Velocity Kinematics II

CS 6301 Special Topics: Introduction to Robot Manipulation and Navigation

Professor Yu Xiang

The University of Texas at Dallas

Jacobian

- Assume end-effector configuration $x \in \mathbb{R}^m$
- End-effector velocity $\dot{x} = dx/dt \in \mathbb{R}^m$
- Forward kinematics $x(t) = f(\theta(t))$ $\theta \in \mathbb{R}^n$ Joint variable
- Chain rule

$$\dot{x} = \frac{\partial f(\theta)}{\partial \theta} \frac{d\theta(t)}{dt} = \frac{\partial f(\theta)}{\partial \theta} \dot{\theta}$$
$$= J(\theta)\dot{\theta},$$

$J(\theta) \in \mathbb{R}^{m \times n}$ Jacobian

$\dot{\theta}$ Joint velocity

Recall Twists

- Spatial twist and body twist

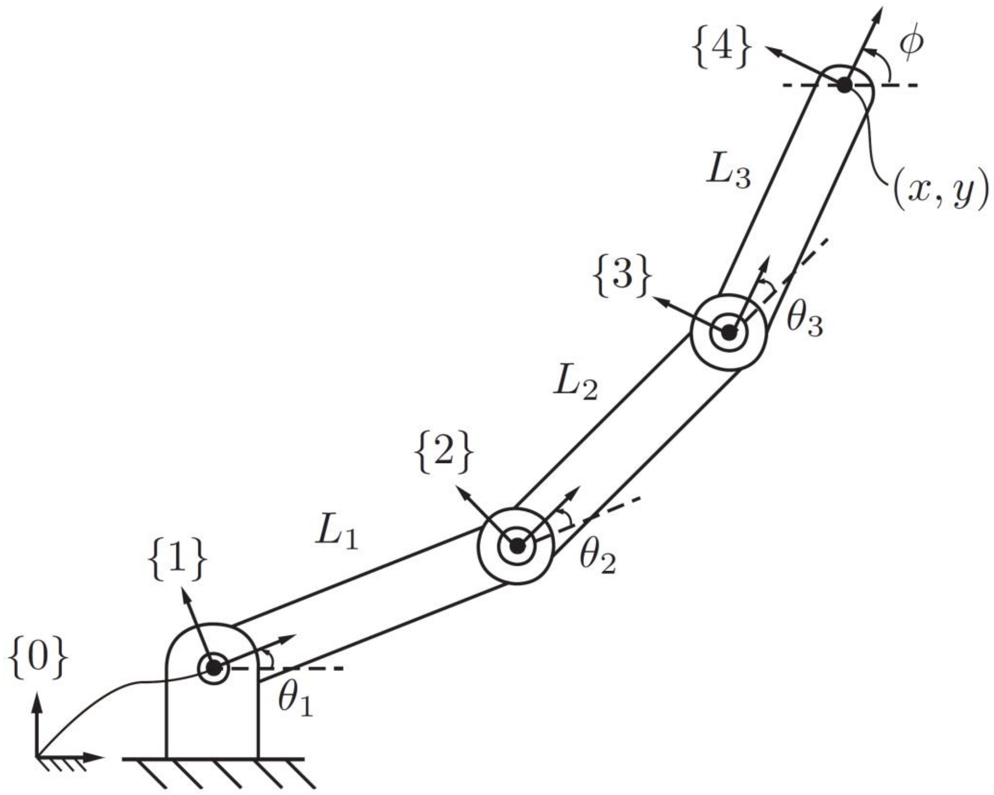
$$\mathcal{V}_s = \begin{bmatrix} \omega_s \\ v_s \end{bmatrix} \in \mathbb{R}^6 \qquad [\mathcal{V}_s] = \begin{bmatrix} [\omega_s] & v_s \\ 0 & 0 \end{bmatrix} = \dot{T}T^{-1} \in se(3)$$

$$\mathcal{V}_b = \begin{bmatrix} \omega_b \\ v_b \end{bmatrix} \qquad [\mathcal{V}_b] = \begin{bmatrix} [\omega_b] & v_b \\ 0 & 0 \end{bmatrix} = T^{-1}\dot{T}$$

- Relationship

$$[\mathcal{V}_b] = T^{-1}[\mathcal{V}_s]T \qquad [\mathcal{V}_s] = T[\mathcal{V}_b]T^{-1}$$

Recall Forward Kinematics



Forward kinematics of a 3R planar open chain.

- Consider each revolute joint as a zero-pitch screw-axis expressed in the {0} frame (fixed frame)

For joint 3

Spatial twist

$$\mathcal{S}_3 = \begin{bmatrix} \omega_3 \\ v_3 \end{bmatrix} \qquad \omega_3 = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

v_3 Linear velocity of the origin of {0} in the {0} frame when joint 3 rotates

$$v_3 = -\omega_3 \times q_3$$

$$q_3 = (L_1 + L_2, 0, 0)$$

$$v_3 = \begin{bmatrix} 0 \\ -(L_1 + L_2) \\ 0 \end{bmatrix}$$

$$\mathcal{S}_3 = \begin{bmatrix} \omega_3 \\ v_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \\ -(L_1 + L_2) \\ 0 \end{bmatrix}$$

Manipulator Jacobian

- Forward kinematics

$$T(\theta_1, \ldots, \theta_n) = e^{[\mathcal{S}_1]\theta_1} e^{[\mathcal{S}_2]\theta_2} \cdots e^{[\mathcal{S}_n]\theta_n} M$$

$$[\mathcal{V}_s] = \dot{T}T^{-1}$$

$$\begin{aligned} \dot{T} &= \left(\frac{d}{dt}e^{[\mathcal{S}_1]\theta_1}\right) \cdots e^{[\mathcal{S}_n]\theta_n} M + e^{[\mathcal{S}_1]\theta_1} \left(\frac{d}{dt}e^{[\mathcal{S}_2]\theta_2}\right) \cdots e^{[\mathcal{S}_n]\theta_n} M + \cdots \\ &= [\mathcal{S}_1]\dot{\theta}_1 e^{[\mathcal{S}_1]\theta_1} \cdots e^{[\mathcal{S}_n]\theta_n} M + e^{[\mathcal{S}_1]\theta_1} [\mathcal{S}_2]\dot{\theta}_2 e^{[\mathcal{S}_2]\theta_2} \cdots e^{[\mathcal{S}_n]\theta_n} M + \cdots \end{aligned}$$

$\dot{\theta}_i$ is a scalar

$$T^{-1} = M^{-1} e^{-[\mathcal{S}_n]\theta_n} \cdots e^{-[\mathcal{S}_1]\theta_1}$$

$$d(e^{A\theta})/dt = Ae^{A\theta}\dot{\theta} = e^{A\theta}A\dot{\theta}$$

Proposition 3.10

Space Jacobian

$$[\mathcal{V}_s] = \dot{T}T^{-1}$$

$$[\mathcal{V}_s] = [\mathcal{S}_1]\dot{\theta}_1 + e^{[\mathcal{S}_1]\theta_1}[\mathcal{S}_2]e^{-[\mathcal{S}_1]\theta_1}\dot{\theta}_2 + e^{[\mathcal{S}_1]\theta_1}e^{[\mathcal{S}_2]\theta_2}[\mathcal{S}_3]e^{-[\mathcal{S}_2]\theta_2}e^{-[\mathcal{S}_1]\theta_1}\dot{\theta}_3 + \cdots$$

Adjoint mapping $[\mathcal{V}_s] = T\,[\mathcal{V}_b]\,T^{-1}$ $\quad \mathcal{V}_s = [\mathrm{Ad}_{T_{sb}}]\mathcal{V}_b$

Adjoint map associated with T

$$[\mathrm{Ad}_T] = \begin{bmatrix} R & 0 \\ [p]R & R \end{bmatrix} \in \mathbb{R}^{6\times 6}$$

$$\mathcal{V}_s = \underbrace{\mathcal{S}_1}_{J_{s1}}\dot{\theta}_1 + \underbrace{\mathrm{Ad}_{e^{[\mathcal{S}_1]\theta_1}}(\mathcal{S}_2)}_{J_{s2}}\dot{\theta}_2 + \underbrace{\mathrm{Ad}_{e^{[\mathcal{S}_1]\theta_1}e^{[\mathcal{S}_2]\theta_2}}(\mathcal{S}_3)}_{J_{s3}}\dot{\theta}_3 + \cdots$$

$$\mathcal{V}_s = J_{s1}\dot{\theta}_1 + J_{s2}(\theta)\dot{\theta}_2 + \cdots + J_{sn}(\theta)\dot{\theta}_n$$

Space Jacobian

Spatial twist
$$\mathcal{V}_s = \begin{bmatrix} J_{s1} & J_{s2}(\theta) & \cdots & J_{sn}(\theta) \end{bmatrix} \begin{bmatrix} \dot{\theta}_1 \\ \vdots \\ \dot{\theta}_n \end{bmatrix} = J_s(\theta)\dot{\theta}.$$

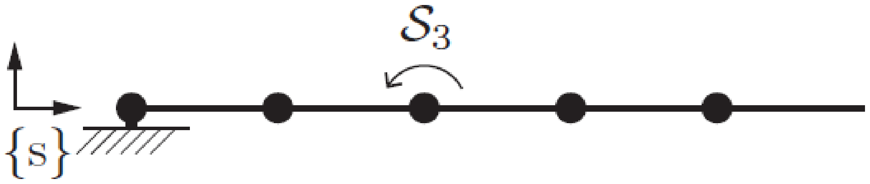
$$J_s(\theta) \in \mathbb{R}^{6\times n} \qquad \dot{\theta} \in \mathbb{R}^n$$

$$J_{si}(\theta) = \mathrm{Ad}_{e^{[\mathcal{S}_1]\theta_1}\cdots e^{[\mathcal{S}_{i-1}]\theta_{i-1}}}(\mathcal{S}_i)$$ ith column $i = 2, \ldots, n,$

$$J_{s1} = \mathcal{S}_1$$

Visualizing the Space Jacobian

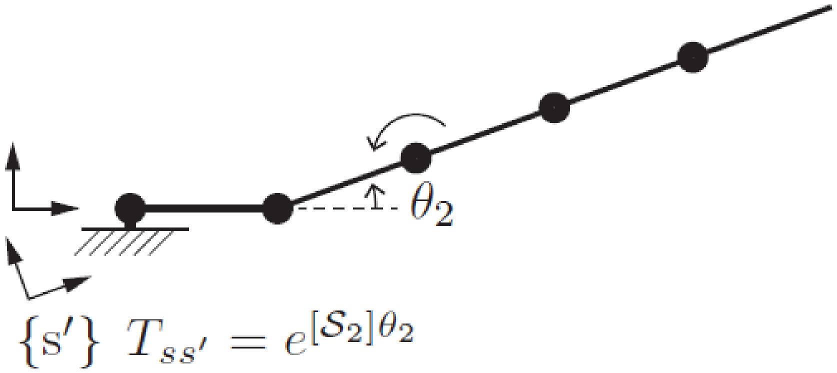
$$\mathcal{V}_s = \underbrace{\mathcal{S}_1}_{J_{s1}} \dot\theta_1 + \underbrace{\mathrm{Ad}_{e^{[\mathcal{S}_1]\theta_1}}(\mathcal{S}_2)}_{J_{s2}} \dot\theta_2 + \underbrace{\mathrm{Ad}_{e^{[\mathcal{S}_1]\theta_1} e^{[\mathcal{S}_2]\theta_2}}(\mathcal{S}_3)}_{J_{s3}} \dot\theta_3 + \cdots$$

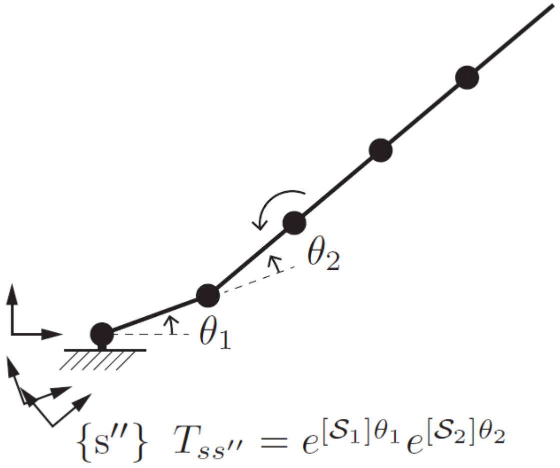


Consider some input $\dot\theta_3$ on $\mathcal{S}_3$

$\theta_3, \theta_4, \theta_5$ won't change $\mathcal{S}_3$ in {s}

No contribution to the twist





$\mathcal{S}_3$ represents the screw relative to $\{s''\}$ for arbitrary θ_1, θ_2

$$[\mathrm{Ad}_{T_{ss''}}] = [\mathrm{Ad}_{e^{[\mathcal{S}_1]\theta_1} e^{[\mathcal{S}_2]\theta_2}}]$$

$$J_{s3} = [\mathrm{Ad}_{T_{ss''}}]\mathcal{S}_3$$

Space Jacobian

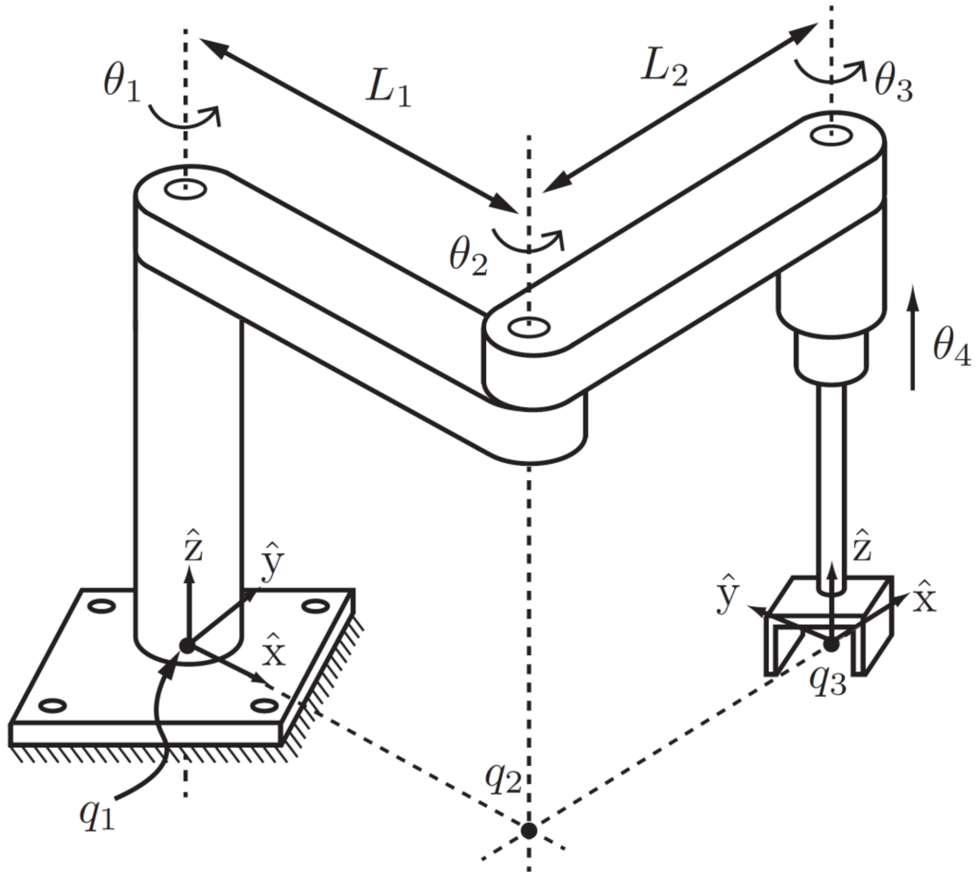
- The ith column of the space Jacobian

$$J_{si}(\theta) = \mathrm{Ad}_{e^{[\mathcal{S}_1]\theta_1} \cdots e^{[\mathcal{S}_{i-1}]\theta_{i-1}}}(\mathcal{S}_i)$$

$$\mathrm{Ad}_{T_{i-1}}(\mathcal{S}_i) \qquad T_{i-1} = e^{[\mathcal{S}_1]\theta_1} \cdots e^{[\mathcal{S}_{i-1}]\theta_{i-1}}$$

$J_{si}(\theta)$ is simply the screw vector describing joint axis i, expressed in fixed-frame coordinates, as a function of the joint variables $\theta_1, \ldots, \theta_{i-1}$.

Space Jacobian



a spatial RRRP chain

$$J_s(\theta) \text{ by } J_{si} = (\omega_{si}, v_{si})$$

$$\omega_{s1} = (0,0,1) \quad v_{s1} = (0,0,0)$$

$$\omega_{s2} = (0,0,1) \quad q_2 \; (L_1 c_1, L_1 s_1, 0)$$

$$v_{s2} = -\omega_2 \times q_2 = (L_1 s_1, -L_1 c_1, 0)$$

$$c_1 = \cos\theta_1, \; s_1 = \sin\theta_1$$

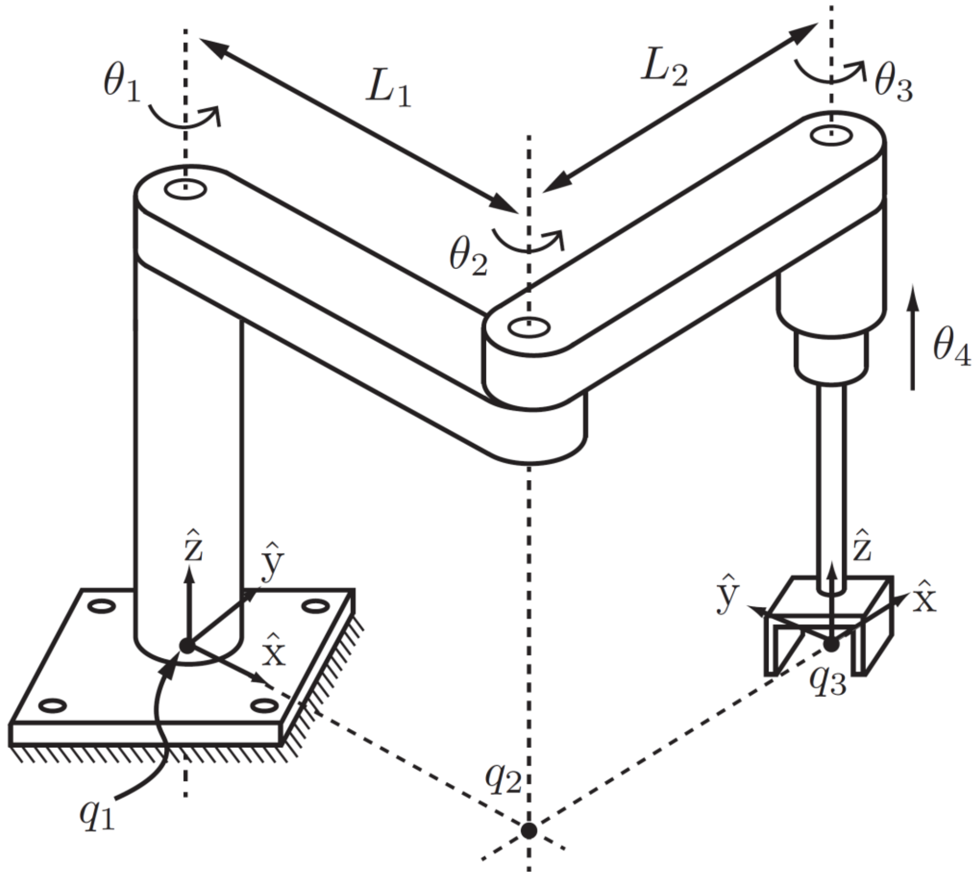
$$\omega_{s3} = (0,0,1) \quad q_3 = (L_1 c_1 + L_2 c_{12}, L_1 s_1 + L_2 s_{12}, 0)$$

$$c_{12} = \cos(\theta_1 + \theta_2), \; s_{12} = \sin(\theta_1 + \theta_2)$$

$$v_{s3} = (L_1 s_1 + L_2 s_{12}, -L_1 c_1 - L_2 c_{12}, 0)$$

$$\omega_{s4} = (0,0,0) \quad v_{s4} = (0,0,1)$$

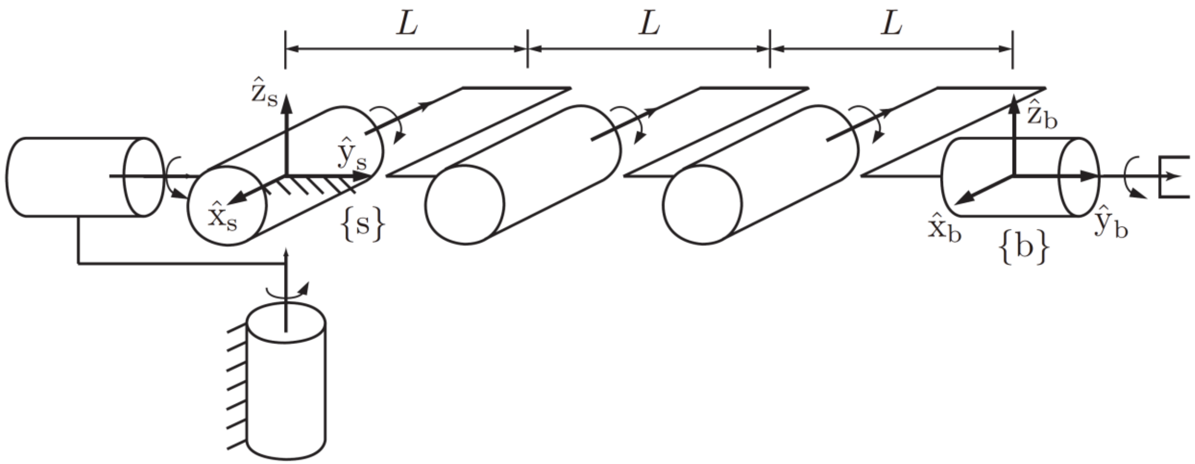
Space Jacobian



a spatial RRRP chain

$$J_s(\theta) = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 \\ 0 & L_1 s_1 & L_1 s_1 + L_2 s_{12} & 0 \\ 0 & -L_1 c_1 & -L_1 c_1 - L_2 c_{12} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Recall Screw Axes in the End-Effector Frame



PoE forward kinematics for the 6R open chain

$$M = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 3L \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

i	ω_i	v_i
1	$(0,0,1)$	$(0,0,0)$
2	$(0,1,0)$	$(0,0,0)$
3	$(-1,0,0)$	$(0,0,0)$
4	$(-1,0,0)$	$(0,0,L)$
5	$(-1,0,0)$	$(0,0,2L)$
6	$(0,1,0)$	$(0,0,0)$

Space form

i	ω_i	v_i
1	$(0,0,1)$	$(-3L,0,0)$
2	$(0,1,0)$	$(0,0,0)$
3	$(-1,0,0)$	$(0,0,-3L)$
4	$(-1,0,0)$	$(0,0,-2L)$
5	$(-1,0,0)$	$(0,0,-L)$
6	$(0,1,0)$	$(0,0,0)$

Body form

Body Jacobian

- End-effect twist in the end-effector frame $[\mathcal{V}_b] = T^{-1}\dot{T}$
- Forward kinematics

$$T(\theta) = Me^{[\mathcal{B}_1]\theta_1} e^{[\mathcal{B}_2]\theta_2} \cdots e^{[\mathcal{B}_n]\theta_n}$$

$$\begin{aligned}
\dot{T} =& Me^{[\mathcal{B}_1]\theta_1} \cdots e^{[\mathcal{B}_{n-1}]\theta_{n-1}} \left(\frac{d}{dt} e^{[\mathcal{B}_n]\theta_n} \right) \\
&+ Me^{[\mathcal{B}_1]\theta_1} \cdots \left(\frac{d}{dt} e^{[\mathcal{B}_{n-1}]\theta_{n-1}} \right) e^{[\mathcal{B}_n]\theta_n} + \cdots \\
=& Me^{[\mathcal{B}_1]\theta_1} \cdots e^{[\mathcal{B}_n]\theta_n} [\mathcal{B}_n]\dot{\theta}_n \\
&+ Me^{[\mathcal{B}_1]\theta_1} \cdots e^{[\mathcal{B}_{n-1}]\theta_{n-1}} [\mathcal{B}_{n-1}] e^{[\mathcal{B}_n]\theta_n} \dot{\theta}_{n-1} + \cdots \\
&+ Me^{[\mathcal{B}_1]\theta_1} [\mathcal{B}_1] e^{[\mathcal{B}_2]\theta_2} \cdots e^{[\mathcal{B}_n]\theta_n} \dot{\theta}_1.
\end{aligned}$$

$$d(e^{A\theta})/dt = Ae^{A\theta}\dot{\theta} = e^{A\theta}A\dot{\theta}$$

$$T^{-1} = e^{-[\mathcal{B}_n]\theta_n} \cdots e^{-[\mathcal{B}_1]\theta_1} M^{-1}$$

Body Jacobian

$$[\mathcal{V}_b] = T^{-1}\dot{T}$$

$$\begin{aligned}[\mathcal{V}_b] &= [\mathcal{B}_n]\dot{\theta}_n + e^{-[\mathcal{B}_n]\theta_n}[\mathcal{B}_{n-1}]e^{[\mathcal{B}_n]\theta_n}\dot{\theta}_{n-1} + \cdots \\ &\quad + e^{-[\mathcal{B}_n]\theta_n} \cdots e^{-[\mathcal{B}_2]\theta_2}[\mathcal{B}_1]e^{[\mathcal{B}_2]\theta_2} \cdots e^{[\mathcal{B}_n]\theta_n}\dot{\theta}_1\end{aligned}$$

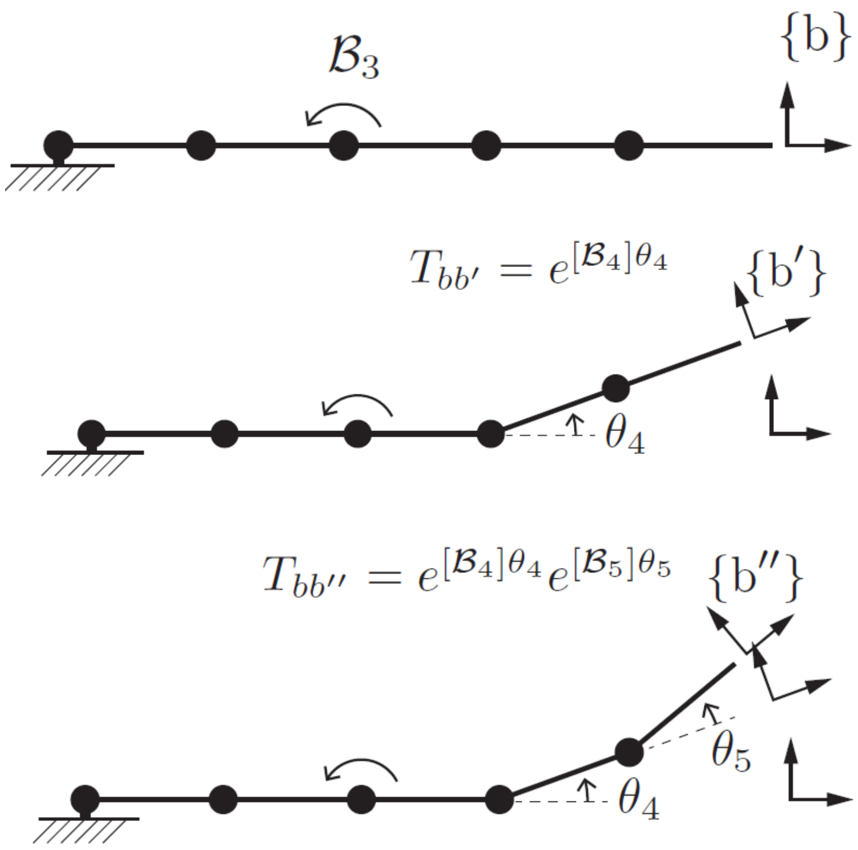
$$\mathcal{V}_b = \underbrace{\mathcal{B}_n}_{J_{bn}}\dot{\theta}_n + \underbrace{\mathrm{Ad}_{e^{-[\mathcal{B}_n]\theta_n}}(\mathcal{B}_{n-1})}_{J_{b,n-1}}\dot{\theta}_{n-1} + \cdots + \underbrace{\mathrm{Ad}_{e^{-[\mathcal{B}_n]\theta_n} \cdots e^{-[\mathcal{B}_2]\theta_2}}(\mathcal{B}_1)}_{J_{b1}}\dot{\theta}_1$$

$$\mathcal{V}_b = J_{b1}(\theta)\dot{\theta}_1 + \cdots + J_{bn-1}(\theta)\dot{\theta}_{n-1} + J_{bn}\dot{\theta}_n$$

$$J_{bi}(\theta) = (\omega_{bi}(\theta), v_{bi}(\theta))$$

Visualizing the Body Jacobian

$$\mathcal{V}_b = \underbrace{\mathcal{B}_n}_{J_{bn}} \dot{\theta}_n + \underbrace{\mathrm{Ad}_{e^{-[\mathcal{B}_n]\theta_n}}(\mathcal{B}_{n-1})}_{J_{b,n-1}} \dot{\theta}_{n-1} + \cdots + \underbrace{\mathrm{Ad}_{e^{-[\mathcal{B}_n]\theta_n} \cdots e^{-[\mathcal{B}_2]\theta_2}}(\mathcal{B}_1)}_{J_{b1}} \dot{\theta}_1$$



Consider some input $\dot{\theta}_3$ on $\mathcal{B}_3$

$\theta_1, \theta_2, \theta_3$ won't change $\mathcal{B}_3$ in {b}

No contribution to the twist

$\mathcal{B}_3$ is expressed in $\{b\}$

$$\begin{aligned} J_{b3} &= [\mathrm{Ad}_{T_{b''b}}]\mathcal{B}_3 \\ &= [\mathrm{Ad}_{T^{-1}_{bb''}}]\mathcal{B}_3 \\ &= [\mathrm{Ad}_{e^{-[\mathcal{B}_5]\theta_5} e^{-[\mathcal{B}_4]\theta_4}}]\mathcal{B}_3 \end{aligned}$$

Body Jacobian

$$\mathcal{V}_b = \begin{bmatrix} J_{b1}(\theta) & \cdots & J_{bn-1}(\theta) & J_{bn} \end{bmatrix} \begin{bmatrix} \dot{\theta}_1 \\ \vdots \\ \dot{\theta}_n \end{bmatrix} = J_b(\theta)\dot{\theta}$$

body Jacobian $J_b(\theta) \in \mathbb{R}^{6\times n}$ $\qquad \dot{\theta} \in \mathbb{R}^n$

$$J_{bi}(\theta) = \mathrm{Ad}_{e^{-[\mathcal{B}_n]\theta_n} \cdots e^{-[\mathcal{B}_{i+1}]\theta_{i+1}}}(\mathcal{B}_i) \qquad i = n-1, \ldots, 1$$

$$J_{bn} = \mathcal{B}_n$$

The screw vector for joint axis i, expressed in the coordinates of the end-effector frame rather than those of the fixed frame

Relationship between the Space and Body Jacobian

- Fixed frame {s}, body frame {b}
- Forward kinematics $T_{sb}(\theta)$
- Twist of the end-effector frame

$$\begin{aligned} [\mathcal{V}_s] &= \dot{T}_{sb} T_{sb}^{-1}, & \mathcal{V}_s &= J_s(\theta)\dot{\theta}, \\ [\mathcal{V}_b] &= T_{sb}^{-1}\dot{T}_{sb}, & \mathcal{V}_b &= J_b(\theta)\dot{\theta}. \end{aligned}$$

$$\mathcal{V}_s = \mathrm{Ad}_{T_{sb}}(\mathcal{V}_b)$$

$$\mathrm{Ad}_{T_{sb}}(\mathcal{V}_b) = J_s(\theta)\dot{\theta}$$

Applying $[\mathrm{Ad}_{T_{bs}}]$ to both sides

$$\mathrm{Ad}_{T_{bs}}(\mathrm{Ad}_{T_{sb}}(\mathcal{V}_b)) = \mathrm{Ad}_{T_{bs}T_{sb}}(\mathcal{V}_b) = \mathcal{V}_b = \mathrm{Ad}_{T_{bs}}(J_s(\theta)\dot{\theta})$$

$$J_b(\theta) = \mathrm{Ad}_{T_{bs}}(J_s(\theta)) = [\mathrm{Ad}_{T_{bs}}]J_s(\theta)$$

$$J_s(\theta) = \mathrm{Ad}_{T_{sb}}(J_b(\theta)) = [\mathrm{Ad}_{T_{sb}}]J_b(\theta)$$

Summary

- Velocity kinematics
- Jacobian
  - Space Jacobian
  - Body Jacobian

Further Reading

- Chapter 5 in Kevin M. Lynch and Frank C. Park. Modern Robotics: Mechanics, Planning, and Control. 1st Edition, 2017.

- T. Yoshikawa. Manipulability of robotic mechanisms. International Journal of Robotics Research, 4(2):3-9, 1985.