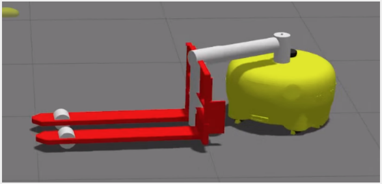
Autonomous Mobile Robotics

Motion Planning and Control

Geesara Kulathunga



January 24, 2023

Control of Mobile Robots

Contents

- **Kinematics** of **wheeled mobile robots**: internal, external, direct, and inverse
  - Differential drive kinematics
  - Bicycle drive kinematics
  - Rear-wheel bicycle drive kinematics
  - Car(Ackermann) drive kinematics
- Wheeled Mobile System Control: **pose** and **orientation**
  - Control to reference pose
  - Control to reference pose via an intermediate point
  - Control to reference pose via an intermediate direction
  - Control by a straight line and a circular arc
  - Reference path control
- Dubins path planning

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- For mobile robotics **kinematic model is sufficient**

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- **Holonomic Systems** - a robot is able to move instantaneously in any the direction in the space of its degree of freedom (**Omnidirectional** robot)
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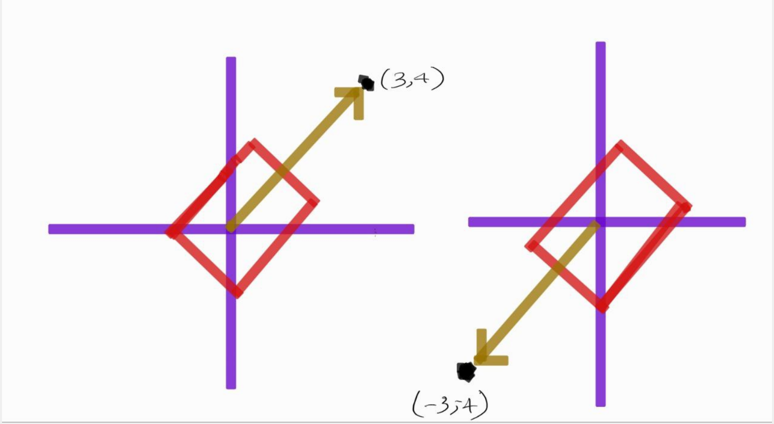
- Inverse kinematics: robot inputs as a function of the desired robot pose

Can you estimate the orientation of the robot?



Quadrant	Angle	sin	cos	tan
I	0 < α < π/2	+	+	+
II	π/2 < α < π	+	-	-
III	π < α < 3π/2	-	-	+
IV	3π/2 < α < 2π	-	+	-

- $|A \cdot B| = |A||B|COS(\theta)$ and $|A \times B| = |A||B|SIN(\theta)$

The difference between atan and atan2

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- $|A \cdot B| = |A||B|COS(\theta)$ and $|A \times B| = |A||B|SIN(\theta)$
- $arctan2(|A \times B| / |A \cdot B|)$

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- If $tan(\alpha)$ is **positive**, it could come from either the **first** or **third** quadrant and if it is negative, it could come from either the second or fourth quadrant. Hence, atan() returns an angle from the first or fourth quadrant (i.e. $-\pi/2 <= atan() <= \pi/2$), regardless of the original input to the tangent

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- To **get full information**, the values of the **sine and cosine** are **considered separately**. And this is what **atan2()** does. It takes both, the $sin(\alpha)$ and $cos(\alpha)$ and **resolves all four quadrants** by adding π to the result of atan() whenever the cosine is negative

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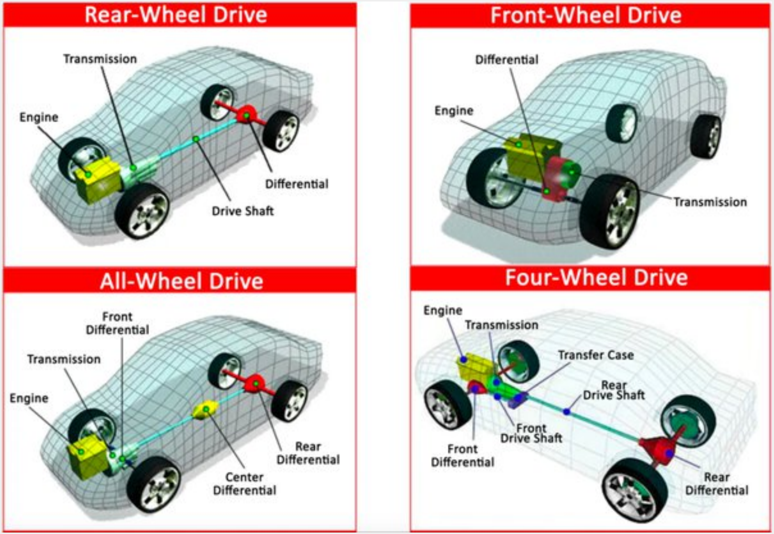
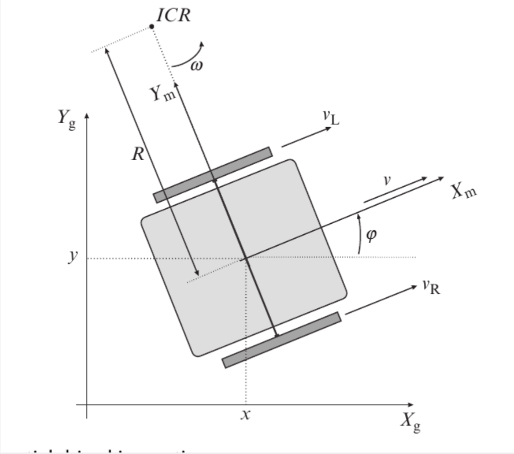
- atan2: -pi < atan2(y,x) <pi and atan: -pi/2 < atan(y/x) < pi/2



https://cartreatments.com/types-of-differentials-how-they-work/

Differential Drive Kinematics



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- Well-fit for **smaller mobile robots**
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- **Velocity** of **each wheel control** separately
- According to Fig. 10,
  - Terms $\mathbf{v}_R(t), \mathbf{v}_L(t)$, denoted velocity of right and left wheels, respectively
  - Wheel radius r, distance between wheels L, and term R(t) depicts the vehicle's instantaneous radios (ICR). **Angular velocity** is the **same** for **both left and right wheels around the ICR**.

- Tangential velocity

$$\mathbf{v}(t) = \omega(t)R(t) = \frac{\mathbf{v}_R(t) + \mathbf{v}_L(t)}{2} \tag{1}$$

, where $\omega = \mathbf{v}_L(t)/(R(t) - L/2) = \mathbf{v}_R(t)/(R(t) + L/2)$. Hence, ω and $R(t)$ can be determined as follows:

$$\begin{aligned} \omega(t) &= \frac{\mathbf{v}_R(t) - \mathbf{v}_L(t)}{L} \\ R(t) &= \frac{L}{2}\frac{\mathbf{v}_R(t) + \mathbf{v}_L(t)}{\mathbf{v}_R(t) - \mathbf{v}_L(t)} \end{aligned} \tag{2}$$

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- Wheels tangential velocities

$$\mathbf{v}_L = r\omega_L(t), \quad \mathbf{v}_R = r\omega_R(t) \tag{3}$$

Differential Drive Kinematics

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$$\begin{bmatrix} \dot{x}_m(t) \\ \dot{y}_m(t) \\ \dot{\Phi}(t) \end{bmatrix} = \begin{bmatrix} v_{X_m}(t) \\ v_{Y_m} \\ \omega(t) \end{bmatrix} = \begin{bmatrix} r/2 & r/2 \\ 0 & 0 \\ -r/L & r/L \end{bmatrix} \begin{bmatrix} \omega_L(t) \\ \omega_R(t) \end{bmatrix} \quad (4)$$

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- Discrete time dynamics using Euler integration

$$\begin{aligned} x(k+1) &= x(k) + v(k)T_s cos(\Phi(k))\\ y(k+1) &= y(k) + v(k)T_s sin(\Phi(k))\\ \Phi(k+1) &= \Phi(k) + \omega(k)T_s \end{aligned} \tag{6}$$

, where discrete time instance $t = kT_s$, k=0,1,2,.., for T_s

- Forward robot kinematics (given a set of wheel speeds, determine robot velocity)

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\end{aligned}
\tag{7}
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  , where discrete time instance $t = kT_s$, k=0,1,2,.., for T_s sampling time

- We can also try trapezoidal numerical integration for better approximation

$$
\begin{aligned}
x(k+1) &= x(k) + v(k)T_s cos(\Phi(k) + \omega(k)T_s/2) \\
y(k+1) &= y(k) + v(k)T_s sin(\Phi(k) + \omega(k)T_s/2) \\
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Differential Drive Kinematics

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- Inverse robot kinematics (given desired robot velocity, determine corresponding wheel velocities)
  - The **most challenging case compared to direct or forward kinematics**
  - Given the target pose **how many possible ways to get there**?
  - What if the **robot** goes can perform only **two types of motions**: **forward and rotations**

$$
\begin{aligned}
\mathbf{v}_R = \mathbf{v}_L = \mathbf{v}_R, \omega(t) = 0, \mathbf{v}(t) = \mathbf{v}_R // \textit{forward} \\
\mathbf{v}_R = -\mathbf{v}_L = \mathbf{v}_R, \omega(t) = 2\mathbf{v}_R/L, \mathbf{v}(t) = 0 // \textit{rotation}
\end{aligned}
\tag{9}
$$

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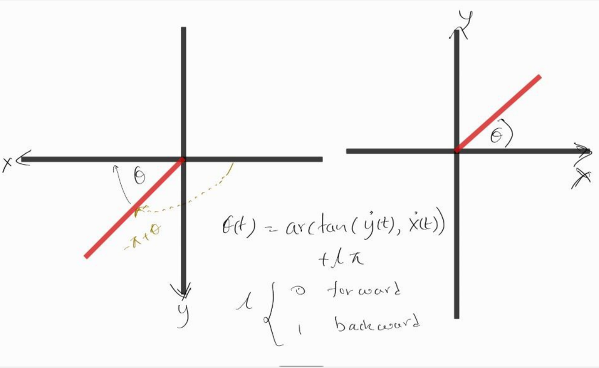
  - If there is a disturbance in the trajectory and know the desired pose at time t, i.e., $x(t), y(t)$

$$\begin{aligned} \mathbf{v}(t) &= \pm\sqrt{\dot{x}^2(t) + \dot{y}^2(t)} // \text{+ forward and - reverse} \\ \Phi(t) &= arctan2(\dot{y}(t), \dot{x}(t)) + l\pi, \quad l \in \{0, 1\} \\ &\quad // \text{ 0 forward and 1 reverse} \\ \omega(t) &= \frac{\dot{x}(t)\ddot{y}(t) - \dot{y}(t)\ddot{x}(t)}{\dot{x}^2(t) + \dot{y}^2(t)} = v(t)k(t) \end{aligned} \tag{10}$$

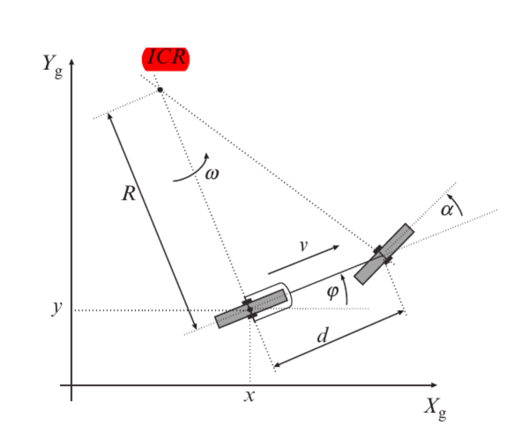
, where k(t) is the **path curvature** and $\omega(t) = \dot{\Phi}(t)$


x
y
θ
−π+θ
θ(t) = arctan(ẏ(t), ẋ(t)) + ℓπ
ℓ
0 forward
1 backward
y
x
θ

Motion control of Bicycle mobile robots

https://helpfulcolin.com/bike-riding-robots-are-helped-by-gyroscopes-cameras/

Motion control of Bicycle mobile robots



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- Angular velocity ω around ICR

$$\omega(t) = \dot{\Phi} = \frac{\mathbf{v}_S(t)}{\sqrt{d^2 + R^2}} = \frac{v_S(t)}{d} sin(\alpha(t)) \tag{12}$$

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- Steering wheel velocity

$$\mathbf{v}_S(t) = \omega_S(t) r \tag{13}$$

- Internal robot kinematics

$$\begin{aligned} \dot{x}_m(t) &= \mathbf{v}_S(t)cos(\alpha(t)) \\ \dot{y}_m(t) &= 0 \\ \Phi\dot{(}t) &= \frac{\mathbf{v}_S(t)}{d}sin(\alpha(t) \end{aligned} \tag{14}$$

Bicycle mobile (front wheel drive)

- Internal robot kinematics

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- External robot kinematics

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$$\begin{bmatrix} \dot{x}(t) \\ \dot{y}(t) \\ \dot{\Phi(t)} \end{bmatrix} = \begin{bmatrix} cos(\Phi(t)) & 0 \\ sin(\Phi(t)) & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \mathbf{v}(t) \\ \omega(t) \end{bmatrix} \tag{16}$$

, where $\mathbf{v}(t) = \mathbf{v}_S(t)cos(\alpha(t))$ and $\omega(t) = \frac{\mathbf{v}_S}{d}sin(\alpha(t))$

Motion control of Rear-Wheel Bicycle mobile robots

- Internal robot kinematics

$$\begin{aligned} \dot{x}_m(t) = \mathbf{v}_S(t)cos(\alpha(t)) = \mathbf{v}_r(t) \\ \dot{y}_m(t) = 0 \\ \Phi\dot(t) = \frac{\mathbf{v}_r(t)}{d}tan(\alpha(t) \end{aligned} \tag{17}$$

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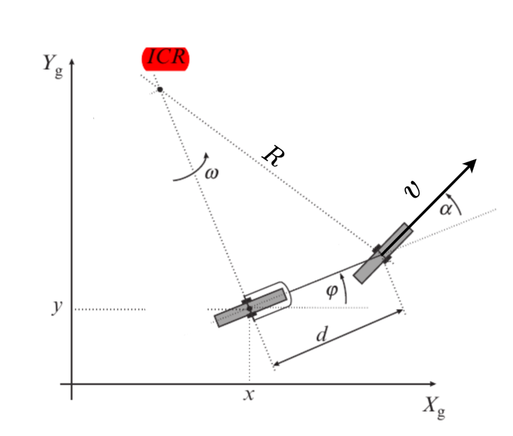
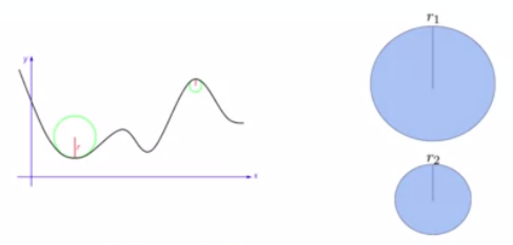
Motion control of Bicycle mobile robots



- External robot kinematics

$$\begin{aligned} \dot{x}(t) &= v \cdot cos(\Phi(t) + \alpha(t)) \\ \dot{y}(t) &= v \cdot sin(\Phi(t) + \alpha(t)) \\ \dot{\Phi}(t) &= v/R = v/(d/sin(\alpha)) = v \cdot sin(\alpha)/d \\ \dot{\alpha} &= \text{input (rate of change of steering angle)} \end{aligned} \tag{19}$$

Motion control of Rear-Wheel Bicycle mobile robots

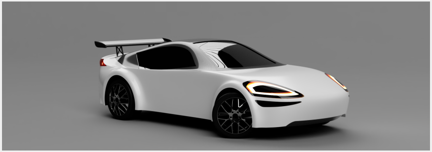


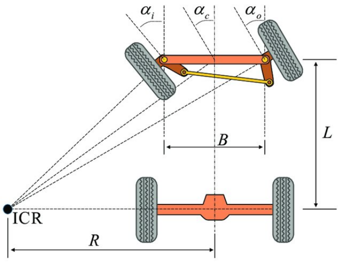
- Bicycle model imposes curvature constraint, where the curvature is defined by

$$k = \frac{\dot{x}(t)\ddot{y}(t) - \dot{y}(t)\ddot{x}(t)}{\left(\dot{x}^2(t) + \dot{y}^2(t)\right)^{3/2}}$$

- Curvature constraint is non-holonomic $v^2 \leq \frac{a_{lat}}{k}$, where $a_{lat} \leq a_{lat_{max}}$

Motion control of Car(Ackermann) drive mobile robots





https://github.com/winstxnhdw/AutoCarROS2, https://doi.org/10.3390/s19214816

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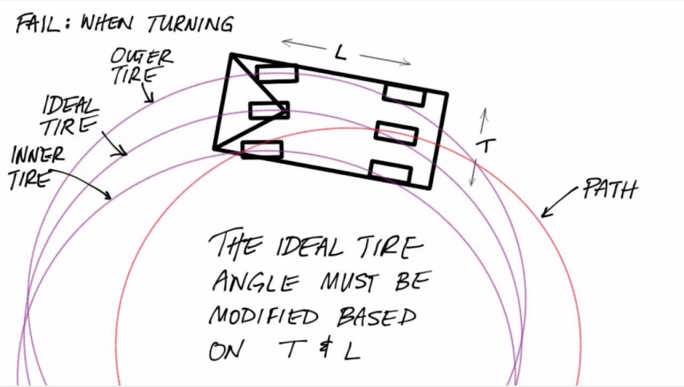

https://www.youtube.com/watch?v=i6uBwudwA5o

Motion control of Car(Ackermann) drive mobile robots

- Uses **steering principle**, i.e., **the inner wheel, which is closer to its ICR, should steer for a bigger angle than the outer wheel**. Consequently, the inner wheel travels at a slower speed than the outer wheel

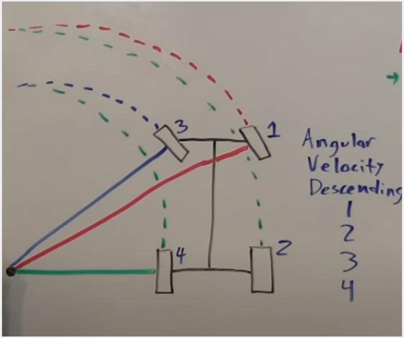

Figure: Angular velocity speed descending order

Motion control of Car(Ackermann) drive mobile robots

- **Ackermann geometry** is to **avoid** the need for tires to **slip sideways** when following the path around a curve which requires that the ICR point lies on a straight line defined by the rear wheels' axis

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- For the differential drive it needs individual drives at each wheel which makes the system more complex

Motion control of Car(Ackermann) drive mobile robots

- **Ackermann geometry** is to **avoid** the need for tires to **slip sideways** when following the path around a curve which requires that the ICR point lies on a straight line defined by the rear wheels' axis
- **Ackermann geometry** can be seen as **two bicycles welded together** side by side
- For the differential drive it needs individual drives at each wheel which makes the system more complex
- **Ackerman steering** adjusts the **relative angles of the steerable wheels** so they both run **around a curve**. Differentials allow the two driven wheels to run at different speeds around a curve, which is quite a different requirement

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