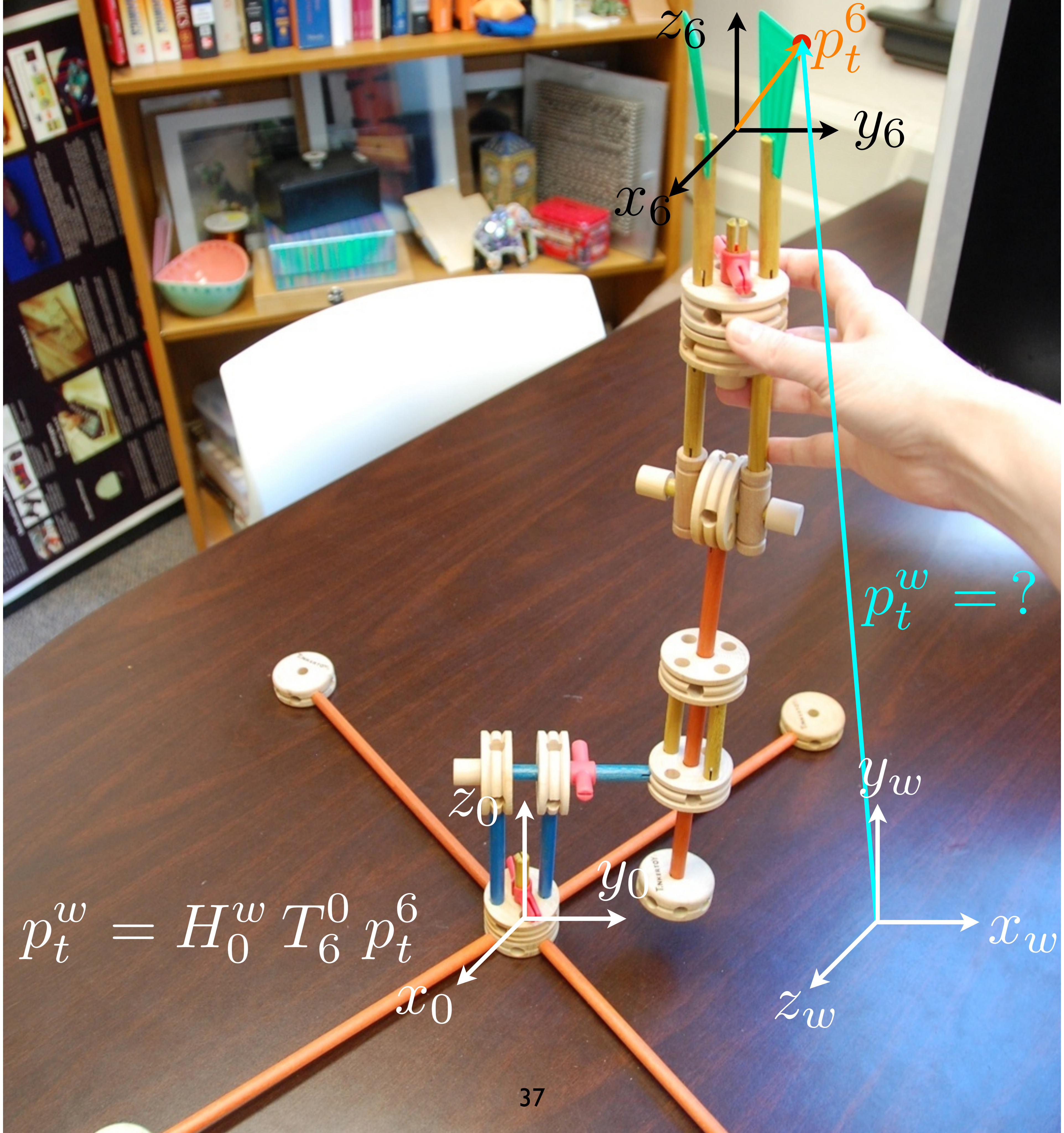
Go to "http://www.youtube.com/watch?v=EzjkBwZtxp4&feature=fvwrel"



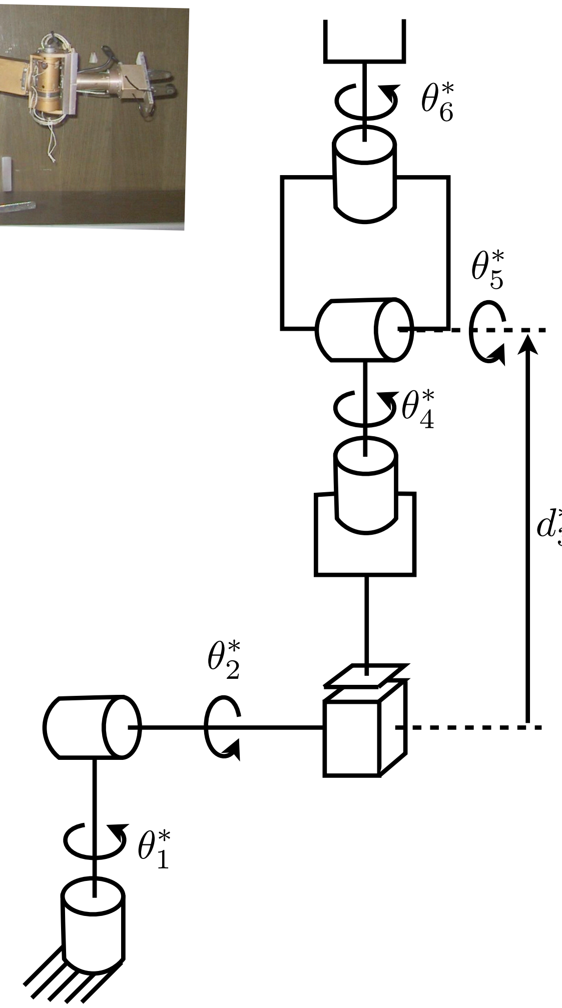


Tinkertoy Version in Zero Configuration

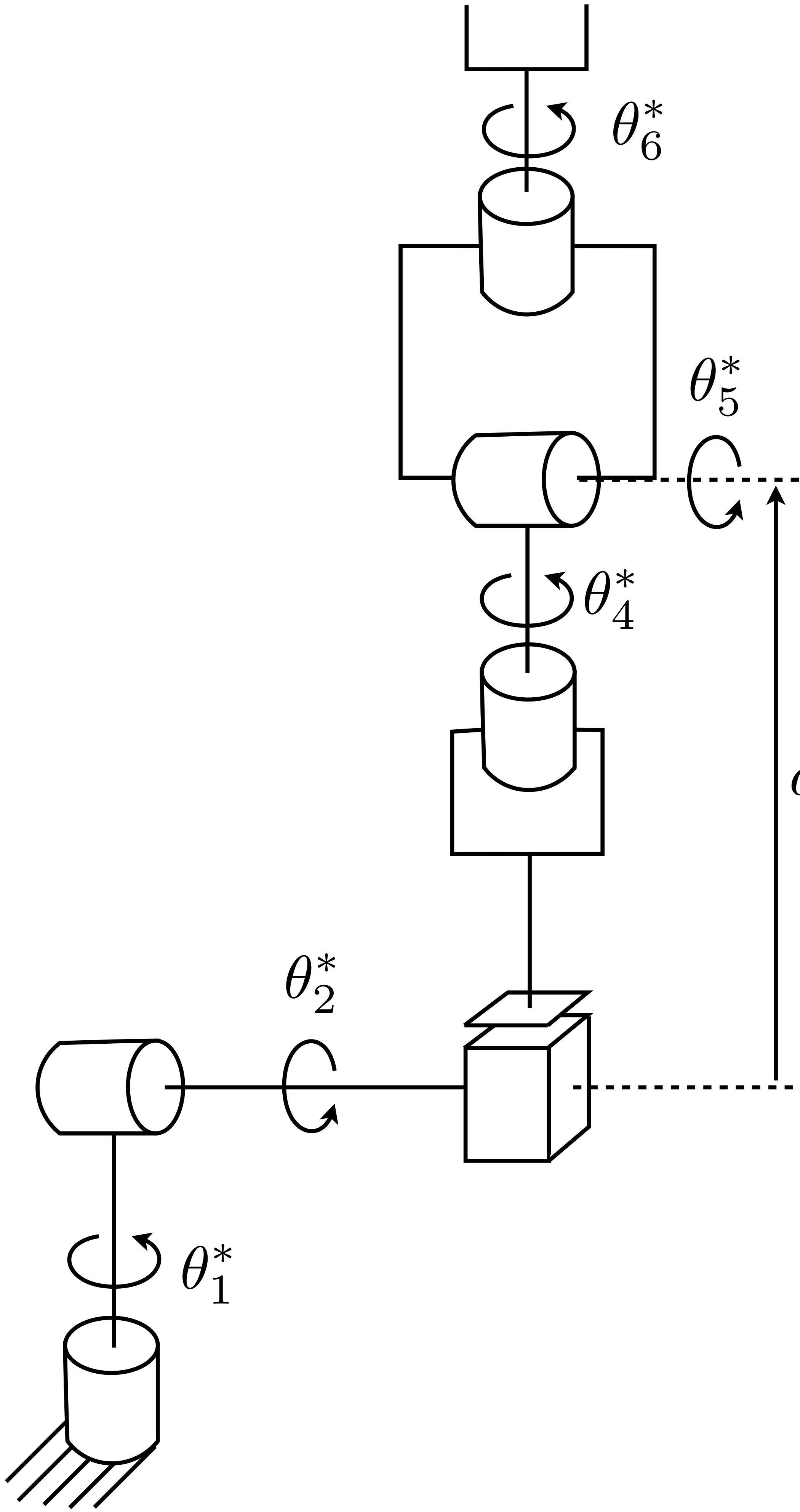


$$p_t^w = H_0^w \, T_6^0 \, p_t^6$$

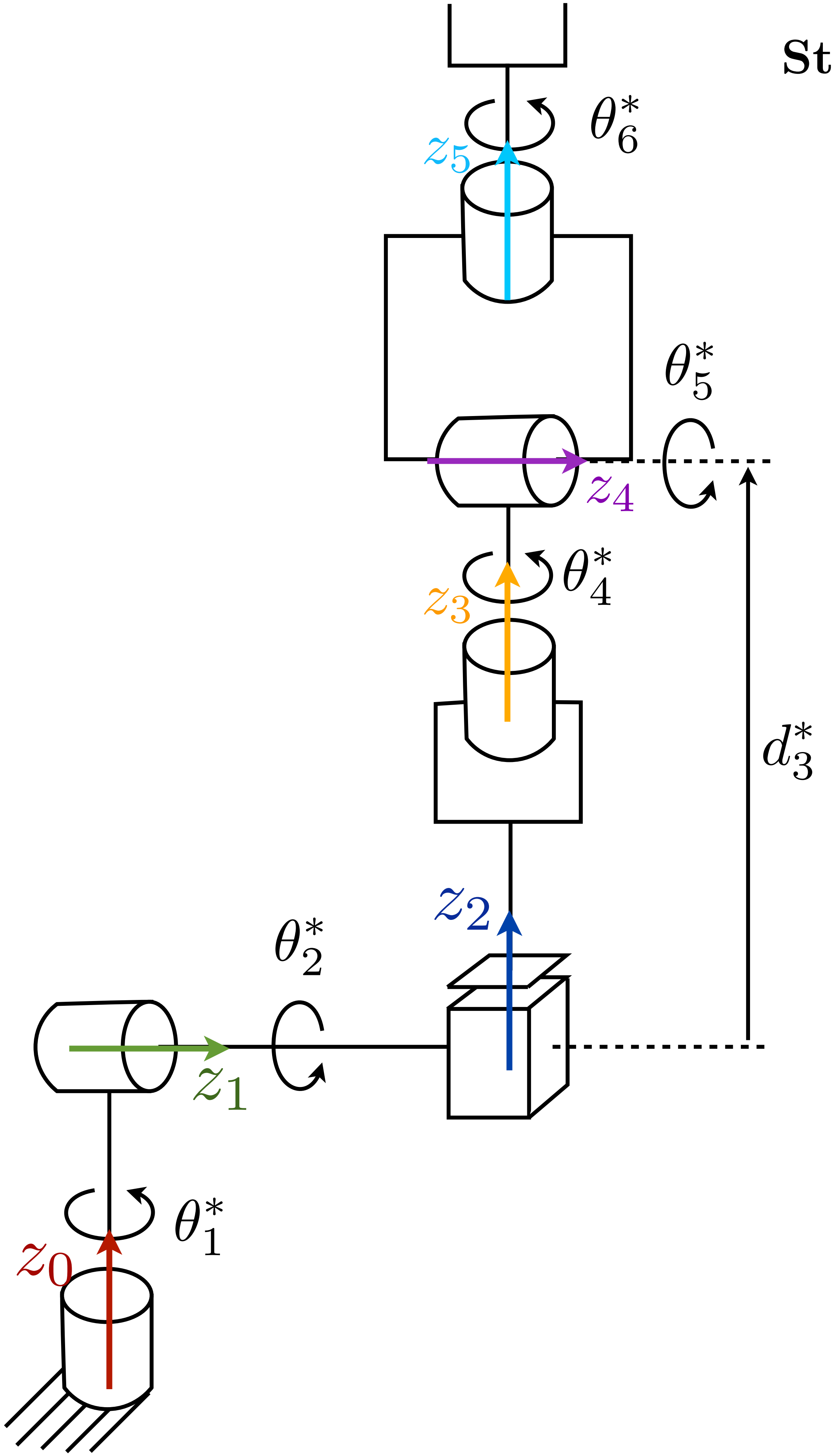
DH Parameters for the Stanford Arm



Link	a_i	α_i	d_i	θ_i



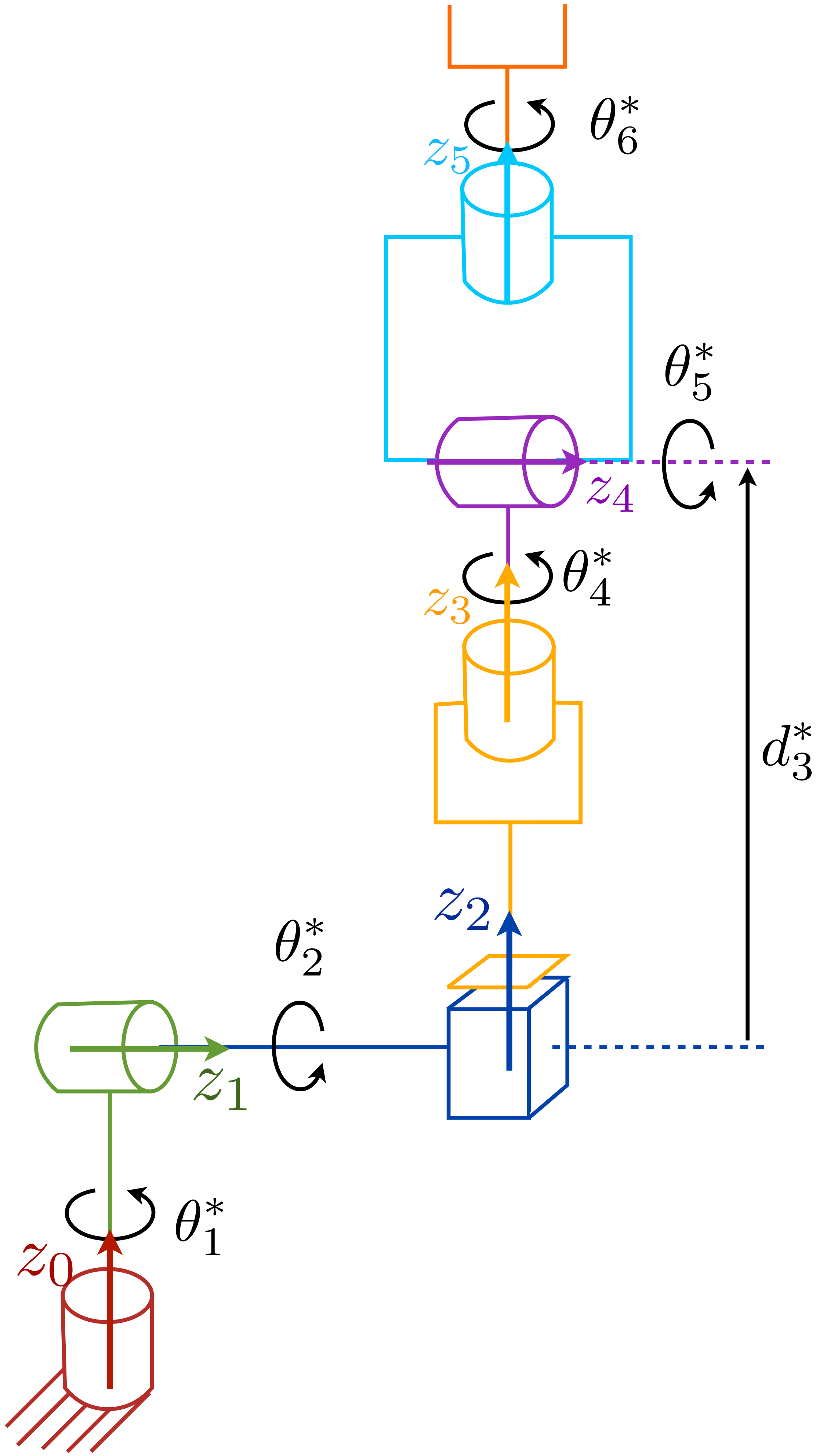
Shown with all $\theta^* = 0$ and $d_3^* = d$



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

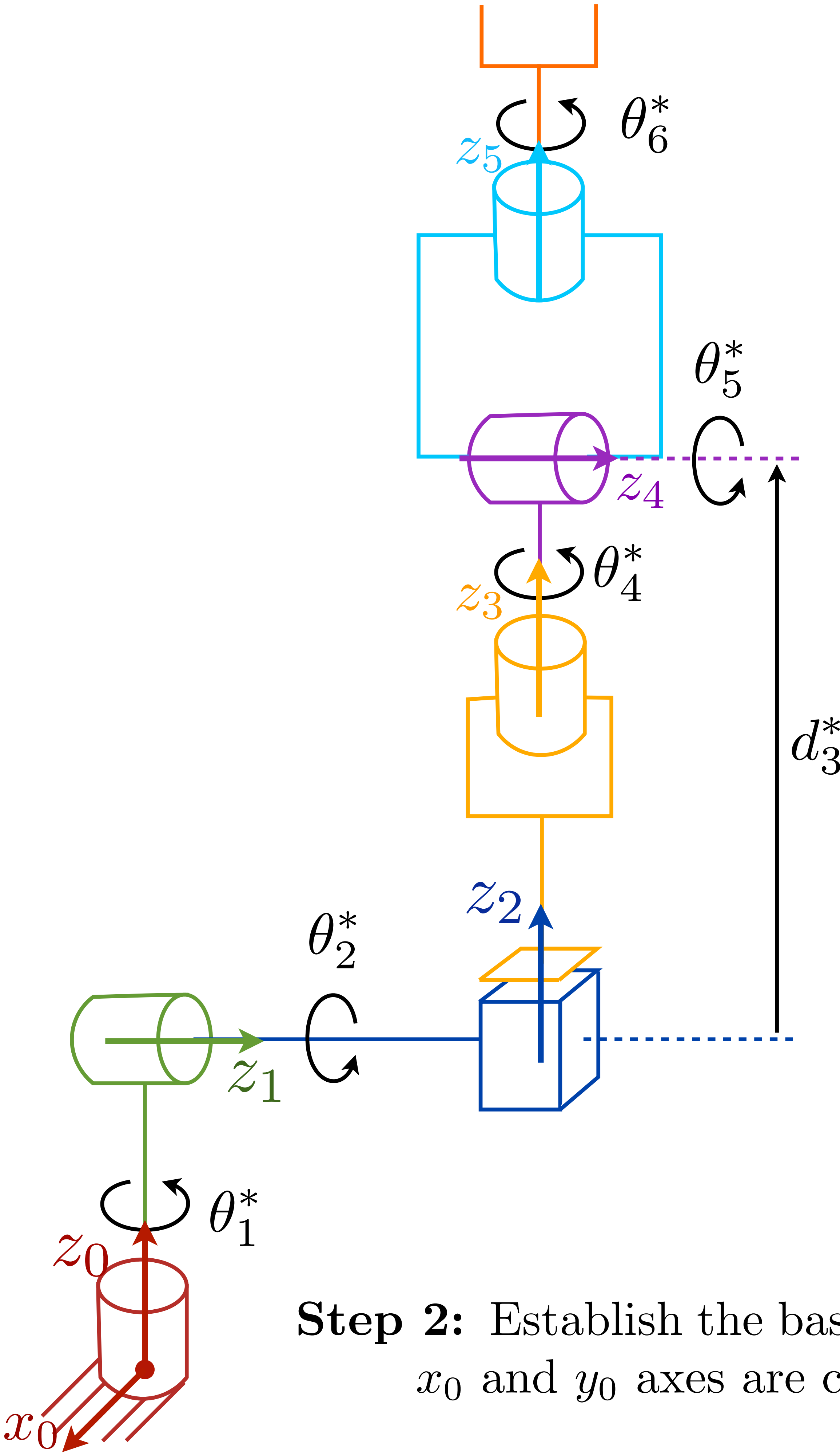
Envision how the links of the robot move relative to one another.

Which frame moves with which link?



Envision how the links of the robot move relative to one another.

Which frame moves with which link?



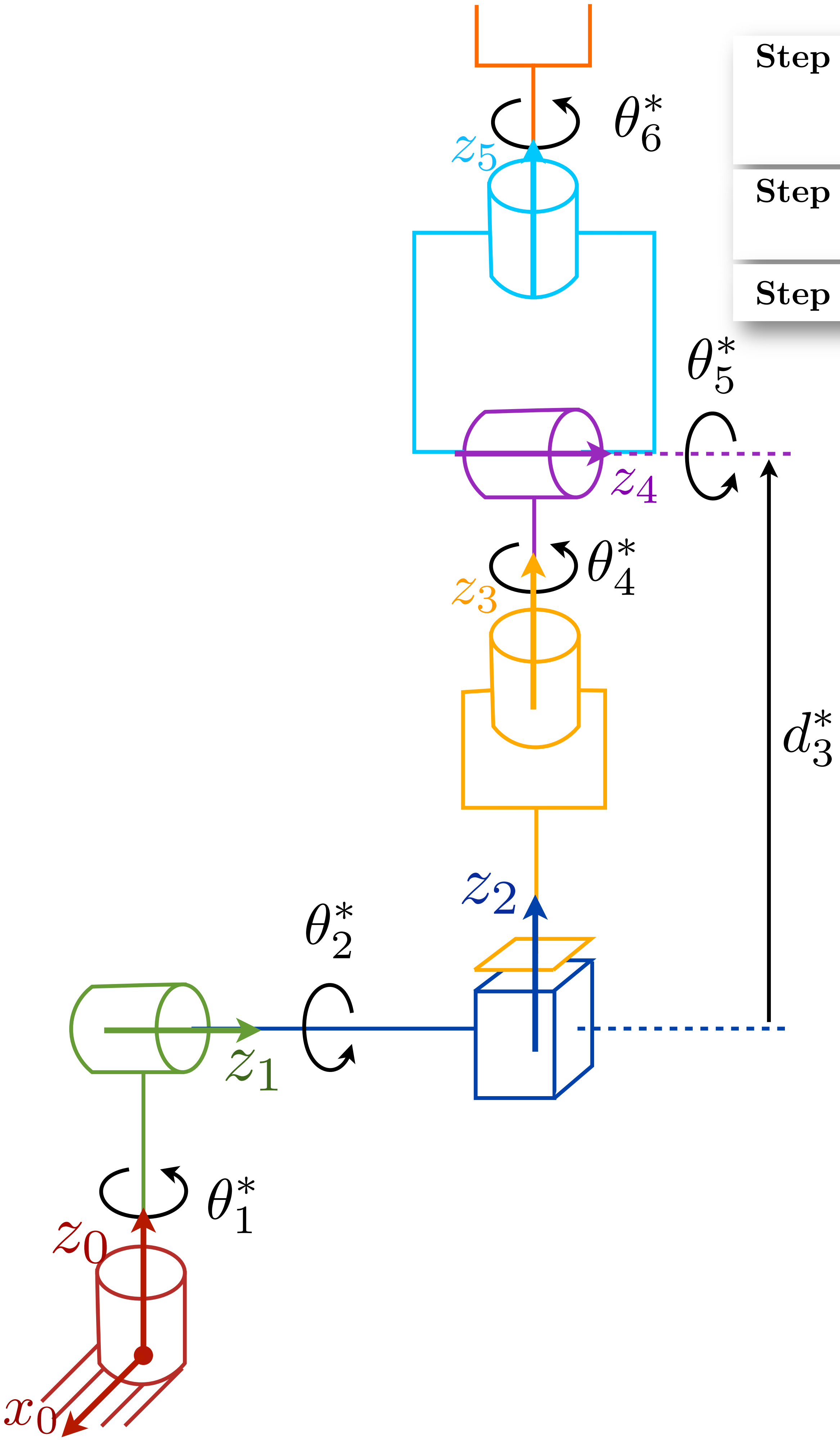
Step 2: Establish the base frame. Set the origin anywhere on the z_0-axis. The x_0 and y_0 axes are chosen conveniently to form a right-handed frame.

For $i = 1, \ldots, n-1$, perform Steps 3 to 5.

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.



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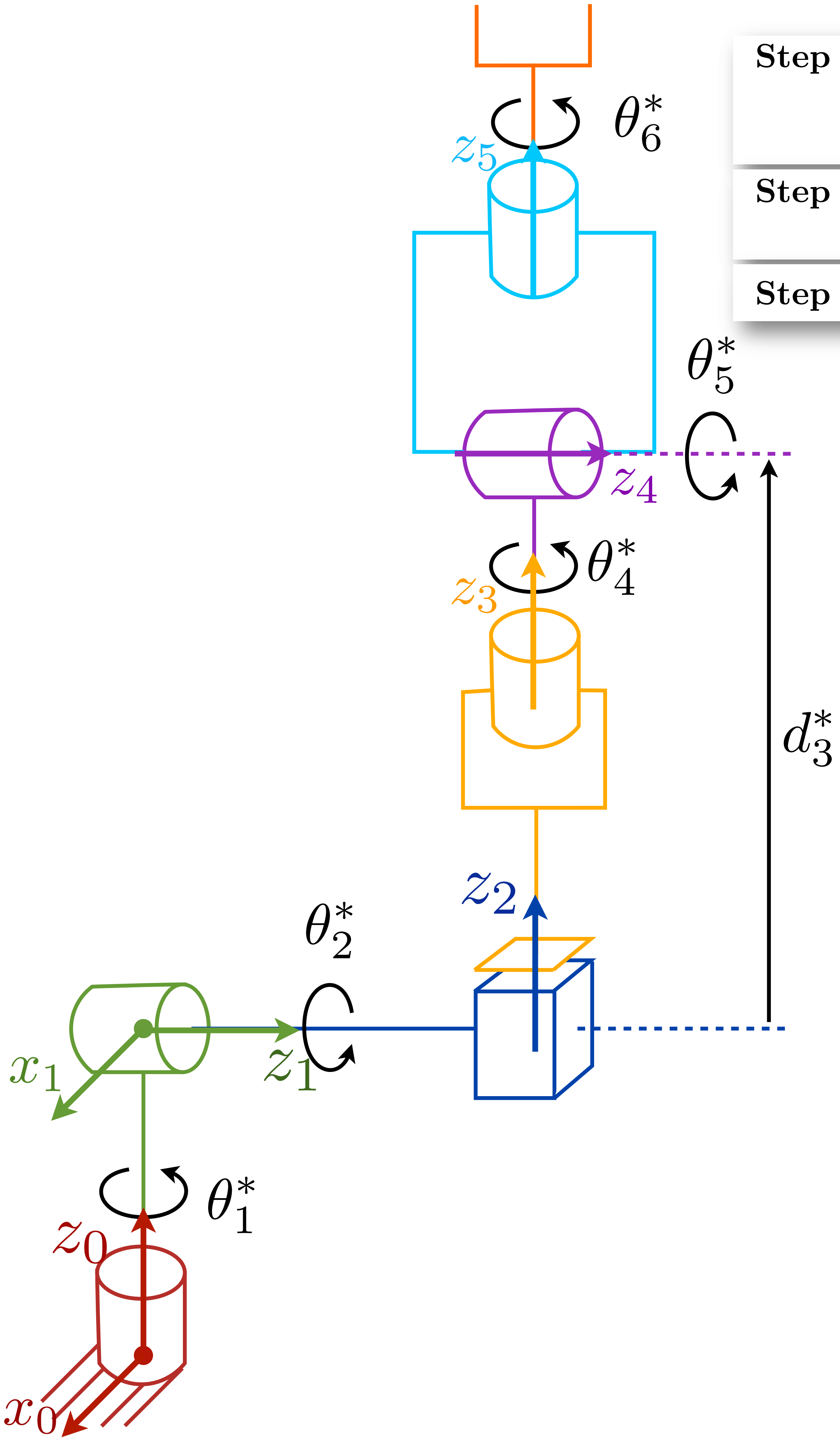
Step 5: Establish y_i to complete a right-handed frame.



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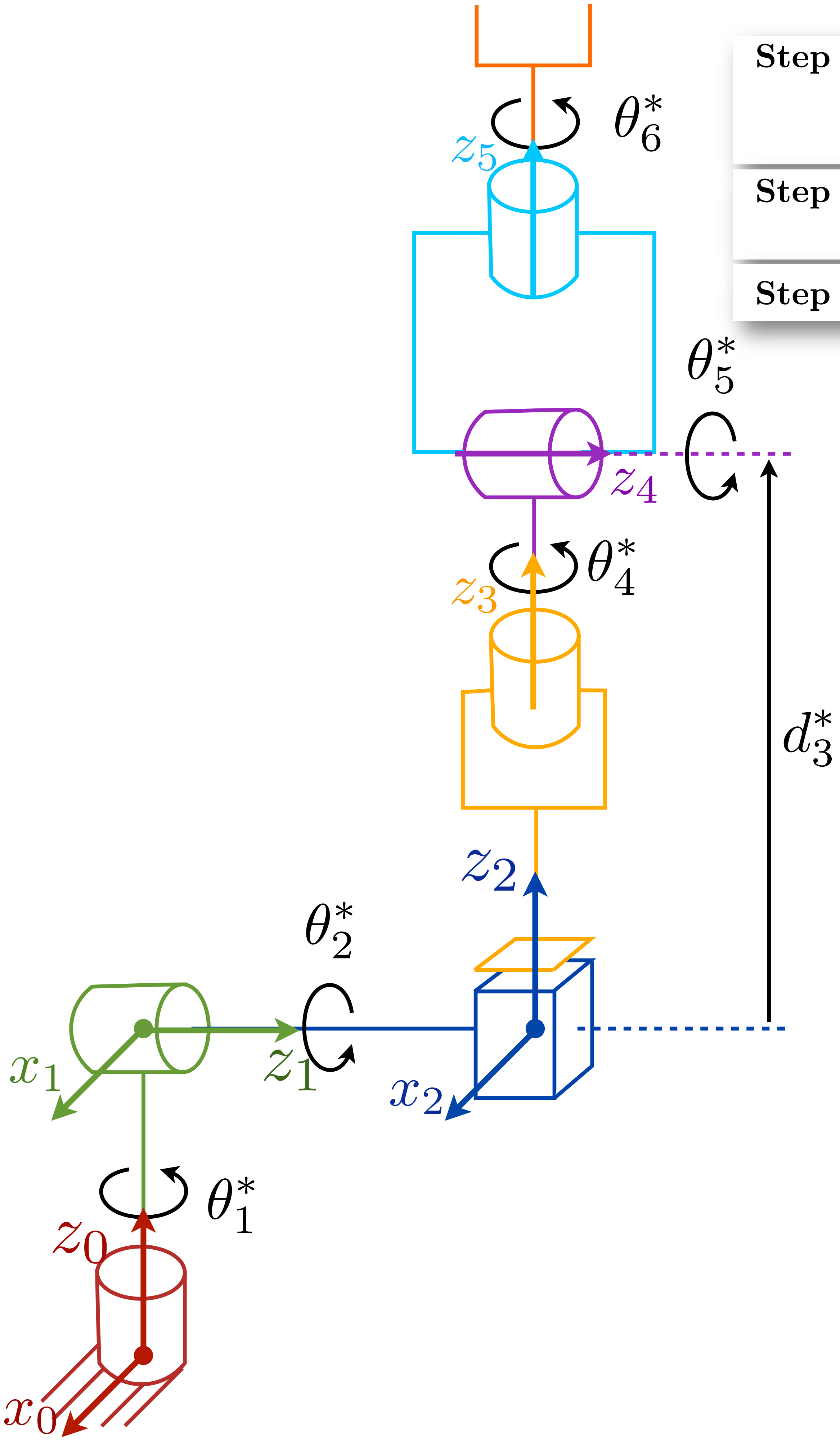
Step 5: Establish y_i to complete a right-handed frame.



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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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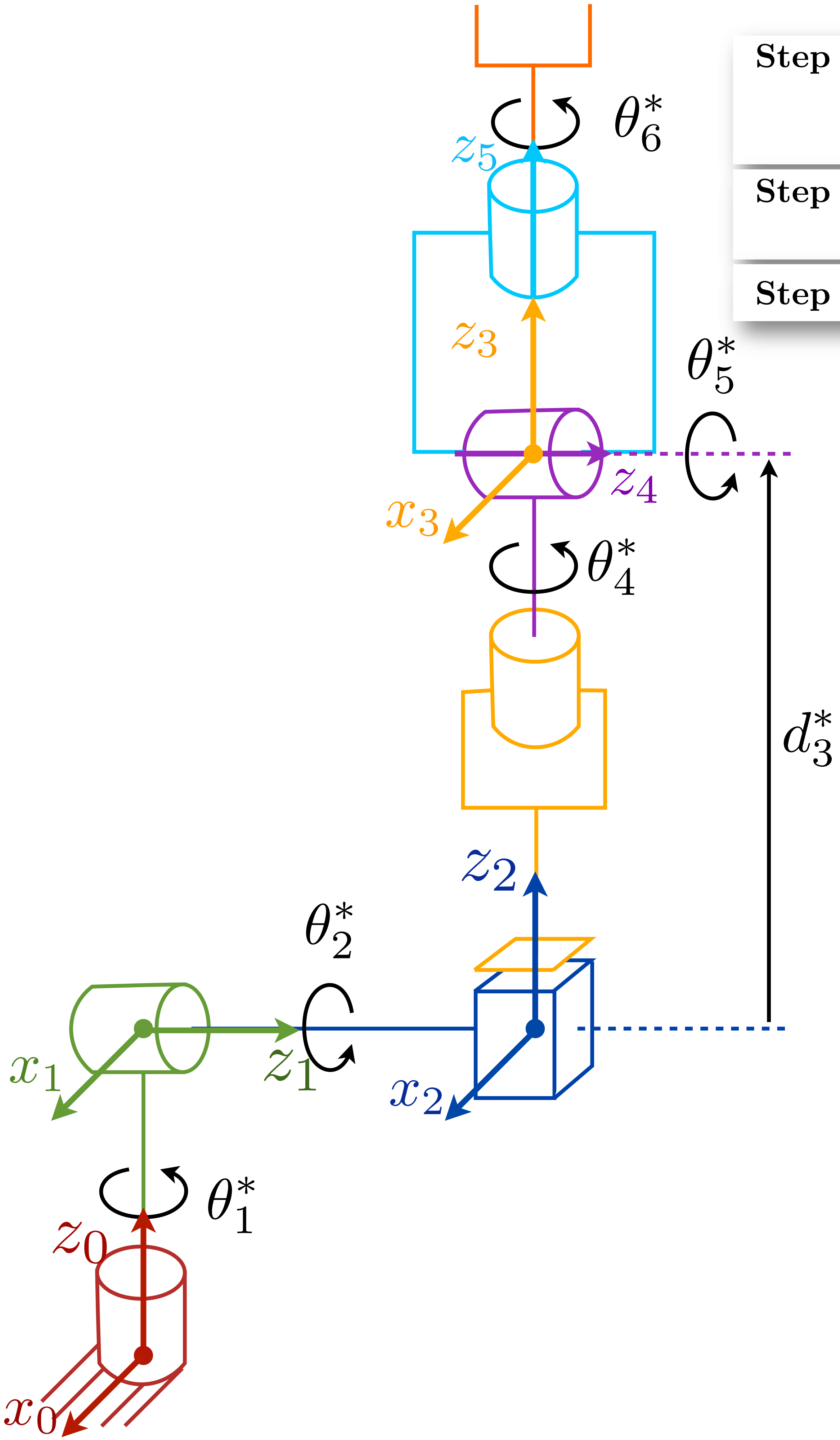

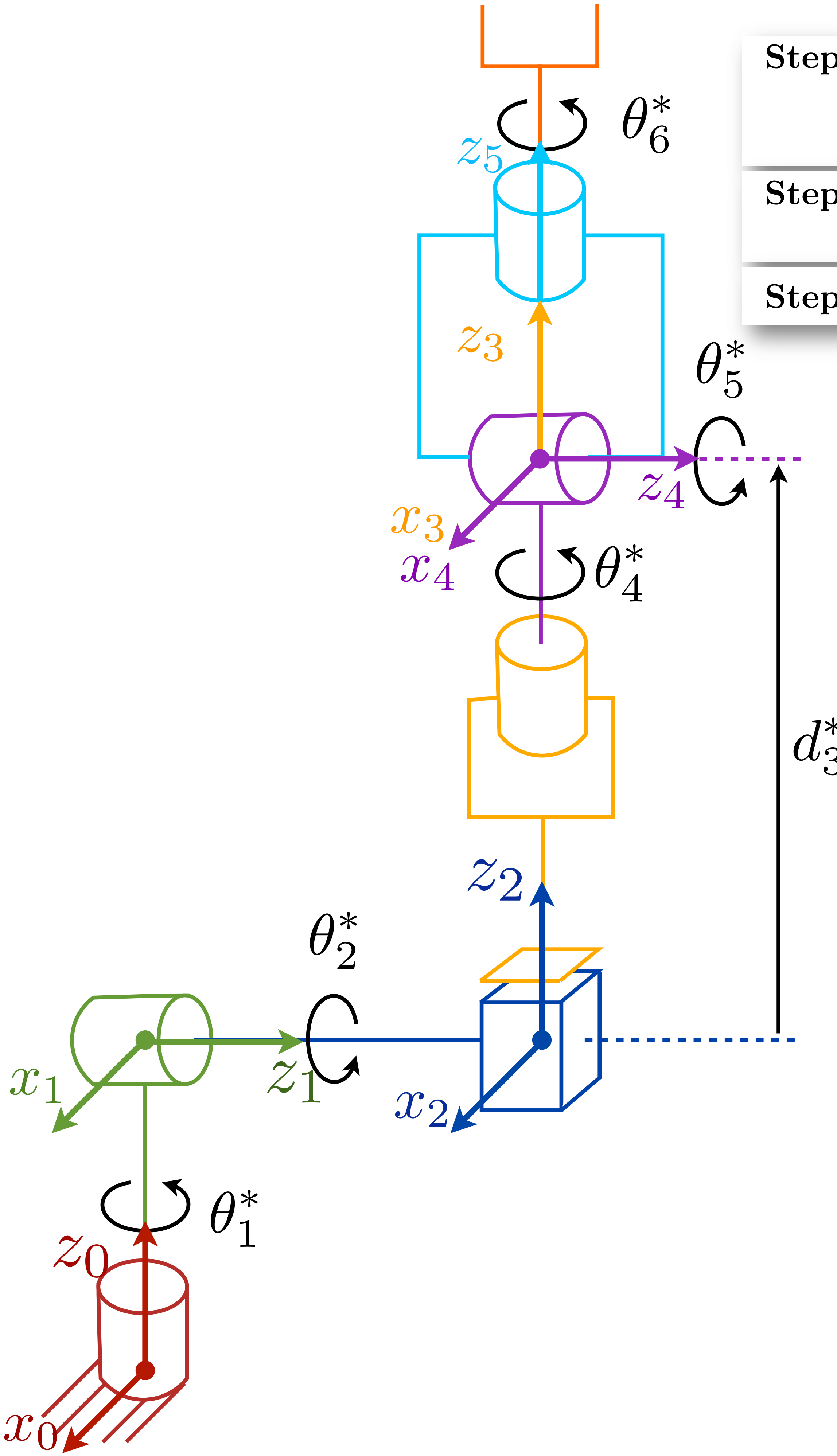

For $i = 1, \ldots, n-1$, perform Steps 3 to 5.

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

For $i = 1, \ldots, n-1$, perform Steps 3 to 5.

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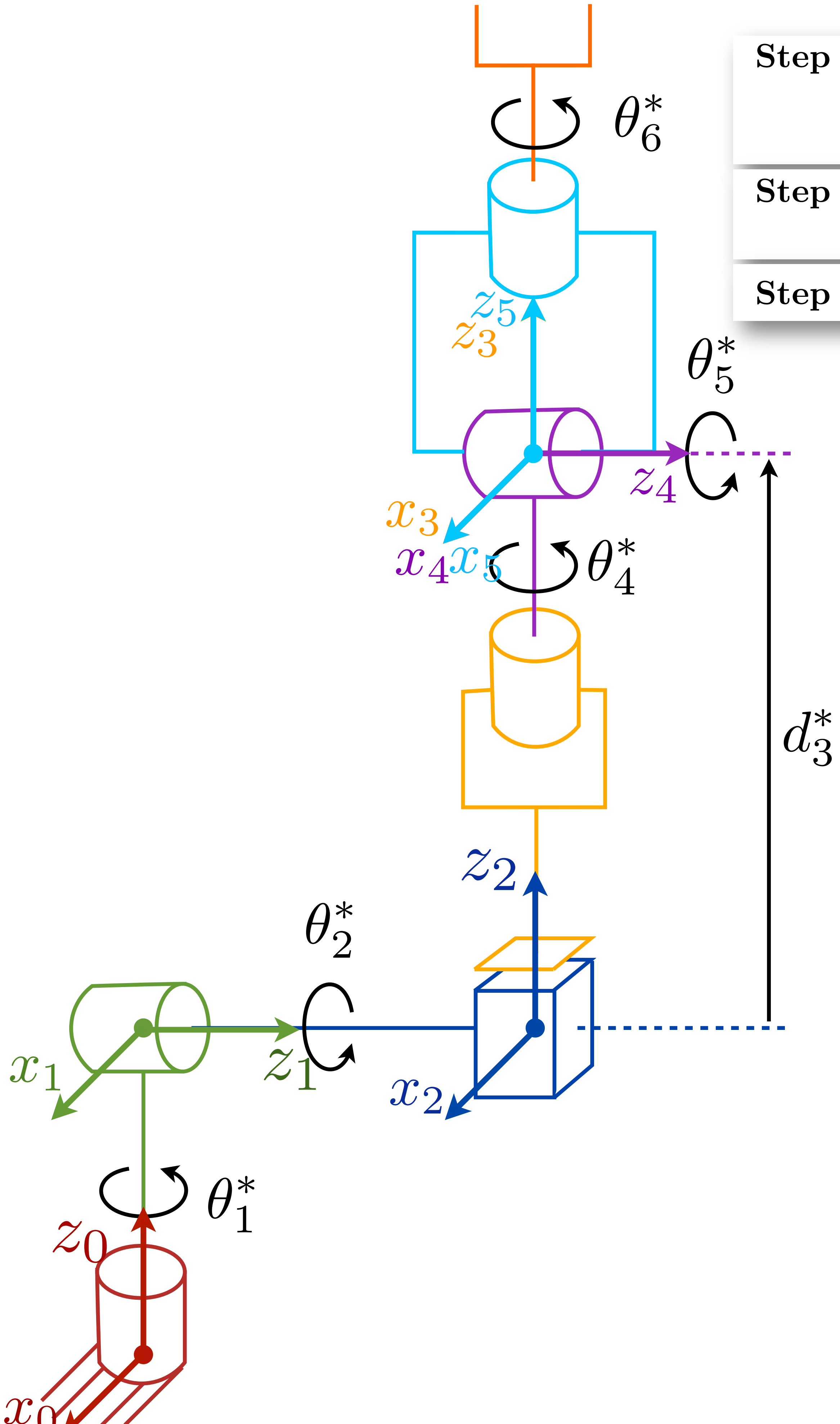
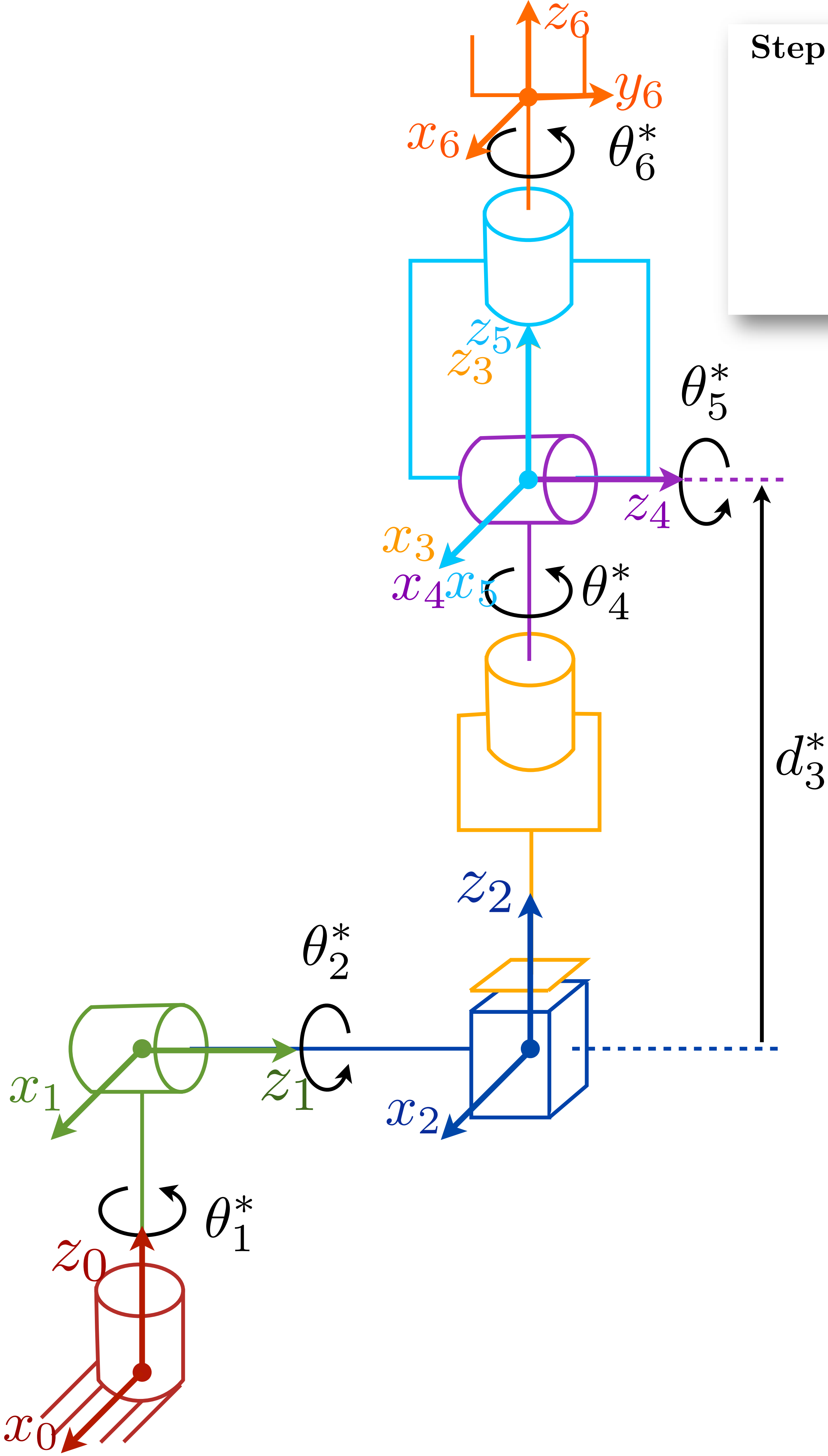
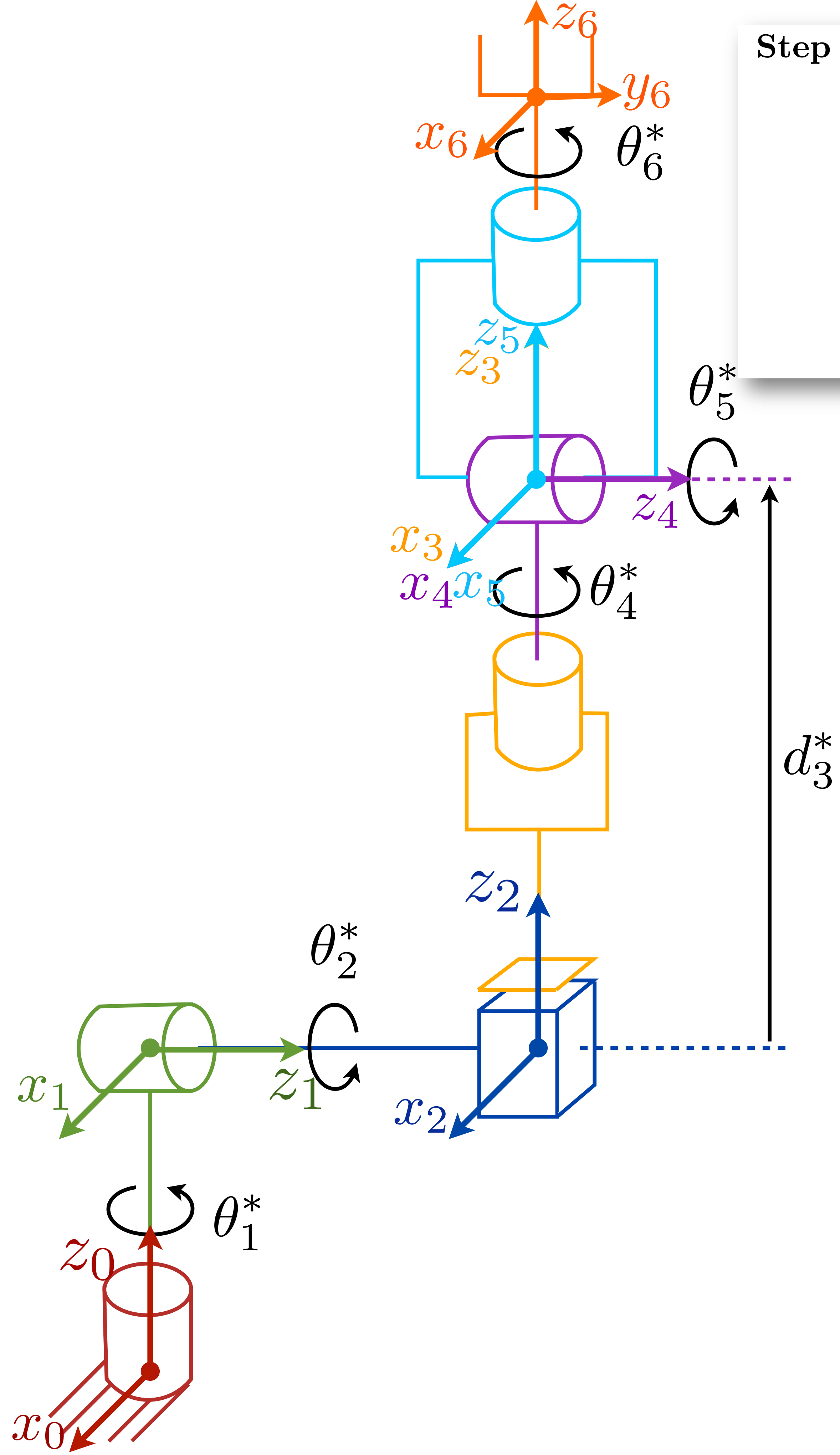
Step 5: Establish y_i to complete a right-handed frame.



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.





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

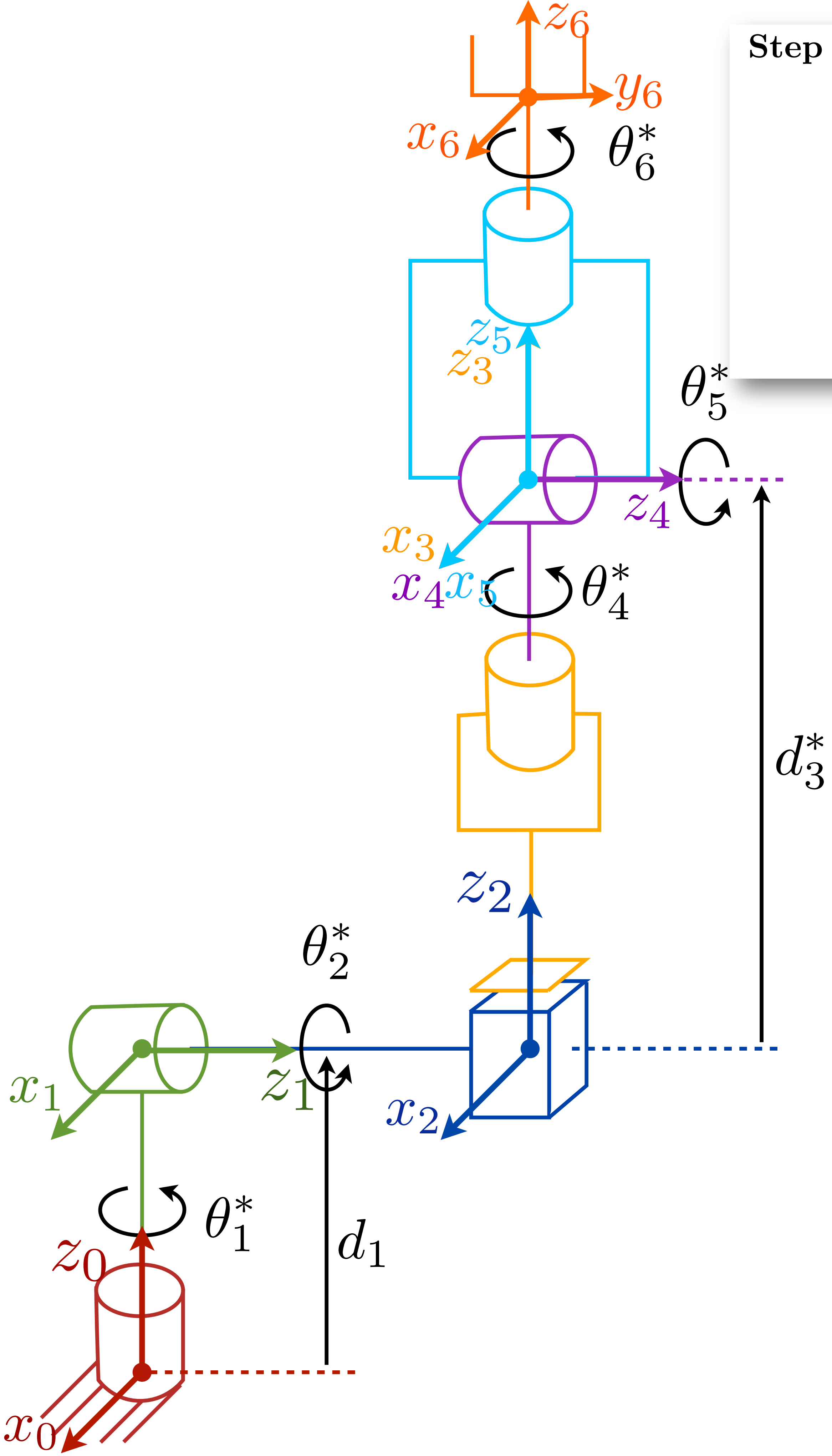
$a_i =$ distance along x_i from the intersection of the x_i and z_{i-1} axes to o_i.

$d_i =$ 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.

	x-step		z-step	
Link	a_i	α_i	d_i	θ_i



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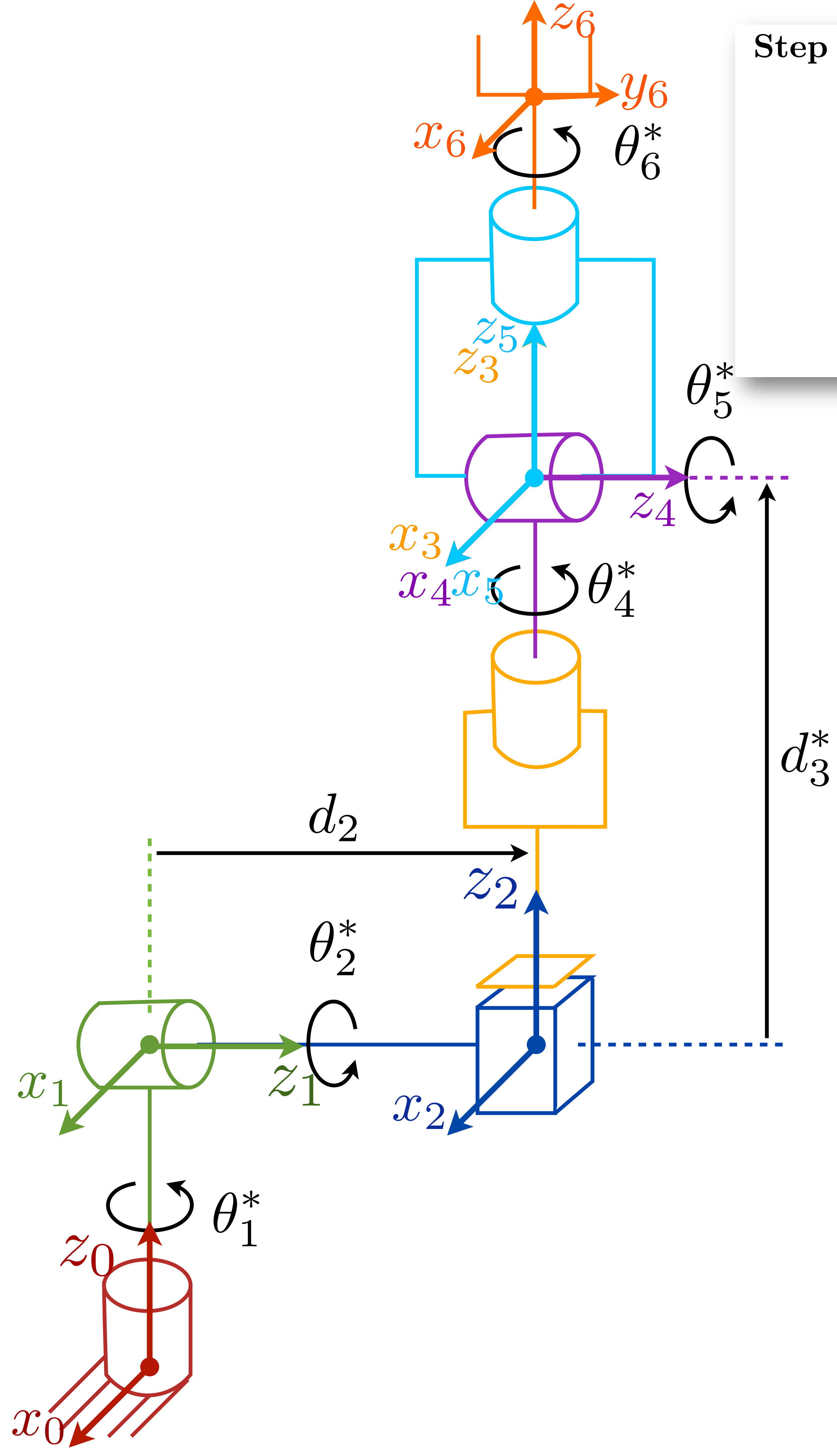
$\theta_i =$ the angle between x_{i-1} and x_i measured about z_{i-1}. θ_i is variable if joint i is revolute.

	x-step		z-step	
Link	a_i	α_i	d_i	θ_i
1	0	$-90°$	d_1	θ_1^*



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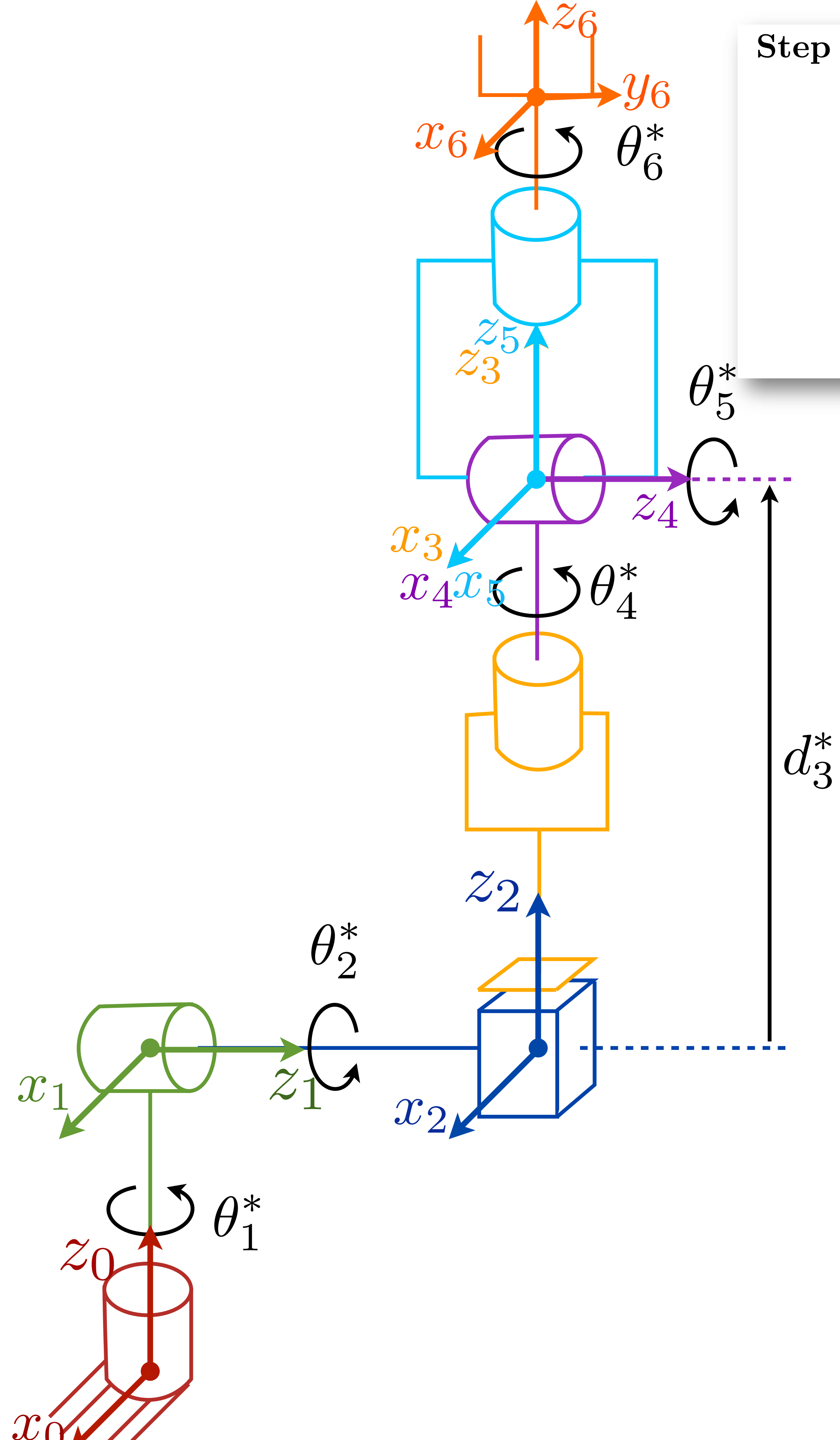
	x-step		z-step	
Link	a_i	α_i	d_i	θ_i
1	0	$-90°$	d_1	θ_1^*
2	0	$+90°$	d_2	θ_2^*



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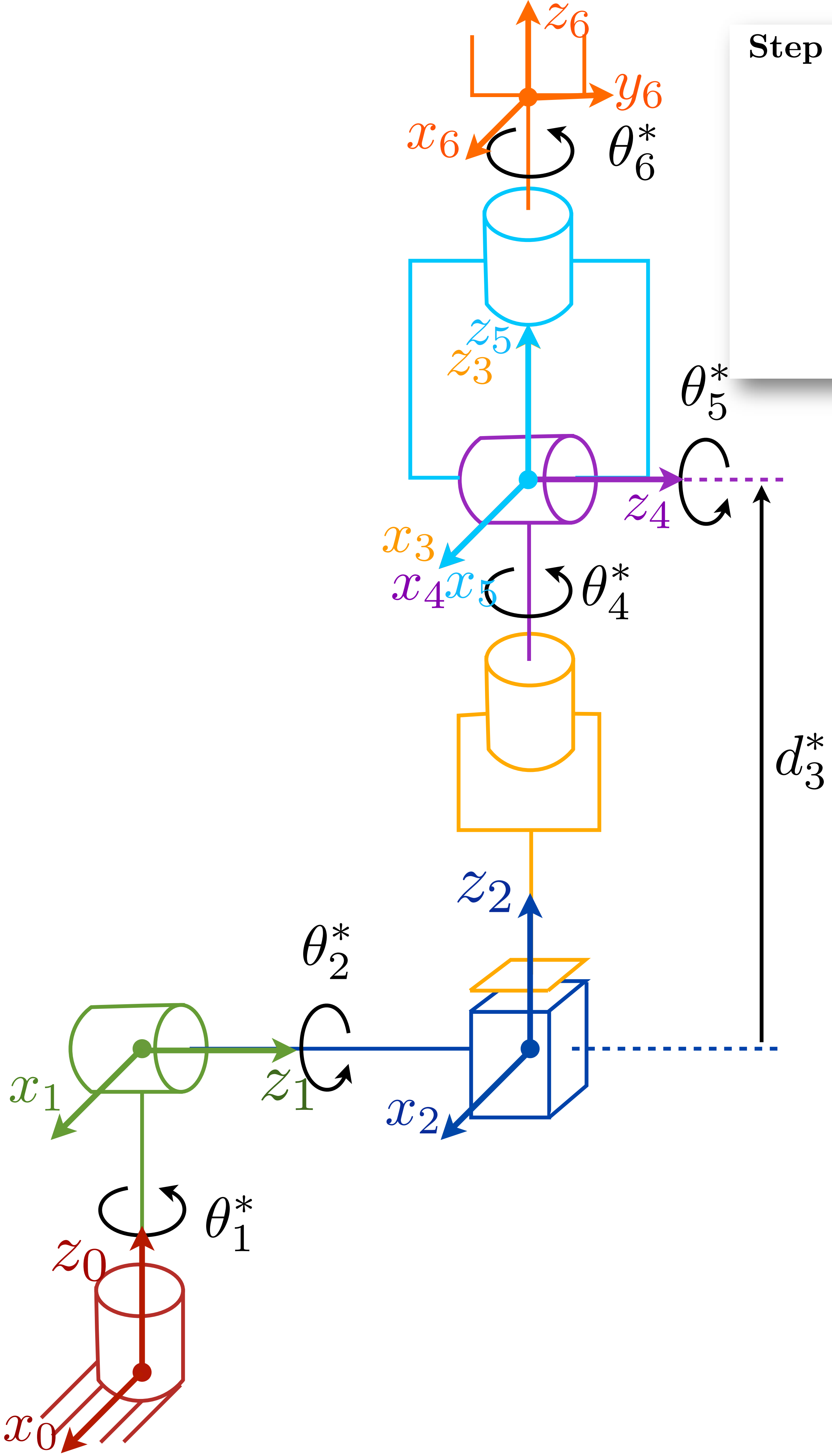
	x-step		z-step	
Link	a_i	α_i	d_i	θ_i
1	0	$-90°$	d_1	θ_1^*
2	0	$+90°$	d_2	θ_2^*
3	0	$0°$	d_3^*	$0°$



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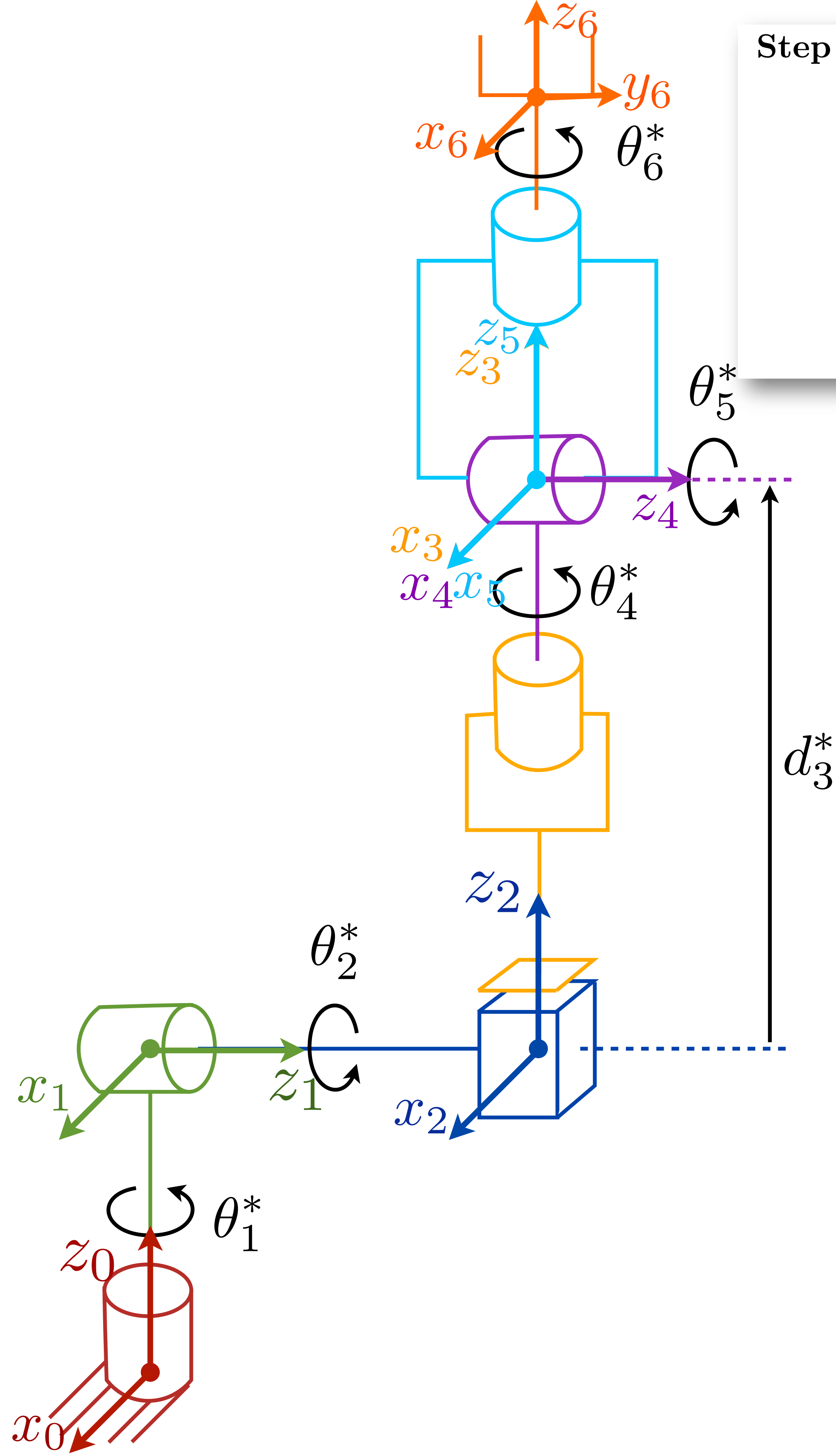
	x-step		z-step	
Link	a_i	α_i	d_i	θ_i
1	0	$-90°$	d_1	θ_1^*
2	0	$+90°$	d_2	θ_2^*
3	0	$0°$	d_3^*	$0°$
4	0	$-90°$	0	θ_4^*



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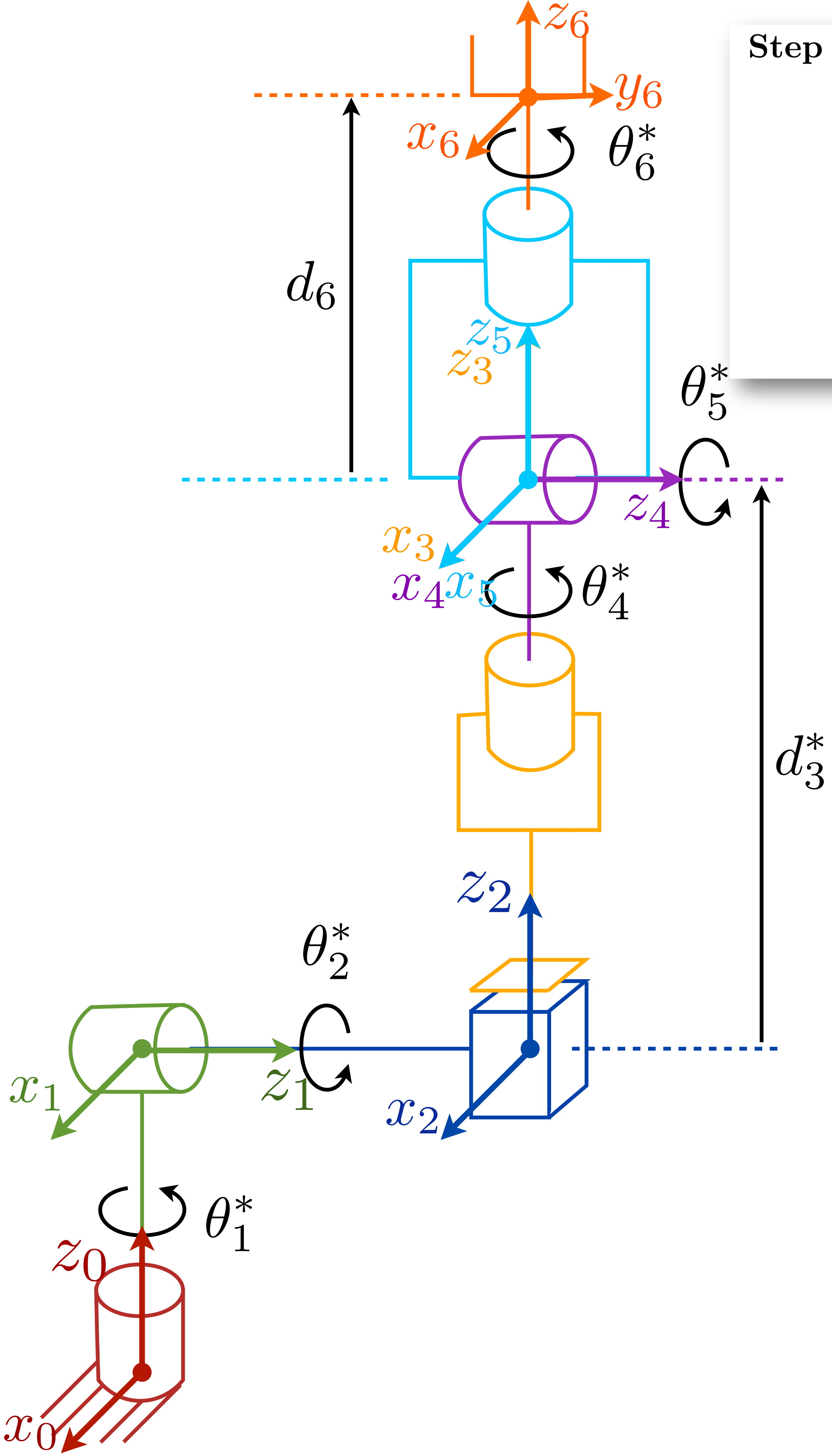
$\theta_i =$ the angle between x_{i-1} and x_i measured about z_{i-1}. θ_i is variable if joint i is revolute.

	x-step		z-step	
Link	a_i	α_i	d_i	θ_i
1	0	$-90°$	d_1	θ_1^*
2	0	$+90°$	d_2	θ_2^*
3	0	$0°$	d_3^*	$0°$
4	0	$-90°$	0	θ_4^*
5	0	$+90°$	0	θ_5^*



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

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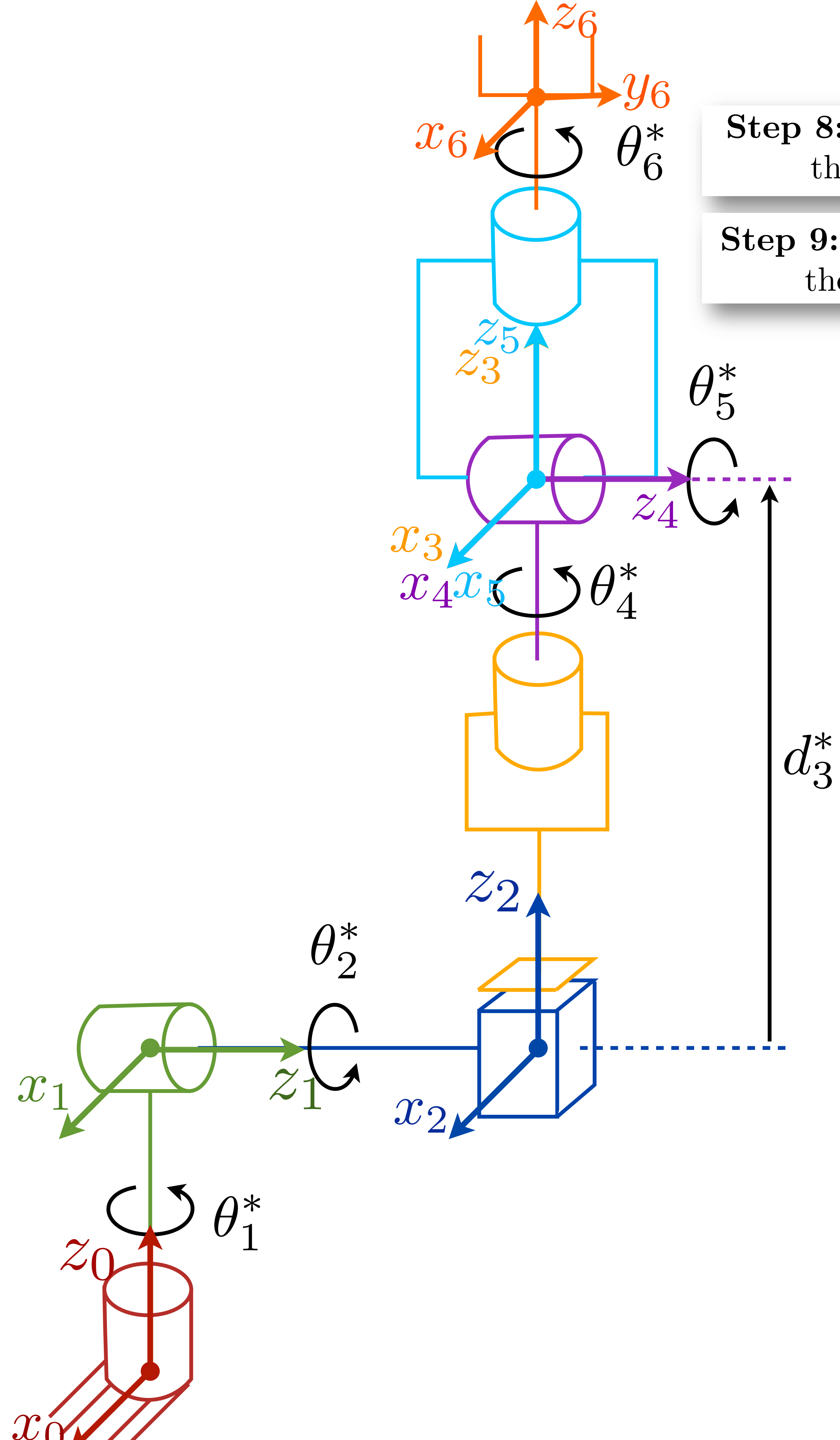
	x-step		z-step		
Link	a_i	α_i	d_i	θ_i	
1	0	$-90°$	d_1	θ_1^*	●→●
2	0	$+90°$	d_2	θ_2^*	●→●
3	0	$0°$	d_3^*	$0°$	●→●
4	0	$-90°$	0	θ_4^*	●→●
5	0	$+90°$	0	θ_5^*	●→●
6	0	$0°$	d_6	θ_6^*	●→●



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

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.

	x-step		z-step	
Link	a_i	α_i	d_i	θ_i
1	0	$-90°$	d_1	θ_1^*
2	0	$+90°$	d_2	θ_2^*
3	0	$0°$	d_3^*	$0°$
4	0	$-90°$	0	θ_4^*
5	0	$+90°$	0	θ_5^*
6	0	$0°$	d_6	θ_6^*

What questions do you have ?