機械手臂 逆向運動學

Manipulator Inverse Kinematics

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引言

- 手臂順向運動學 Forward kinematics (FK)

  給予 θ_i（可計算出 ${}^{i-1}_{i}T$），求得 $\{H\}$ 或 ${}^{W}P$

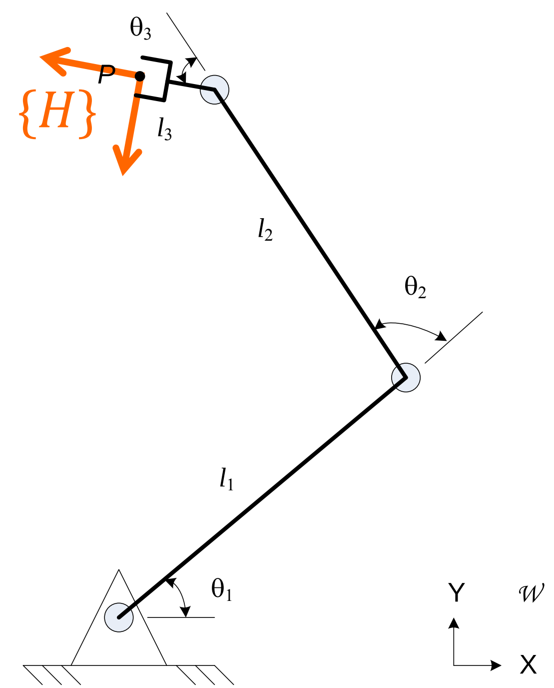
  $${}^{W}_{H}T = f(\theta_1, \dots, \theta_i, \dots, \theta_n)$$

  $${}^{W}P = {}^{W}_{H}T\,{}^{H}P$$

- 手臂逆向運動學 Inverse kinematics (IK)

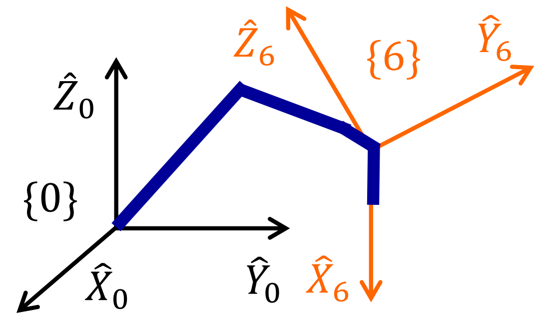
  給予 $\{H\}$ 或 ${}^{W}P$，求得 θ_i

  $$[\theta_1, \dots, \theta_i, \dots, \theta_n] = f^{-1}({}^{W}_{H}T)$$



求解概念 -1

- 假設手臂有6 DOFs
  - 6 個未知的joint angles（θ_i或d_i，$i=1,\ldots,6$）



- 在${}^W_HT$中擷取出含未知數的${}^0_6T$，16個數字

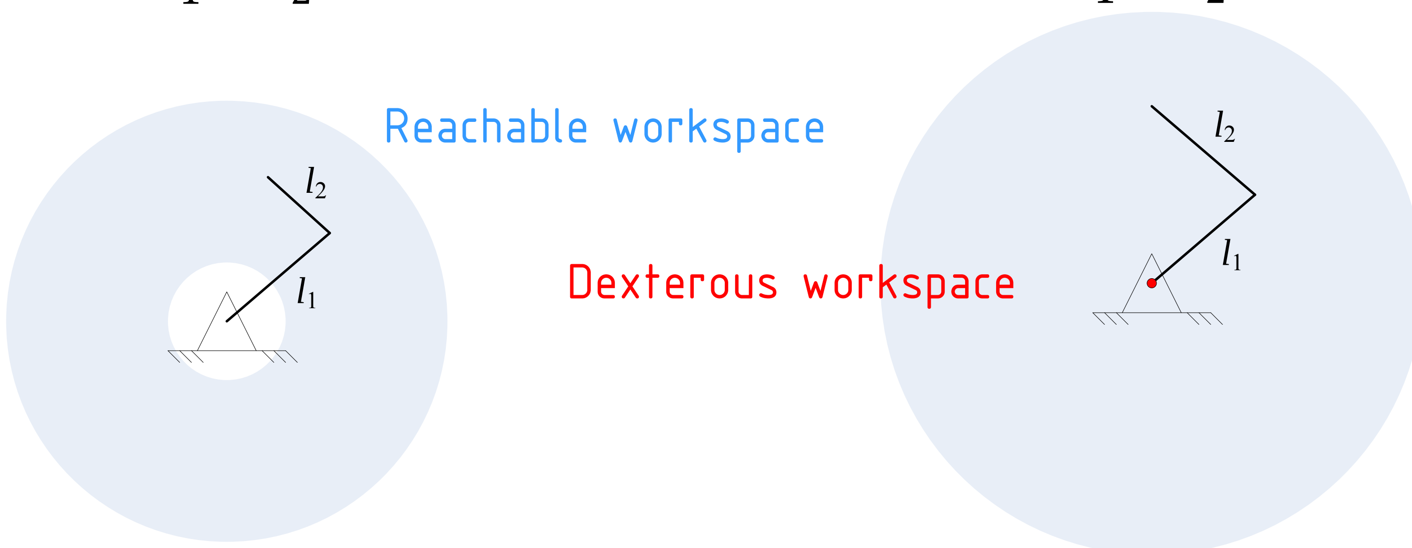
$$
{}^0_6T = \left[\begin{array}{ccc|c} & {}^0_6R_{3\times3} & & {}^0P_{6\,org\,3\times1} \\ \hline 0 & 0 & 0 & 1 \end{array}\right]_{4\times4} = \left[\begin{array}{ccc|c} | & | & | & | \\ {}^0\hat{X}_6 & {}^0\hat{Y}_6 & {}^0\hat{Z}_6 & {}^0P_{6\,org} \\ | & | & | & | \\ \hline 0 & 0 & 0 & 1 \end{array}\right]
$$

- 求解
  - 12個nonlinear transcendental equations方程式
  - 6個未知數，6個限制條件

求解概念 -2

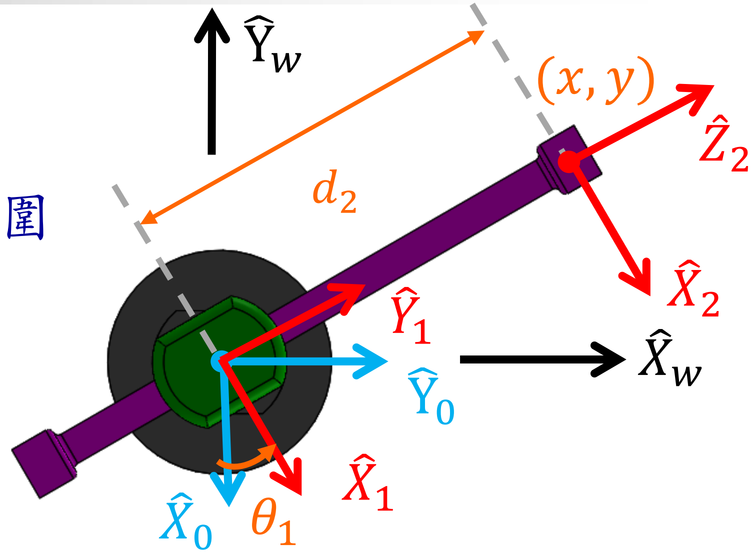
- Reachable workspace
  - 手臂可以用一種以上的姿態到達的位置
- Dexterous workspace
  - 手臂可以用任何的姿態到達的位置
- Ex: A RR manipulator

If $l_1 > l_2$ If $l_1 = l_2$

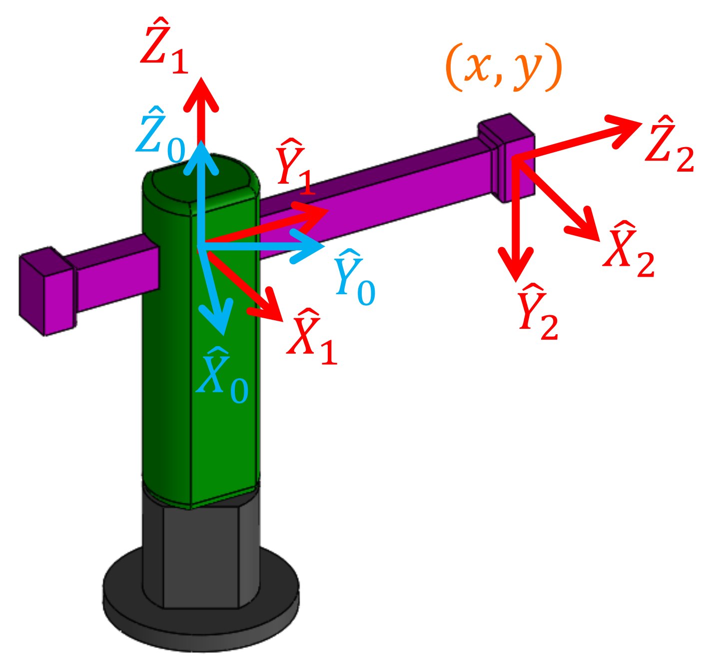


求解概念 -3

- Subspace
  - 手臂在定義頭尾的T所能達到的變動範圍
- Ex: A RP manipulator
  - 2-DOF, Variables: (x, y)



$$
\begin{array}{cc}
 & \begin{array}{cccc} \phantom{\frac{y}{\sqrt{x^2+y^2}}} & & {}^{0}\hat{Z}_2 & {}^{0}P_{2\,ORG} \end{array} \\
{}^{w}_{2}T = & \begin{bmatrix} \frac{y}{\sqrt{x^2+y^2}} & 0 & \frac{x}{\sqrt{x^2+y^2}} & x \\ \frac{-x}{\sqrt{x^2+y^2}} & 0 & \frac{y}{\sqrt{x^2+y^2}} & y \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
\end{array}
$$



多重解 -1

- 解的數目
  - 由於是nonlinear transcendental equations，6未知數6方程式不代表具有唯一解
  - 是由joint數目和link參數所決定

    Ex: A RRRRRR manipulator

a_i	解的數目
$a_1 = a_3 = a_5 = 0$	≤ 4
$a_3 = a_5 = 0$	≤ 8
$a_3 = 0$	≤ 16
$All\ a_i \neq 0$	≤ 16

多重解 -2

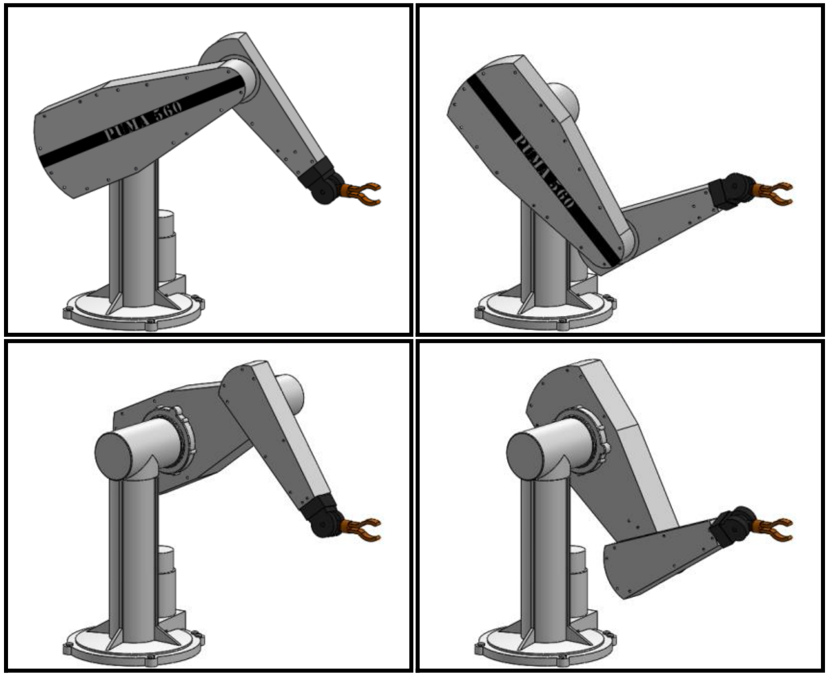
- Ex: PUMA (6 rotational joints)
  - 針對特定工作點，8組解
  - 前3軸具有4種姿態

    如右圖所示
  - 每一個姿態中，具有2組手腕轉動姿態

    $$\theta_4' = \theta_4 + 180^\circ$$

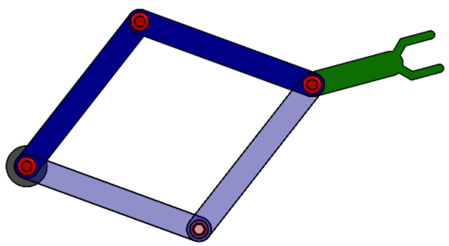
    $$\theta_5' = -\theta_5$$

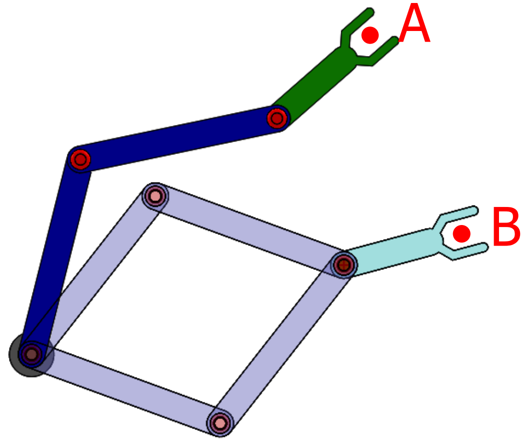
    $$\theta_6' = \theta_6 + 180^\circ$$
  - 若手臂本身有幾何限制，並非每一種解都可以運作

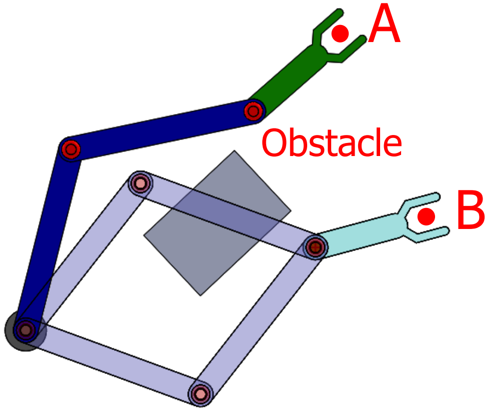


多重解 -3

- 若具有多重解，解的選擇方式
  - 離目前狀態最近的解
    - 最快
    - 最省能
    - ....
  - 避開障礙物







求解方法

- 解析法 Closed-form solutions
  - 用 代數algebraic 或 幾何geometric 方法
- 數值法 Numerical solutions
- 目前大多機械手臂設計成具有解析解
  - Pieper's solution: 相鄰三軸相交一點

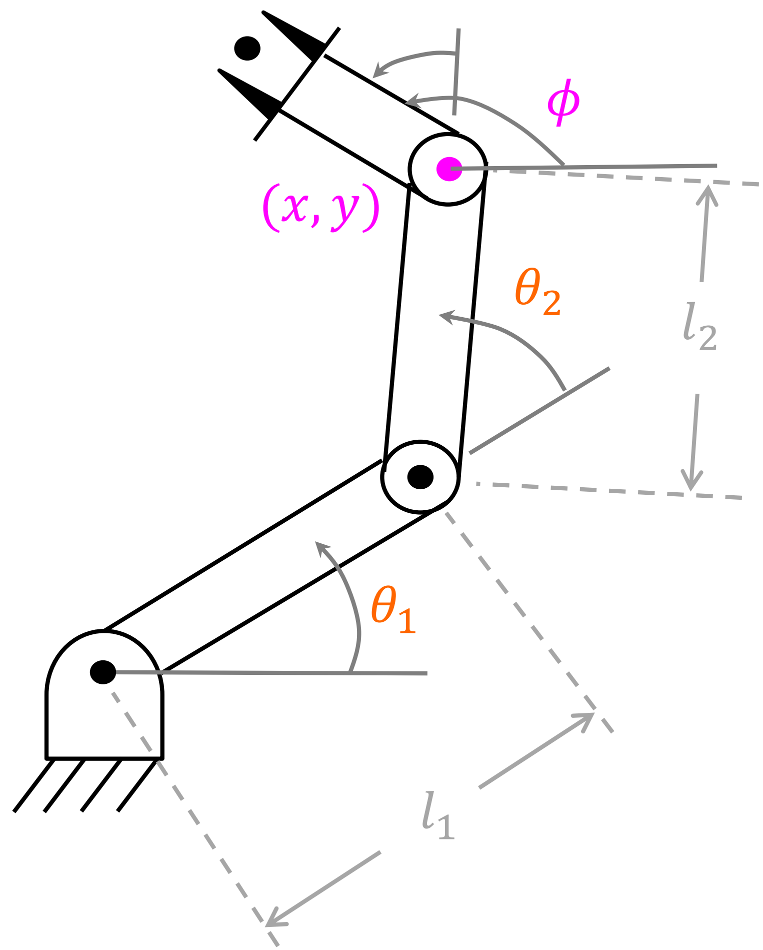
Example: A RRR Manipulator -1

- Ik problem: given (x, y, ϕ), $(\theta_1, \theta_2, \theta_3) = ?$
  - Forward kinematics

$$ {}^0_3T = \begin{bmatrix} c_{123} & -s_{123} & 0.0 & l_1c_1 + l_2c_{12} \\ s_{123} & c_{123} & 0.0 & l_1s_1 + l_2s_{12} \\ 0.0 & 0.0 & 1.0 & 0.0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

  - Goal point

$$ {}^0_3T = \begin{bmatrix} c_\phi & -s_\phi & 0.0 & x \\ s_\phi & c_\phi & 0.0 & y \\ 0.0 & 0.0 & 1.0 & 0.0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$



Example: A RRR Manipulator -2

- 幾何法：將空間幾何切割成平面幾何

$$x^2 + y^2 = l_1^2 + l_2^2 - 2l_1 l_2 \cos(180^\circ - \theta_2)$$

$$c_2 = \frac{x^2 + y^2 - l_1^2 - l_2^2}{2l_1 l_2}$$

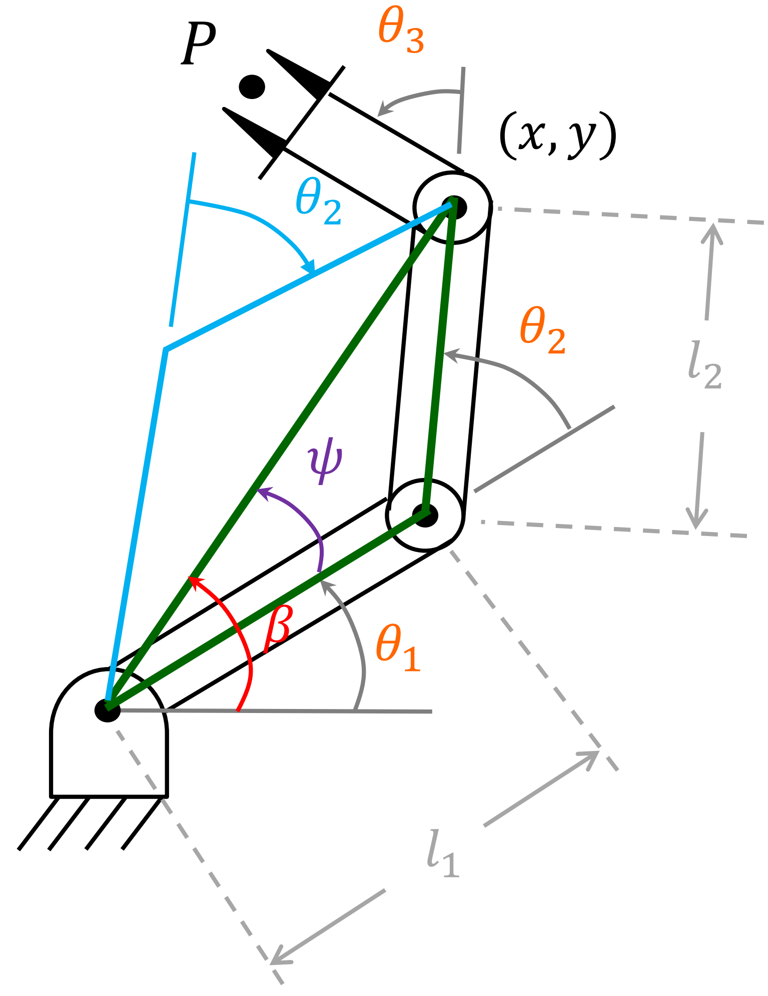
餘弦定理

$$cos\psi = \frac{l_2^2 - (x^2 + y^2) - l_1^2}{-2l_1\sqrt{x^2 + y^2}}$$

三角形內角 $0^\circ < \psi < 180^\circ$

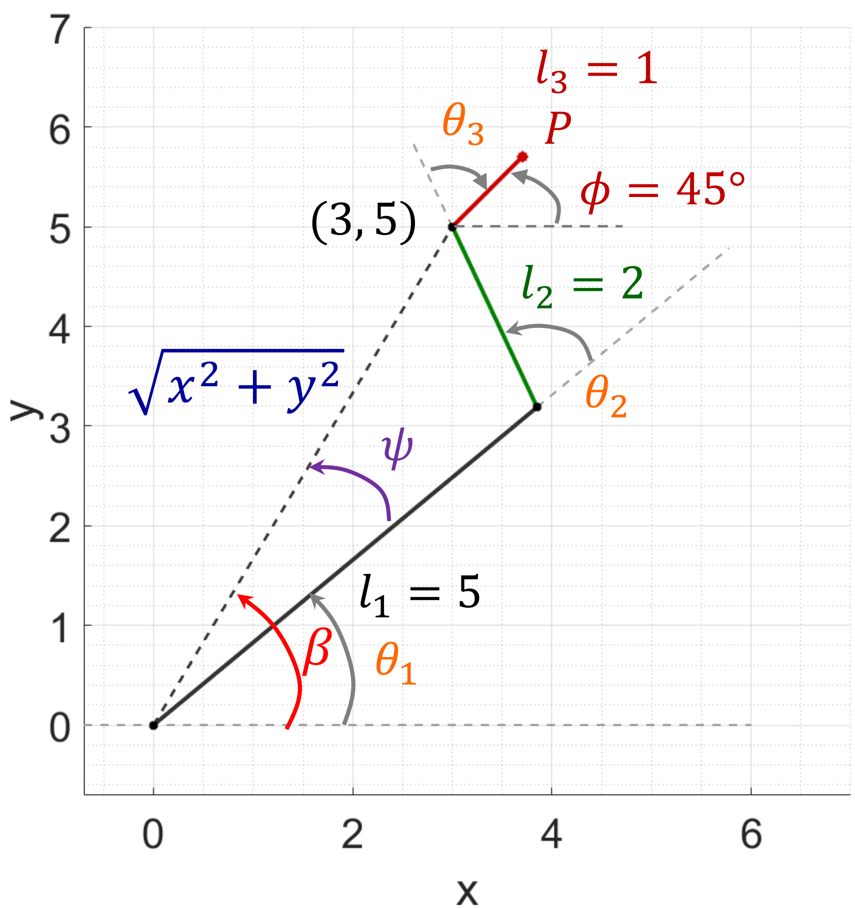
$$\theta_1 = \begin{cases} atan2(y,x) + \psi & \theta_2 < 0^\circ \\ atan2(y,x) - \psi & \theta_2 > 0^\circ \end{cases}$$

$$\theta_3 = \phi - \theta_1 - \theta_2$$



Example: A RRR Manipulator -3

- Ex: 量化計算



$$c_2 = \frac{x^2 + y^2 - l_1^2 - l_2^2}{2 l_1 l_2}$$

$$\theta_2 = 75.5°$$

$$cos\psi = \frac{l_2^2 - (x^2 + y^2) - l_1^2}{-2 l_1 \sqrt{x^2 + y^2}}$$

$$\psi = 19.4°$$

$$\theta_1 = atan2(y, x) - \psi$$

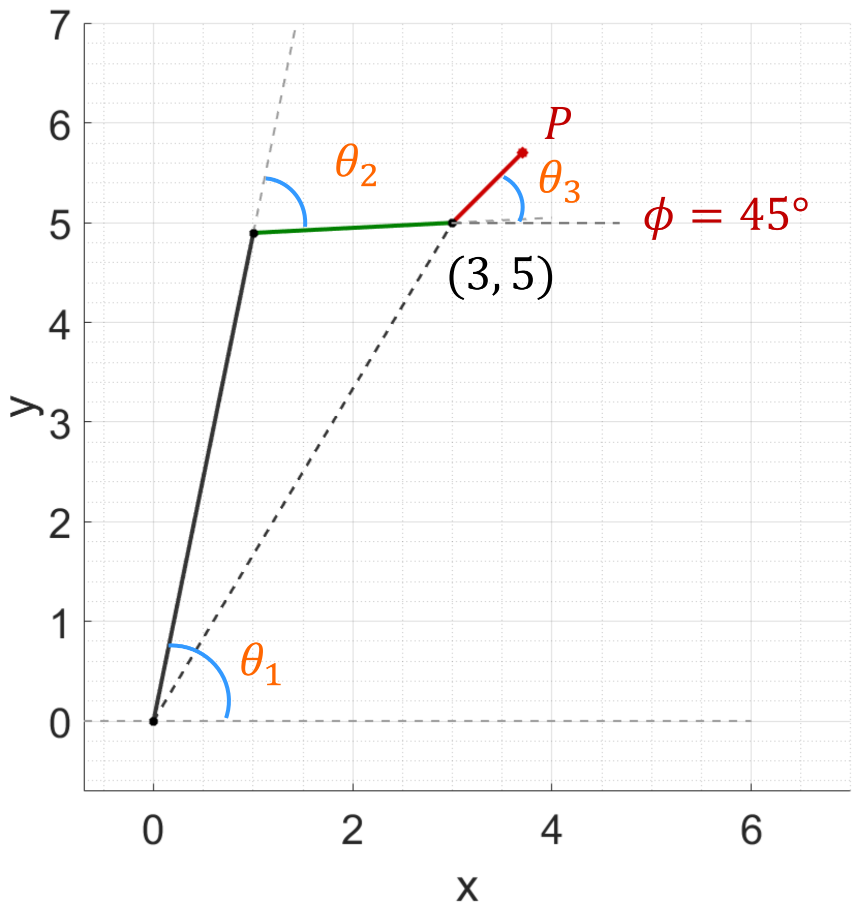
$$\theta_1 = 39.6°$$

$$\theta_3 = \phi - \theta_1 - \theta_2$$

$$\theta_3 = -70.2°$$

Example: A RRR Manipulator -4

- In-Video Quiz: 針對同一個位移和姿態，求得另一組 $(\theta_1, \theta_2, \theta_3)$ 的解



(A)
$\theta_1 = 75.5$
$\theta_2 = -78.4$
$\theta_3 = 42.1$

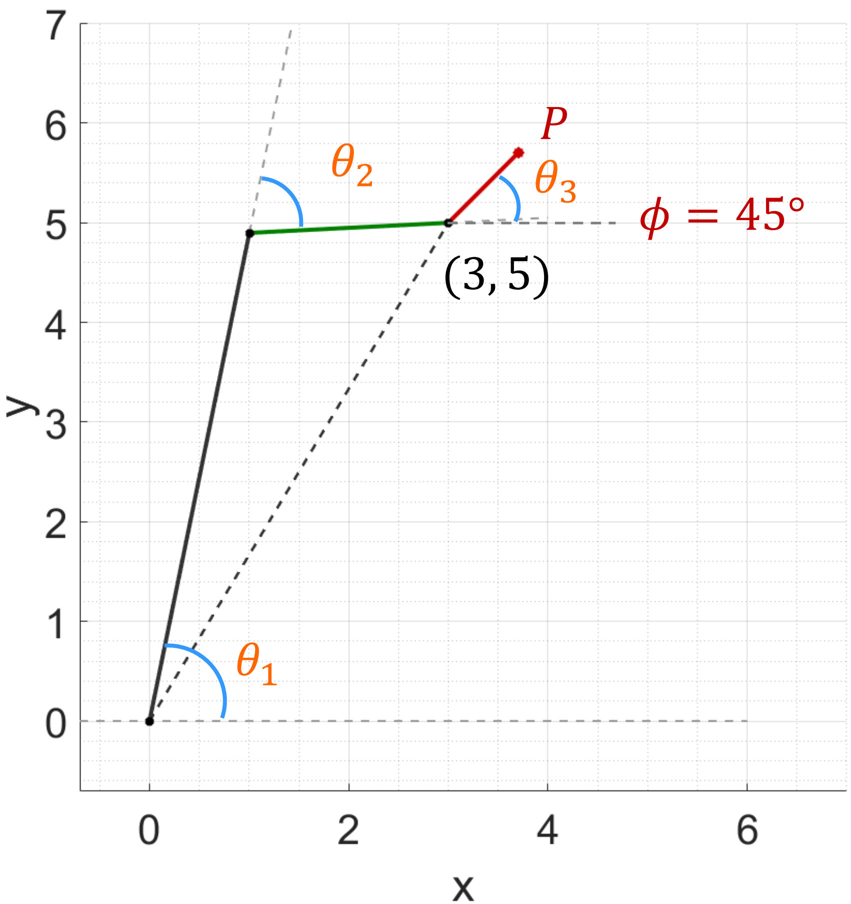
(B)
$\theta_1 = 78.4$
$\theta_2 = -75.5$
$\theta_3 = 42.1$

(C)
$\theta_1 = -78.4$
$\theta_2 = 75.5$
$\theta_3 = 42.1$

(D)
$\theta_1 = 59$
$\theta_2 = -75.5$
$\theta_3 = 42.1$

Example: A RRR Manipulator -4

- In-Video Quiz: 針對同一個位移和姿態，求得另一組 $(\theta_1, \theta_2, \theta_3)$ 的解



(A)
$\theta_1 = 75.5$
$\theta_2 = -78.4$
$\theta_3 = 42.1$

(B)
$\theta_1 = 78.4$
$\theta_2 = -75.5$
$\theta_3 = 42.1$

(C)
$\theta_1 = -78.4$
$\theta_2 = 75.5$
$\theta_3 = 42.1$

(D)
$\theta_1 = 59$
$\theta_2 = -75.5$
$\theta_3 = 42.1$

Example: A RRR Manipulator -5

- 代數解
  - 建立方程式

$$c_\phi = c_{123}$$

$$s_\phi = s_{123}$$

$$x = l_1c_1 + l_2c_{12}$$

$$y = l_1s_1 + l_2s_{12}$$

$$ {}^0_3T = \begin{bmatrix} c_{123} & -s_{123} & 0.0 & l_1c_1 + l_2c_{12} \\ s_{123} & c_{123} & 0.0 & l_1s_1 + l_2s_{12} \\ 0.0 & 0.0 & 1.0 & 0.0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} c_\phi & -s_\phi & 0.0 & x \\ s_\phi & c_\phi & 0.0 & y \\ 0.0 & 0.0 & 1.0 & 0.0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

  - 解 θ_2

$$x^2 + y^2 = {l_1}^2 + {l_2}^2 + 2l_1l_2c_2$$

$$c_2 = \frac{x^2 + y^2 - {l_1}^2 - {l_2}^2}{2l_1l_2}$$

> 1 or < 1: too far for the manipulator to reach

$-1 \leq \quad \leq 1$: "two solutions" $\theta_2 = cos^{-1}(c_2)$

Example: A RRR Manipulator -6

- 將求得的 θ_2 帶入方程式

$$x = l_1 c_1 + l_2 c_{12} = (l_1 + l_2 c_2) c_1 + (-l_2 s_2) s_1 \triangleq k_1 c_1 - k_2 s_1$$

$$y = l_1 s_1 + l_2 s_{12} = (l_1 + l_2 c_2) s_1 + \quad (l_2 s_2) c_1 \triangleq k_1 s_1 + k_2 c_1$$

- 變數變換

define

$$r = +\sqrt{{k_1}^2 + {k_2}^2}$$

$$\gamma = Atan2(k_2, k_1)$$

then

$$k_1 = r \cos \gamma$$

$$k_2 = r \sin \gamma$$

And then

$$\frac{x}{r} = \cos \gamma \cos \theta_1 - \sin \gamma \sin \theta_1 = \cos(\gamma + \theta_1)$$

$$\frac{y}{r} = \cos \gamma \sin \theta_1 + \sin \gamma \cos \theta_1 = \sin(\gamma + \theta_1)$$

Example: A RRR Manipulator -7

- 解 θ_1

$$\gamma + \theta_1 = Atan2\left(\frac{y}{r}, \frac{x}{r}\right) = Atan2(y, x)$$

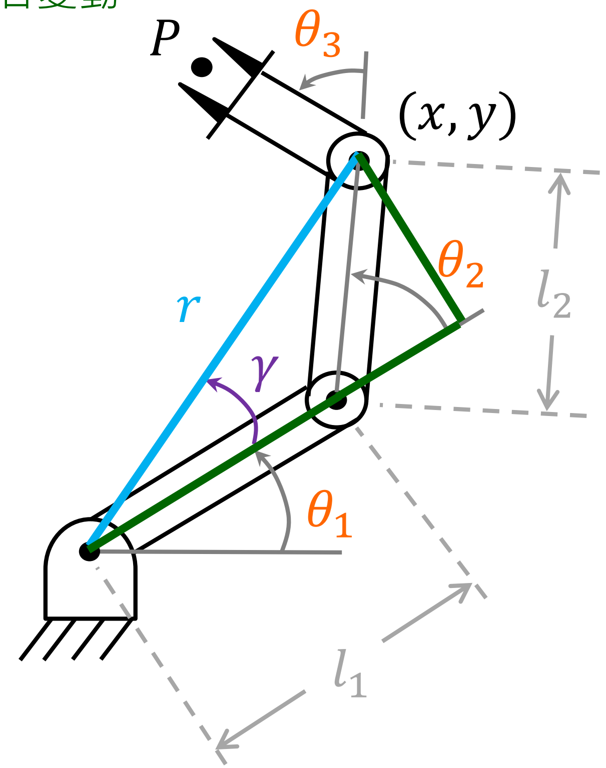
$$\Rightarrow \quad \theta_1 = Atan2(y, x) - Atan2(k_2, k_1)$$

當θ_2選不同解， $c2$和$s2$變動，k_1和k_2變動，θ_1也跟者變動

- 解 θ_3

$$\theta_1 + \theta_2 + \theta_3 = Atan2(s_\phi, c_\phi) = \phi$$

$$\Rightarrow \quad \theta_3 = \phi - \theta_1 - \theta_2$$



三角函數方程式求解

- Ex: 如何求得 $acos\theta + \mathrm{bsin}\theta = c$ 的 θ？
  - 方法：變換到polynomials （4階以下有解析解）

$$\tan\left(\frac{\theta}{2}\right) = u, \qquad \cos\theta = \frac{1-u^2}{1+u^2}, \qquad \sin\theta = \frac{2u}{1+u^2}$$

  - 步驟：

$$acos\theta + \mathrm{bsin}\theta = c$$

$$a\frac{1-u^2}{1+u^2} + \mathrm{b}\frac{2\mathrm{u}}{1+u^2} = c$$

$$(a+c)u^2 - 2bu + (c-a) = 0$$

$$u = \frac{\mathrm{b} \pm \sqrt{b^2+a^2-c^2}}{\mathrm{a+c}}$$

a, b, c大小有限制, 不一定有解

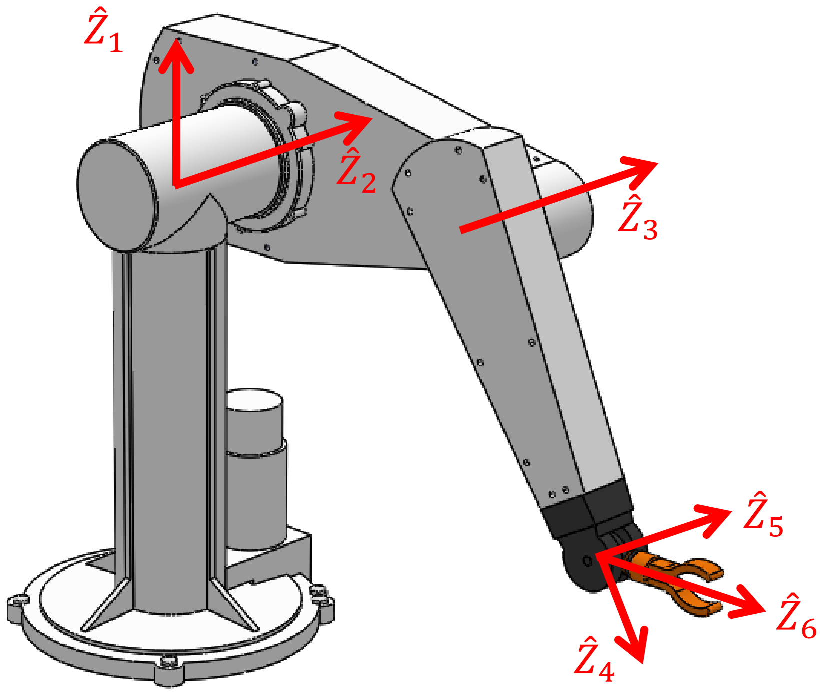
$$\theta = 2\tan^{-1}\left(\frac{\mathrm{b} \pm \sqrt{b^2+a^2-c^2}}{\mathrm{a+c}}\right) \qquad a+c \neq 0$$

$$\theta = 180^{\circ} \qquad a+c = 0$$

Pieper's Solution -1

- 若6-DOF manipulator具有三個連續的軸交在同一點，則手臂有解析解
- 一般，會把後三軸如此設計
  - 前三軸：產生移動
  - 後三軸：產生轉動
- Ex: A RRRRRR manipulator
  - 因後三軸交一點

$$^{0}P_{6\,ORG} = {}^{0}P_{4\,ORG}$$



Pieper's Solution -2

- Positioning structure
  - 法則：讓$\theta_1, \theta_2, \theta_3$層層分離

Note: $${}^{i-1}_{i}T = \begin{bmatrix} c\theta_i & -s\theta_i & 0 & a_{i-1} \\ s\theta_i c\alpha_{i-1} & c\theta_i c\alpha_{i-1} & -s\alpha_{i-1} & -s\alpha_{i-1} d_i \\ s\theta_i s\alpha_{i-1} & c\theta_i s\alpha_{i-1} & c\alpha_{i-1} & c\alpha_{i-1} d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = {}^{0}P_{4\,ORG} = {}^{0}_{1}T\,{}^{1}_{2}T\,{}^{2}_{3}T\;{}^{3}P_{4\,ORG}$$

$$\cos\theta_i = c\theta_i = c_i$$
$$\sin\theta_i = s\theta_i = s_i$$

$$= {}^{0}_{1}T\,{}^{1}_{2}T\,{}^{2}_{3}T \begin{bmatrix} a_3 \\ -d_4 s\alpha_3 \\ d_4 c\alpha_3 \\ 1 \end{bmatrix} = {}^{0}_{1}T\,{}^{1}_{2}T \begin{bmatrix} f_1(\theta_3) \\ f_2(\theta_3) \\ f_3(\theta_3) \\ 1 \end{bmatrix}$$

so

4^{th} column of ${}^{3}_{4}T$

$$\begin{bmatrix} f_1(\theta_3) \\ f_2(\theta_3) \\ f_3(\theta_3) \\ 1 \end{bmatrix} = {}^{2}_{3}T \begin{bmatrix} a_3 \\ -d_4 s\alpha_3 \\ d_4 c\alpha_3 \\ 1 \end{bmatrix}$$

讓$\theta_1, \theta_2, \theta_3$層層分離，$f$為$\theta_3$函數

$$f_1(\theta_3) = a_3 c_3 + d_4 s\alpha_3 s_3 + a_2$$
$$f_2(\theta_3) = a_3 c\alpha_2 s_3 - d_4 s\alpha_3 c\alpha_2 c_3 - d_4 s\alpha_2 c\alpha_3 - d_3 s\alpha_2$$
$$f_3(\theta_3) = a_3 s\alpha_2 s_3 - d_4 s\alpha_3 s\alpha_2 c_3 + d_4 c\alpha_2 c\alpha_3 + d_3 c\alpha_2$$

Pieper's Solution -3

- 下一步

$$
{}^{0}P_{4ORG} = \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = {}^{0}_{1}T\,{}^{1}_{2}T \begin{bmatrix} f_1(\theta_3) \\ f_2(\theta_3) \\ f_3(\theta_3) \\ 1 \end{bmatrix} = {}^{0}_{1}T \begin{bmatrix} g_1(\theta_2,\theta_3) \\ g_2(\theta_2,\theta_3) \\ g_3(\theta_2,\theta_3) \\ 1 \end{bmatrix} = \begin{bmatrix} c_1 g_1 - s_1 g_2 \\ s_1 g_1 + c_1 g_2 \\ g_3 \\ 1 \end{bmatrix}
$$

讓$\theta_1, \theta_2, \theta_3$層層分離， g為θ_2, θ_3函數

$$
\begin{aligned}
g_1(\theta_2,\theta_3) &= c_2 f_1 - s_2 f_2 + a_1 \\
g_2(\theta_2,\theta_3) &= s_2 c\alpha_1 f_1 + c_2 c\alpha_1 f_2 - s\alpha_1 f_3 - d_2 s\alpha_1 \\
g_3(\theta_2,\theta_3) &= s_2 s\alpha_1 f_1 + c_2 s\alpha_1 f_2 + c\alpha_1 f_3 + d_2 c\alpha_1
\end{aligned}
$$

$$
\begin{aligned}
r &= x^2 + y^2 + z^2 = g_1^2 + g_2^2 + g_3^2 \\
&= f_1^2 + f_2^2 + f_3^2 + a_1^2 + d_2^2 + 2d_2 f_3 + 2a_1(c_2 f_1 - s_2 f_2) \\
&= (k_1 c_2 + k_2 s_2)2a_1 + k_3
\end{aligned}
$$

r僅為θ_2, θ_3函數

$$
\begin{aligned}
k_1(\theta_3) &= f_1 \\
k_2(\theta_3) &= -f_2 \\
k_3(\theta_3) &= f_1^2 + f_2^2 + f_3^2 + a_1^2 + d_2^2 + 2d_2 f_3
\end{aligned}
$$

Pieper's Solution -4

- 此外

$$z = g_3 = (k_1 s_2 - k_2 c_2) s\alpha_1 + k_4$$

z僅為θ_2, θ_3函數

$$k_1(\theta_3) = f_1$$
$$k_2(\theta_3) = -f_2$$
$$k_4(\theta_3) = f_3 c\alpha_1 + d_2 c\alpha_1$$

- 整合 r 和 z 一起考量

$$\begin{cases} r = (k_1 c_2 + k_2 s_2) 2a_1 + k_3 \\ z = (k_1 s_2 - k_2 c_2) s\alpha_1 + k_4 \end{cases}$$

  - If $a_1 = 0$, $r = k_3(\theta_3) = f_1^2 + f_2^2 + f_3^2 + a_1^2 + d_2^2 + 2d_2 f_3$
  - If $s\alpha_1 = 0$, $z = k_4(\theta_3) = f_3 c\alpha_1 + d_2 c\alpha_1$
  - Else

$$\frac{(r - k_3)^2}{4a_1^2} + \frac{(z - k_4)^2}{s^2\alpha_1} = k_1^2 + k_2^2$$

⇨ Solve θ_3 of all three cases by using "$u = \tan\left(\frac{\theta_3}{2}\right)$"

Pieper's Solution -5

- 最後

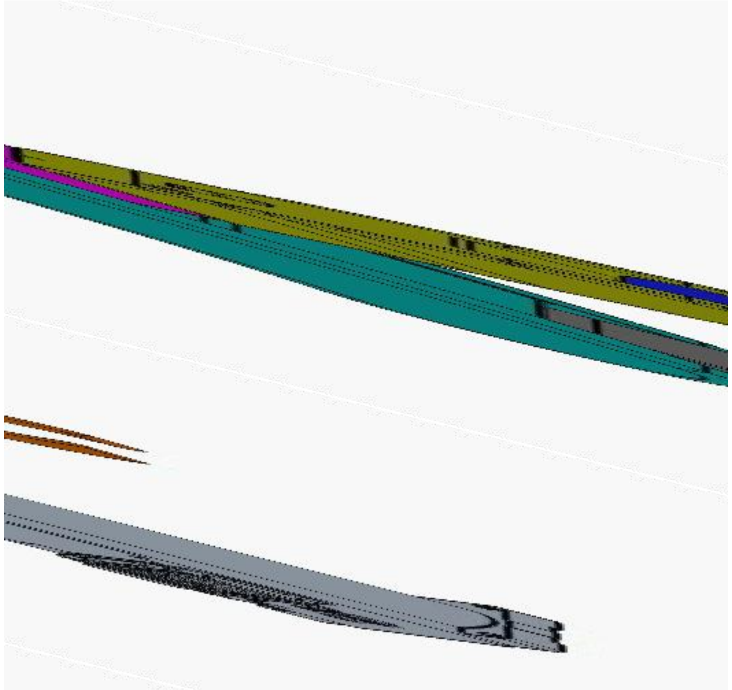
  Using $r = (k_1 c_2 + k_2 s_2)2a_1 + k_3$ to solve θ_2

  Using $x = c_1 g_1(\theta_2, \theta_3) - s_1 g_2(\theta_2, \theta_3)$ to solve θ_1

- Orientation
  - θ_1, θ_2, θ_3 已知

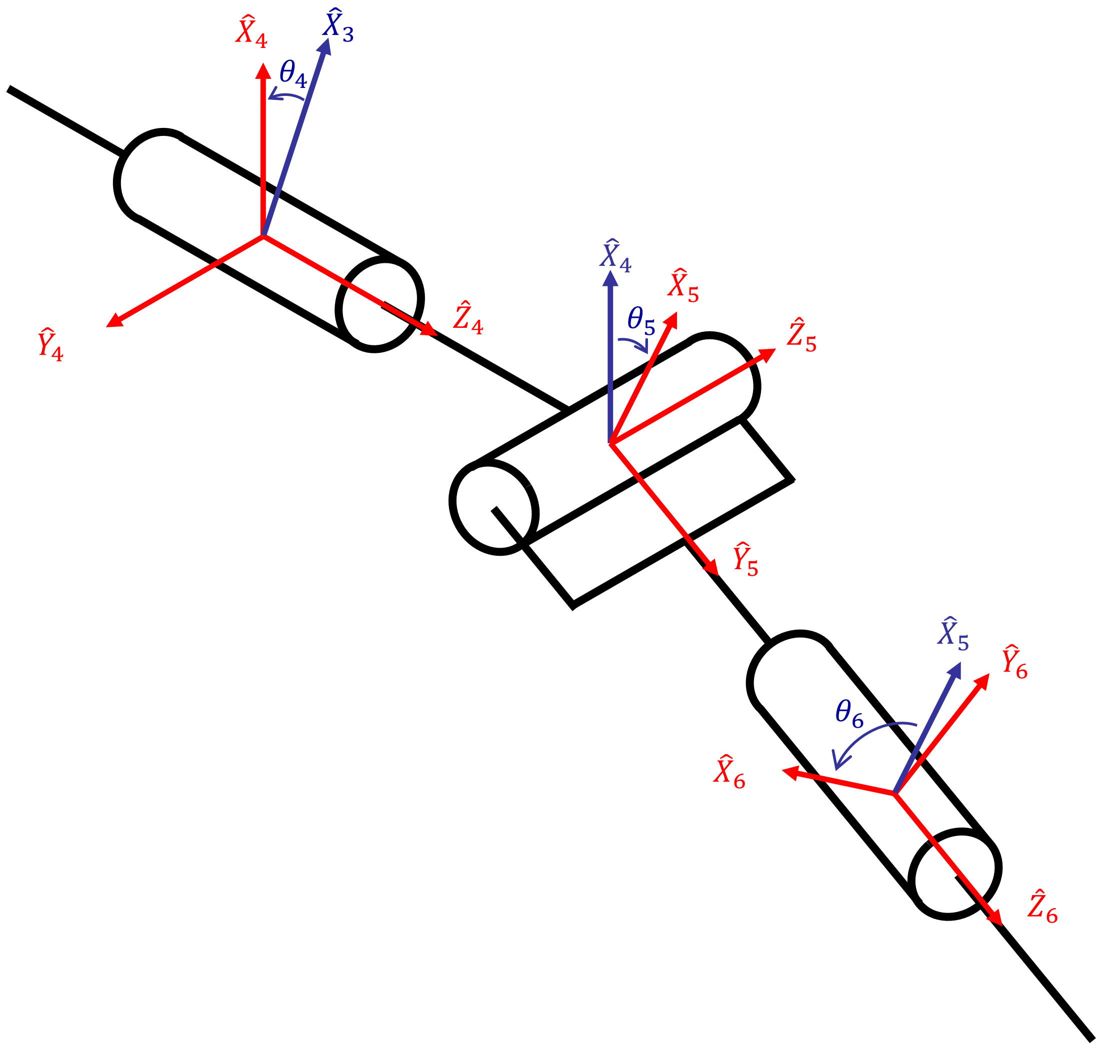
    $${}^3_6R = {}^0_3R^{-1}\,{}^0_6R$$

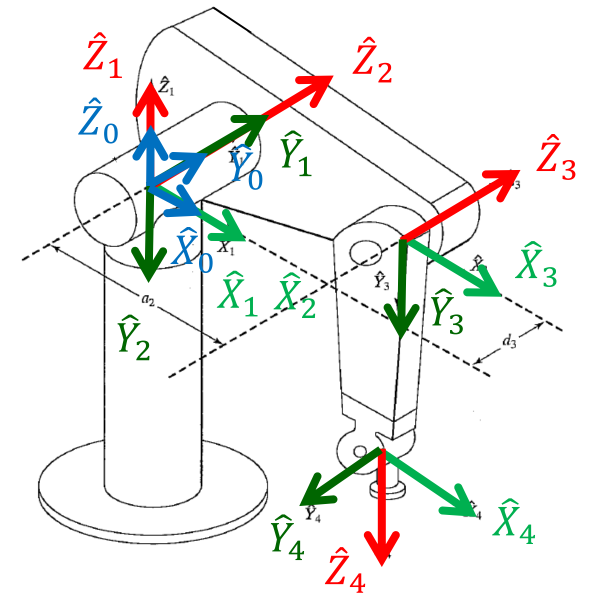
  - 以 Z-Y-Z Euler angle 求解 θ_4, θ_5, θ_6

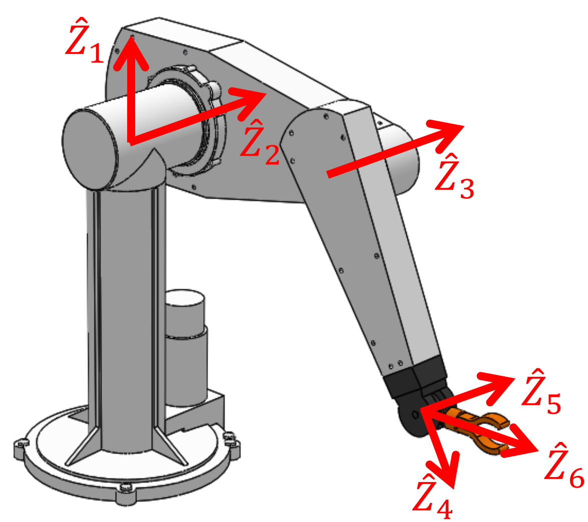


Pieper's Solution -6

- Joints 4-6, DH definition

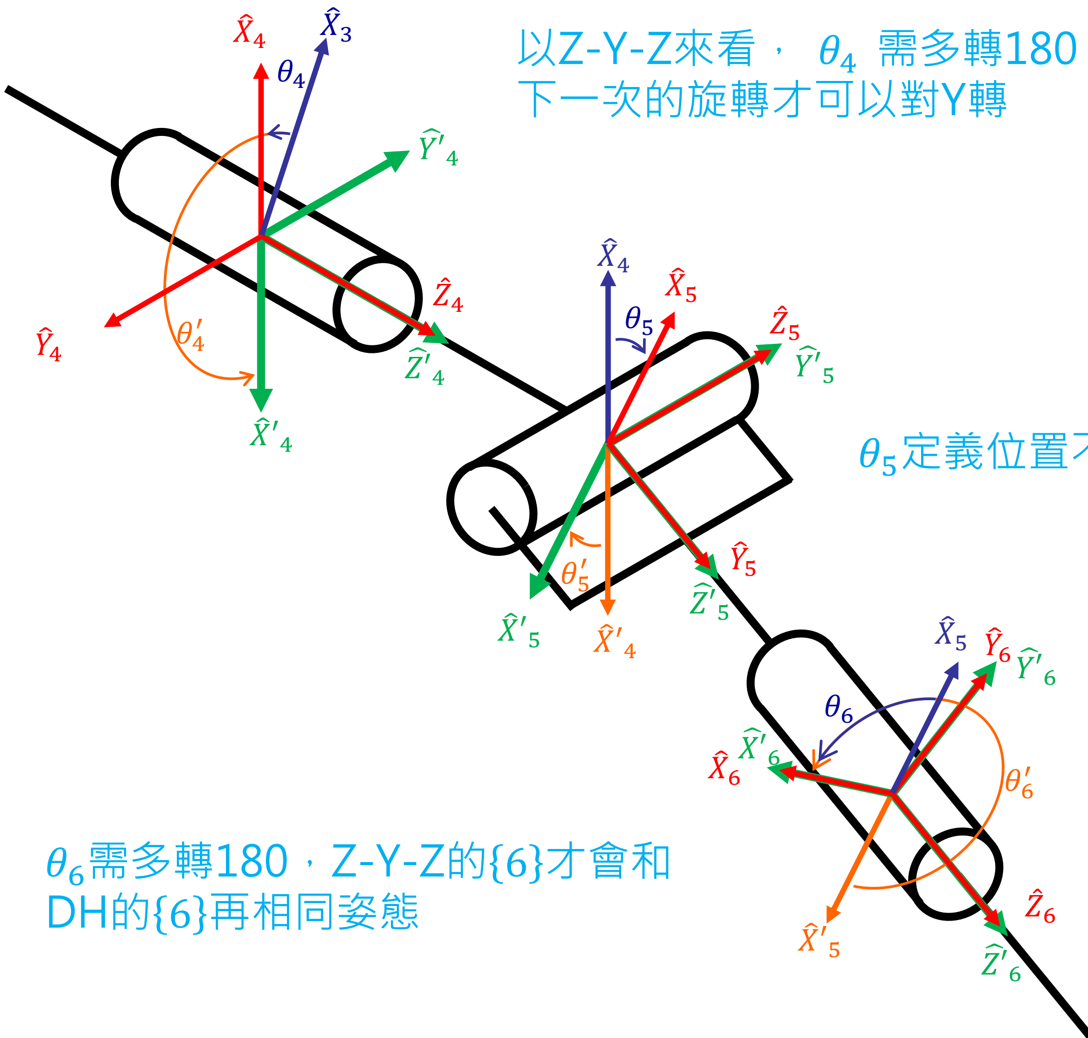






Pieper's Solution -7

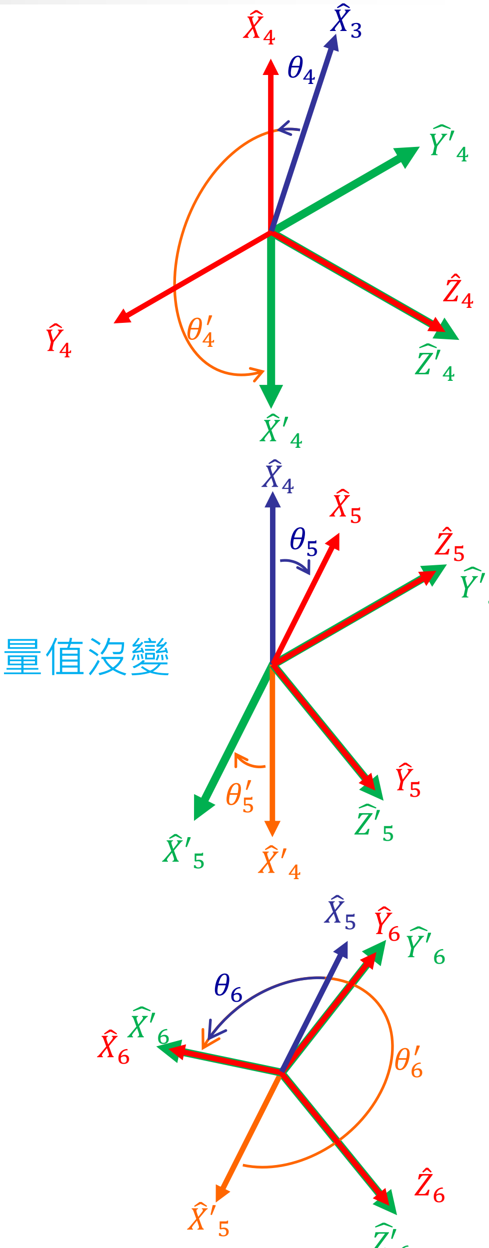
- DH definition vs. Z-Y-Z Euler Angles



以Z-Y-Z來看， θ_4 需多轉180，
下一次的旋轉才可以對Y轉

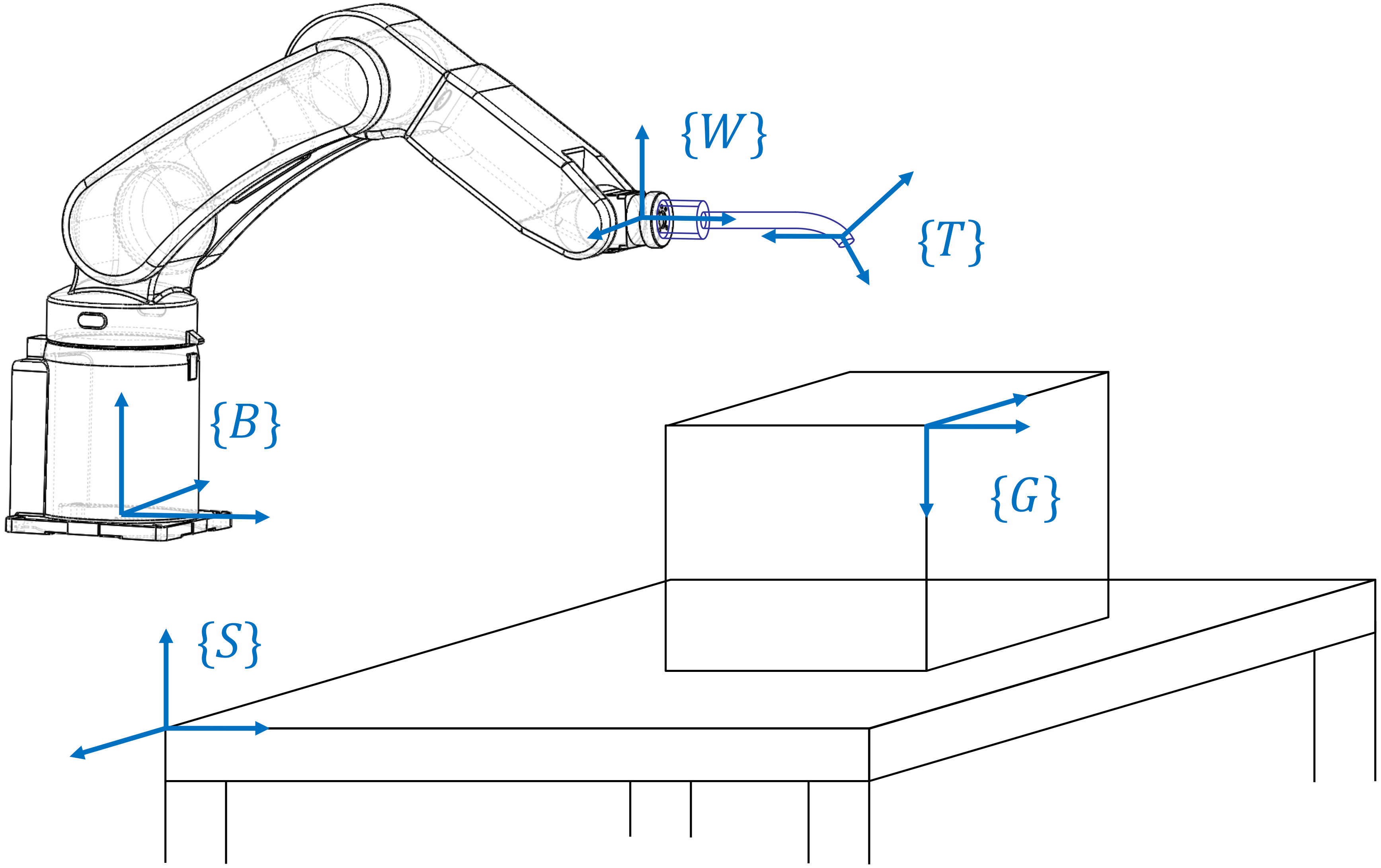
θ_5定義位置不同，但量值沒變

θ_6需多轉180，Z-Y-Z的{6}才會和
DH的{6}再相同姿態



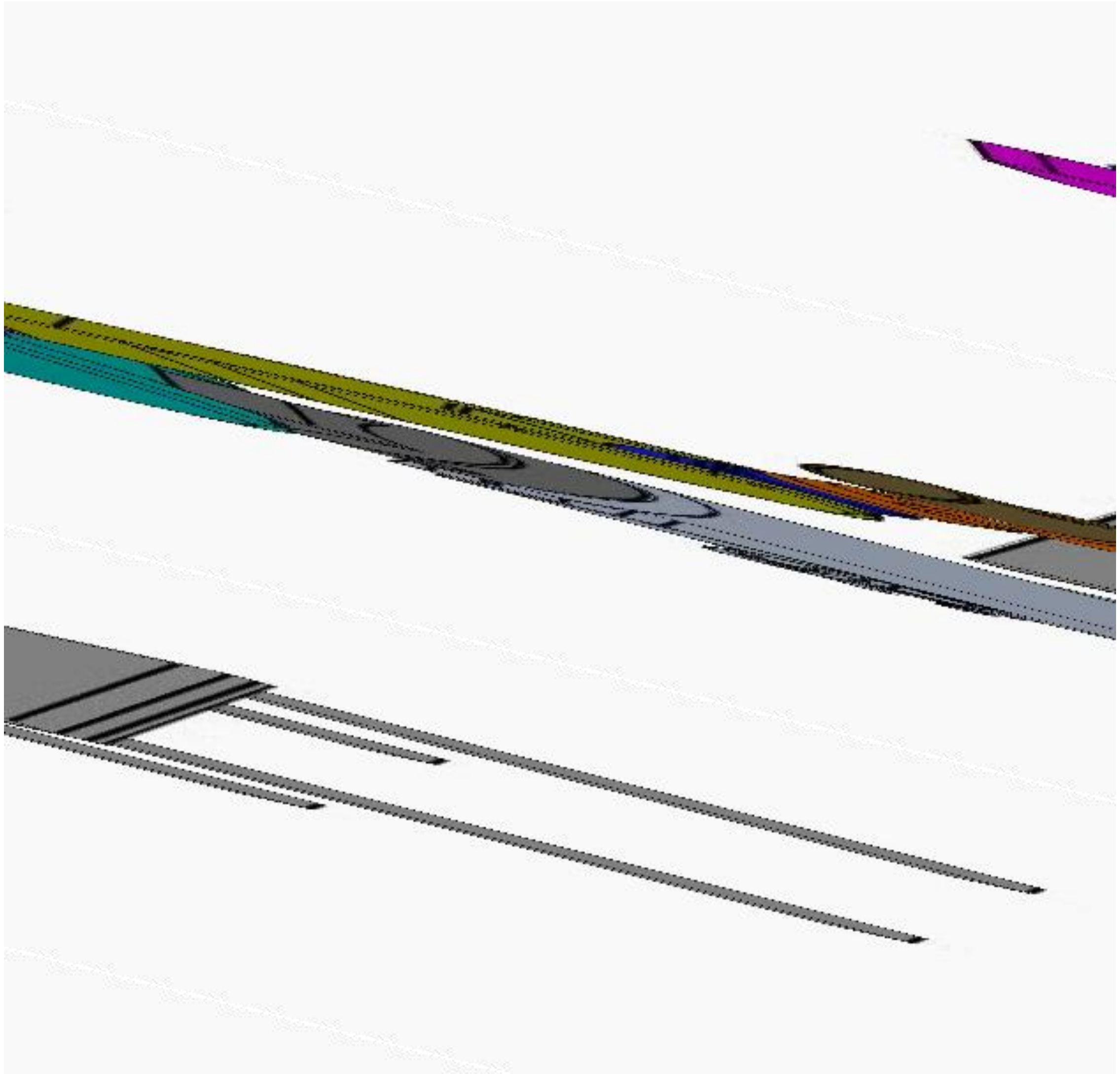
座標系

- Base, wrist, tool, station, and goal frames



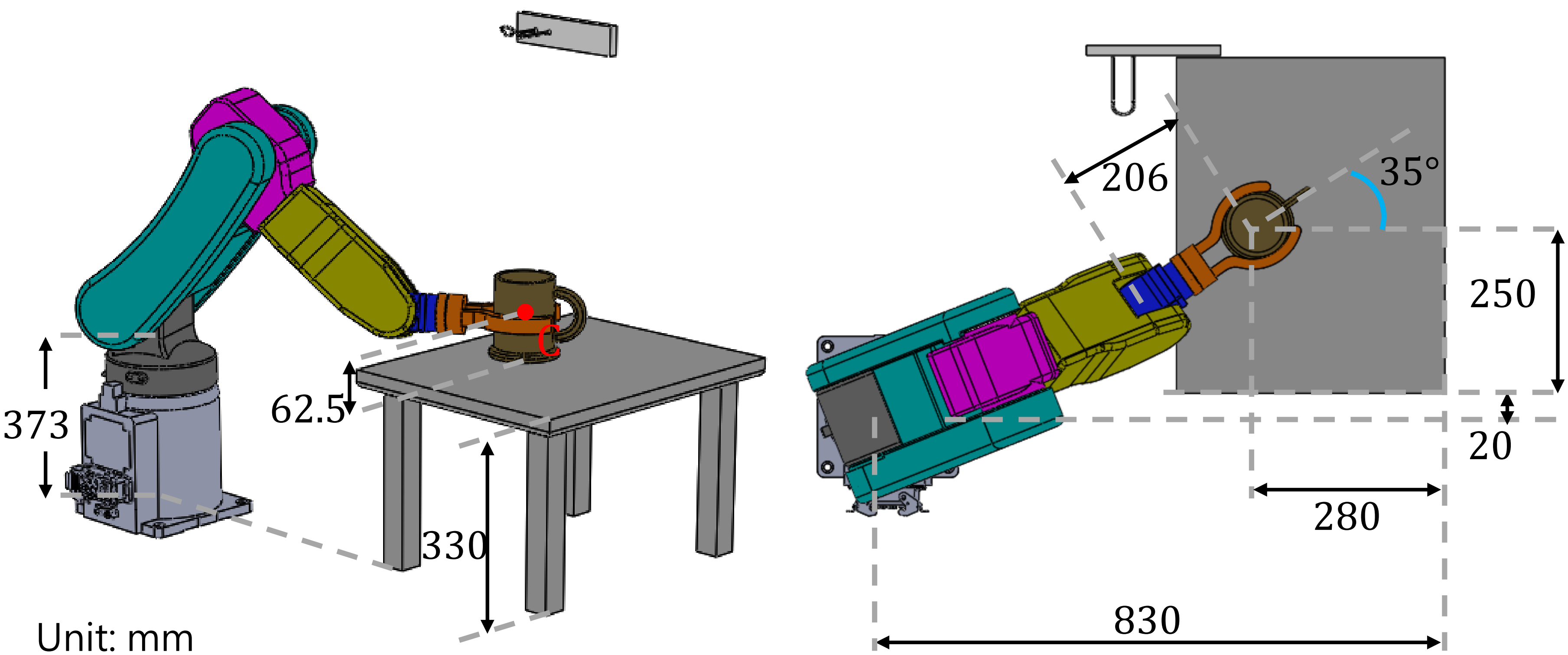
Example: 物件取放任務 -1

- 情境：機械手臂夾住放在桌上的杯子，移動手臂將杯子掛到牆上的杯架



Example: 物件取放任務 -2

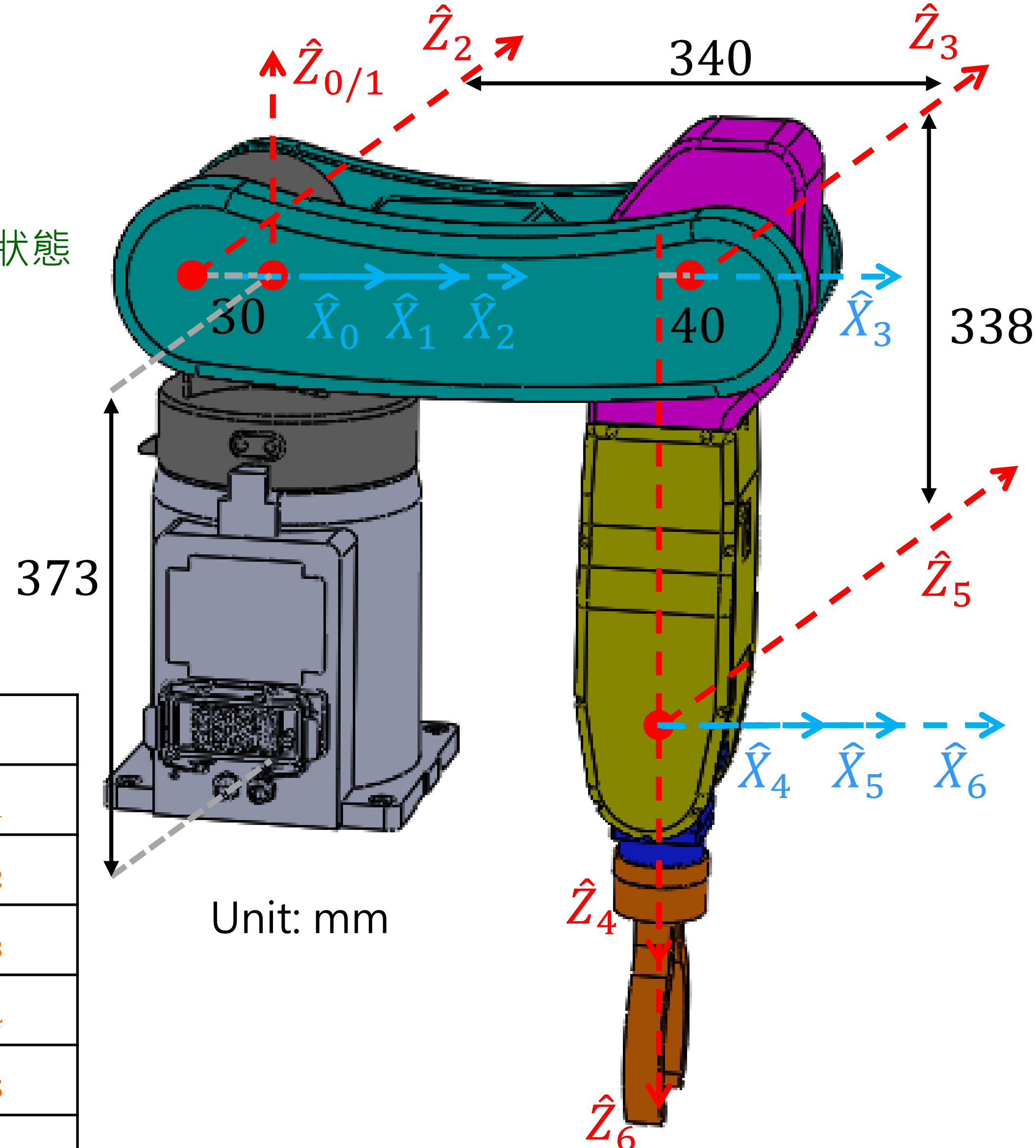
- 現階段任務：為使RRRRRR手臂能以下圖姿態夾住杯子（任務的起始點C ），手臂的6個joint angles需為何?



Example: 物件取放任務 -3

- Step 1: 定義DH Table

圖中顯示各軸為0°的狀態



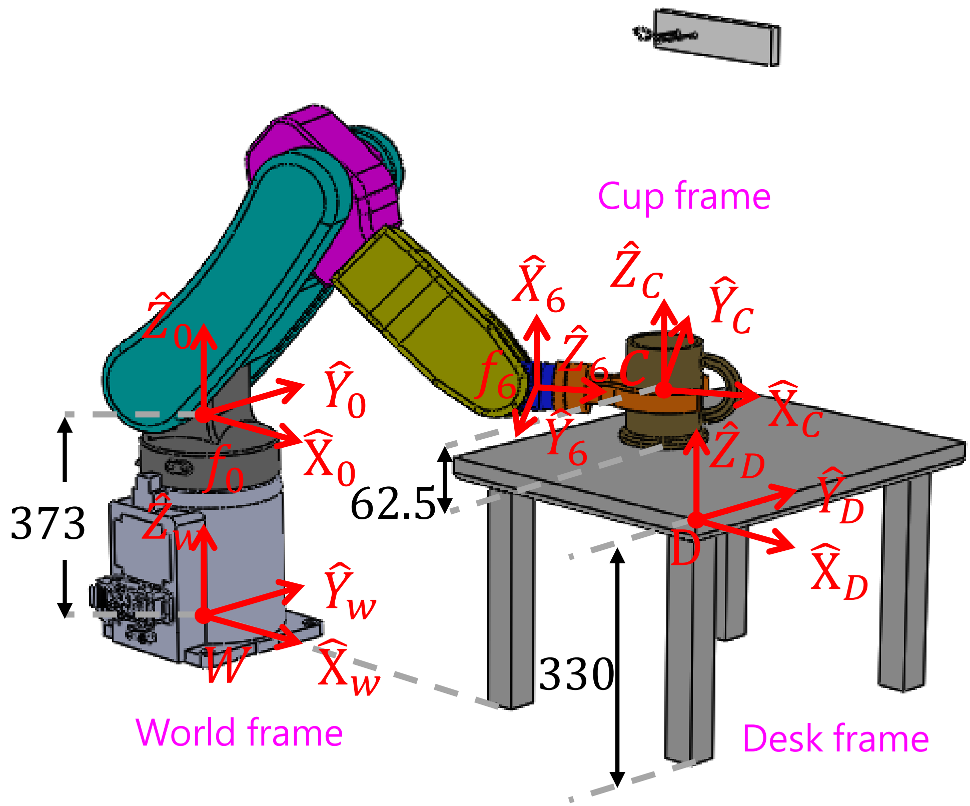
i	α_{i-1}	a_{i-1}	d_i	θ_i
1	0°	0	0	θ_1
2	-90°	$a_1 = -30$	0	θ_2
3	0°	$a_2 = 340$	0	θ_3
4	-90°	$a_3 = -40$	$d_4 = 338$	θ_4
5	90°	0	0	θ_5
6	-90°	0	0	θ_6

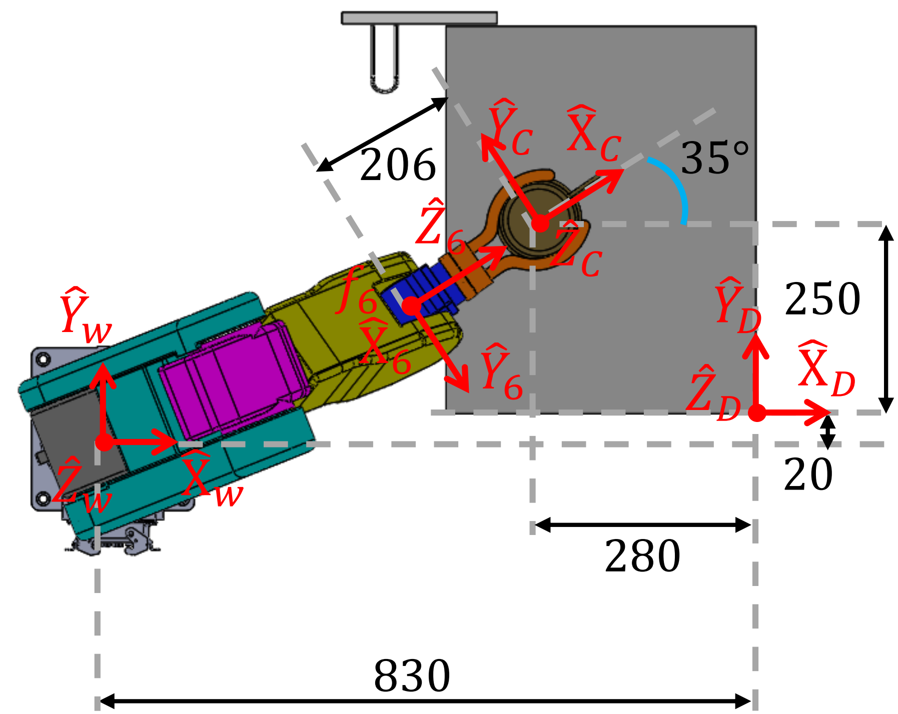
Example: 物件取放任務 -4

- Step 2: 找出${}^{W}_{C}T$，再進一步找出${}^{0}_{6}T$

$$
{}^{W}_{C}T = {}^{W}_{D}T\,{}^{D}_{C}T = \begin{bmatrix} 1 & 0 & 0 & 830 \\ 0 & 1 & 0 & 20 \\ 0 & 0 & 1 & 330 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos 35^\circ & -\sin 35^\circ & 0 & -280 \\ \sin 35^\circ & \cos 35^\circ & 0 & 250 \\ 0 & 0 & 1 & 62.5 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

由「桌子相對於手臂」和「杯子相對於桌子」的相對關係推得

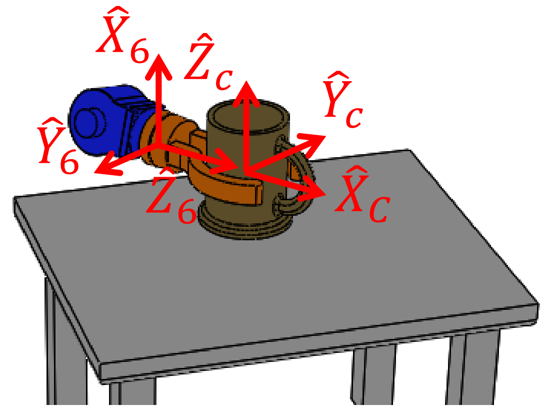




Example: 物件取放任務 -5

$$ {}^{W}_{C}T = {}^{W}_{0}T\,{}^{0}_{6}T\,{}^{6}_{C}T $$

$$ = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 373 \\ 0 & 0 & 0 & 1 \end{bmatrix} {}^{0}_{6}T \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 206 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

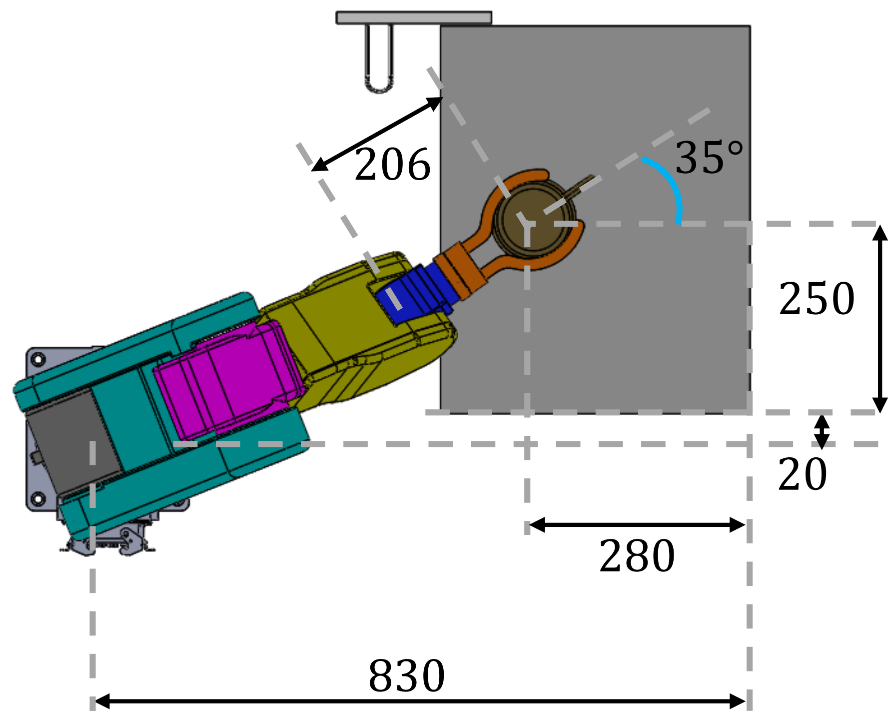


$$ {}^{0}_{6}T = {}^{W}_{0}T^{-1}\,{}^{W}_{C}T\,{}^{6}_{C}T^{-1} $$

$$ = \begin{bmatrix} 0 & 0.5736 & 0.8192 & 381.3 \\ 0 & -0.8192 & 0.5736 & 151.8 \\ 1 & 0 & 0 & 19.5 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$ {}^{0}_{6}R = \begin{bmatrix} 0 & 0.5736 & 0.8192 \\ 0 & -0.8192 & 0.5736 \\ 1 & 0 & 0 \end{bmatrix} $$

$$ {}^{0}P_{6\,ORG} = \begin{bmatrix} 381.3 \\ 151.8 \\ 19.5 \end{bmatrix} $$



Example: 物件取放任務 -6

- Step 3: 找出$\theta_1-\theta_6$
  - $\theta_1\ \theta_2\ \theta_3$角度求解

$$\begin{bmatrix} f_1(\theta_3) \\ f_2(\theta_3) \\ f_3(\theta_3) \\ 1 \end{bmatrix} = {}_3^2T\ {}^3P_{4\,ORG}$$

$$= \begin{bmatrix} c_3 & -s_3 & 0 & 340 \\ s_3 & c_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} -40 \\ 338 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 340-338s_3-40c_3 \\ 338c_3-40s_3 \\ 0 \\ 1 \end{bmatrix}$$

$$\begin{bmatrix} g_1(\theta_2,\theta_3) \\ g_2(\theta_2,\theta_3) \\ g_3(\theta_2,\theta_3) \\ 1 \end{bmatrix} = {}_2^1T \begin{bmatrix} f_1(\theta_3) \\ f_2(\theta_3) \\ f_3(\theta_3) \\ 1 \end{bmatrix}$$

$$= \begin{bmatrix} c_2 & -s_2 & 0 & -30 \\ 0 & 0 & 1 & 0 \\ -s_2 & -c_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} f_1(\theta_3) \\ f_2(\theta_3) \\ f_3(\theta_3) \\ 1 \end{bmatrix} = \begin{bmatrix} 340c_2-40c_{23}-338s_{23}-30 \\ 0 \\ 40s_{23}-338c_{23}-340s_2 \\ 1 \end{bmatrix}$$

Example: 物件取放任務 -7

$$r = (k_1 c_2 + k_2 s_2) 2a_1 + k_3 = ||P||^2 = 168813.18$$

$$z = (k_1 s_2 - k_2 c_2) s\alpha_1 + k_4 = 19.5$$

計算θ_1 θ_2 θ_3角度

$\frac{(r-k_3)^2}{4a_1^2} + \frac{(z-k_4)^2}{s^2\alpha_1} = k_1^2 + k_2^2$ $\Rightarrow solve\ \theta_3 = 2.5°$

$r = (k_1 c_2 + k_2 s_2) 2a_1 + k_3$ $\Rightarrow solve\ \theta_2 = -52.2°$

$x = c_1 g_1(\theta_2, \theta_3) - s_1 g_2(\theta_2, \theta_3)$ $\Rightarrow solve\ \theta_1 = 21.8°$

Example: 物件取放任務 -8

- $\theta_4\ \theta_5\ \theta_6$ 角度求解

$$ {}^0_3\mathrm{R} = \begin{bmatrix} 0.6006 & 0.7082 & -0.3710 \\ 0.24 & 0.2830 & 0.9286 \\ 0.7627 & -0.6468 & 0 \end{bmatrix} $$

$$ {}^3_6R = {}^0_3R^{-1}\,{}^0_6R = \begin{bmatrix} 0.7627 & 0.1477 & 0.6297 \\ -0.6468 & 0.1744 & 0.7424 \\ 0 & -0.9735 & 0.2286 \end{bmatrix} $$

使用Z-Y-Z Euler angle求得剩下的joint angles

$\theta_4 = -20°$ $\theta_5 = -42°$ $\theta_6 = 15°$

Example: 物件取放任務 -8

- Class Exercise: 要讓夾爪到杯子的末端點E，6個轉軸的轉角又分別是?