Lecture 07

Velocity Propagation

Acknowledgement :
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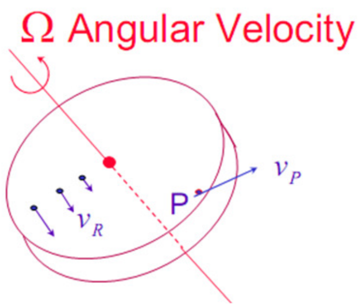
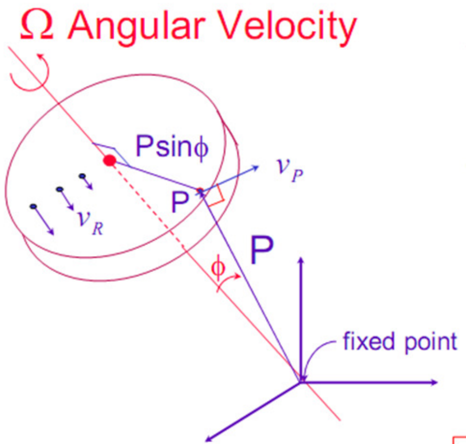
Rotational Motion



$$v_P = ?$$

Rotational Motion



v_P is proportional to:

- ||Ω||
- ||Psinϕ||

and

- $v_P \perp \Omega$
- $v_P \perp P$

$$v_P = \Omega \times P$$

Eg: Ω=<1,3,2>, P=<-2, 0, 1>
Ω × P = <(3×1), -(1×1)+2×-2, -(3×-2)>
Ω × P = <3, -5, 6>

Cross Product Operator

$$a = \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix}, b = \begin{bmatrix} b_x \\ b_y \\ b_z \end{bmatrix}$$

$$c = a \times b \Rightarrow c = \hat{a}b$$

vectors ⇨ matrices

$$a\times \Rightarrow \hat{a}$$: a skew-symmetric matrix

$$c = \hat{a}b = \begin{bmatrix} 0 & -a_z & a_y \\ a_z & 0 & -a_x \\ -a_y & a_x & 0 \end{bmatrix} \begin{bmatrix} b_x \\ b_y \\ b_z \end{bmatrix}$$

$$c = \hat{a}b$$

Cross Product Operator

$$v_P = \Omega \times P \Rightarrow v_P = \hat{\Omega} P$$

$\Omega\times \Rightarrow \hat{\Omega}$: a skew-symmetric matrix

$$\Omega = \begin{bmatrix}\Omega_x\\ \Omega_y\\ \Omega_z\end{bmatrix}; P = \begin{bmatrix}P_x\\ P_y\\ P_z\end{bmatrix}$$

$$v_P = \hat{\Omega}P = \begin{bmatrix}0 & -\Omega_z & \Omega_y\\ \Omega_z & 0 & -\Omega_x\\ -\Omega_y & \Omega_x & 0\end{bmatrix}\cdot\begin{bmatrix}P_x\\ P_y\\ P_z\end{bmatrix}$$

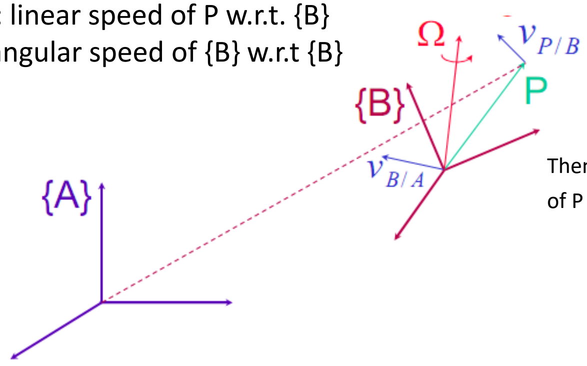
$$\boxed{v_P = \hat{\Omega}P}$$

Eg: Ω=<1,3,2>, P=<-2, 0, 1>

$$\Omega\times P = \hat{\Omega}P = \begin{bmatrix}0 & -2 & 3\\ 2 & 0 & -1\\ -3 & 1 & 0\end{bmatrix}\begin{bmatrix}-2\\ 0\\ 1\end{bmatrix} = \begin{bmatrix}3\\ -5\\ 6\end{bmatrix}$$

Linear and Angular Velocity

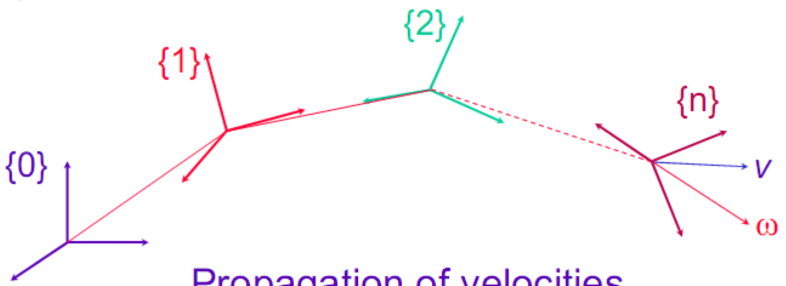
$v_{B/A}$: linear speed of {B} w.r.t. {A}
$v_{P/B}$: linear speed of P w.r.t. {B}
Ω : angular speed of {B} w.r.t {B}



Then what's the linear speed of P w.r.t {A}, $v_{P/A}$=?

Velocity Propagates from Base to End

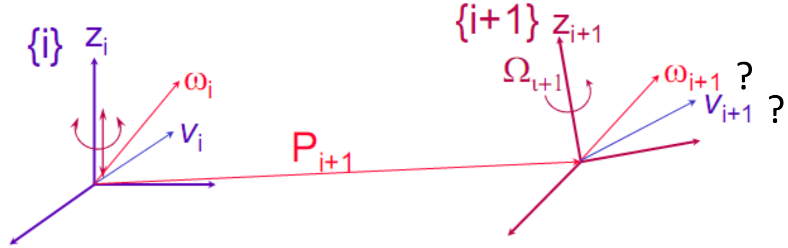
Spatial Mechanisms



Propagation of velocities

$\dot{x}$ < v : linear velocity; ω : angular velocity

Velocity Propagation from {i} to {i+1}

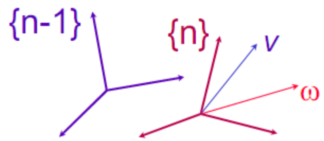


$$^{i+1}\omega_{i+1} = {}^{i+1}_{i}R.{}^{i}\omega_i + \dot{\theta}_{i+1}.{}^{i+1}Z_{i+1}$$

$$^{i+1}v_{i+1} = {}^{i+1}_{i}R.({}^{i}v_i + {}^{i}\omega_i \times {}^{i}P_{i+1}) + \dot{d}_{i+1}.{}^{i+1}Z_{i+1}$$

$\Rightarrow$ $^{n}\omega_n$ and $^{n}v_n$

$$\begin{pmatrix}^{0}v_n\\ ^{0}\omega_n\end{pmatrix} = \begin{pmatrix}^{0}_{n}R & 0\\ 0 & ^{0}_{n}R\end{pmatrix}\cdot\begin{pmatrix}^{n}v_n\\ ^{n}\omega_n\end{pmatrix}$$

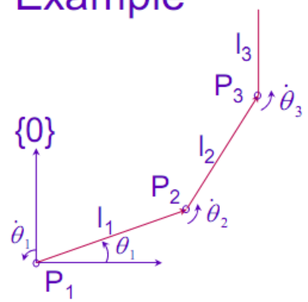


Computationally Complex because of frame transformation

Tutorial

Example

If a single frame of reference {0} is used



$$v_{i+1} = v_i + \omega_i \times P_{i+1}$$

- $v_{P_1} = 0$ ${}^0\omega_1 = \dot\theta_1 . {}^0 Z_1$
- $v_{P_2} = v_{P_1} + \omega_1 \times P_2$
- $v_{P_3} = v_{P_2} + \omega_2 \times P_3$

w.r.t. {0}

$${}^0 v_{P_2} = 0 + \begin{bmatrix} 0 & -\dot\theta_1 & 0 \\ \dot\theta_1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} . \begin{bmatrix} l_1 . c_1 \\ l_1 . s_1 \\ 0 \end{bmatrix} = \begin{bmatrix} -l_1 . s_1 \\ l_1 . c_1 \\ 0 \end{bmatrix} . \dot\theta_1$$

Computationally efficient because of fixed frame of Ref. {0}

$${}^0\omega_2 = {}^0\omega_1 + {}^0\dot\theta_2 \hat z_2 = \begin{bmatrix} 0 & 0 & (\dot\theta_1 + \dot\theta_2) \end{bmatrix}^T$$

$${}^0 v_{P_3} = {}^0 v_{P_2} + {}^0\omega_2 \times {}^0 P_3$$

Angular velocity of P3 w.r.t {0}   **2^{nd} link w.r.t {0}**

$${}^0 v_{P_3} = \begin{bmatrix} -l_1 . s_1 \\ l_1 . c_1 \\ 0 \end{bmatrix} . \dot\theta_1 + \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} . (\dot\theta_1 + \dot\theta_2) . {}^0 P_3 \qquad {}^0 P_3 = \begin{bmatrix} l_2 . c_{12} \\ l_2 . s_{12} \\ 0 \end{bmatrix}$$

$$= \begin{bmatrix} -l_1 . s_1 \\ l_1 . c_1 \\ 0 \end{bmatrix} . \dot\theta_1 + \begin{bmatrix} -l_2 . s_{12} \\ l_2 . c_{12} \\ 0 \end{bmatrix} . (\dot\theta_1 + \dot\theta_2)$$

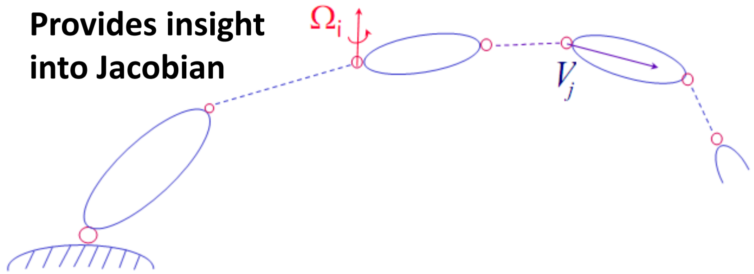
$${}^0 v_{P_3} = \underbrace{\begin{bmatrix} -(l_1 s_1 + l_2 s_{12}) & -l_2 s_{12} & 0 \\ l_1 c_1 + l_2 c_{12} & l_2 c_{12} & 0 \\ 0 & 0 & 0 \end{bmatrix}}_{J_v} . \begin{bmatrix} \dot\theta_1 \\ \dot\theta_2 \\ \dot\theta_3 \end{bmatrix}$$

$${}^0\omega_3 = \underbrace{\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 1 & 1 & 1 \end{bmatrix}}_{J_\omega} . \begin{bmatrix} \dot\theta_1 \\ \dot\theta_2 \\ \dot\theta_3 \end{bmatrix} \Leftarrow {}^0\omega_3 = {}^0\omega_2 + {}^0\dot\theta_3 \hat z_3 = \begin{bmatrix} 0 \\ 0 \\ \dot\theta_1 + \dot\theta_2 + \dot\theta_3 \end{bmatrix}$$

$$\begin{pmatrix} v \\ \omega \end{pmatrix} = J . \begin{pmatrix} \dot\theta_1 \\ \dot\theta_2 \\ \dot\theta_3 \end{pmatrix}$$

The Jacobian (EXPLICIT FORM)

Provides insight into Jacobian



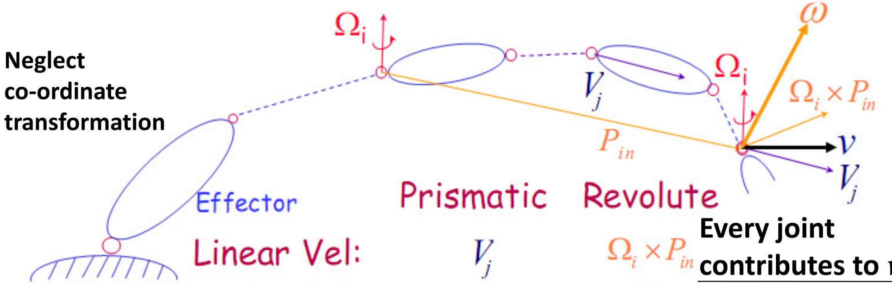
Revolute Joint $\Omega_i = Z_i \dot q_i$

Prismatic Joint $V_i = Z_i \dot q_i$

Describe how each joint contributes to V and ω of the end-effector

The Jacobian (EXPLICIT FORM)

Neglect co-ordinate transformation



	Prismatic	Revolute
Linear Vel:	V_j	$\Omega_i \times P_{in}$
Angular Vel:	none	Ω_i

Every joint contributes to v

Only R joints contribute to ω

Effector Linear Velocity

$$v = \sum_{i=1}^{n} [\epsilon_i V_i + \bar{\epsilon}_i (\Omega_i \times P_{in})] \quad \Leftarrow \quad V_i = Z_i \dot{q}_i$$

Effector Angular Velocity

$$\omega = \sum_{i=1}^{n} \bar{\epsilon}_i \Omega_i \quad \Leftarrow \quad \Omega_i = Z_i \dot{q}_i$$

Contributes only if the last joint is prismatic

$$v = [\epsilon_1 Z_1 + \bar{\epsilon}_1 (Z_1 \times P_{1n})]\dot{q}_1 + \cdots$$
$$+ [\epsilon_{n-1} Z_{n-1} + \bar{\epsilon}_{n-1} (Z_{n-1} \times P_{(n-1)n})]\dot{q}_{n-1} + \epsilon_n Z_n \dot{q}_n$$

$$v = [\epsilon_1 Z_1 + \bar{\epsilon}_1 (Z_1 \times P_{1n}) \quad \epsilon_2 Z_2 + \bar{\epsilon}_2 (Z_2 \times P_{2n}) \quad \cdots] \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \\ \vdots \\ \dot{q}_n \end{bmatrix}$$

$$\boxed{v = J_v \dot{q}}$$

There is an easier way to determine J_v using T

$$\omega = \bar{\epsilon}_1 Z_1 \dot{q}_1 + \bar{\epsilon}_2 Z_2 \dot{q}_2 + \cdots + \bar{\epsilon}_n Z_n \dot{q}_n$$

$$\omega = [\bar{\epsilon}_1 Z_1 \quad \bar{\epsilon}_2 Z_2 \quad \cdots \quad \bar{\epsilon}_n Z_n] \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \\ \vdots \\ \dot{q}_n \end{bmatrix}$$

$$\boxed{\omega = J_\omega \dot{q}}$$

Jacobian of a 6dof manipulator

All rotary manipulator (eg. Puma560)

Without frame transformation

$$\begin{pmatrix} v \\ \omega \end{pmatrix} = \begin{bmatrix} z_1 \times P_{16} & z_2 \times P_{26} & z_3 \times P_{36} & z_4 \times P_{46} & z_5 \times P_{56} & z_6 \times P_{66} \\ z_1 & z_3 & z_3 & z_4 & z_5 & z_6 \end{bmatrix} \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \\ \dot{q}_4 \\ \dot{q}_5 \\ \dot{q}_6 \end{bmatrix}$$

With co-ordinate transformation

$$\begin{pmatrix} {}^0v \\ {}^0\omega \end{pmatrix} = \begin{bmatrix} {}^0_1R(z_1 \times P_{16}) & {}^0_2R(z_2 \times P_{26}) & {}^0_3R(z_3 \times P_{36}) & {}^0_4R(z_4 \times P_{46}) & {}^0_5R(z_5 \times P_{56}) & {}^0_6R(z_6 \times P_{66}) = 0 \\ {}^0_1Rz_1 & {}^0_2Rz_3 & {}^0_3Rz_3 & {}^0_4Rz_4 & {}^0_5Rz_5 & {}^0_6Rz_6 \end{bmatrix} \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \\ \dot{q}_4 \\ \dot{q}_5 \\ \dot{q}_6 \end{bmatrix}$$

Jacobian of a 6dof manipulator

Stanford Schinman Arm (RR**P**RRR)

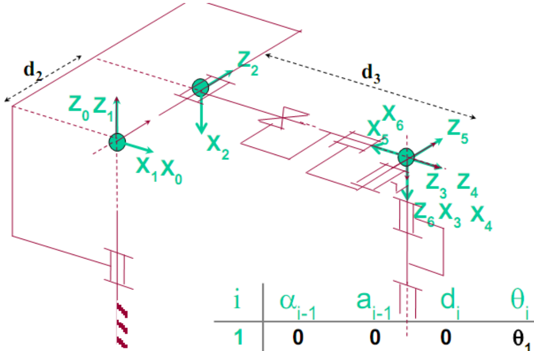
Without frame transformation

$$\begin{pmatrix} v \\ \omega \end{pmatrix} = \begin{bmatrix} z_1 \times P_{16} & z_2 \times P_{26} & z_3 & z_4 \times P_{46} = 0 & z_5 \times P_{56} = 0 & z_6 \times P_{66} = 0 \\ z_1 & z_3 & 0 & z_4 & z_5 & z_6 \end{bmatrix} \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \\ \dot{q}_4 \\ \dot{q}_5 \\ \dot{q}_6 \end{bmatrix}$$

With co-ordinate transformation

$$\begin{pmatrix} {}^0v \\ {}^0\omega \end{pmatrix} = \begin{bmatrix} {}^0_1R(z_1 \times P_{16}) & {}^0_2R(z_2 \times P_{26}) & {}^0_3Rz_3 & 0 & 0 & 0 \\ {}^0_1Rz_1 & {}^0_2Rz_2 & 0 & {}^0_4Rz_4 & {}^0_5Rz_5 & {}^0_6Rz_6 \end{bmatrix} \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \\ \dot{q}_4 \\ \dot{q}_5 \\ \dot{q}_6 \end{bmatrix}$$

Stanford Scheinman Arm



i	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	0	θ_1
2	-90	0	d_2	θ_2
3	90	0	d_3	0
4	0	0	0	θ_4
5	-90	0	0	θ_5
6	90	0	0	θ_6

$$\begin{pmatrix} v \\ \omega \end{pmatrix} = J\dot{q} = \begin{bmatrix} J_v \\ J_\omega \end{bmatrix} \dot{q}$$

$$J = \left(\begin{array}{c|c|c|c|c|c} \textbf{R} & \textbf{R} & \textbf{P} & \textbf{R} & \textbf{R} & \textbf{R} \\ Z_1 \times P_{13} & Z_2 \times P_{23} & Z_3 & 0 & 0 & 0 \\ \hline Z_1 & Z_2 & 0 & Z_4 & Z_5 & Z_6 \end{array} \right)$$

Jacobian in a Frame

Vector Representation

$$J = \begin{pmatrix} \dfrac{\partial x_P}{\partial q_1} & \dfrac{\partial x_P}{\partial q_2} & \cdots & \dfrac{\partial x_P}{\partial q_n} \\ \bar{\epsilon}_1 . Z_1 & \bar{\epsilon}_2 . Z_2 & \cdots & \bar{\epsilon}_n . Z_n \end{pmatrix}$$

In {0}

$${}^0J = \begin{pmatrix} \dfrac{\partial\, {}^0x_P}{\partial q_1} & \dfrac{\partial\, {}^0x_P}{\partial q_2} & \cdots & \dfrac{\partial\, {}^0x_P}{\partial q_n} \\ \bar{\epsilon}_1 . {}^0Z_1 & \bar{\epsilon}_2 . {}^0Z_2 & \cdots & \bar{\epsilon}_n . {}^0Z_n \end{pmatrix}$$

J in Frame {0}

$${}^0Z_i = {}^0_iR\, {}^iZ_i; \quad {}^iZ_i = Z = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

3rd colomn in ${}^0_iR$

$${}^0J = \begin{pmatrix} \dfrac{\partial}{\partial q_1}({}^0x_P) & \dfrac{\partial}{\partial q_2}({}^0x_P) & \cdots & \dfrac{\partial}{\partial q_n}({}^0x_P) \\ \bar{\epsilon}_1 .({}^0_1R.Z) & \bar{\epsilon}_2 .({}^0_2R.Z) & \cdots & \bar{\epsilon}_n .({}^0_nR.Z) \end{pmatrix}$$

3rd colomn in ${}^0_1R$ **3rd colomn in** ${}^0_2R$ **3rd colomn in** ${}^0_nR$

Matrix J_v (direct differentiation)

$$v = \begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{pmatrix} = \dot{x}_P = \underbrace{\frac{\partial x_P}{\partial q_1}}_{3\times1}.\dot{q}_1 + \underbrace{\frac{\partial x_P}{\partial q_2}}_{3\times1}.\dot{q}_2 + \cdots + \underbrace{\frac{\partial x_P}{\partial q_n}}_{3\times1}.\dot{q}_n$$

3×n

$$J_v = \begin{pmatrix} \dfrac{\partial x_P}{\partial q_1} & \dfrac{\partial x_P}{\partial q_2} & \cdots & \dfrac{\partial x_P}{\partial q_n} \end{pmatrix}$$

x_p

$${}^0_nT = \begin{bmatrix} & & & x \\ & & & y \\ & & & z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

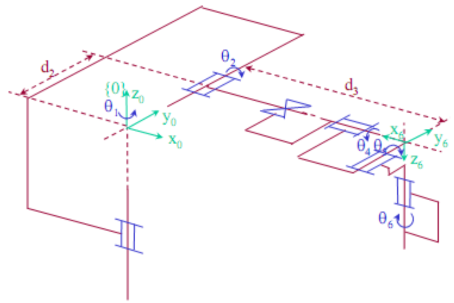
SCA Jacobian from HTMs

$$
J = \left(\begin{array}{c|c|c|c|c|c}
\overset{\mathbf{R}}{Z_1 \times P_{13}} & \overset{\mathbf{R}}{Z_2 \times P_{23}} & \overset{\mathbf{P}}{Z_3} & \overset{\mathbf{R}}{0} & \overset{\mathbf{R}}{0} & \overset{\mathbf{R}}{0} \\ \hline
Z_1 & Z_2 & 0 & Z_4 & Z_5 & Z_6
\end{array}\right)
$$

Annotations above the columns: $\dfrac{\partial {}^0_6T(:4)}{\partial q_1}$, $\dfrac{\partial {}^0_6T(:4)}{\partial q_2}$, ${}^0_3R(:3)$ ${}^0\hat{Z}_3$

Annotations below the columns: ${}^0\hat{Z}_1$, ${}^0\hat{Z}_2$, ${}^0\hat{Z}_4$, ${}^0\hat{Z}_5$, ${}^0\hat{Z}_6$

${}^0_1R(:3)$ ${}^0_2R(:3)$ ${}^0_4R(:3)$ ${}^0_5R(:3)$ ${}^0_6R(:3)$



i	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	0	θ_1
2	-90	0	d_2	θ_2
3	90	0	d_3	0
4	0	0	0	θ_4
5	-90	0	0	θ_5
6	90	0	0	θ_6

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

Forward Kinematics: ${}^0_N\mathbf{T} = {}^0_1\mathbf{T}\ {}^1_2\mathbf{T} \ \ldots\ {}^{N-1}_{\ \ N}\mathbf{T}$

$$
{}^0_1T = \begin{bmatrix} c_1 & -s_1 & 0 & 0 \\ s_1 & c_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^1_2T = \begin{bmatrix} c_2 & -s_2 & 0 & 0 \\ 0 & 0 & 1 & d_2 \\ -s_2 & c_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^2_3T = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & -d_3 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^3_4T = \begin{bmatrix} c_4 & -s_4 & 0 & 0 \\ s_4 & c_4 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^4_5T = \begin{bmatrix} c_5 & -s_5 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -s_5 & -c_5 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^5_6T = \begin{bmatrix} c_6 & -s_6 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ s_6 & c_6 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$ {}^{0}_{1}R(:3) $$

$$ {}^{0}_{1}T = \begin{bmatrix} c_1 & -s_1 & 0 & 0 \\ s_1 & c_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$ {}^{0}_{2}R(:3) $$

$$ {}^{0}_{2}T = \begin{bmatrix} c_1c_2 & -c_1s_2 & -s_1 & -s_1d_2 \\ s_1c_2 & -s_1s_2 & c_1 & c_1d_2 \\ -s_2 & -c_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$ {}^{0}_{3}T = \begin{bmatrix} c_1c_2 & -s_1 & c_1s_2 & c_1d_3s_2 - s_1d_2 \\ s_1c_2 & c_1 & s_1s_2 & s_1d_3s_2 + c_1d_2 \\ -s_2 & 0 & c_2 & d_3c_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$ {}^{0}_{3}R(:3) $$

$$ {}^{0}_{4}T = \begin{bmatrix} c_1c_2c_4 - s_1s_4 & -c_1c_2s_4 - s_1c_4 & c_1s_2 & c_1d_3s_2 - s_1d_2 \\ s_1c_2c_4 + c_1s_4 & -s_1c_2s_4 + c_1c_4 & s_1s_2 & s_1d_3s_2 + c_1d_2 \\ -s_2c_4 & s_2s_4 & c_2 & d_3c_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$ {}^{0}_{4}R(:3) $$

$$ {}^{0}_{5}T = \begin{bmatrix} X & X & -c_1c_2s_4 - s_1c_4 & c_1d_3s_2 - s_1d_2 \\ X & X & -s_1c_2s_4 + c_1c_4 & s_1d_3s_2 + c_1d_2 \\ X & X & s_2s_4 & d_3c_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$ {}^{0}_{5}R(:3) $$

$$ {}^{0}_{6}T = \begin{bmatrix} X & X & c_1c_2c_4s_5 - s_1s_4s_5 + c_1s_2s_5 & c_1d_3s_2 - s_1d_2 \\ X & X & s_1c_2c_4s_5 + c_1s_4s_5 + s_1s_2c_5 & s_1d_3s_2 + c_1d_2 \\ X & X & -s_2c_4s_5 + c_5c_2 & d_3c_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$ {}^{0}_{6}R(:3) $$

Stanford Scheinman Arm Jacobian

$$ {}^{0}J = \begin{pmatrix} \frac{\partial^{0} x_P}{\partial q_1} & \frac{\partial^{0} x_P}{\partial q_2} & \frac{\partial^{0} x_P}{\partial q_3} & 0 & 0 & 0 \\ {}^{0}Z_1 & {}^{0}Z_2 & 0 & {}^{0}Z_4 & {}^{0}Z_5 & {}^{0}Z_6 \end{pmatrix} $$

$$ \begin{bmatrix} -c_1d_2 - s_1s_2d_3 & c_1c_2d_3 & c_1s_2 & 0 & 0 & 0 \\ -s_1d_2 + c_1s_2d_3 & s_1c_2d_3 & s_1s_2 & 0 & 0 & 0 \\ 0 & -s_2d_3 & c_2 & 0 & 0 & 0 \\ 0 & -s_1 & 0 & c_1s_2 & -c_1c_2s_4 - s_1c_4 & c_1c_2c_4s_5 - s_1s_4s_5 + c_1s_2c_5 \\ 0 & c_1 & 0 & s_1s_2 & -s_1c_2s_4 + c_1c_4 & s_1c_2c_4s_5 + c_1s_4s_5 + s_1s_2c_5 \\ 1 & 0 & 0 & c_2 & s_2s_4 & -s_2c_4s_5 + c_5c_2 \end{bmatrix} $$