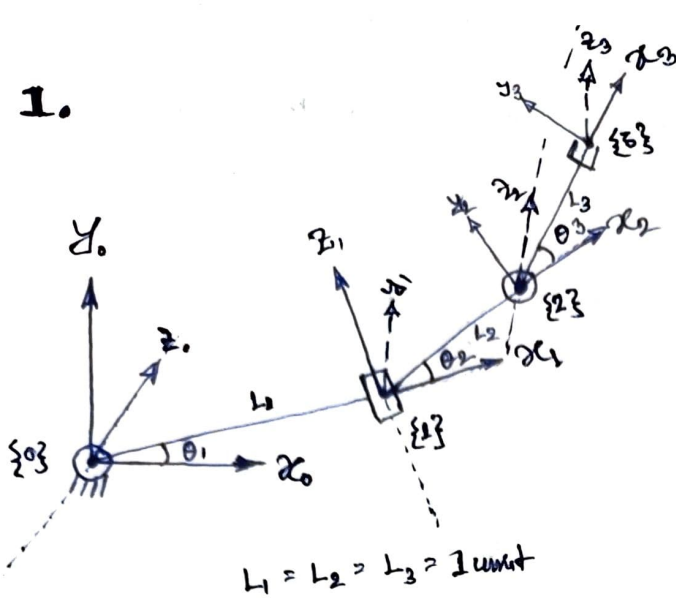


1.



$\{0\}$ - base frame

$\{i\}$ → frames attached to the distal joint of that link (i)

α_i = angle b/w z_{i-1} to z_i about $(+)$ x_{i-1} (ccw)

d_i = L distance b/w x_{i-1} to x_i along $(+)$ z_{i-1}

a_i = L distance from z_{i-1} to z_i along $(+)$ x_i

θ_i = angle b/w x_{i-1} to x_i about $(+)$ z_{i-1} (ccw)

	Joint Parameter		Link parameter	
	θ_i	d_i	a_i	α_i
1.	θ_1	0	1	-90°
2.	θ_2	0	1	90°
3.	θ_3	0	1	0

$${}^i_{i-1}T = \begin{bmatrix} \cos \theta_i & -\sin \theta_i \cos \alpha_i & \sin \theta_i \sin \alpha_i & a_i \cos \theta_i \\ \sin \theta_i & \cos \theta_i \cos \alpha_i & -\cos \theta_i \sin \alpha_i & a_i \sin \theta_i \\ 0 & \sin \alpha_i & \cos \alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$${}^0_1T = \begin{bmatrix} \cos \theta_1 & 0 & -\sin \theta_1 & 0 \\ \sin \theta_1 & 0 & \cos \theta_1 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

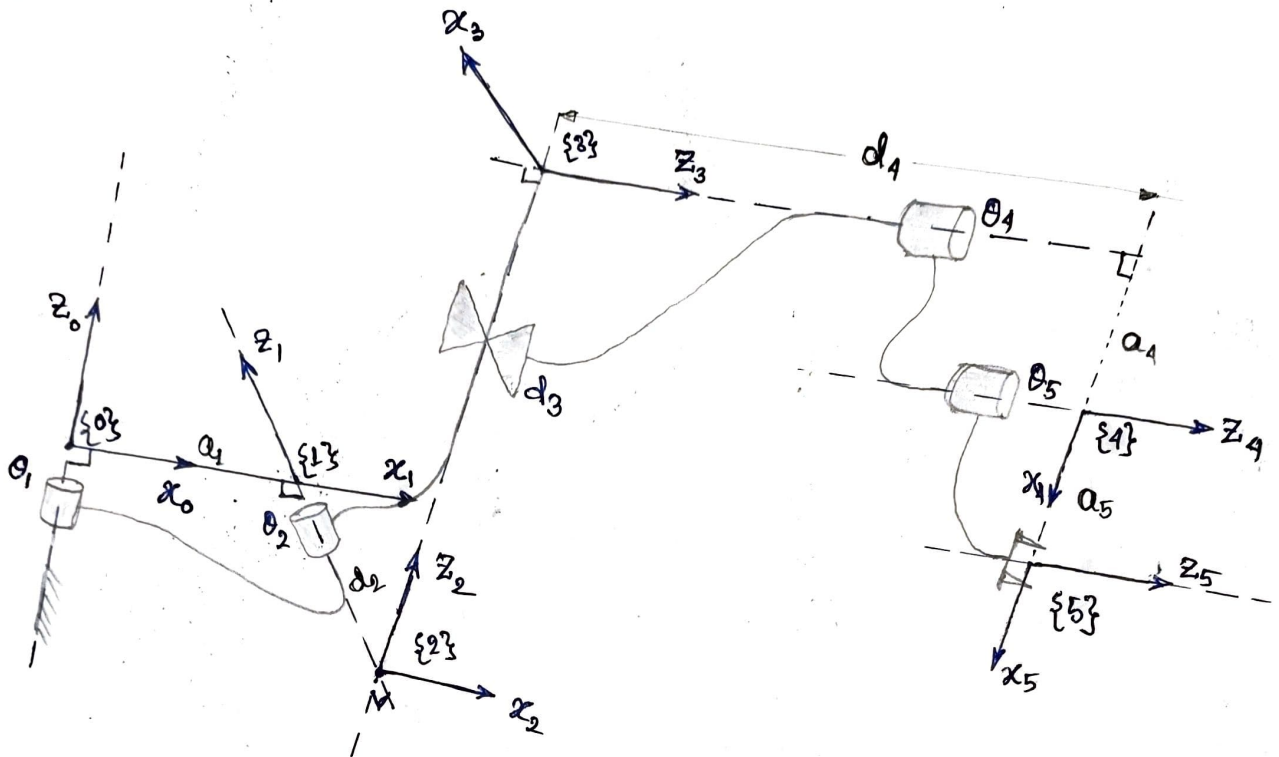
$${}^1_2T = \begin{bmatrix} \cos \theta_2 & 0 & \sin \theta_2 & 0 \\ \sin \theta_2 & 0 & -\cos \theta_2 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$${}^2_3T = \begin{bmatrix} \cos \theta_3 & -\sin \theta_3 & 0 & 0 \\ \sin \theta_3 & \cos \theta_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$${}^0_3T = {}^0_1T {}^1_2T {}^2_3T$$

$$= \begin{bmatrix} \cos \theta_1 \cos \theta_2 \cos \theta_3 - \sin \theta_1 \sin \theta_3 & -\cos \theta_1 \cos \theta_2 \sin \theta_3 - \sin \theta_1 \cos \theta_3 & \cos \theta_1 \sin \theta_2 & \cos \theta_1 \cos \theta_2 \cos \theta_3 - \sin \theta_1 \sin \theta_3 + \cos \theta_1 \cos \theta_2 + \cos \theta_1 \\ \sin \theta_1 \cos \theta_2 \cos \theta_3 + \cos \theta_1 \sin \theta_3 & -\sin \theta_1 \cos \theta_2 \sin \theta_3 + \cos \theta_1 \cos \theta_3 & \sin \theta_1 \sin \theta_2 & \sin \theta_1 \cos \theta_2 \cos \theta_3 + \cos \theta_1 \sin \theta_3 + \sin \theta_1 \cos \theta_2 + \sin \theta_1 \\ -\sin \theta_2 \cos \theta_3 & +\sin \theta_2 \sin \theta_3 & \cos \theta_2 & -\sin \theta_2 \cos \theta_3 - \sin \theta_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

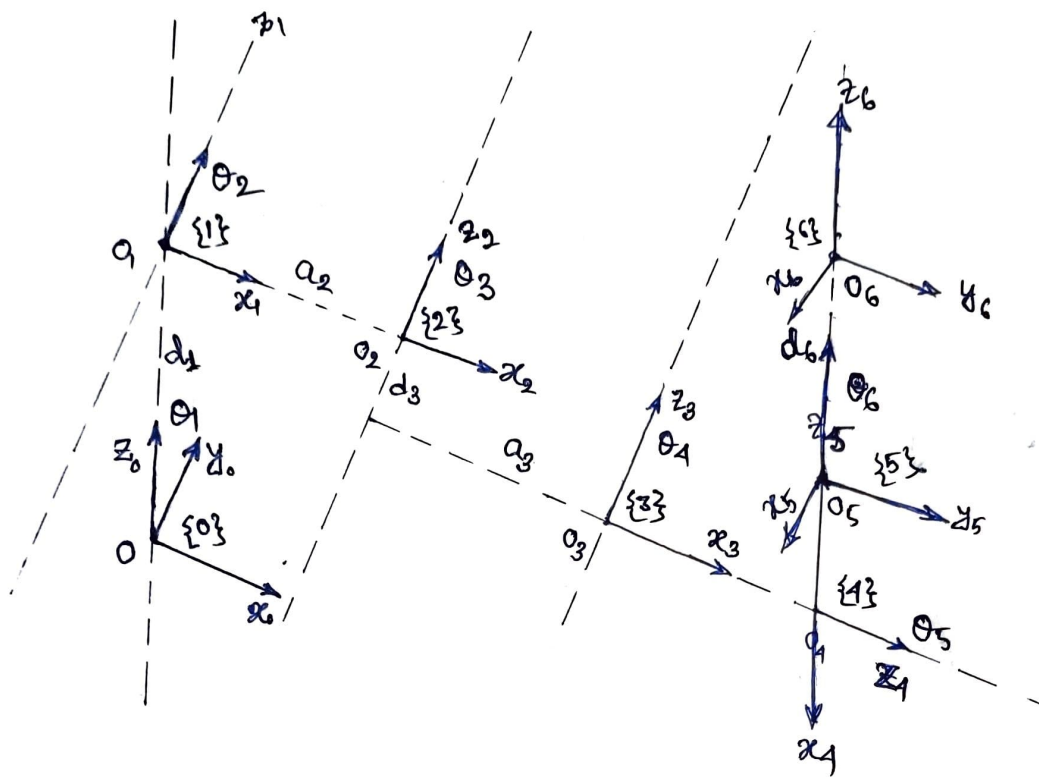
2.



θ_i	d_i	a_i	α_i
θ_1	0	a_1	α_1
θ_2	$-d_2$ (const.)	0	$-\pi/2$
$-\pi/2$	d_3	0	$-\pi/2$
θ_4	d_4 (const.)	a_4	0
θ_5	0	a_5	0

* Always try to keep minimum non-zero parameters and frames need to be attached accordingly.

3. PUMA manipulator:



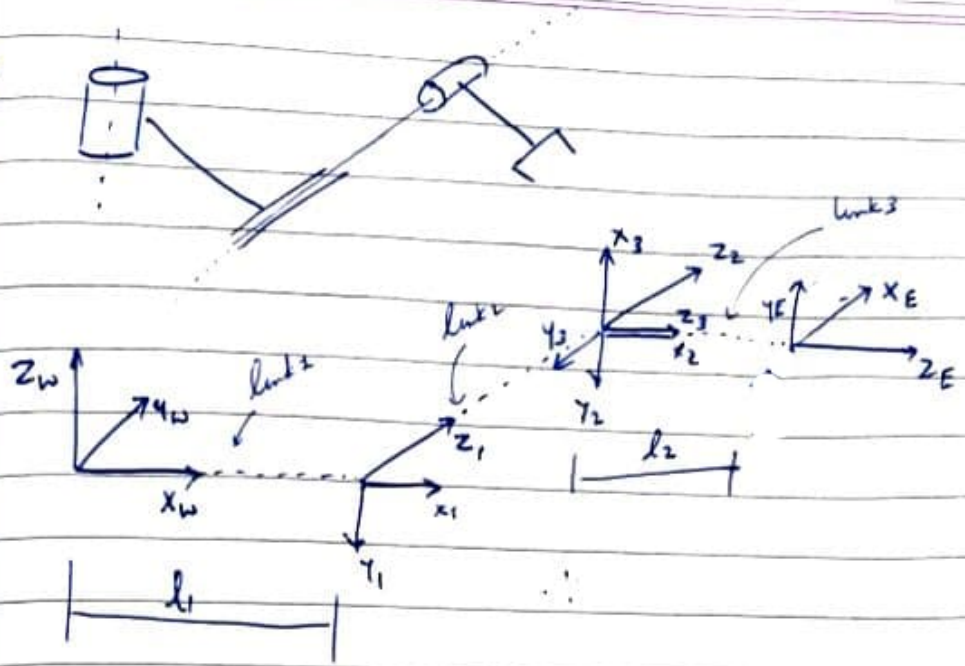
	θ_i	d_i	a_i	α_i
$({}^0T_1)$	θ_1	13	0	$-\pi/2$
$({}^1T_2)$	θ_2	0	8	0
$({}^2T_3)$	θ_3	-4	8	0
$({}^3T_4)$	θ_4	0	0	$\pi/2$
$({}^4T_5)$	θ_5	0	0	$\pi/2$
$({}^5T_6)$	θ_6	1	0	0

$\{1\} \rightarrow$ shoulder rotation, z_1
 $\{2\} \rightarrow$ Elbow rotation, z_2
 $\{3\} \rightarrow$ Wrist rotation, z_3
 $\{5\} \rightarrow$ Flange rotation, z_5

$O_3 = O_4 = O_5$ (same point)
 So, link length & joint distances will be zero.

- $d_1 = 13 \text{ in}$, $d_3 = 4 \text{ in}$, $d_6 = 1 \text{ in}$
- $a_2 = a_3 = 8 \text{ in}$

Q4)



DH parameter table

Link	a	α	d	θ
1	l_1	-90°	0	θ_1^*
2	0	0	d_2^*	0
3	0	-90°	0	$\theta_3^* - 90^\circ$

a_i = dist b/w Z_{i-1} - Z_i along X_i
 α_i = Angle b/w Z_{i-1} - Z_i about X_i
 d_i = dist b/w X_{i-1} - X_i along Z_{i-1}
 θ_i = angle b/w X_{i-1} - X_i about Z_{i-1}

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

← General Homogeneous transformation matrix

$$A_1 = \begin{bmatrix} \cos \theta_1 & 0 & -\sin \theta_1 & l_1 \cos \theta_1 \\ \sin \theta_1 & 0 & \cos \theta_1 & l_1 \sin \theta_1 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_2 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_3 = \begin{bmatrix} \cos \theta_3 & 0 & \sin \theta_3 & 0 \\ -\sin \theta_3 & 0 & \cos \theta_3 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

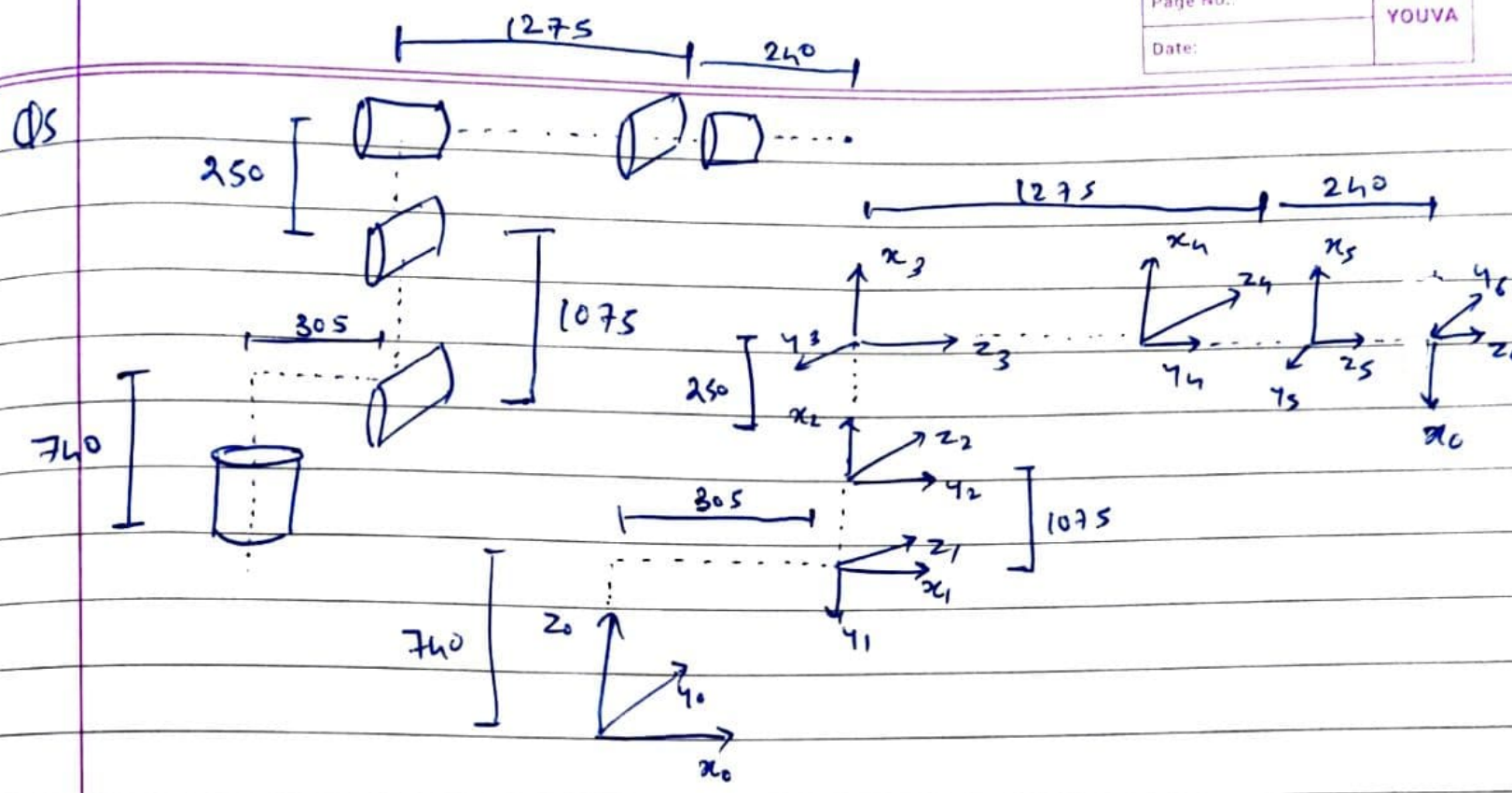
$$W_3 T = A_1 A_2 A_3$$

$$= \begin{bmatrix} CO_1 \cdot SO_3 & SO_1 & CO_1 \cdot CO_3 & l_1 CO_1 - d_2 SO_1 \\ SO_1 SO_3 & -CO_1 & CO_3 \cdot SO_1 & d_2 CO_1 + l_1 SO_1 \\ CO_3 & 0 & -SO_3 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

From the sketch we see an additional D-H per frame is added to include given end-effector frame

$$\text{Hence } {}^3_T E = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 1 & l_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$${}^W_E T = {}^W_3 T \cdot {}^3_T E = \begin{bmatrix} -s\theta_1 & c\theta_1 s\theta_3 & c\theta_1 c\theta_3 & l_1 c\theta_1 - d_2 s\theta_1 + l_2 (c\theta_1 c\theta_3) \\ c\theta_1 & s\theta_1 s\theta_3 & s\theta_1 c\theta_3 & d_1 c\theta_1 + l_1 s\theta_1 + l_2 (s\theta_1 c\theta_3) \\ 0 & c\theta_3 & -s\theta_3 & -l_2 s\theta_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$



Links a α d θ

1	305	-90°	740	θ_1^+
2	1075	0	0	$\theta_2^+ - 90^\circ$
3	250	-90°	0	θ_3^+
4	0	90°	1275	θ_4^+
5	0	-90°	0	θ_5^+
6	0	0	240	$180^\circ + \theta_6^+$