

Tele-Experiment

Kinematics of Mobile Robots

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Submission Date: January 2, 2026

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1 Simplified Car-Like Robot Model

Proving the relationship between the steering angle of the virtual wheel φ and the steering angles of the two front wheels φ_l and φ_r .

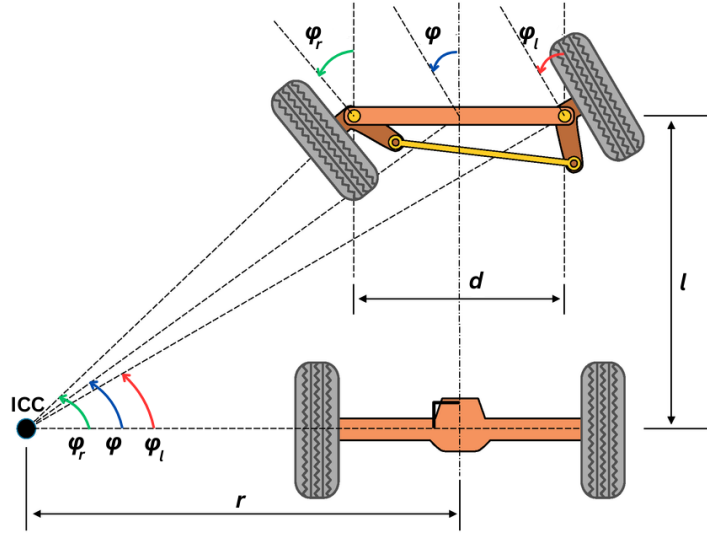


Figure 1.1: Simplified Car-Like Robot Model.

Since the track width d , the wheel base l and the radius r from the Instantaneous Center of Curvature ICC forms a right angle triangle, the steering angles can be written as:

$$\tan \varphi = \frac{l}{r}$$

$$\tan \varphi_r = \frac{l}{(r + \frac{d}{2})}$$

$$\tan \varphi_l = \frac{l}{(r - \frac{d}{2})}$$

The equation for right steering angle can be rearranged by isolating for radius r .

$$\tan \varphi_r = \frac{l}{\left(r + \frac{d}{2}\right)}$$

$$r + \frac{d}{2} = \frac{l}{\tan \varphi_r}$$

$$r = \frac{l}{\tan \varphi_r} - \frac{d}{2}$$

Substituting the radius into equation for steering angle of the virtual wheel,

$$\tan \varphi = \frac{l}{\frac{l}{\tan \varphi_r} - \frac{d}{2}}$$

Dividing numerator and denominator of right hand side by l ,

$$\tan \varphi = \frac{1}{\frac{1}{\tan \varphi_r} - \frac{d}{2l}}$$

$$\tan \varphi = \frac{1}{\left(\frac{2l - d \cdot \tan \varphi_r}{2l \cdot \tan \varphi_r}\right)}$$

$$\tan \varphi = \frac{2l \cdot \tan \varphi_r}{2l - d \cdot \tan \varphi_r}$$

Dividing numerator and denominator of right hand side by $2l$,

$$\tan \varphi = \frac{\tan \varphi_r}{1 - \frac{d}{2l} \cdot \tan \varphi_r}$$

$$\therefore \varphi = \arctan \left(\frac{\tan \varphi_r}{1 - \frac{d}{2l} \cdot \tan \varphi_r} \right)$$

The equation for left steering angle can be rearranged by isolating for radius r .

$$\tan \varphi_l = \frac{l}{\left(r - \frac{d}{2}\right)}$$

$$r - \frac{d}{2} = \frac{l}{\tan \varphi_l}$$

$$r = \frac{l}{\tan \varphi_l} + \frac{d}{2}$$

Substituting the radius into equation for steering angle of the virtual wheel,

$$\tan \varphi = \frac{l}{\frac{l}{\tan \varphi_l} + \frac{d}{2}}$$

Dividing numerator and denominator of right hand side by l ,

$$\tan \varphi = \frac{1}{\frac{1}{\tan \varphi_l} + \frac{d}{2l}}$$

$$\tan \varphi = \frac{1}{\left(\frac{2l + d \cdot \tan \varphi_l}{2l \cdot \tan \varphi_l}\right)}$$

$$\tan \varphi = \frac{2l \cdot \tan \varphi_l}{2l + d \cdot \tan \varphi_l}$$

Dividing numerator and denominator of right hand side by $2l$,

$$\tan \varphi = \frac{\tan \varphi_l}{1 + \frac{d}{2l} \cdot \tan \varphi_l}$$

$$\therefore \varphi = \arctan \left(\frac{\tan \varphi_l}{1 + \frac{d}{2l} \cdot \tan \varphi_l} \right)$$

2 Pose Determination from Kinematics Model

2.1 Differential Drive Robot

Case 1: Non-Straight-Line Motion

Since linear velocity v_l and v_r are constant, the angular velocity ω is also assumed to be constant. Therefore, instead of notating them as a function of time, they will be notated as constants v and ω .

Finding $\Delta\theta$ with respect to time t_1 and t_2 .

$$\begin{aligned}\Delta\theta &= \int_{t_1}^{t_2} \omega dt \\ &= \omega[t]_{t_1}^{t_2} \\ &= \omega(t_2 - t_1)\end{aligned}$$

Finding Δx with respect to time t_1 and t_2 .

$$\begin{aligned}\Delta x &= \int_{t_1}^{t_2} v \cdot \cos \theta(t) dt \\ &= v \int_{t_1}^{t_2} \cos(\theta(t_1) + \omega(t - t_1)) dt\end{aligned}$$

Let $u = \theta(t_1) + \omega(t - t_1)$.

$$du = \omega dt$$

$$dt = \frac{du}{\omega}$$

Using $\theta(t_1)$ and $\theta(t_2)$ as lower and upper bounds and substituting u and du ,

$$\begin{aligned}
 \Delta x &= v \int_{\theta(t_1)}^{\theta(t_2)} \cos(u) \frac{du}{\omega} \\
 &= \frac{v}{\omega} \int_{\theta(t_1)}^{\theta(t_2)} \cos(u) du \\
 &= \frac{v}{\omega} [\sin(u)]_{\theta(t_1)}^{\theta(t_2)} \\
 &= \frac{v}{\omega} [\sin(\theta(t_2)) - \sin(\theta(t_1))]
 \end{aligned}$$

Finding Δy with respect to time t_1 and t_2 ..

$$\begin{aligned}
 \Delta y &= \int_{t_1}^{t_2} v \cdot \sin \theta(t) dt \\
 &= v \int_{t_1}^{t_2} \sin(\theta(t_1) + \omega(t - t_1)) dt
 \end{aligned}$$

Let $u = \theta(t_1) + \omega(t - t_1)$.

$$du = \omega dt$$

$$dt = \frac{du}{\omega}$$

Using $\theta(t_1)$ and $\theta(t_2)$ as lower and upper bounds and substituting u and du ,

$$\begin{aligned}
 \Delta y &= v \int_{\theta(t_1)}^{\theta(t_2)} \sin(u) \frac{du}{\omega} \\
 &= \frac{v}{\omega} \int_{\theta(t_1)}^{\theta(t_2)} \sin(u) du \\
 &= \frac{v}{\omega} [-\cos(u)]_{\theta(t_1)}^{\theta(t_2)} \\
 &= \frac{v}{\omega} [\cos(\theta(t_1)) - \cos(\theta(t_2))]
 \end{aligned}$$

Therefore, for a differential-drive robot that is not moving in a straight line motion,

$$\Delta\theta = \omega(t_2 - t_1)$$

$$\Delta x = \frac{v}{\omega}[\sin(\theta(t_2)) - \sin(\theta(t_1))]$$

$$\Delta y = \frac{v}{\omega}[\cos(\theta(t_1)) - \cos(\theta(t_2))]$$

Case 2. Straight Line Motion

In case of a straight line motion, the equations would not be the same. For the robot to move in a straight line motion, linear velocity v_l and v_r must be equal and angular velocity ω must be 0.

Finding $\Delta\theta$ with respect to time t_1 and t_2 .

$$\begin{aligned}\Delta\theta &= \int_{t_1}^{t_2} \omega dt \\ &= 0[t]_{t_1}^{t_2} \\ &= 0\end{aligned}$$

Since $\Delta\theta$ is 0, $\theta(t_1)$ remains constant.

Finding Δx with respect to time t_1 and t_2 .

$$\begin{aligned}\Delta x &= \int_{t_1}^{t_2} v \cdot \cos \theta(t_1) dt \\ &= v \cdot \cos \theta(t_1) \int_{t_1}^{t_2} dt \\ &= v \cdot \cos \theta(t_1) [t]_{t_1}^{t_2} \\ &= v \cdot \cos \theta(t_1) \cdot (t_2 - t_1)\end{aligned}$$

Finding Δy with respect to time t_1 and t_2 .

$$\begin{aligned}
\Delta y &= \int_{t_1}^{t_2} v \cdot \sin \theta(t_1) dt \\
&= v \cdot \sin \theta(t_1) \int_{t_1}^{t_2} dt \\
&= v \cdot \sin \theta(t_1) [t]_{t_1}^{t_2} \\
&= v \cdot \sin \theta(t_1) \cdot (t_2 - t_1)
\end{aligned}$$

Therefore, for a differential-drive robot that is moving in a straight line motion,

$$\Delta \theta = 0$$

$$\Delta x = v \cdot \cos \theta(t_1) \cdot (t_2 - t_1)$$

$$\Delta y = v \cdot \sin \theta(t_1) \cdot (t_2 - t_1)$$

2.2 Car-Like Robot

Case 1: Non-Straight-Line Motion

Steering angle φ and linear velocity v are constant.

Finding $\Delta \theta$ with respect to time t_1 and t_2 .

$$\begin{aligned}
\Delta \theta &= \int_{t_1}^{t_2} v \cdot \frac{\tan \varphi}{l} dt \\
&= v \cdot \frac{\tan \varphi}{l} \int_{t_1}^{t_2} dt \\
&= v \cdot \frac{\tan \varphi}{l} [t]_{t_1}^{t_2} \\
&= v \cdot \frac{\tan \varphi}{l} (t_2 - t_1)
\end{aligned}$$

Finding Δx with respect to time t_1 and t_2 .

$$\begin{aligned}
\Delta x &= \int_{t_1}^{t_2} v \cdot \cos \theta(t) dt \\
&= v \int_{t_1}^{t_2} \cos \left(\theta(t_1) + v \cdot \frac{\tan \varphi}{l} (t - t_1) \right) dt
\end{aligned}$$

Let $u = \theta(t_1) + v \cdot \frac{\tan \varphi}{l} (t - t_1)$.

$$du = \frac{v \cdot \tan \varphi}{l} dt$$

$$dt = \frac{l}{v \cdot \tan \varphi} du$$

Using $\theta(t_1)$ and $\theta(t_2)$ as lower and upper bounds and substituting u and du ,

$$\begin{aligned} \Delta x &= v \int_{\theta(t_1)}^{\theta(t_2)} \cos(u) \cdot \frac{l}{v \cdot \tan \varphi} du \\ &= \frac{l}{\tan \varphi} \int_{\theta(t_1)}^{\theta(t_2)} \cos(u) du \\ &= \frac{l}{\tan \varphi} [\sin(u)]_{\theta(t_1)}^{\theta(t_2)} \\ &= \frac{l}{\tan \varphi} [\sin(\theta(t_2)) - \sin(\theta(t_1))] \end{aligned}$$

Finding Δy with respect to time t_1 and t_2 .

$$\begin{aligned} \Delta y &= \int_{t_1}^{t_2} v \cdot \sin \theta(t) dt \\ &= v \int_{t_1}^{t_2} \sin \left(\theta(t_1) + v \cdot \frac{\tan \varphi}{l} (t - t_1) \right) dt \end{aligned}$$

Let $u = \theta(t_1) + v \cdot \frac{\tan \varphi}{l} (t - t_1)$.

$$du = \frac{v \cdot \tan \varphi}{l} dt$$

$$dt = \frac{l}{v \cdot \tan \varphi} du$$

Using $\theta(t_1)$ and $\theta(t_2)$ as lower and upper bounds and substituting u and du ,

$$\begin{aligned}
\Delta x &= v \int_{\theta(t_1)}^{\theta(t_2)} \sin(u) \cdot \frac{l}{v \cdot \tan \varphi} du \\
&= \frac{l}{\tan \varphi} \int_{\theta(t_1)}^{\theta(t_2)} \sin(u) du \\
&= \frac{l}{\tan \varphi} [-\cos(u)]_{\theta(t_1)}^{\theta(t_2)} \\
&= \frac{l}{\tan \varphi} [\cos(\theta(t_1)) - \cos(\theta(t_2))]
\end{aligned}$$

Therefore, for a differential-drive robot that is moving in a straight line motion,

$$\begin{aligned}
\Delta \theta &= v \cdot \frac{\tan \varphi}{l} (t_2 - t_1) \\
\Delta x &= \frac{l}{\tan \varphi} [\sin(\theta(t_2)) - \sin(\theta(t_1))] \\
\Delta y &= \frac{l}{\tan \varphi} [\cos(\theta(t_1)) - \cos(\theta(t_2))]
\end{aligned}$$

Case 2. Straight Line Motion

The equations for Straight line motion for the car-like robot will also be different from the non-straight-line motion. For the robot moving in straight line motion, the steering angle φ is 0.

Finding $\Delta \theta$ with respect to time t_1 and t_2 .

$$\begin{aligned}
\Delta \theta &= \int_{t_1}^{t_2} v \cdot \frac{\tan \varphi}{l} dt \\
&= v \cdot \frac{\tan \varphi}{l} \int_{t_1}^{t_2} dt \\
&= 0[t]_{t_1}^{t_2} \\
&= 0
\end{aligned}$$

Since $\Delta \theta$ is 0, $\theta(t_1)$ remains constant.

Finding Δx with respect to time t_1 and t_2 .

$$\begin{aligned}\Delta x &= \int_{t_1}^{t_2} v \cdot \cos \theta(t_1) dt \\ &= v \cdot \cos \theta(t_1) \int_{t_1}^{t_2} dt \\ &= v \cdot \cos \theta(t_1) [t]_{t_1}^{t_2} \\ &= v \cdot \cos \theta(t_1) \cdot (t_2 - t_1)\end{aligned}$$

Finding Δy with respect to time t_1 and t_2 .

$$\begin{aligned}\Delta y &= \int_{t_1}^{t_2} v \cdot \sin \theta(t_1) dt \\ &= v \cdot \sin \theta(t_1) \int_{t_1}^{t_2} dt \\ &= v \cdot \sin \theta(t_1) [t]_{t_1}^{t_2} \\ &= v \cdot \sin \theta(t_1) \cdot (t_2 - t_1)\end{aligned}$$

Therefore, for a car-like robot that is moving in a straight line motion,

$$\Delta \theta = 0$$

$$\Delta x = v \cdot \cos \theta(t_1) \cdot (t_2 - t_1)$$

$$\Delta y = v \cdot \sin \theta(t_1) \cdot (t_2 - t_1)$$

3 Kinematics of Bicycles and Tricycles

The kinematic differences between the Ackermann steering robot and the standard bicycle or tricycle model can be seen the in the following table.

Ackermann Steering	Bicycles and Tricycles
two forward steering wheels	only one single steering front wheel
two independent steering angles φ_l and φ_r and a virtual steering angle φ	only one steering angle φ
the orientation of both front wheels must be perpendicular to ICC	the orientation of front wheel must be perpendicular to ICC φ

Table 3.2: Differences between Ackermann steering and standard bicycles or tricycles

When the ICC falls between the rear wheels in a rear wheel driven tricycle, assuming that the steering angle is not zero ($\varphi \neq 0$) the robot will move in circles around the ICC.

4 Inverse Kinematics