

# Path Planning Optimization

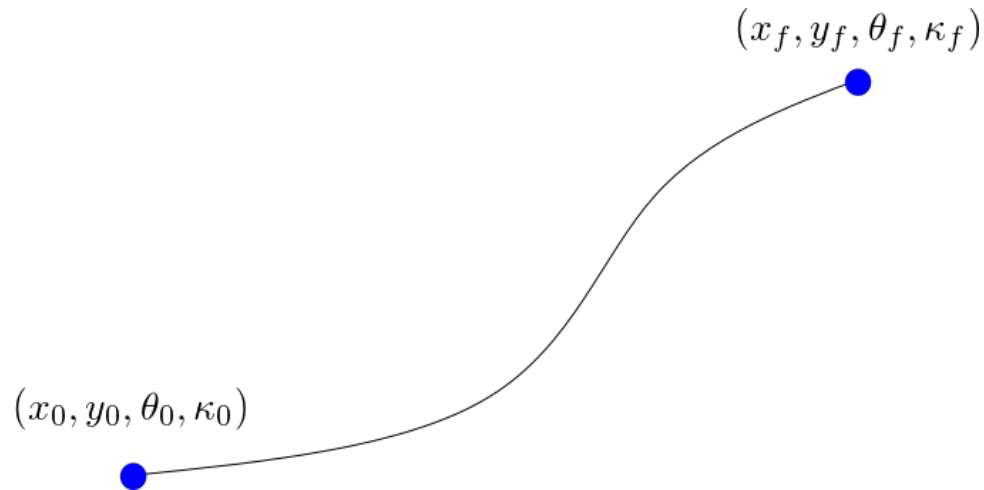
Course 4, Module 7, Lesson 2



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# Cubic Spiral and Boundary Conditions

- Boundary conditions specify starting state and required ending state
- Spiral end position lacks closed form solution, requires numerical approximation



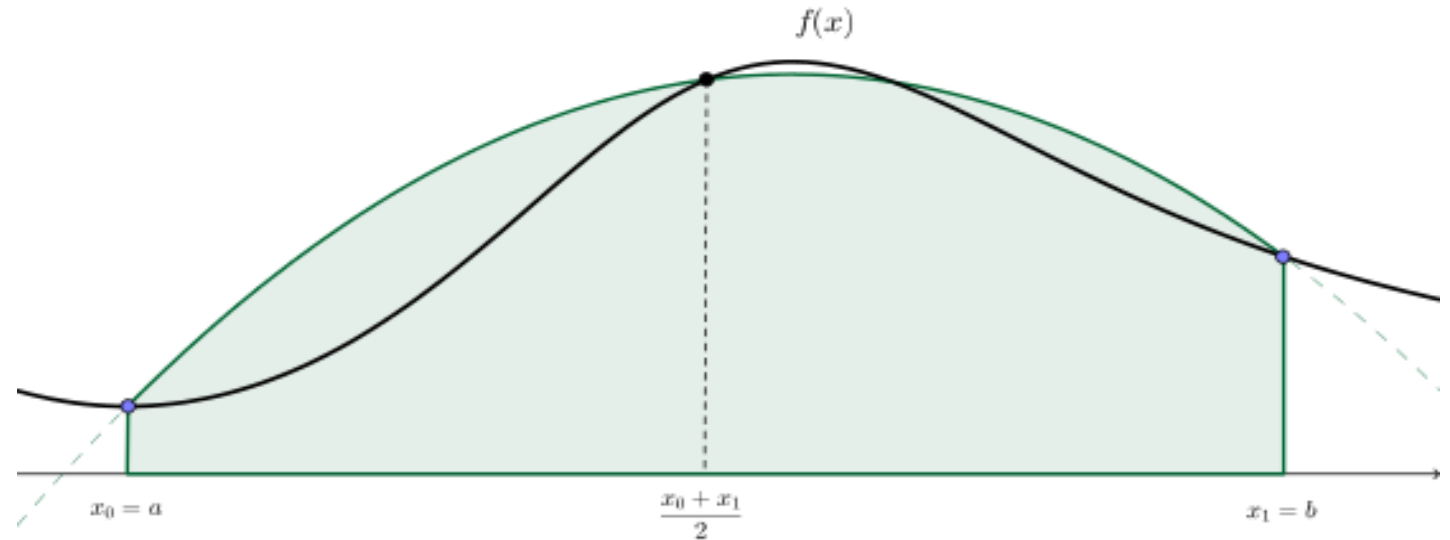
$$\kappa(s) = a_3s^3 + a_2s^2 + a_1s + a_0$$

$$x(s) = x_0 + \int_0^s \cos(\theta(s'))ds'$$

$$y(s) = y_0 + \int_0^s \sin(\theta(s'))ds'$$

# Position Integrals and Simpson's Rule

- Simpson's rule has improved accuracy over other methods
- Divides the integration interval into  $n$  regions, and evaluates the function at each region boundary



$$\int_0^s f(s') ds' \approx \frac{s}{3n} \left( f(0) + 4f\left(\frac{s}{n}\right) + 2f\left(\frac{2s}{n}\right) + \cdots + f(s) \right)$$

# Applying Simpson's Rule

- Applying Simpson's rule with  $n = 8$
- $\theta(s)$  has a closed form solution
- Substituting our integrand for  $x(s)$  and  $y(s)$  into Simpson's rule gives us our approximations  $x_s(s)$  and  $y_s(s)$

arc length parameter

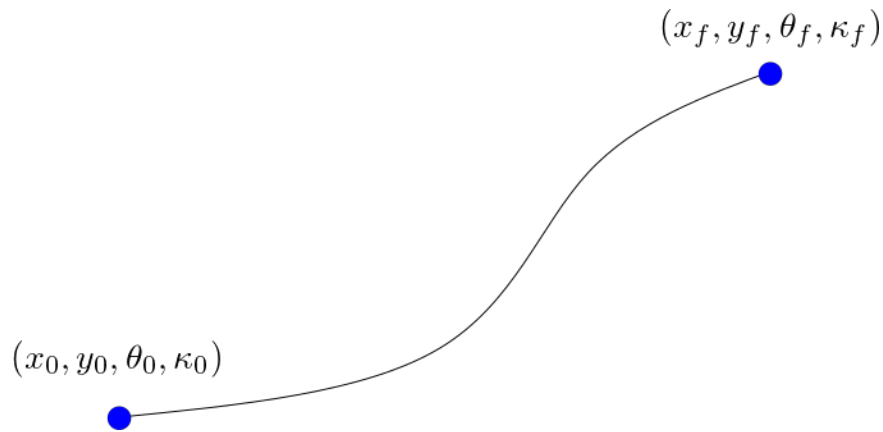
$$\kappa(s) = a_3 s^3 + a_2 s^2 + a_1 s + a_0$$

$$\begin{aligned}\theta(s) &= \theta_0 + \int_0^s \underbrace{a_3 s'^3 + a_2 s'^2 + a_1 s' + a_0}_{\kappa} ds' \\ &= \theta_0 + a_3 \frac{s^4}{4} + a_2 \frac{s^3}{3} + a_1 \frac{s^2}{2} + a_0 s\end{aligned}$$

$$\begin{aligned}x_s(s) &= x_0 + \frac{s}{24} \left[ \cos(\theta(0)) + 4 \cos\left(\theta\left(\frac{s}{8}\right)\right) + 2 \cos\left(\theta\left(\frac{2s}{8}\right)\right) + 4 \cos\left(\theta\left(\frac{3s}{8}\right)\right) + 2 \cos\left(\theta\left(\frac{4s}{8}\right)\right) \right. \\ &\quad \left. + 4 \cos\left(\theta\left(\frac{5s}{8}\right)\right) + 2 \cos\left(\theta\left(\frac{6s}{8}\right)\right) + 4 \cos\left(\theta\left(\frac{7s}{8}\right)\right) + \cos(\theta(s)) \right] \\ y_s(s) &= y_0 + \frac{s}{24} \left[ \sin(\theta(0)) + 4 \sin\left(\theta\left(\frac{s}{8}\right)\right) + 2 \sin\left(\theta\left(\frac{2s}{8}\right)\right) + 4 \sin\left(\theta\left(\frac{3s}{8}\right)\right) + 2 \sin\left(\theta\left(\frac{4s}{8}\right)\right) \right. \\ &\quad \left. + 4 \sin\left(\theta\left(\frac{5s}{8}\right)\right) + 2 \sin\left(\theta\left(\frac{6s}{8}\right)\right) + 4 \sin\left(\theta\left(\frac{7s}{8}\right)\right) + \sin(\theta(s)) \right]\end{aligned}$$

# Boundary Conditions via Simpson's Rule

- Using our Simpson's approximations, we can now write out the full boundary conditions in terms of spiral parameters
- Can now generate a spiral that satisfies boundary conditions by optimizing its spiral parameters and its length,  $s_f$



$$x_S(s_f) = x_f$$

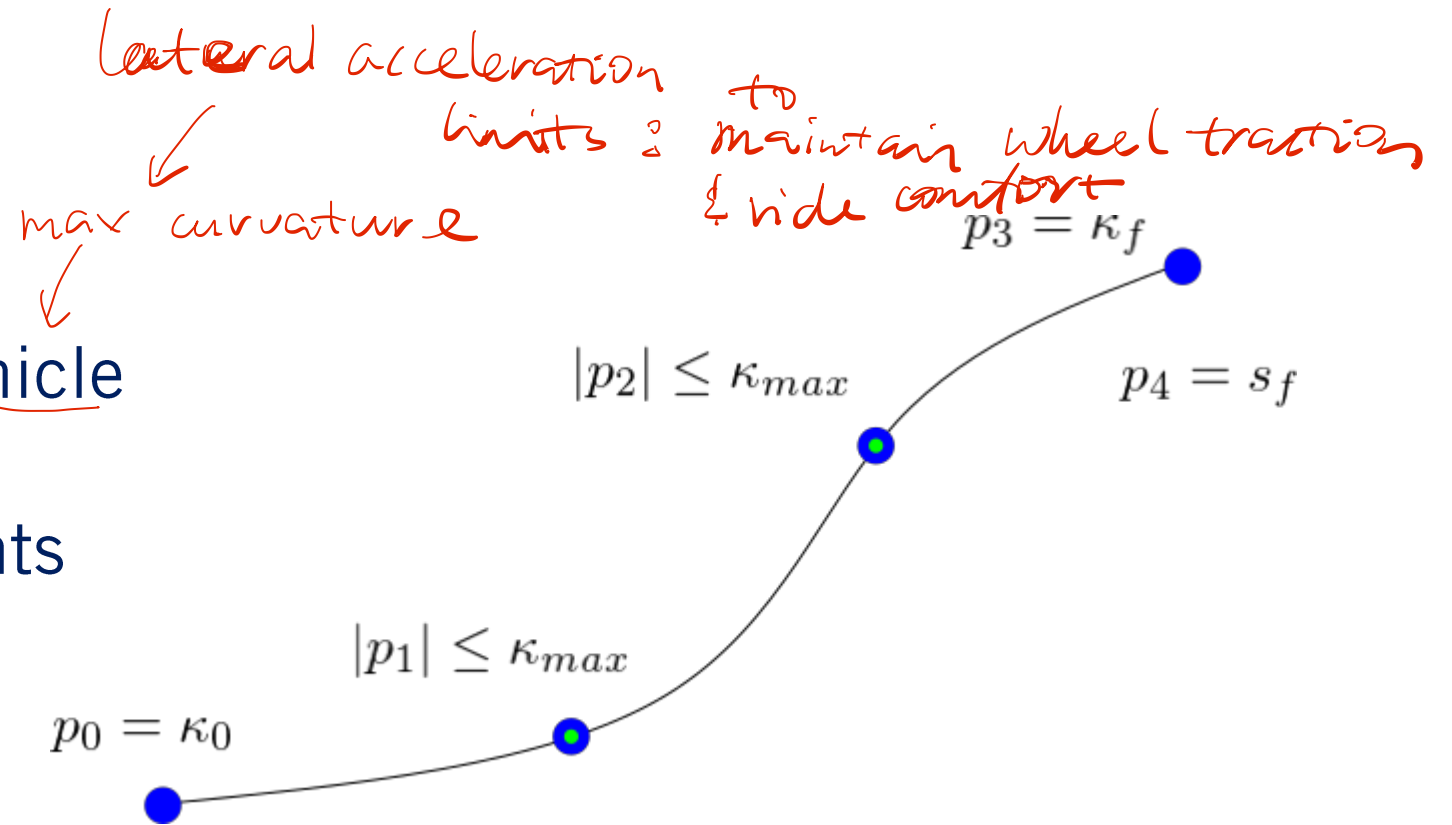
$$y_S(s_f) = y_f$$

$$\theta(s_f) = \theta_f$$

$$\kappa(s_f) = \kappa_f$$

# Approximate Curvature Constraints

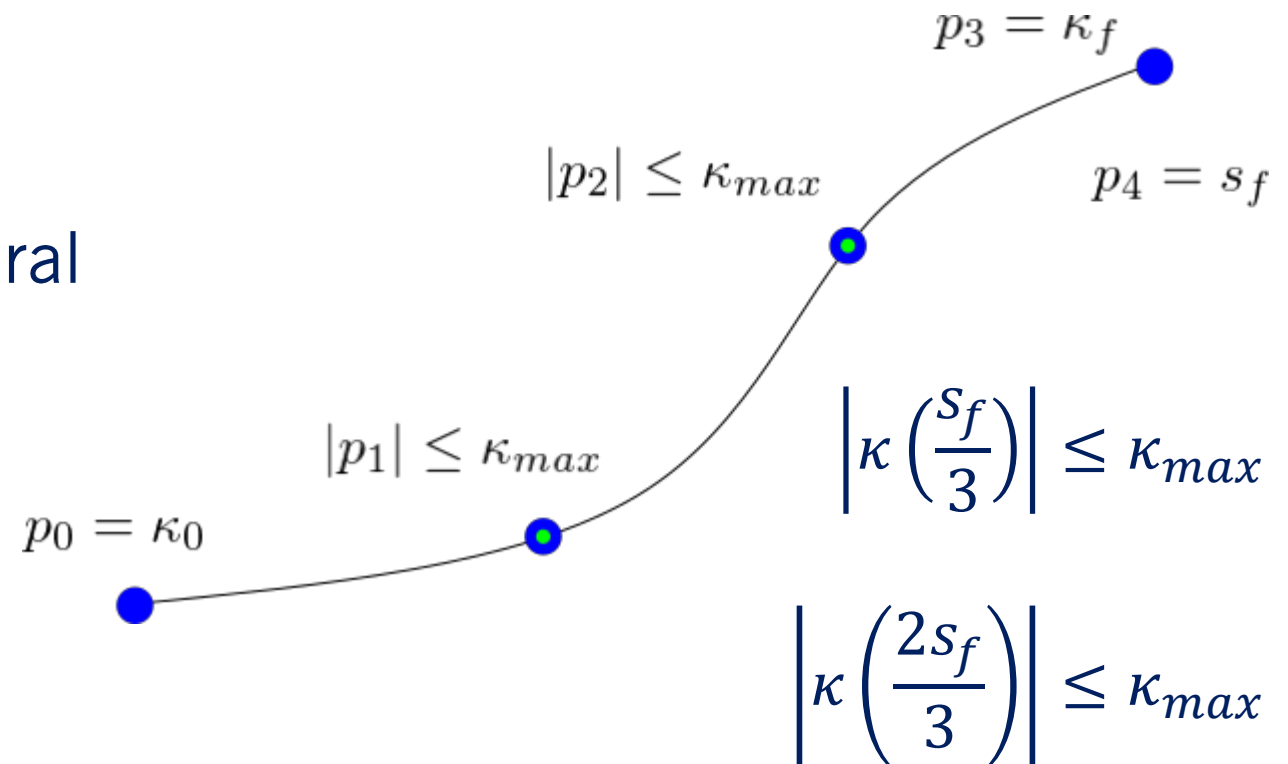
- Want to apply curvature constraints to path so it is drivable by the vehicle
- Curvature constraints correspond to minimum vehicle turning radius
- Can constrain sampled points along the path due to well-behaved nature of spiral's curvature



Ex: assume minimum turning radius 2m  
= maximum curvature of 0.5 arc meters

# Approximate Curvature Constraints

- Can constrain curvature at 1/3rd and 2/3rd's of the way along the path
- Now all constraints and boundary conditions are complete to generate the spiral



# Bending Energy Objective

*To minimize bending energy .*

$$f_{be}(a_0, a_1, a_2, a_3, s_f) = \int_0^{s_f} (a_3 s^3 + a_2 s^2 + a_1 s + a_0)^2 ds$$

*$\propto^2$*

- Bending energy distributes curvature evenly along spiral to promote comfort
  - Equal to integral of square curvature along path, which has closed form for spirals
- Gradient also has a closed form solution
  - Has many terms, so best left to a symbolic solver



# Initial Optimization Problem

- Can bring constraints and objective together to form the full optimization problem
  - Can perform optimization in the vehicle's body attached frame to set starting boundary condition to zero

$$\min f_{be}(a_0, a_1, a_2, a_3, s_f) \text{ s. t. } \left\{ \begin{array}{ll} \left| \kappa \left( \frac{s_f}{3} \right) \right| \leq \kappa_{max}, & \left| \kappa \left( \frac{2s_f}{3} \right) \right| \leq \kappa_{max} \\ x_s(0) = x_0, & x_s(s_f) = x_f \\ y_s(0) = y_0, & y_s(s_f) = y_f \\ \theta(0) = \theta_0, & \theta(s_f) = \theta_f \\ \kappa(0) = \kappa_0, & \kappa(s_f) = \kappa_f \end{array} \right. \left. \begin{array}{l} \text{hard for a numerical} \\ \text{optimizer to generate} \\ \text{a feasible solution} \\ \text{from an infeasible} \\ \text{starting point.} \end{array} \right\}$$

# Soft Constraints

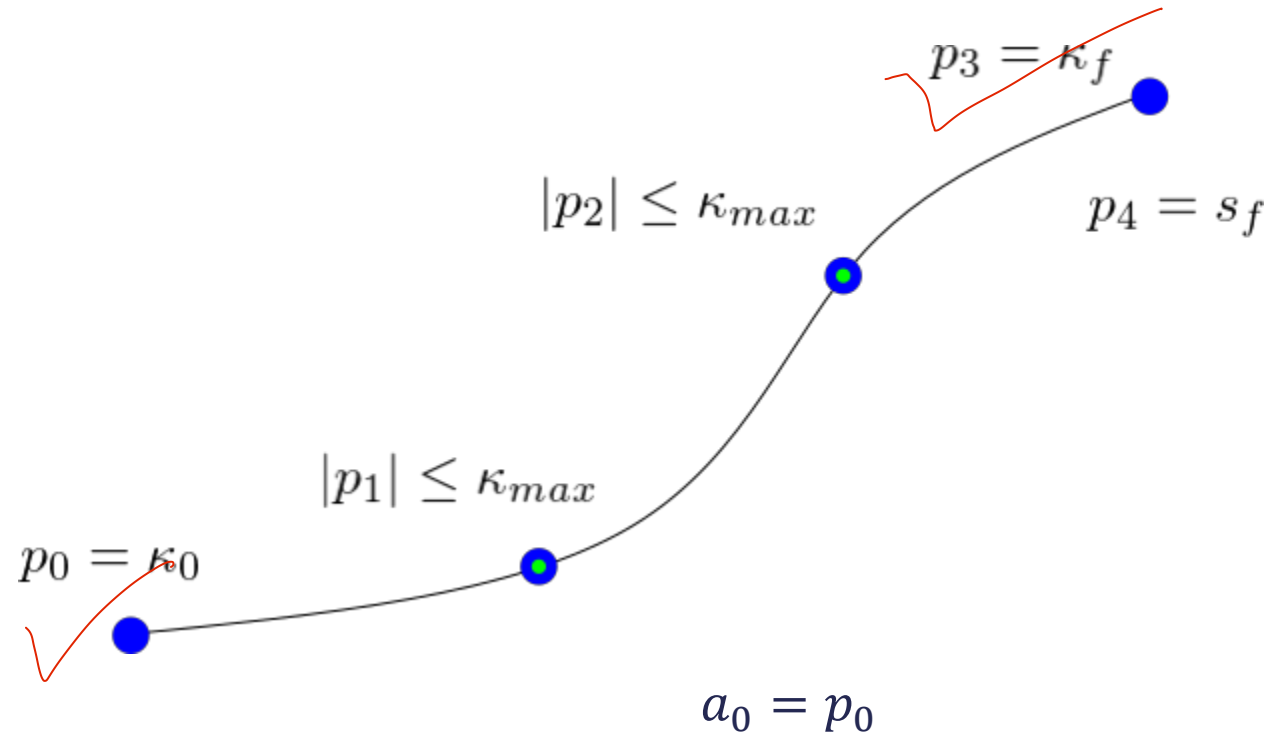
- Challenging for optimizer to satisfy constraints exactly
- Can soften equality constraints by penalizing deviation heavily in the objective function
- We also assume initial curvature is known, which corresponds to  $a_0$

$$\min f_{be}(\underbrace{a_0}_{\substack{|| \\ 0}}, a_1, a_2, a_3, s_f) + \underbrace{\alpha(x_s(s_f) - x_f)}_{\text{at least an order of magnitude larger}} + \underbrace{\beta(y_s(s_f) - y_f)}_{\text{at least an order of magnitude larger}} + \underbrace{\gamma(\theta_s(s_f) - \theta_f)}_{\text{at least an order of magnitude larger}}$$

$$\text{s. t.} \begin{cases} \left| \kappa\left(\frac{s_f}{3}\right) \right| \leq \kappa_{max} \\ \left| \kappa\left(\frac{2s_f}{3}\right) \right| \leq \kappa_{max} \\ \kappa(s_f) = \kappa_f \end{cases}$$

# Parameter Remapping

- Can remap spiral parameters
- $p_0$  to  $p_3$  corresponds to curvature at 4 points equally spaced along path
- $p_4$  corresponds to the arc length of the spiral
- Since initial and final curvature are known,  $p_0$  and  $p_3$  eliminated from optimization, reducing dimensionality



$$a_1 = -\frac{11p_0/2 - 9p_1 + 9p_2/2 - p_3}{p_4}$$

$$a_2 = \frac{9p_0 - 45p_1/2 + 18p_2 - 9p_3/2}{p_4^2}$$

$$a_3 = -\frac{9p_0/2 - 27p_1/2 + 27p_2/2 - 9p_3/2}{p_4^3}$$

# Final Optimization Problem

- Replacing spiral parameters with new parameters leads to new optimization formulation
- Curvature constraints correspond directly to new parameters
- Boundary conditions handled by soft constraints and constant  $p_0$  and  $p_3$

$$\min f_{be}(a_0, a_1, a_2, a_3, s_f) + \alpha(x_S(p_4) - x_f) + \beta(y_S(p_4) - y_f) + \gamma(\theta_S(p_4) - \theta_f)$$

$$\text{s. t.} \begin{cases} |p_1| \leq \kappa_{max} \\ |p_2| \leq \kappa_{max} \end{cases}$$

# Summary

- Reviewed boundary conditions on state and curvature constraints
- Introduced Simpson's rule to compute spiral end position
- Devised optimization problem using bending energy
- Developed method to re-map parameters to improve optimization convergence speed