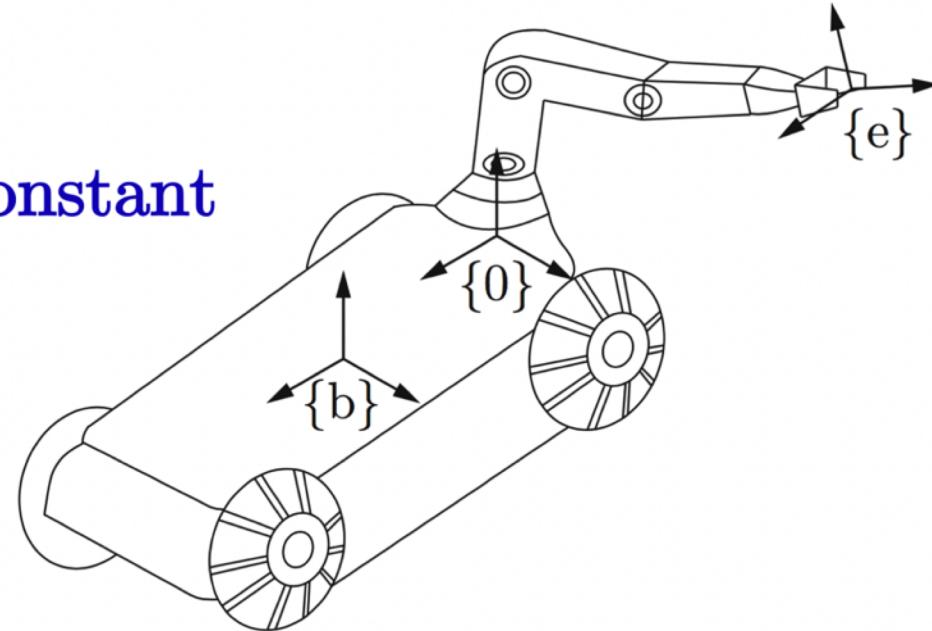
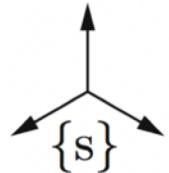


Chapter 2	Configuration Space
Chapter 3	Rigid-Body Motions
Chapter 4	Forward Kinematics
Chapter 5	Velocity Kinematics and Statics
Chapter 6	Inverse Kinematics
Chapter 7	Kinematics of Closed Chains
Chapter 8	Dynamics of Open Chains
Chapter 9	Trajectory Generation
Chapter 10	Motion Planning
Chapter 11	Robot Control
Chapter 12	Grasping and Manipulation
Chapter 13	Wheeled Mobile Robots
	13.1 Types of Wheeled Mobile Robots
	13.2 Omnidirectional Wheeled Mobile Robots
	13.3 Nonholonomic Wheeled Mobile Robots
	13.4 Odometry
	13.5 Mobile Manipulation

## Important concepts, symbols, and equations

$$T_{sb}(q) = \begin{bmatrix} \cos \phi & -\sin \phi & 0 & x \\ \sin \phi & \cos \phi & 0 & y \\ 0 & 0 & 1 & z \\ 0 & 0 & 0 & 1 \end{bmatrix} \text{constant}$$



$$X(q, \theta) = T_{se}(q, \theta) = T_{sb}(q) T_{b0} T_{0e}(\theta)$$

## Important concepts, symbols, and equations (cont.)

Mobile manipulator Jacobian  $J_e(\theta)$  (not a function of  $q$ )

$$\mathcal{V}_e = J_e(\theta) \begin{bmatrix} u \\ \dot{\theta} \end{bmatrix} = [J_{\text{base}}(\theta) \ J_{\text{arm}}(\theta)] \begin{bmatrix} u \\ \dot{\theta} \end{bmatrix}$$

$6 \times (m+n)$        $6 \times m$        $6 \times n$

$$\mathcal{V}_b = Fu, \ F \in \mathbb{R}^{3 \times m} \quad (\text{from odometry})$$

$$F_6 = \begin{bmatrix} 0_m \\ 0_m \\ F \\ 0_m \end{bmatrix} \in \mathbb{R}^{6 \times m} \quad [ \text{Ad}_{T_{eb}(\theta)} ] \mathcal{V}_{b6} = [ \text{Ad}_{T_{0e}^{-1}(\theta) T_{b0}^{-1}} ] F_6 u$$

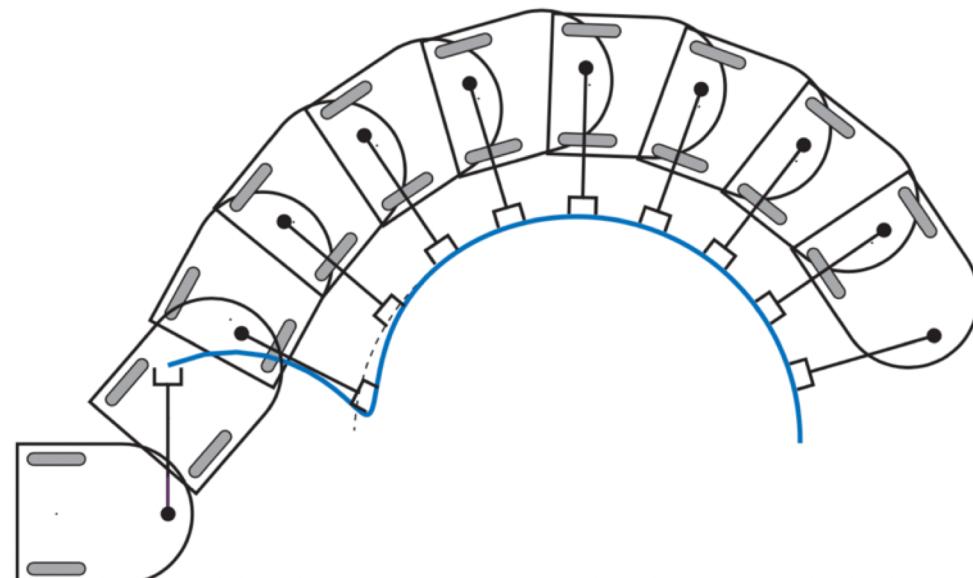
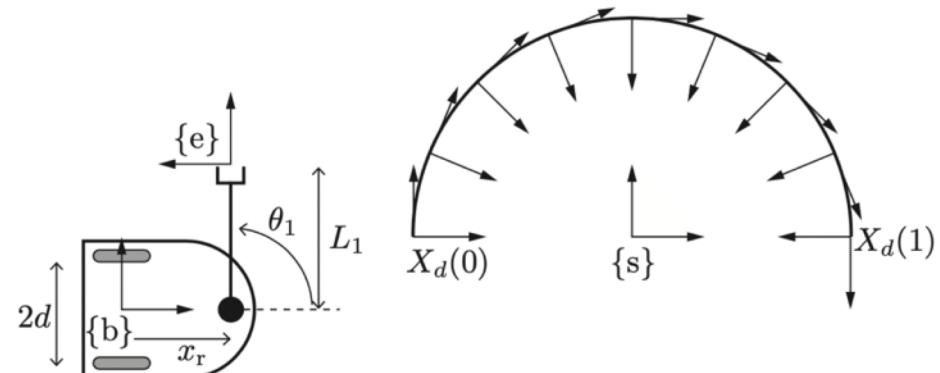
$$\mathcal{V}_{b6} = F_6 u$$

## Important concepts, symbols, and equations (cont.)

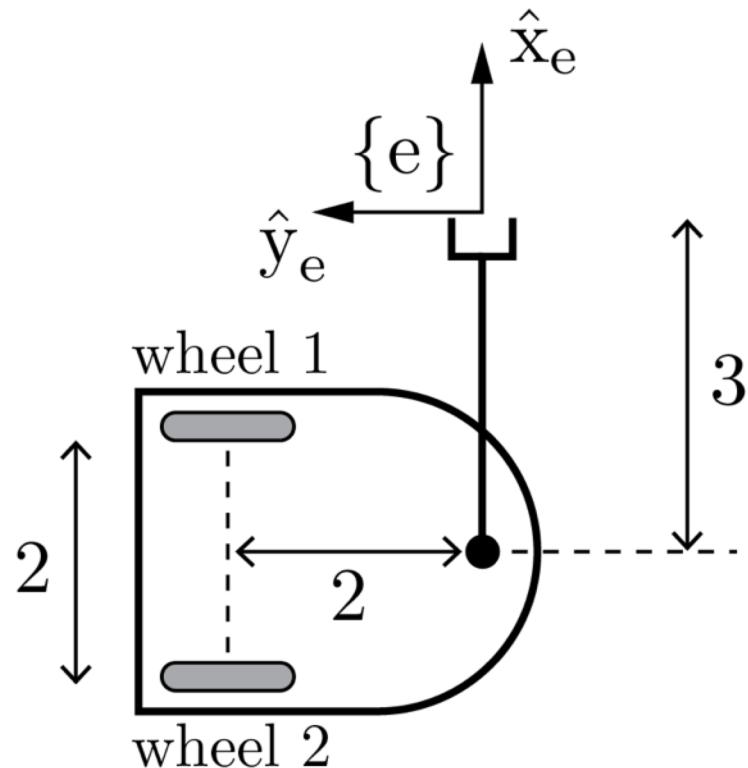
### Task-space feedforward + PI feedback control

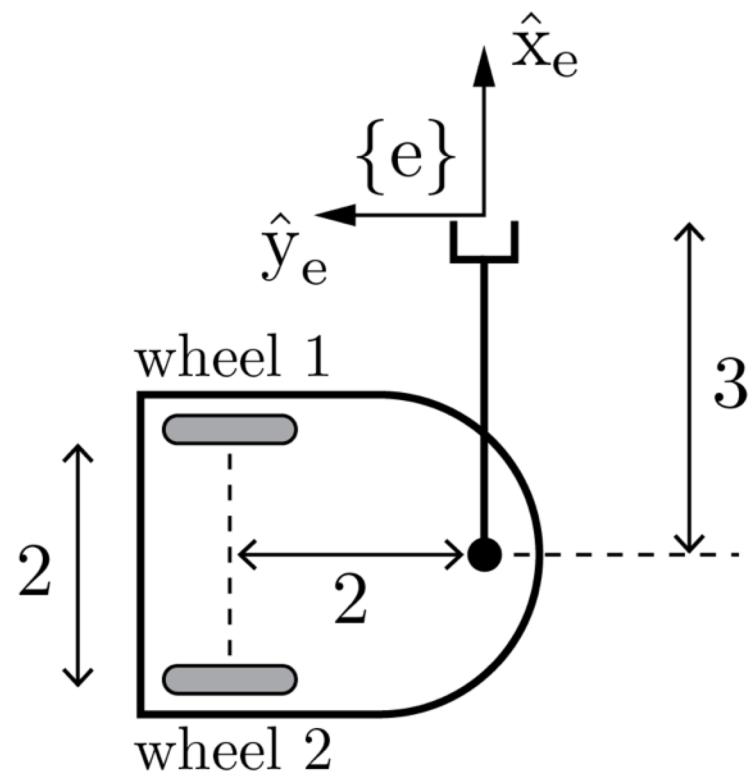
$$\mathcal{V}_e(t) = [\text{Ad}_{X^{-1}X_d}] \mathcal{V}_d(t) + K_p X_{\text{err}}(t) + K_i \int_0^t X_{\text{err}}(t) dt$$

$$\begin{bmatrix} u \\ \dot{\theta} \end{bmatrix} = J_e^\dagger(\theta) \mathcal{V}_e \quad [X_{\text{err}}] = \log(X^{-1}X_d)$$



The planar mobile manipulator below has a diff-drive mobile base and a 1R robot arm. Each wheel radius is 0.5. The positive driving direction for each wheel moves the robot forward, and positive rotation for the arm joint is about an axis out of the page. At the configuration below, give the Jacobian  $J_e$ .





Why does the arm stretch out before the wheels move?  
Would anything change if the wheels had a larger radius?

$$\begin{bmatrix} u \\ \dot{\theta} \end{bmatrix} = J_e^\dagger(\theta) \mathcal{V}_e$$

