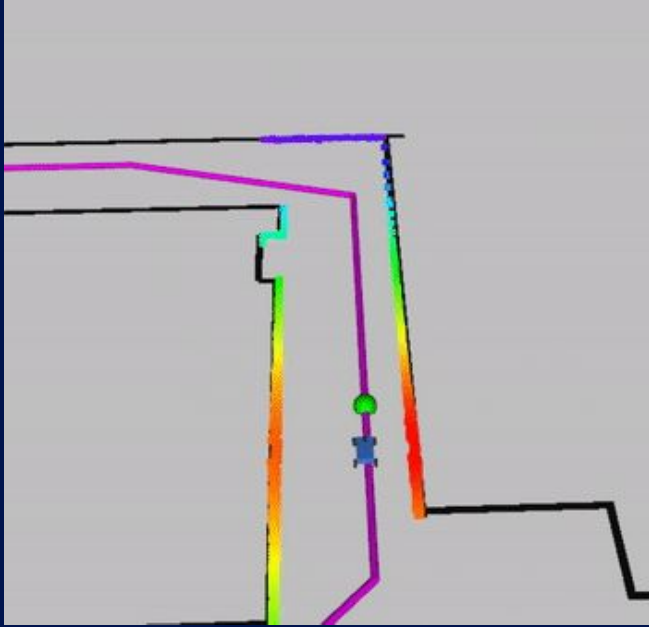
F1TENTH Autonomous Racing

Motion Planning

Pure Pursuit



Rahul Mangharam
University of Pennsylvania
rahulm@seas.upenn.edu

Hongrui Zheng
University of Pennsylvania
hongruiz@seas.upenn.edu

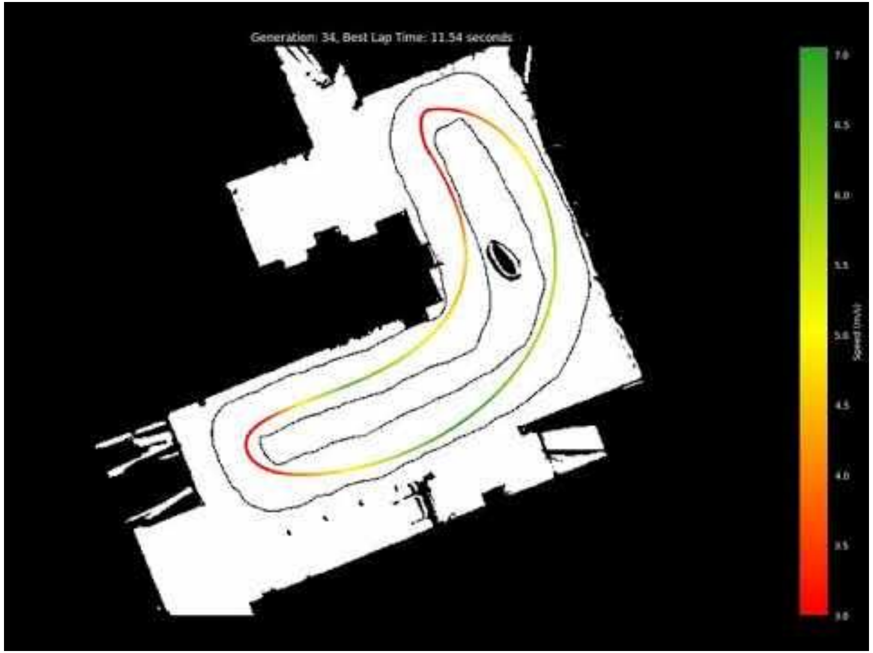
F1 TENTH

Safe Autonomy Lab
University of Pennsylvania

Penn Engineering

The story so far:

Given a map made with SLAM and the ability to Localize with Particle Filters

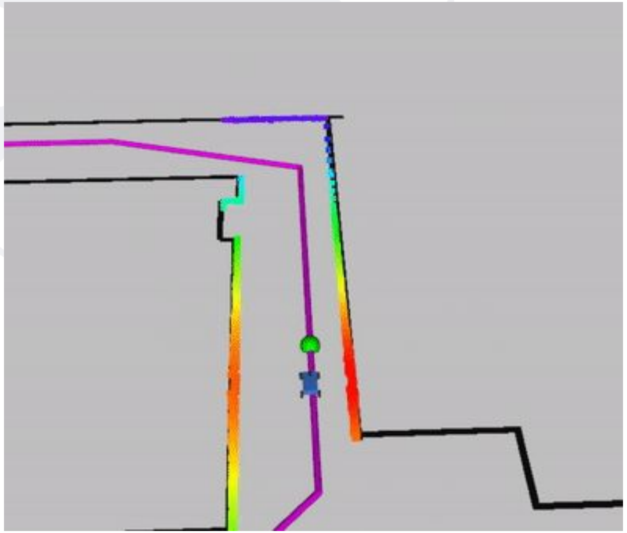


We want to specify a raceline for the vehicle to track and race *really fast!*

1x
EXIT

Lesson Plan

- Autonomous Vehicle planning and control stack
- Pure pursuit tracking algorithm
  - By the end of this lecture …



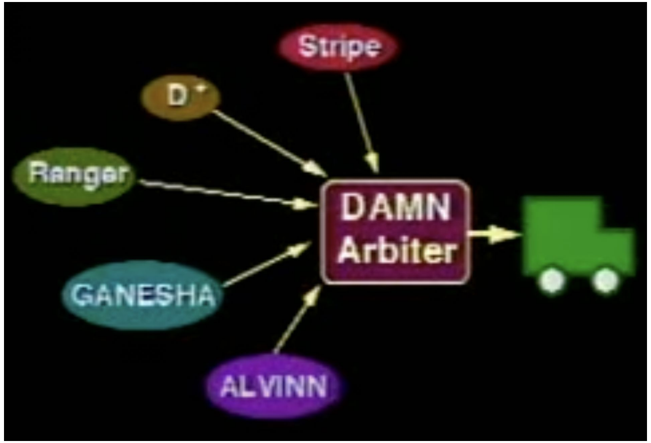
Reading Assignment

Implementation of the Pure Pursuit Path Tracking Algorithm:

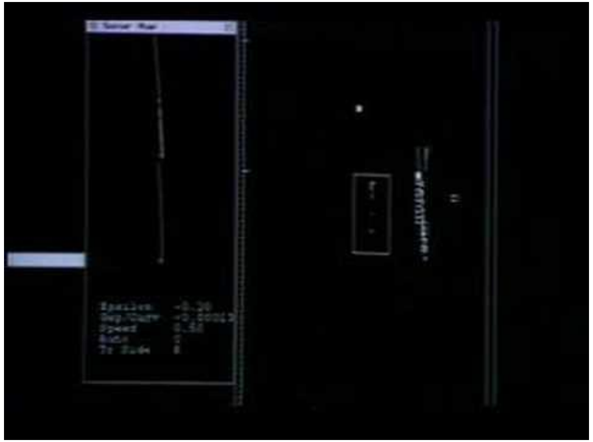
https://www.ri.cmu.edu/pub_files/pub3/coulter_r_craig_1992_1/coulter_r_craig_1992_1.pdf

Terragator - 1984 CMU Robotics

Late 1980's AV pipeline: D* mission planner, GANESHA map server, Stripe local tracker

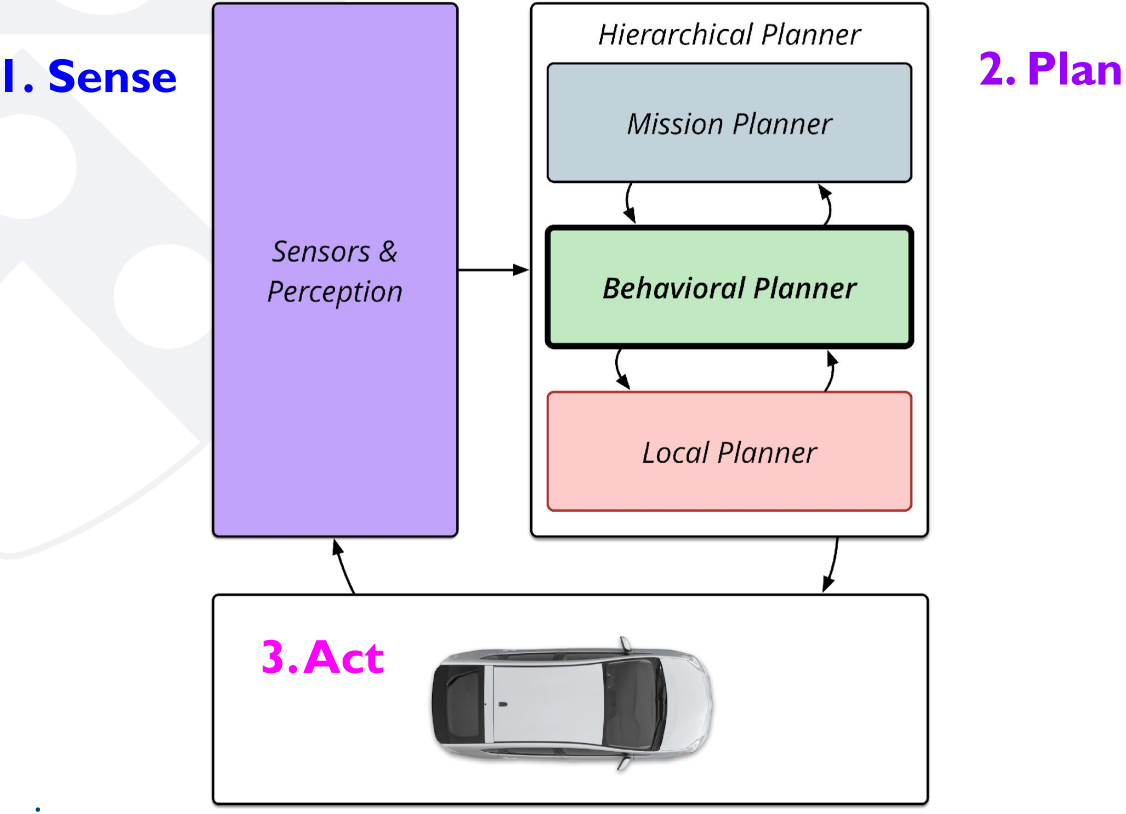


The first uses of Pure Pursuit



Planning and Control stack

Autonomous Vehicles: Perception, Planning & Control Stack



1. Sense

Sensors & Perception

Hierarchical Planner

Mission Planner

Behavioral Planner

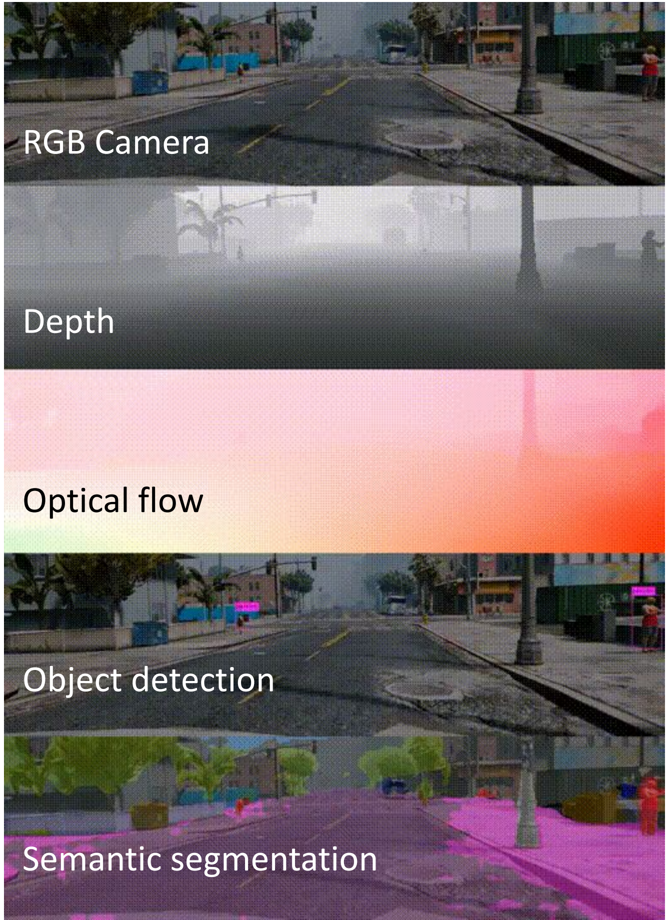
Local Planner

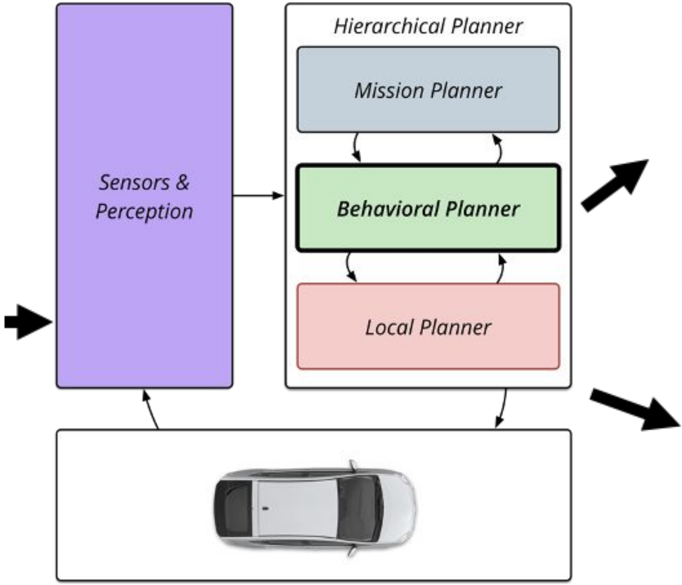
2. Plan

3. Act

AV Perception, Planning, Control pipeline

Sense





Sensors & Perception

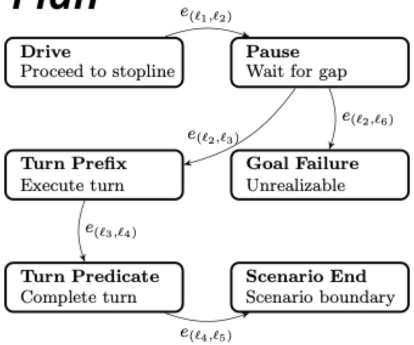
Hierarchical Planner

Mission Planner

Behavioral Planner

Local Planner

Plan



Drive Proceed to stopline

Pause Wait for gap

Turn Prefix Execute turn

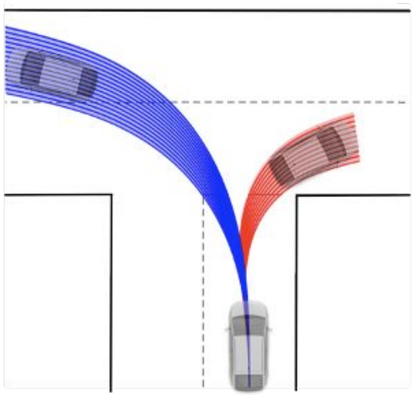
Goal Failure Unrealizable

Turn Predicate Complete turn

Scenario End Scenario boundary

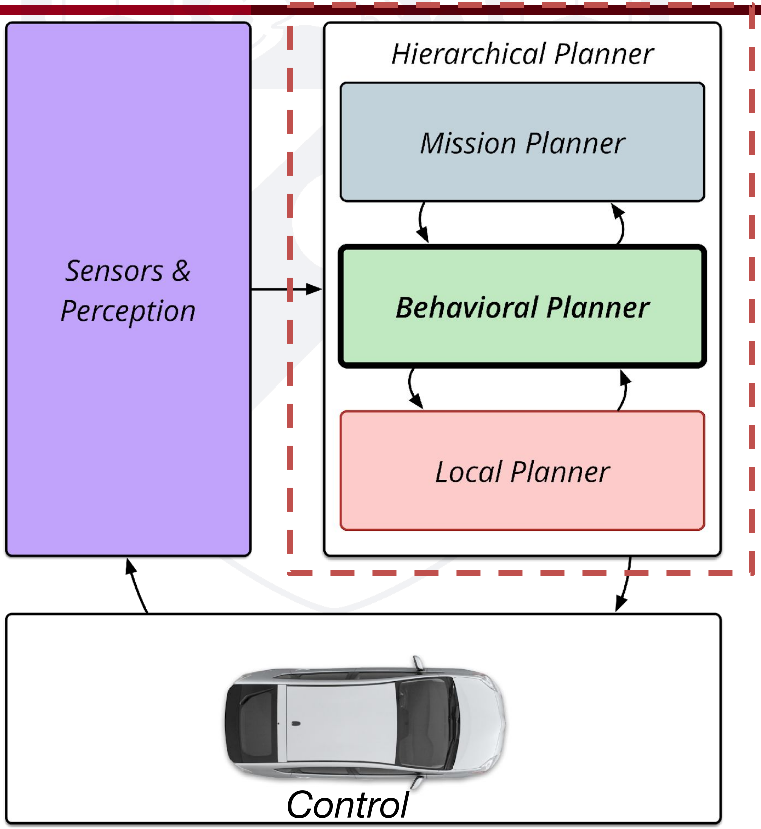
$e_{(\ell_1,\ell_2)}$ $e_{(\ell_2,\ell_6)}$ $e_{(\ell_2,\ell_3)}$ $e_{(\ell_3,\ell_4)}$ $e_{(\ell_4,\ell_5)}$

Act

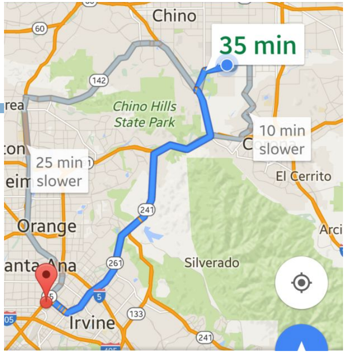


Everything combined:
a function that *generates* a sequence of ***steering*** and ***acceleration*** inputs…

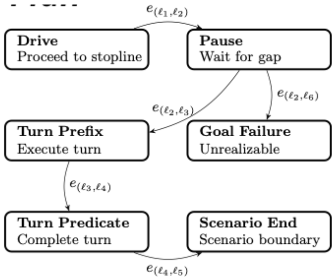
The Planning module



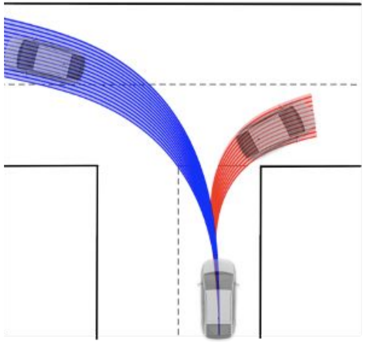
Mission Planner:
What is the overall goal of the vehicle?



Behavioral Planner:
What rules should the vehicle follow in different situations?



Local Planner:
What is the optimal trajectory from position to a goal?

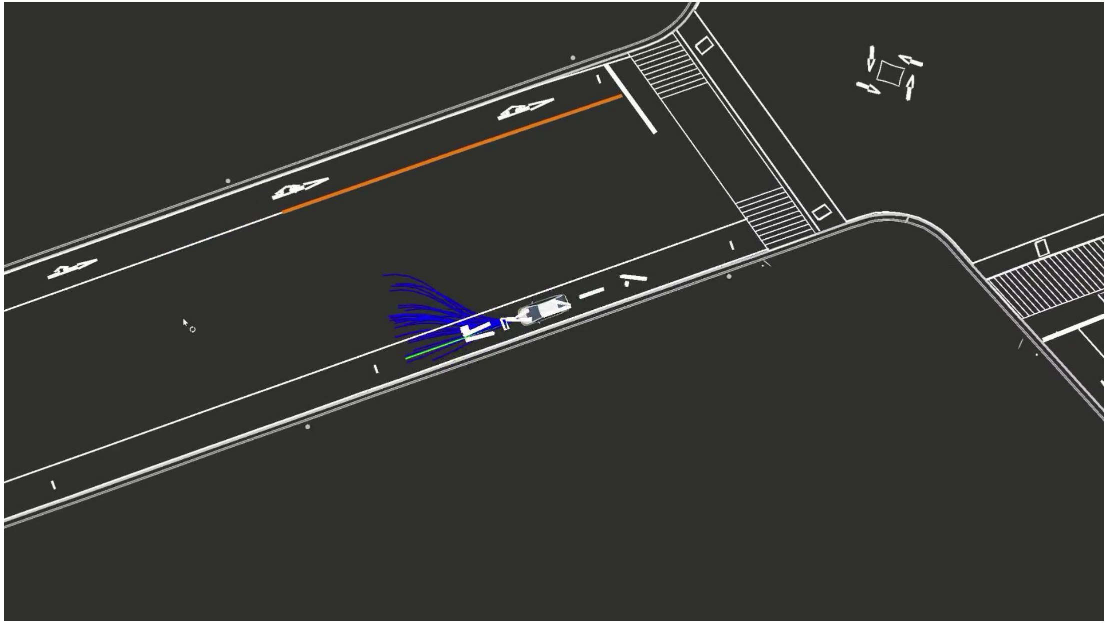


The Planning module

Mission Planner:
What is the overall goal of the vehicle?

Behavioral Planner:
What rules should the vehicle follow in different situations?

Local Planner:
What is the optimal trajectory from position to a goal?

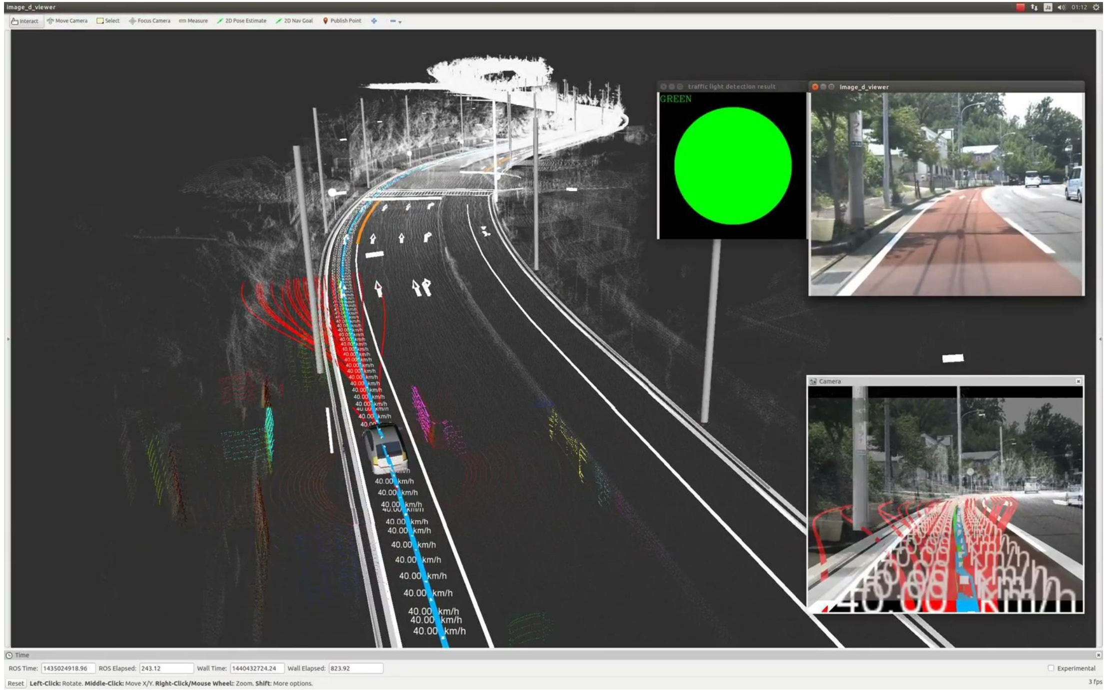


The Planning module

Mission Planner:
What is the overall goal of the vehicle?

Behavioral Planner:
What rules should the vehicle follow in different situations?

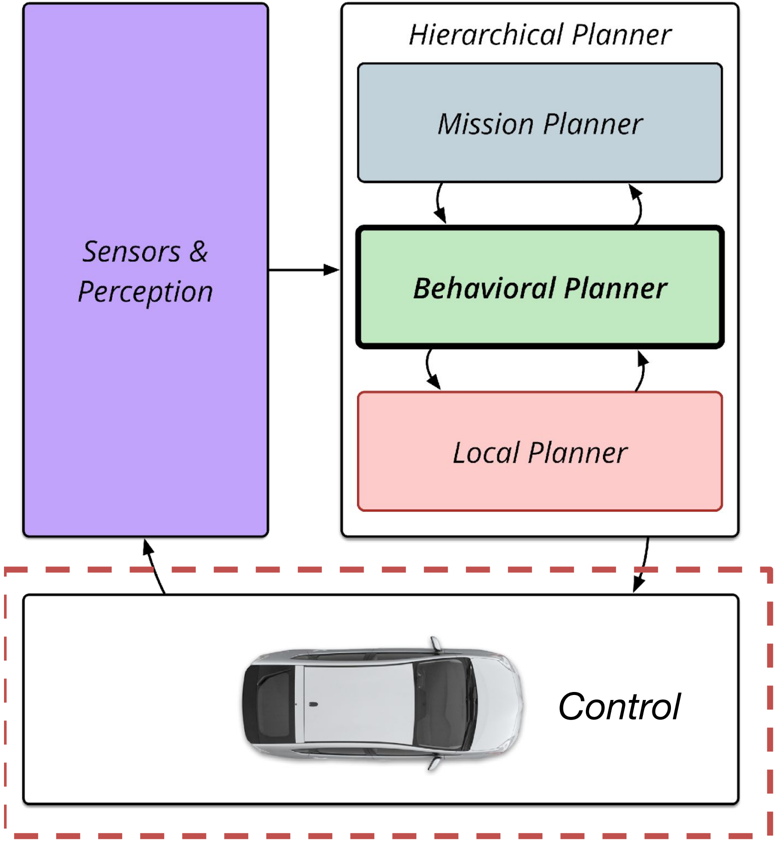
Local Planner:
What is the optimal trajectory from position to a goal?



ROS Time: 1435024918.96 ROS Elapsed: 243.12 Wall Time: 1440432724.24 Wall Elapsed: 823.92

Left-Click: Rotate. **Middle-Click:** Move X/Y. **Right-Click/Mouse Wheel:**: Zoom. **Shift**: More options.

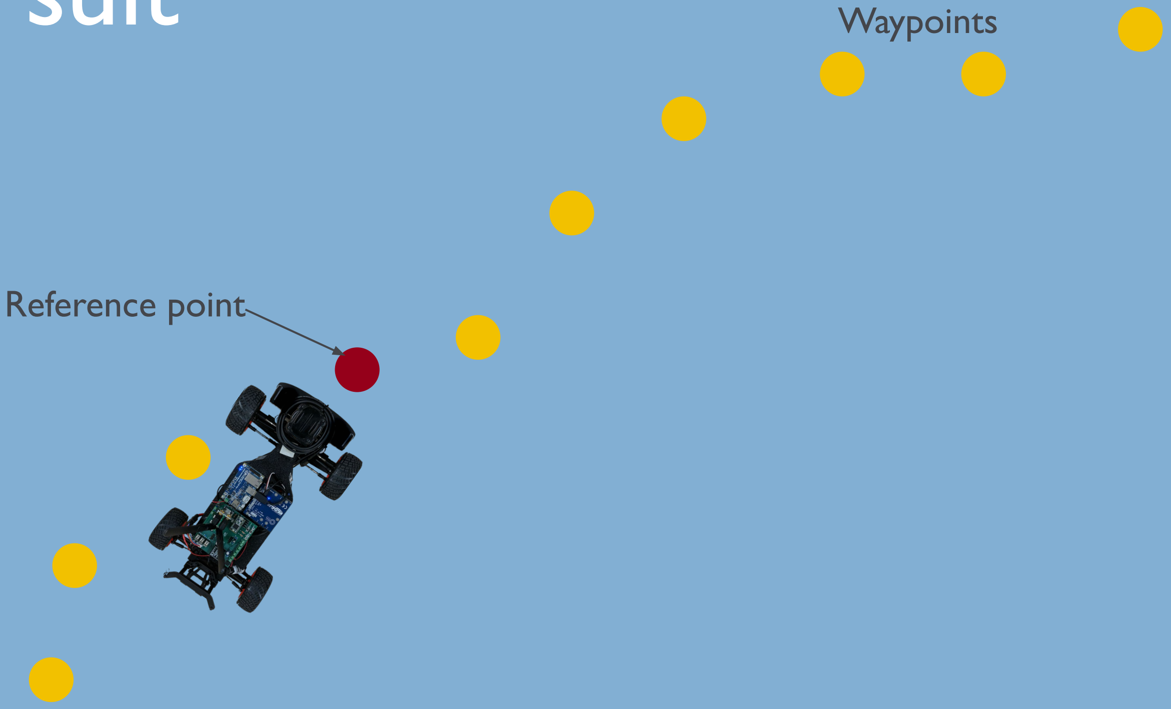
The Control module



- How do we track a given trajectory?
- How do we correct for actuation errors?
- How do we drive as fast as possible?

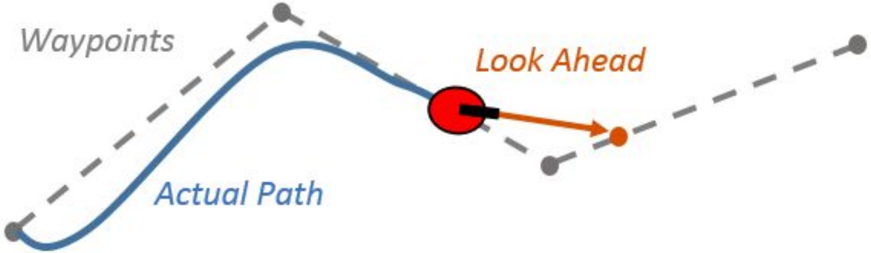
This is the focus of today's lecture!

Pure Pursuit

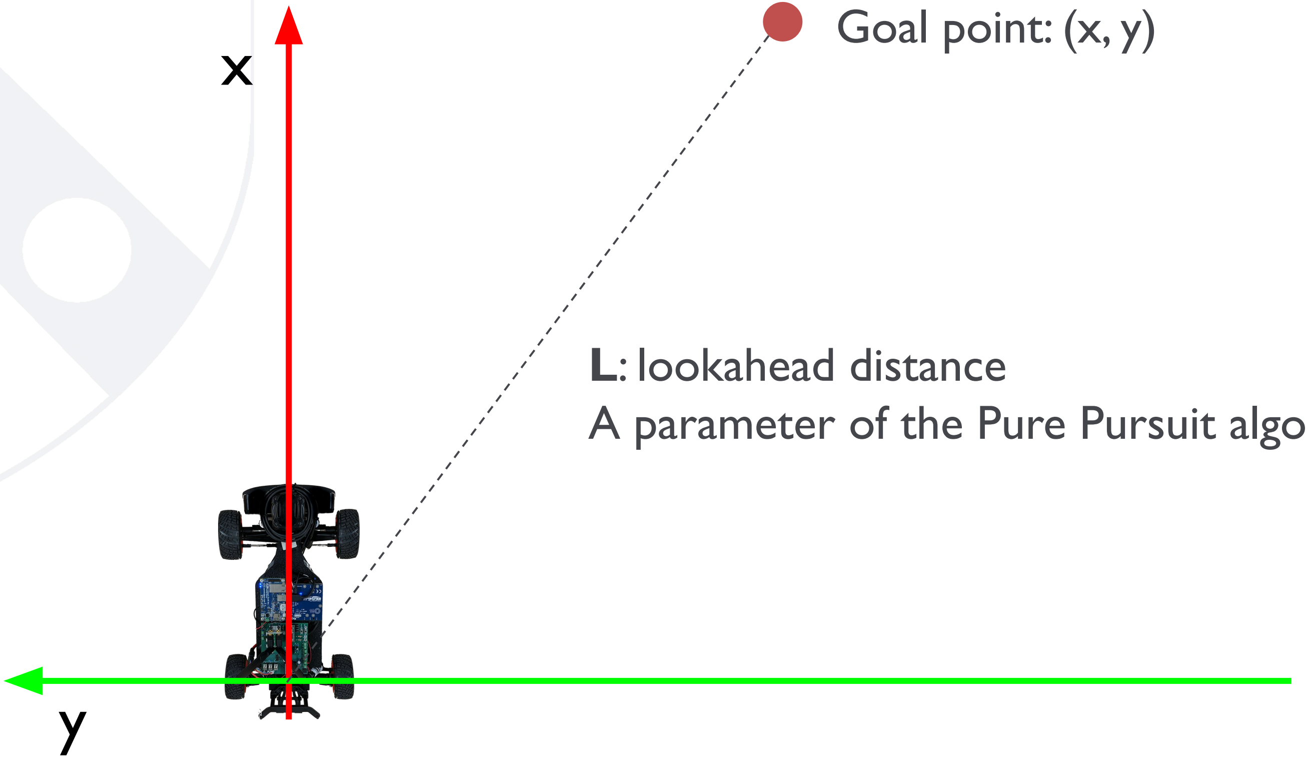


Assumptions

- Vehicle is given a sequence of 2D positions, *i.e. waypoints,* to follow
- Vehicle knows where the given waypoints are in the vehicle's frame of reference
  - Underlying assumptions that the vehicle can localize itself
- Goal is to follow these waypoints



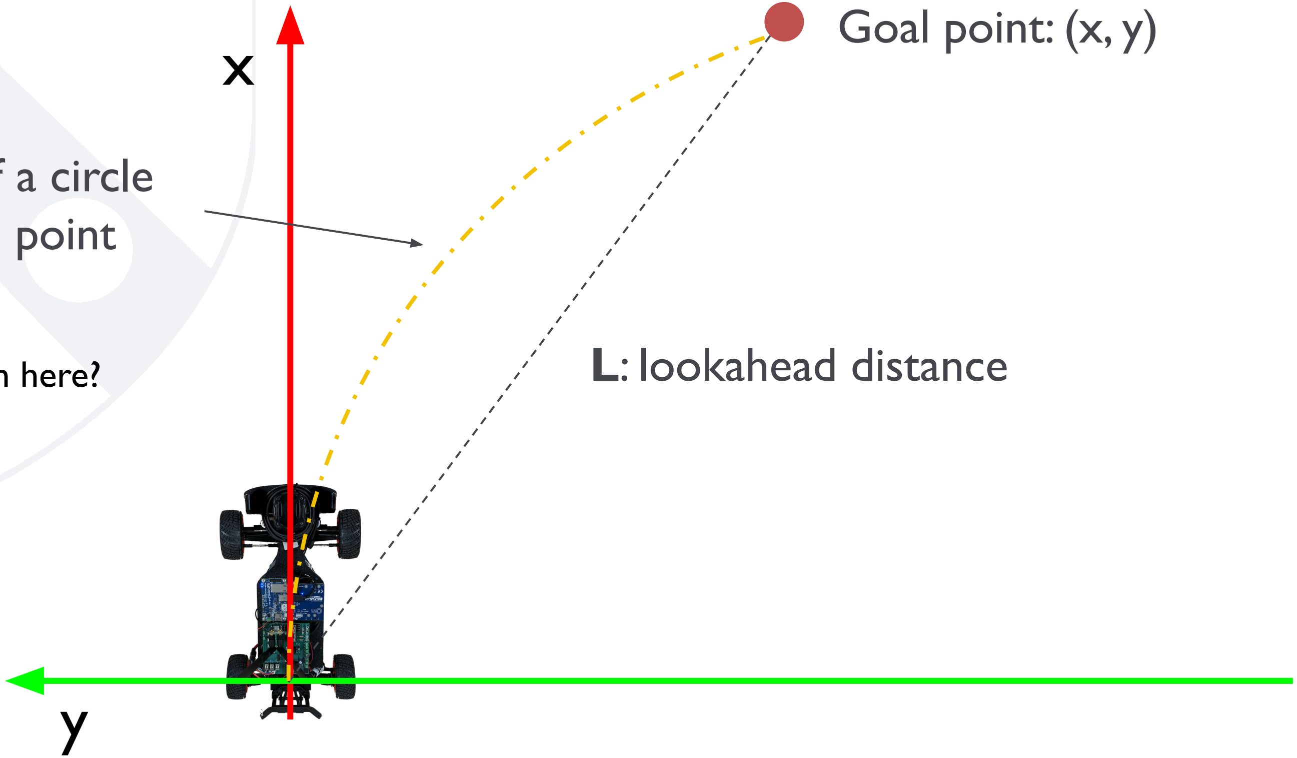
Geometric Interpretation



Goal point: (x, y)

L: lookahead distance
A parameter of the Pure Pursuit algorithm

Geometric Interpretation



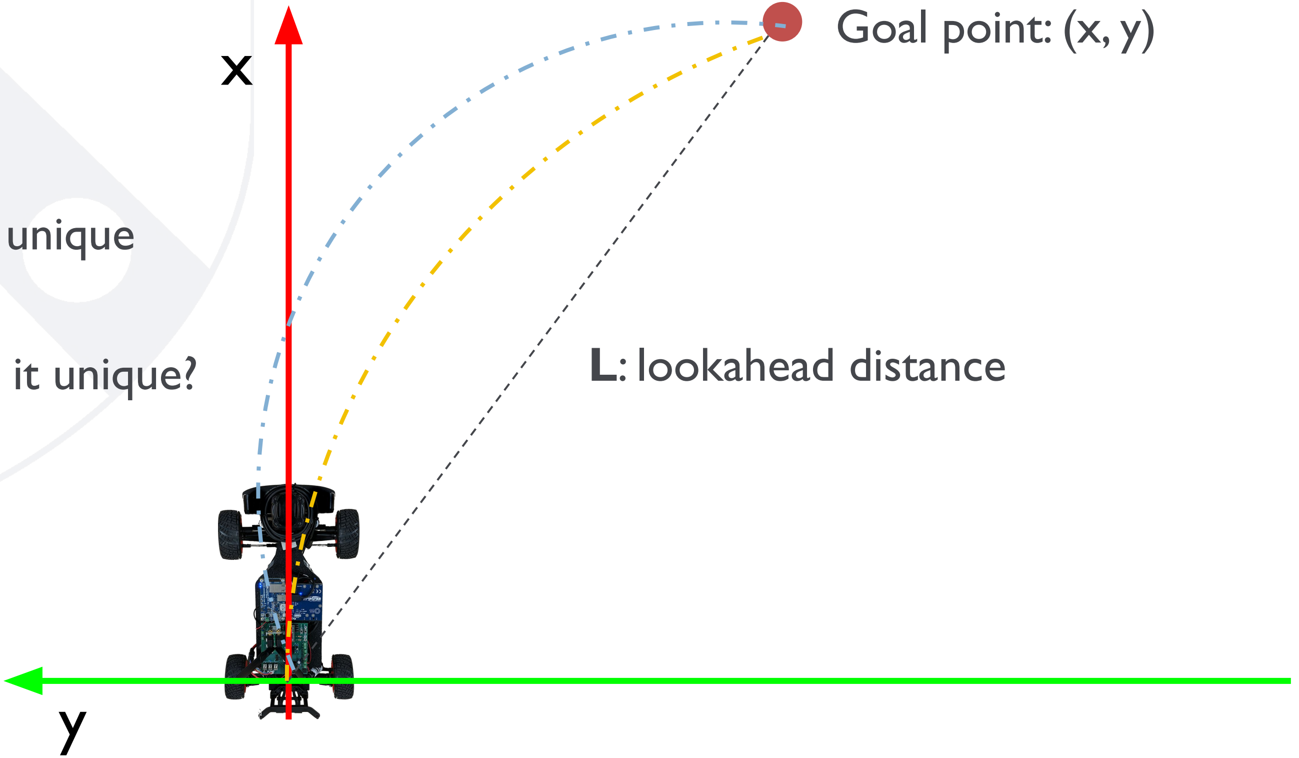
Follow the arc of a circle to reach the goal point

Do you see a problem here?

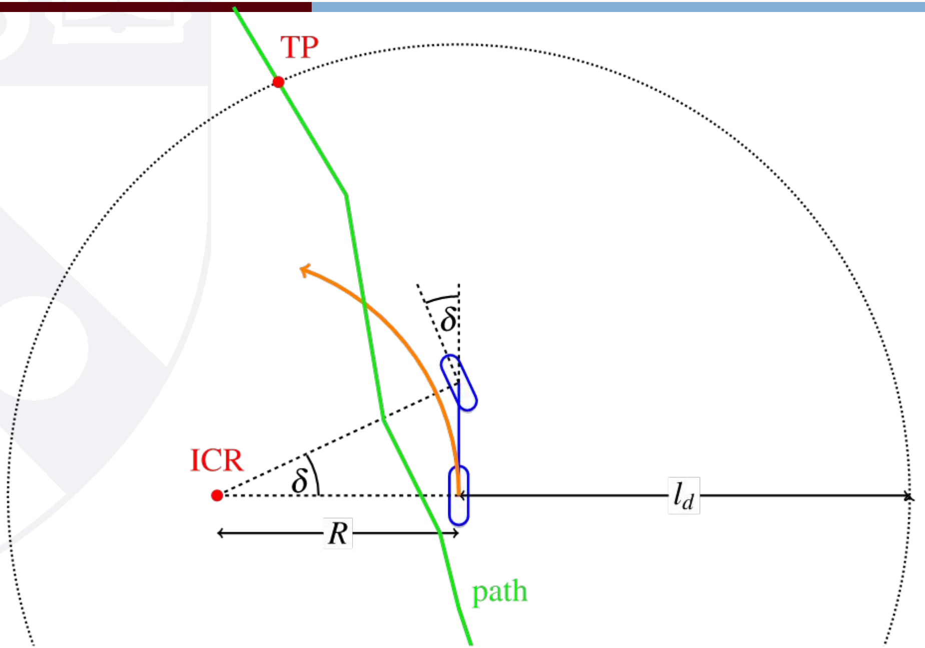
Geometric Interpretation

But the arc is not unique

How do we make it unique?



Finding the right arc to the next waypoint

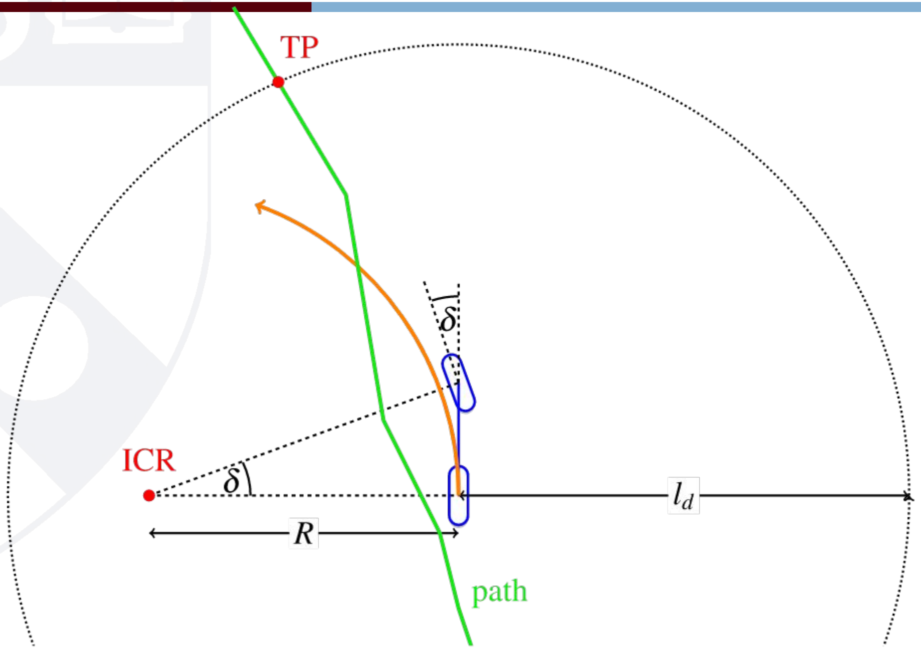


$\delta = 25°$

Penn Engineering

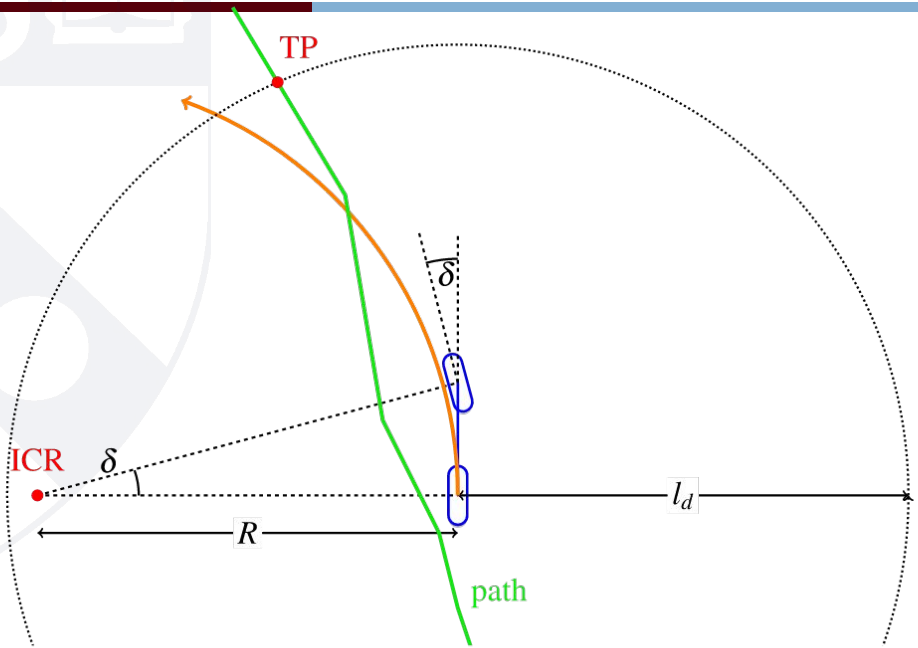
Image credit: https://github.com/thomasfermi/Algorithms-for-Automated-Driving

Finding the right arc to the next waypoint



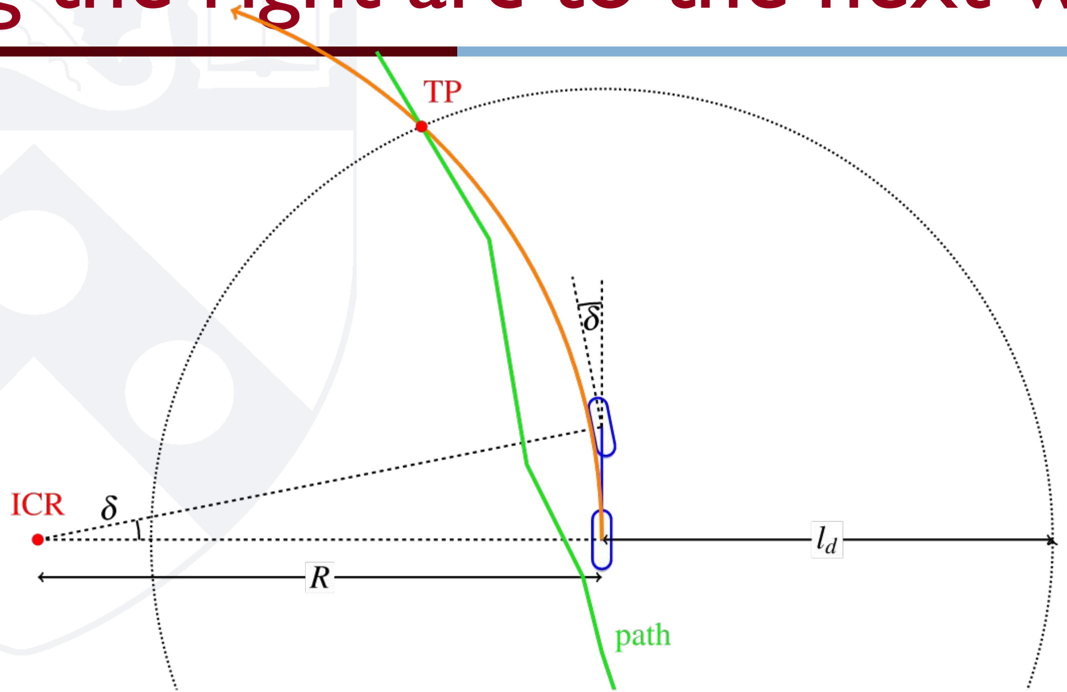
δ = 20°

Finding the right arc to the next waypoint



$\delta = 15°$

Finding the right arc to the next waypoint

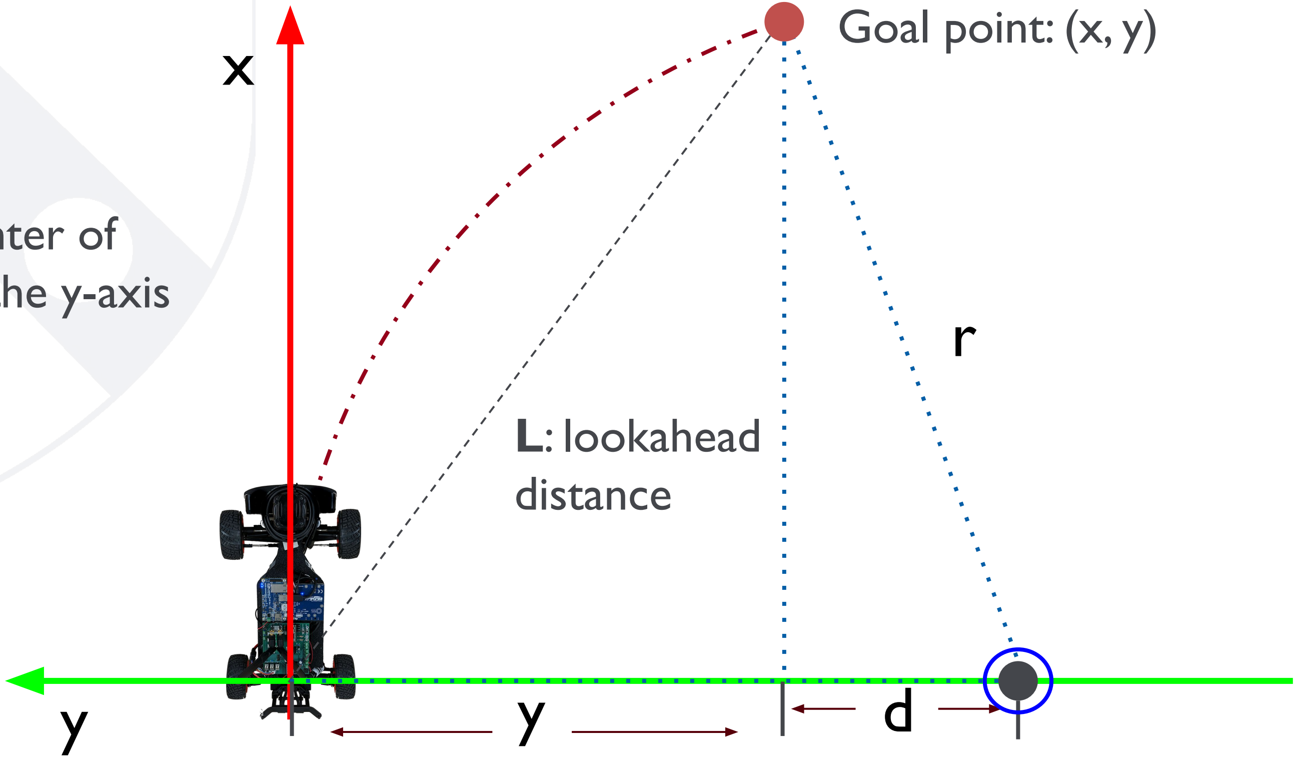


δ = 11.3°

The distance from ICR to TP is equal to *R*, since TP lies on the orange circle of radius *R* around ICR.

Geometric Interpretation

Constrain the center of the arc to be on the y-axis



Some simple math

$$r = |y| + d$$

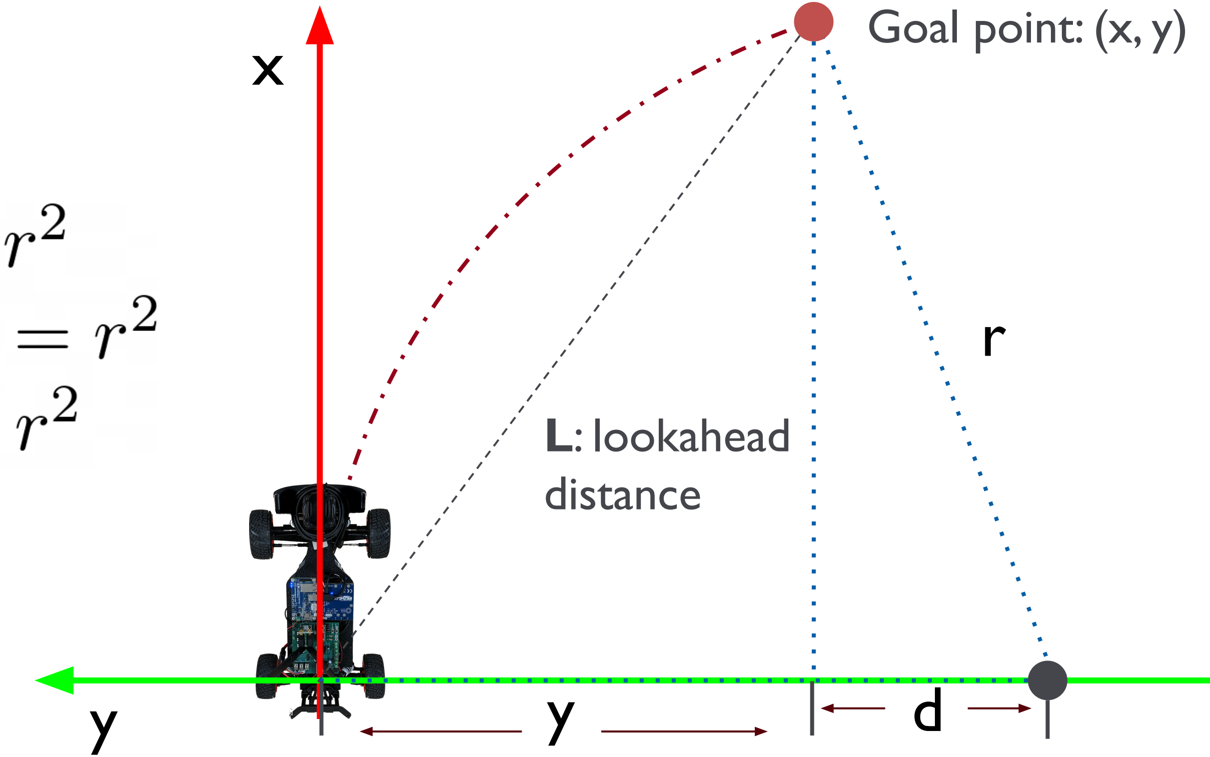
$$d^2 + x^2 = r^2$$

$$(r - |y|)^2 + x^2 = r^2$$

$$r^2 + y^2 - 2r|y| + x^2 = r^2$$

$$r^2 + L^2 - 2r|y| = r^2$$

$$r = \frac{L^2}{2|y|}$$



How do we get steering angle?

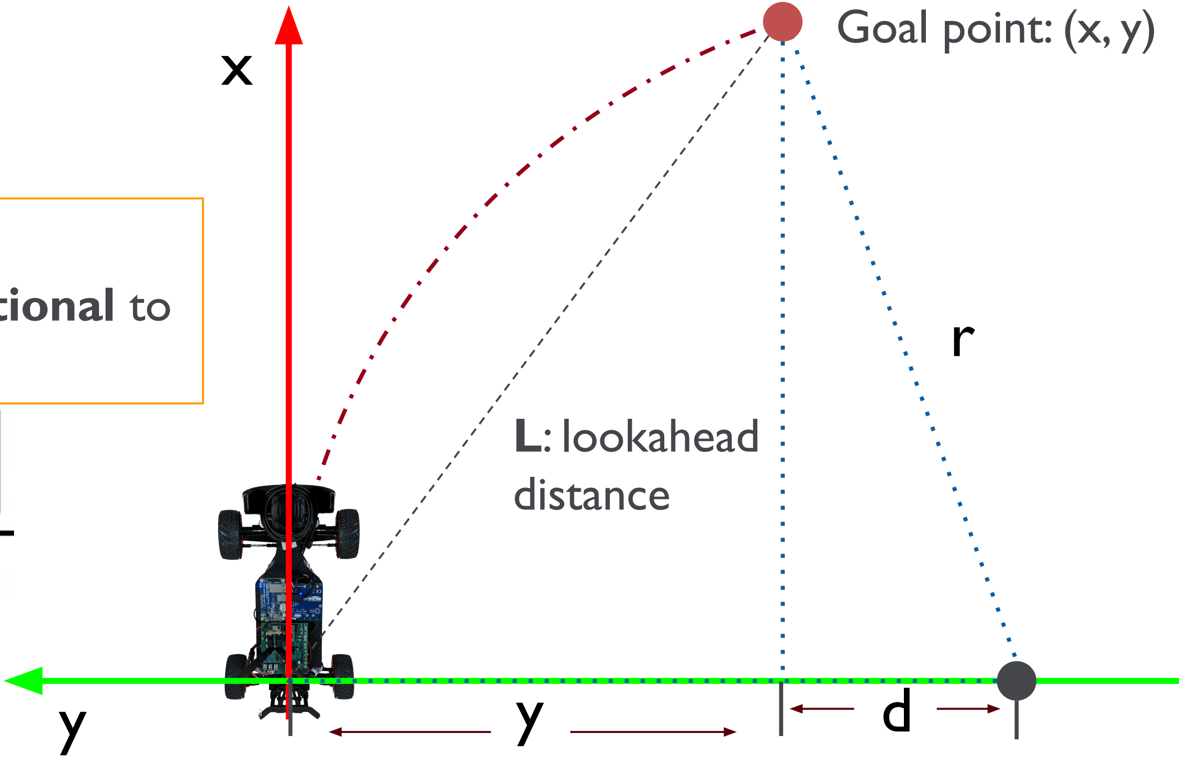
$$r = \frac{L^2}{2|y|}$$

Curvature is the inverse of radius
Steering angle should be **proportional** to the curvature of the arc

$$\gamma = \frac{1}{r} = \frac{2|y|}{L^2}$$

Looks familiar?

P control

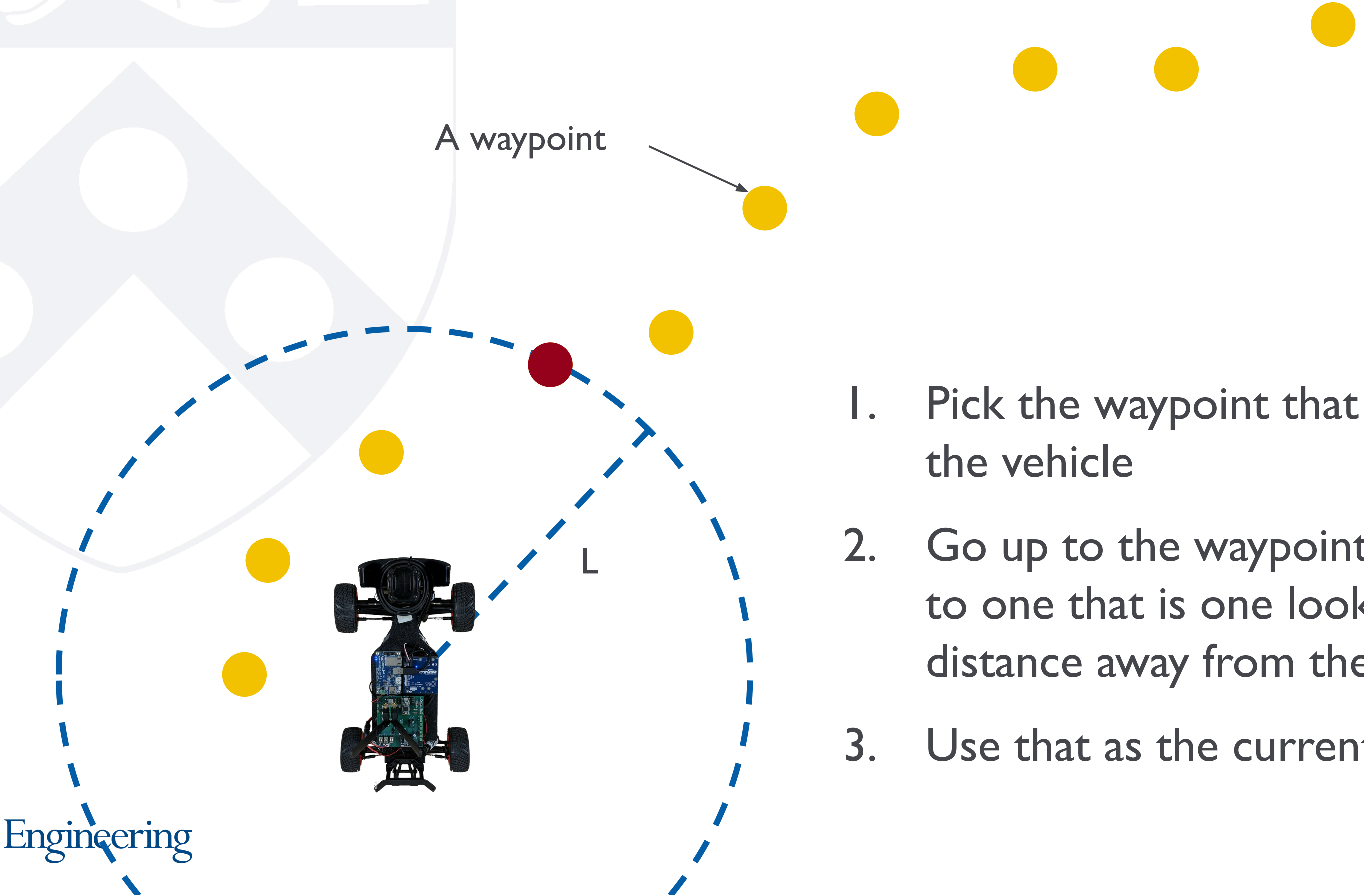


Penn Engineering

Picking a goal point

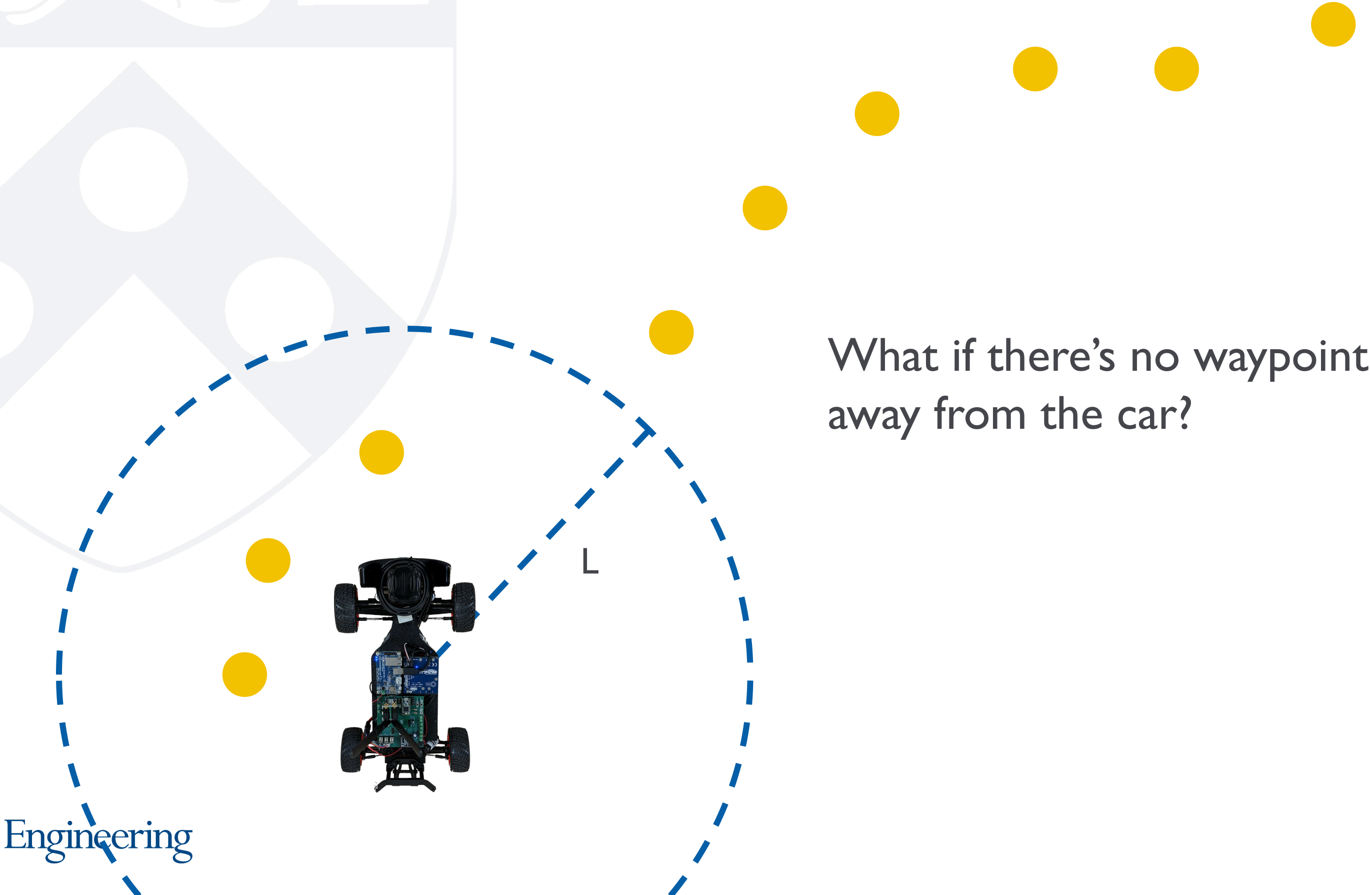
Now that we know how to find the arc to a given waypoint, how to we pick a current waypoint from a list of waypoints?

Picking a goal point



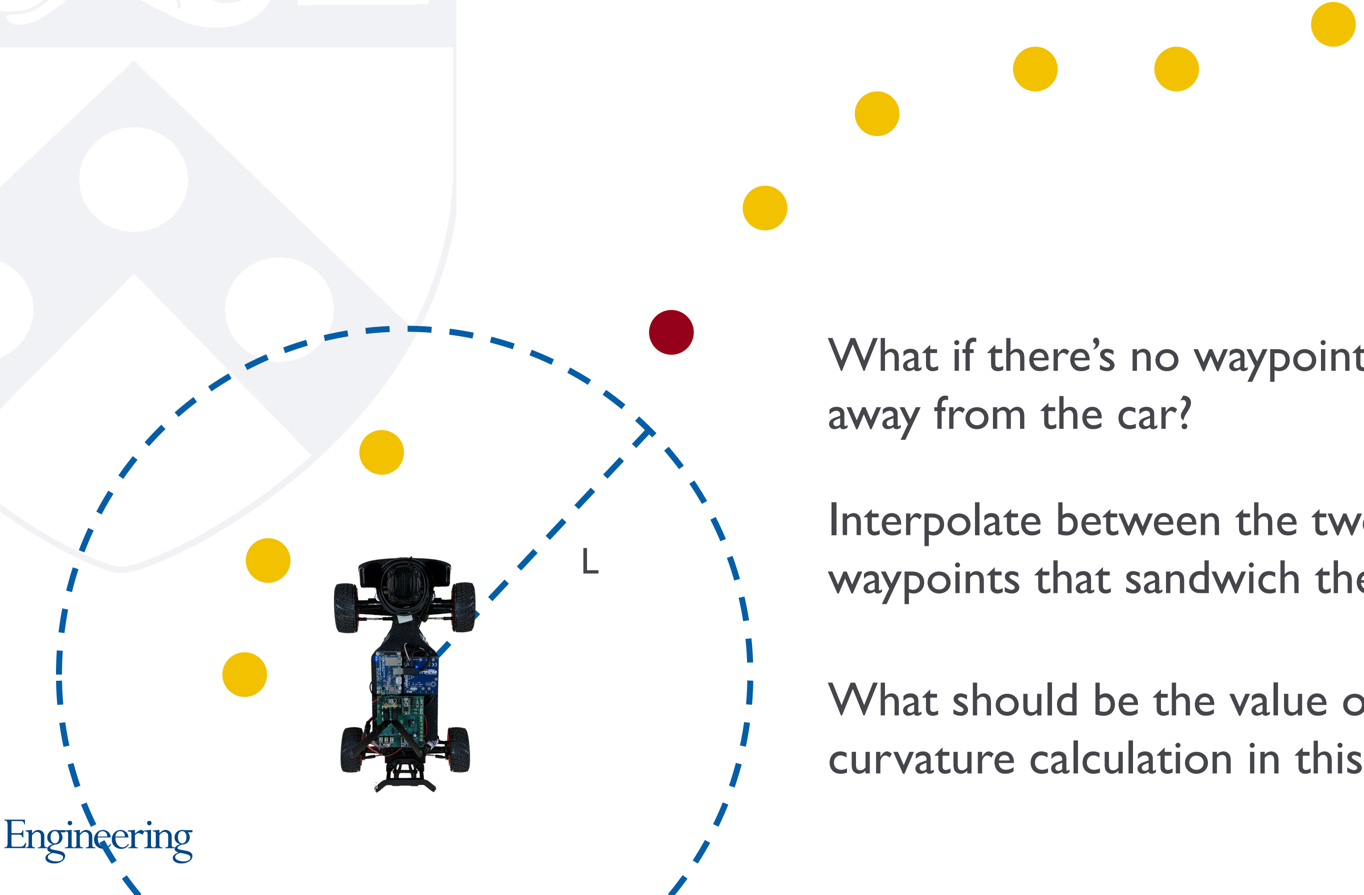
1. Pick the waypoint that is closest to the vehicle
2. Go up to the waypoint until you get to one that is one lookahead distance away from the car
3. Use that as the current waypoint

Picking a goal point



What if there's no waypoints exactly L away from the car?

Picking a goal point

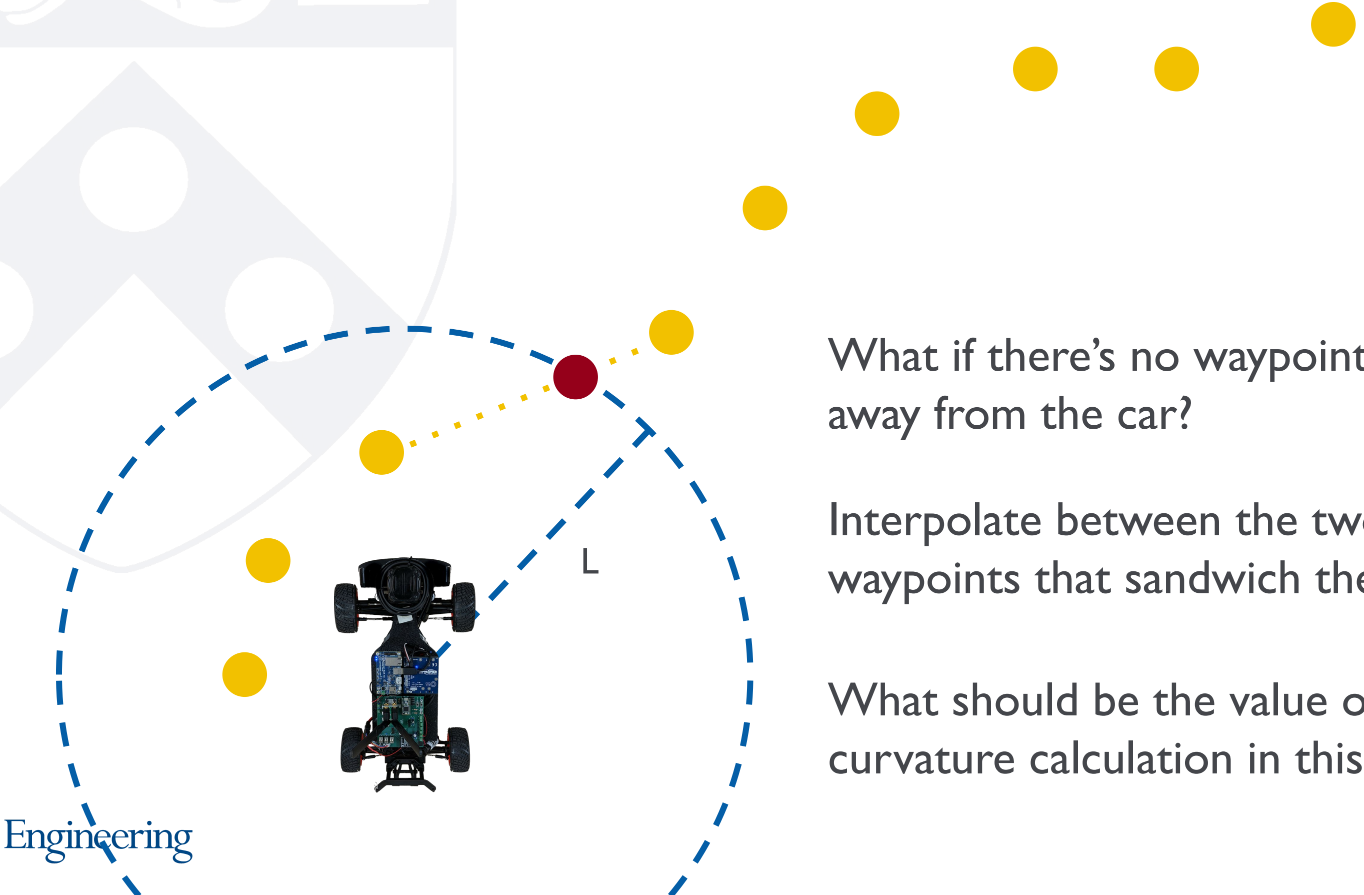


What if there's no waypoints exactly L away from the car?

Interpolate between the two waypoints that sandwich the distance L

What should be the value of L in your curvature calculation in this case?

Picking a goal point

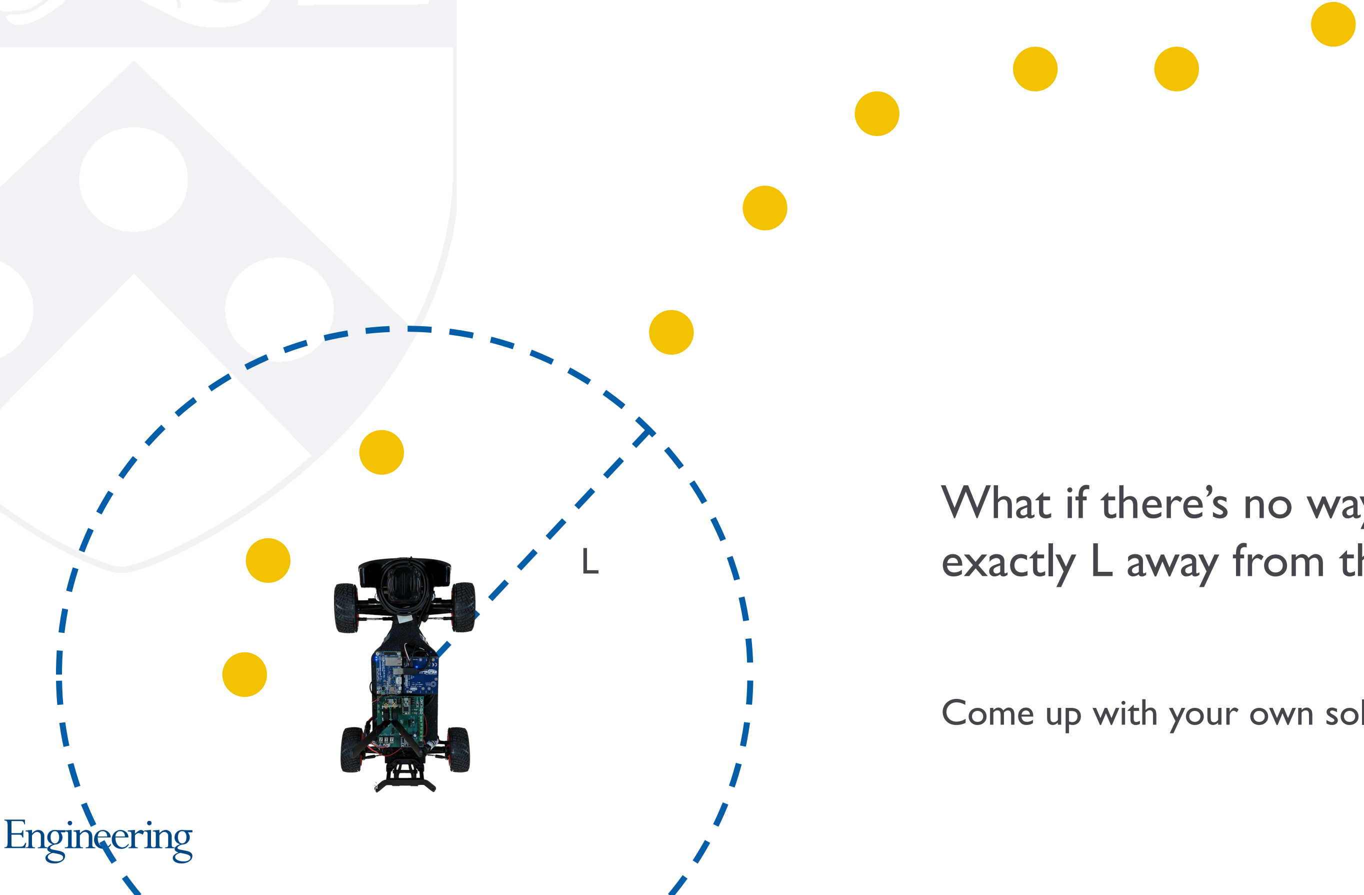


What if there's no waypoints exactly L away from the car?

Interpolate between the two waypoints that sandwich the distance L

What should be the value of L in your curvature calculation in this case?

Picking a goal point



What if there's no waypoints exactly L away from the car?

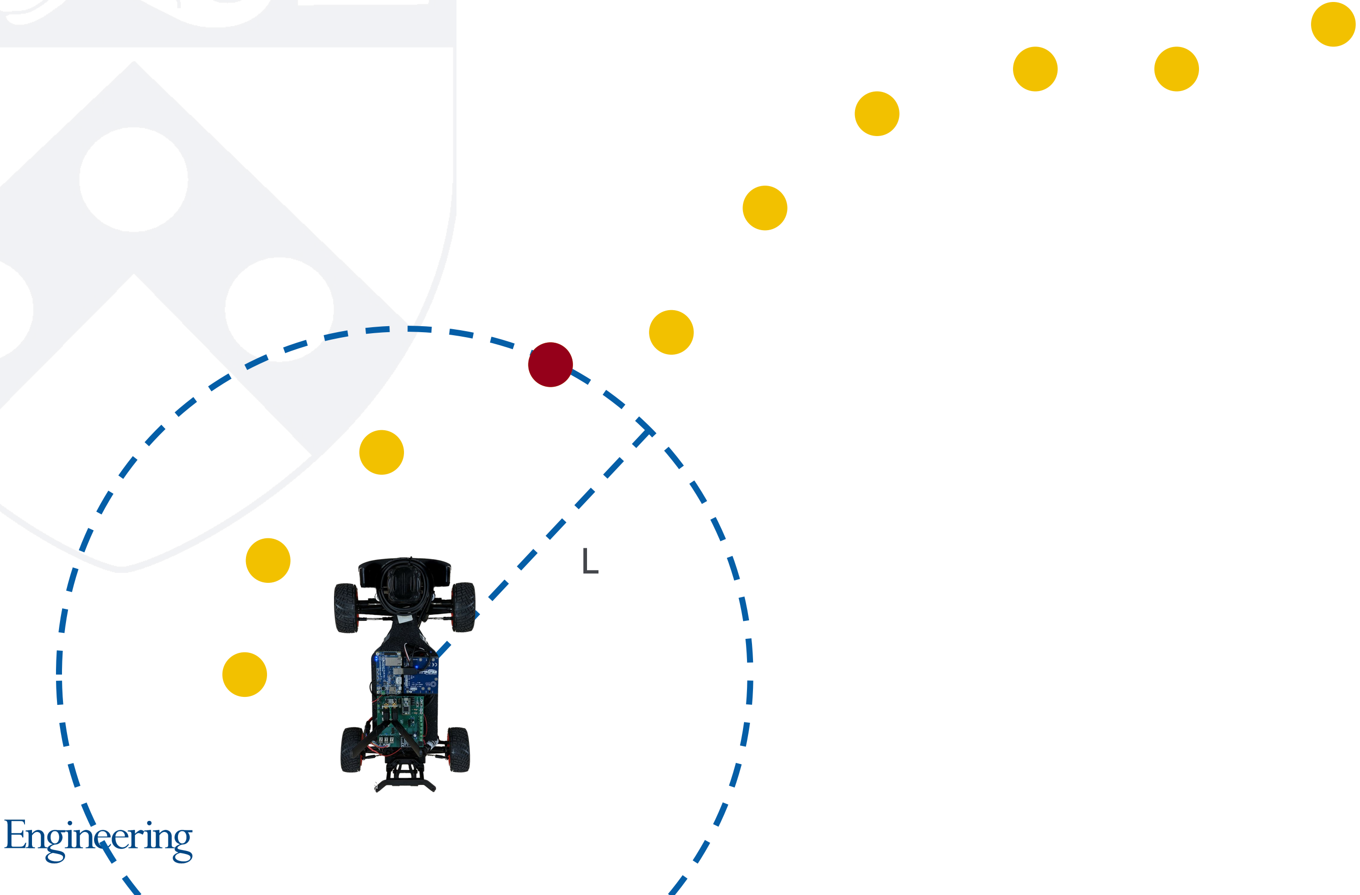
Come up with your own solution!

Updating the goal point (one way to do it)

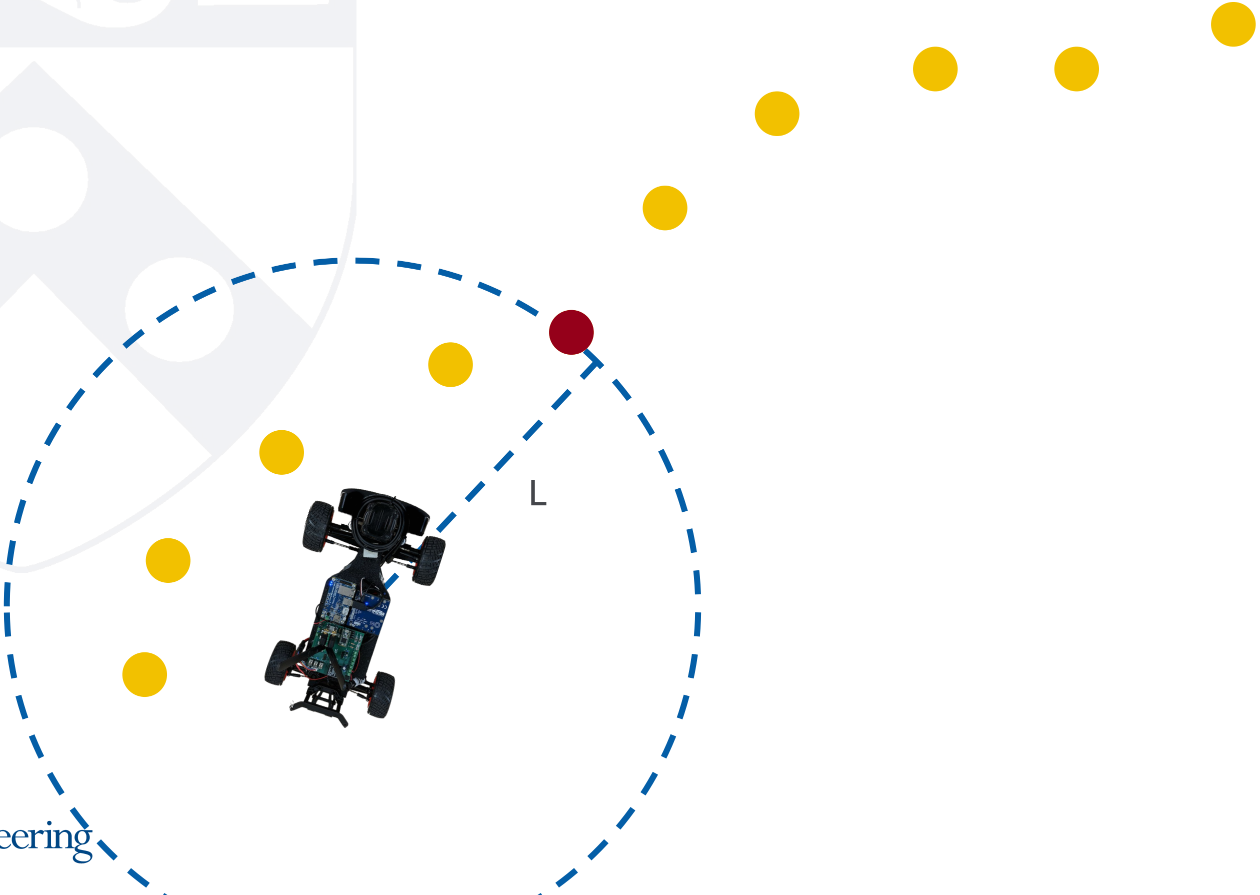
Each time we have a new pose of the car, we could:

1. Find the current waypoint
2. Actuate towards that waypoint with calculated steering angle
3. Localize to find the new pose, repeat

Updating the goal point

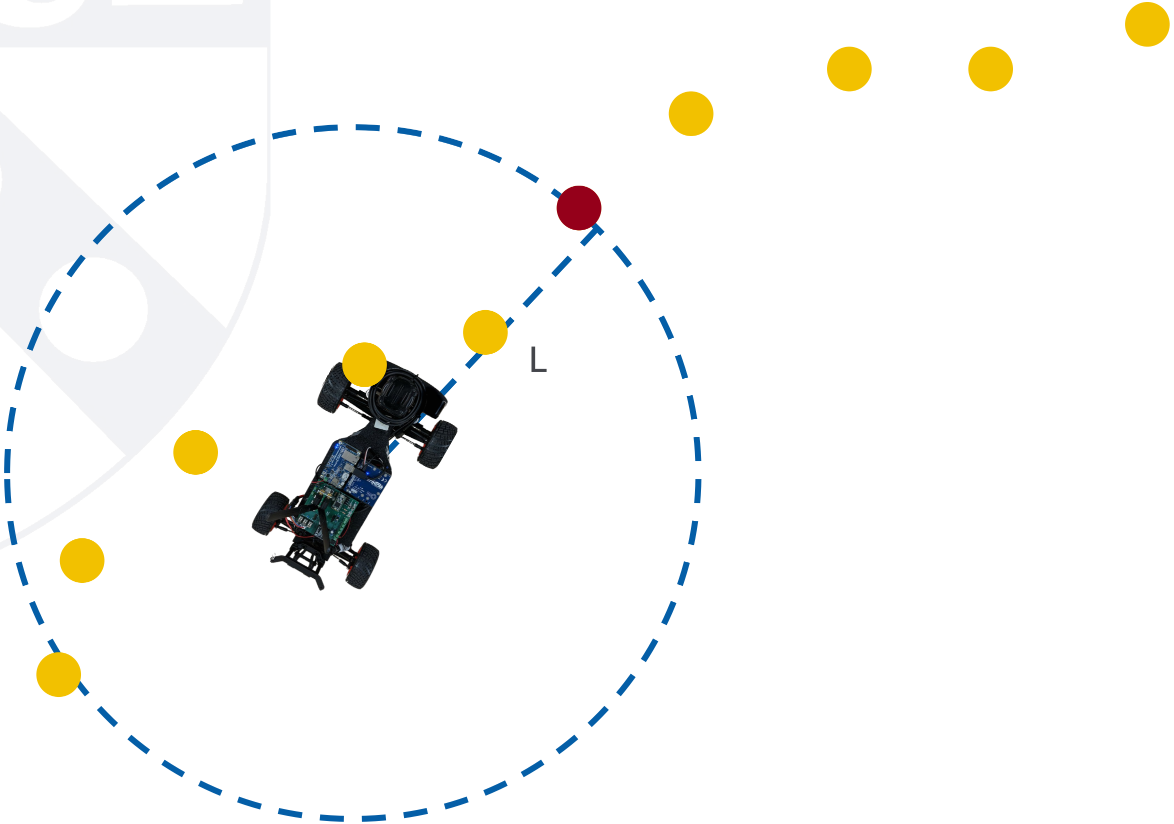


Updating the goal point

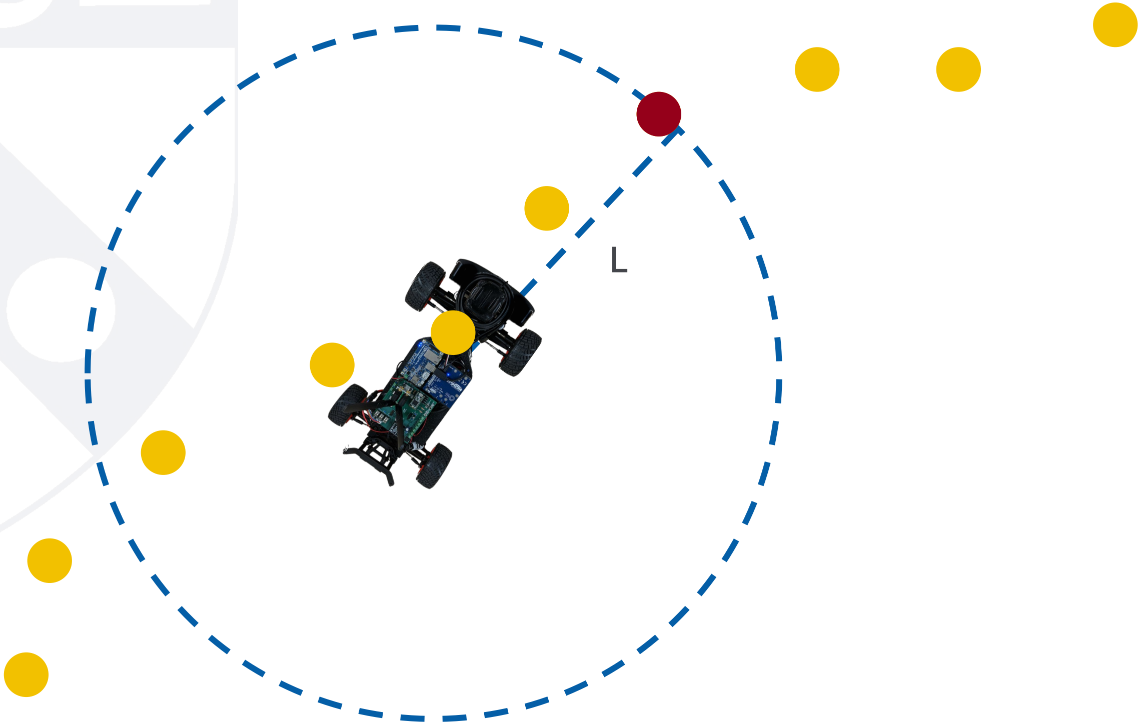


Penn Engineering

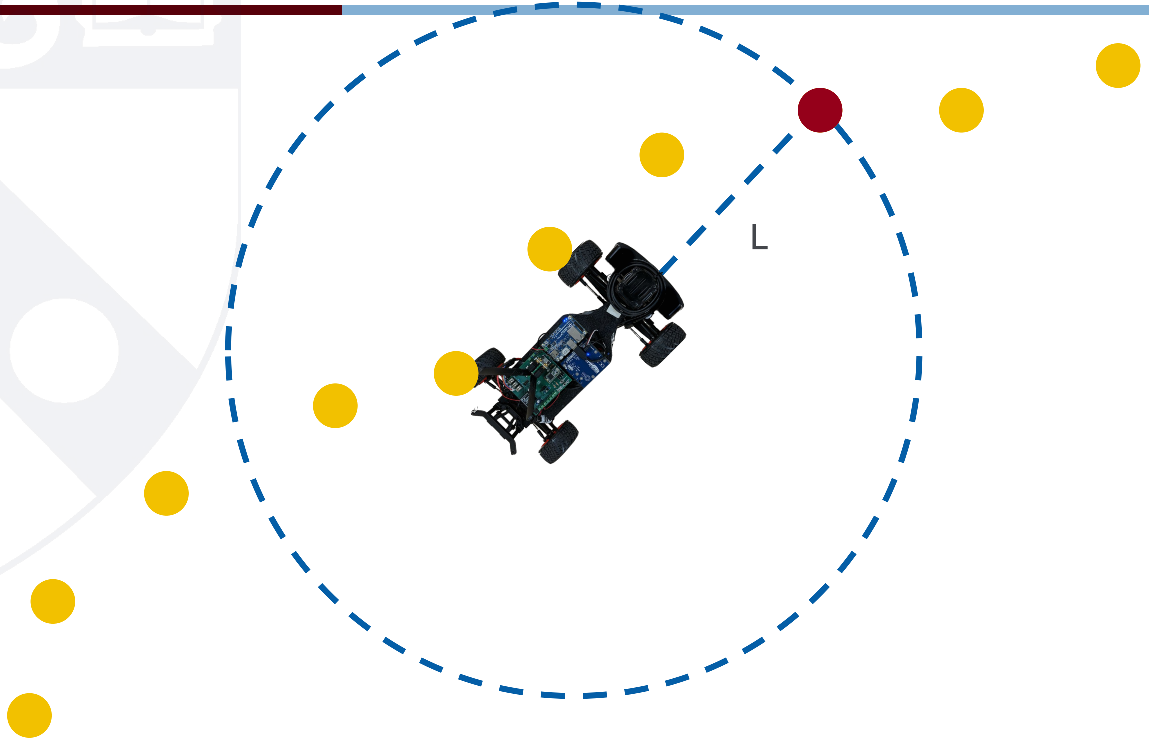
Updating the goal point



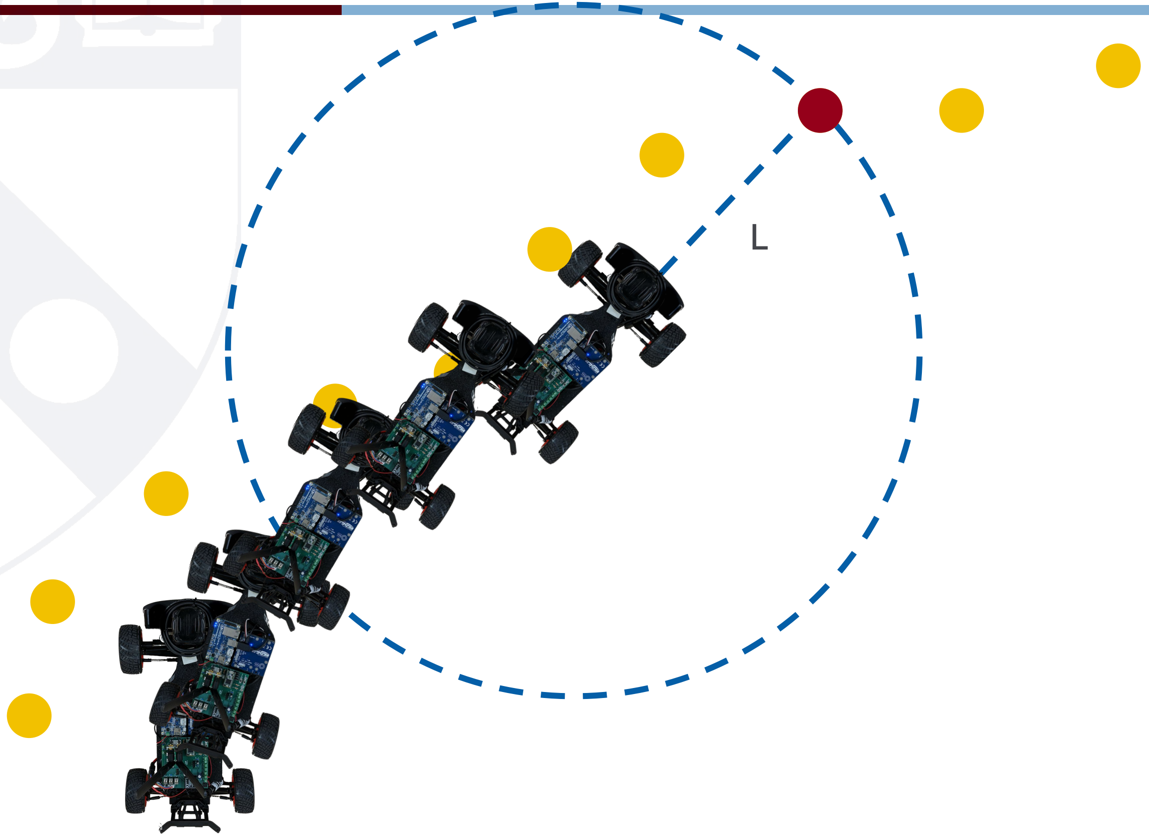
Updating the goal point



Updating the goal point



Updating the goal point

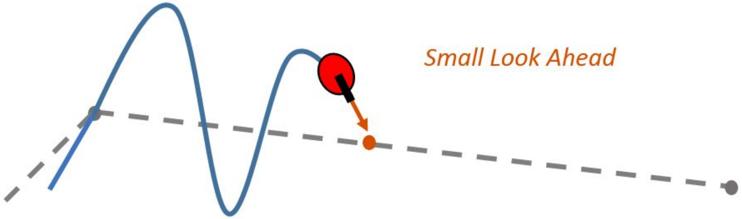


Effects of Changing the Lookahead Distance

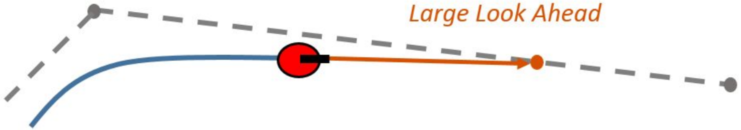
- The parameter **L** (lookahead distance) is a parameter of pure pursuit.
- Smaller **L** leads to more aggressive maneuvering to track tighter arc, and the tighter arcs might be against dynamical limits of the car.
- Larger **L** leads to smoother trajectory but larger tracking errors, might lead to close calls with obstacles.

$$\gamma = \frac{1}{r} = \frac{2|y|}{L^2}$$

- Small lookahead distance
  - Oscillatory path
  - Accurate tracking

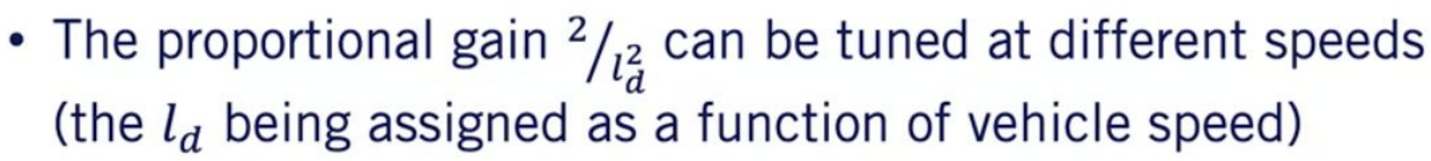


- Large lookahead distance
  - Less oscillatory path
  - Poor tracking
    - Larger curvature near the corners



Notes (1)

- Tuning **L** will change the behavior of pure pursuit the most.
- The waypoints are a sequence of positions, and could also have a velocity component at positions.



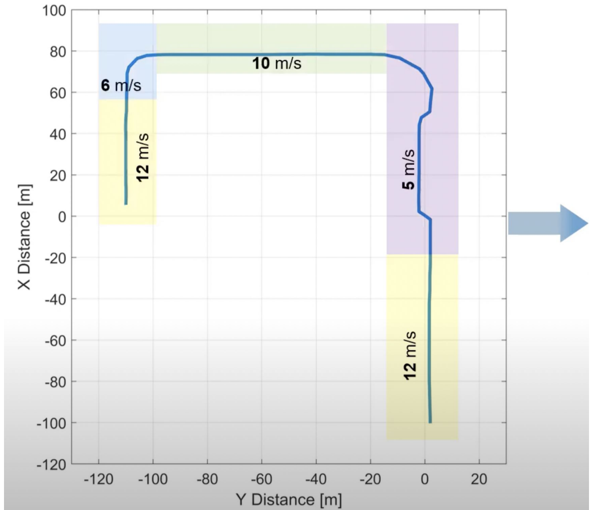
- The proportional gain ${}^{2}/_{l_d^2}$ can be tuned at different speeds (the l_d being assigned as a function of vehicle speed)

- Pure pursuit doesn’t take dynamics into account, thus it might produce dynamically infeasible arcs

Notes (2)

- The waypoints are a sequence of positions, and could also have a velocity component at positions.

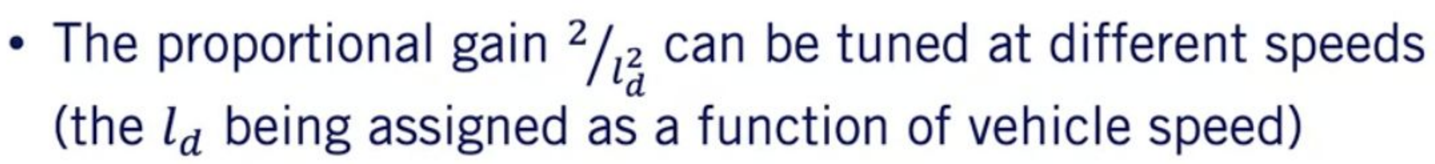
- The proportional gain $^2/_{l_d^2}$ can be tuned at different speeds (the l_d being assigned as a function of vehicle speed)



Velocity lookup table

Notes (3)

- Tuning **L** will change the behavior of pure pursuit the most.
- The waypoints are a sequence of positions, and could also have a velocity component at positions.



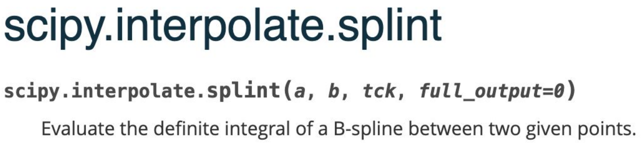
- The proportional gain ${}^{2}/_{l_d^2}$ can be tuned at different speeds (the l_d being assigned as a function of vehicle speed)

- **Pure pursuit doesn't take dynamics into account, thus it might produce dynamically infeasible arcs**

Putting it All Together

The pipeline of using pure pursuit

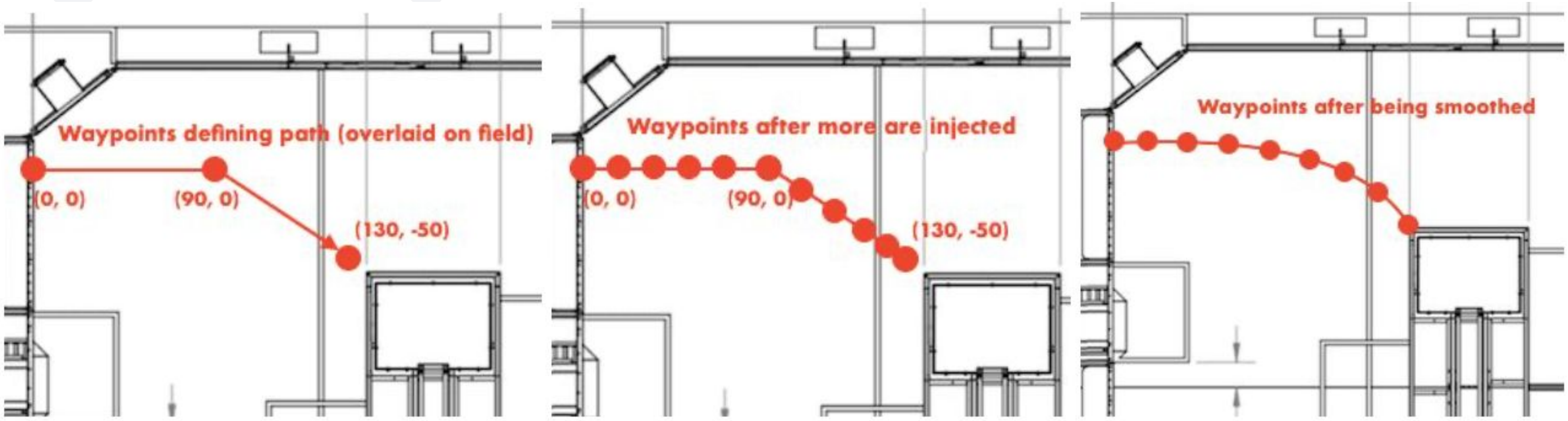
1. Create a new map using SLAM in ROS2
2. Create a list of waypoints using a global planner
   - Easiest way is to record waypoints driven by teleop
3. Pick waypoints to track at each frame
4. Set steering angle to track the current waypoint
5. Update the waypoint to track as you go



scipy.interpolate.splint

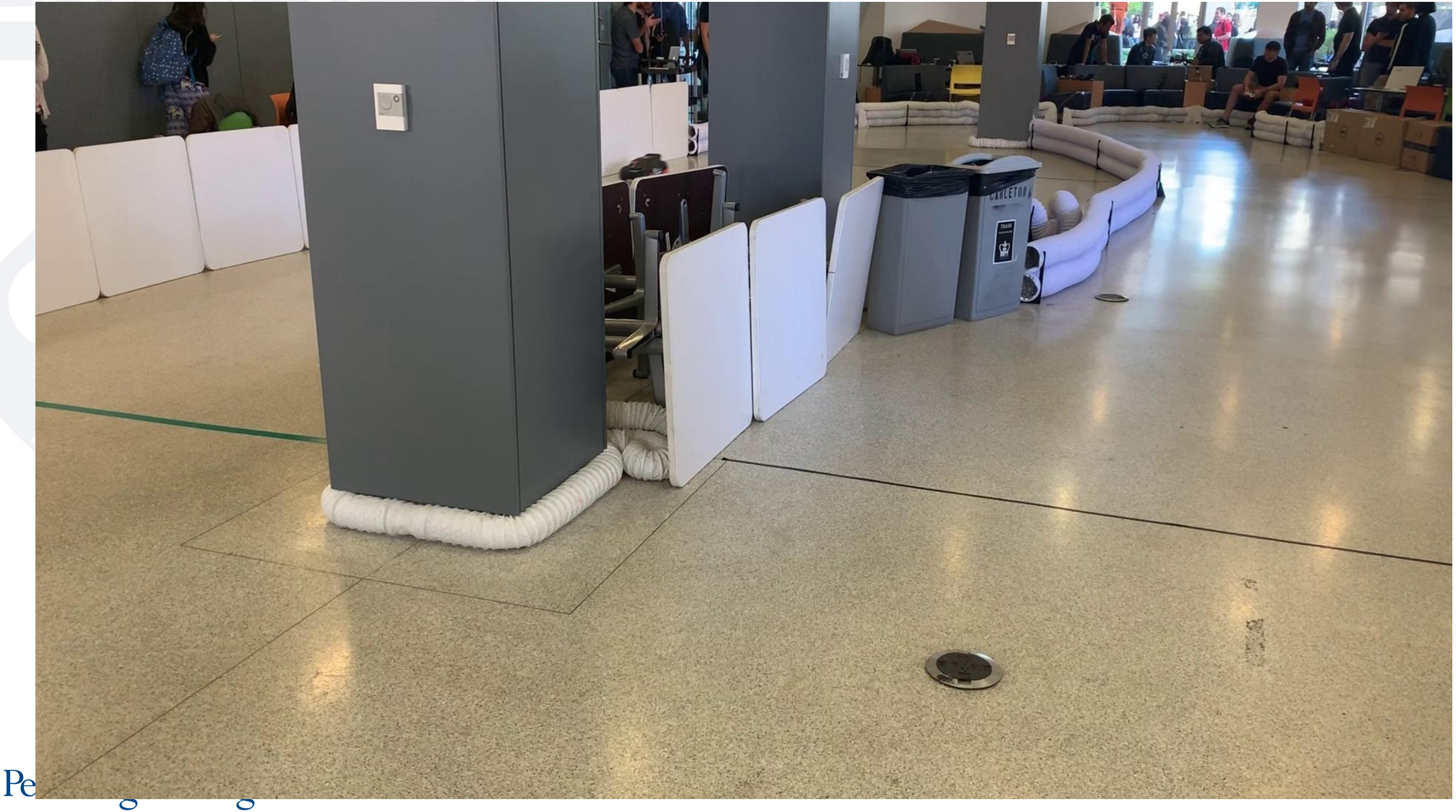
```
scipy.interpolate.splint(a, b, tck, full_output=0)
```

Evaluate the definite integral of a B-spline between two given points.


Waypoints defining path (overlaid on field)
(0, 0)
(90, 0)
(130, -50)
Waypoints after more are injected
(0, 0)
(90, 0)
(130, -50)
Waypoints after being smoothed

Pure pursuit in action

Pure pursuit in action



Acknowledgements

This course is a collaborative development with significant contributions from:
Hongrui Zheng (lead), Matthew O'Kelly (lead), Johannes Betz, Madhur Behl, Joseph Auckley, Luca Carlone, Jack Harkins, Kuk Jang, Paril Jain, Sertac Karaman, Dhruv Karthik, Nischal KN, Thejas Kesari, Venkat Krovi, Matthew Lebermann, Kim Luong, Yash Pant, Varundev Shukla, Nitesh Singh, Siddharth Singh, Cyrill Stachniss, Rosa Zheng, Xiyuan Zhu and many others.

We are grateful for learning from each other

Questions?

Today's Lab

1. Show that Cartographer works on your car, and try to make a map of the Levine loop
2. Install Particle Filter, and test localization with the map you made with Cartographer
3. Start implementing pure pursuit

Installing VNC server

- Install X11VNC

  -
    ```
    sudo apt install x11vnc
    ```
- Create a password file

  -
    ```
    echo mypassword > /home/nvidia/.vnc/password
    ```
  - Change this to your own password
  - You might have to create the .vnc directory
- Press windows/command/super key and search for ‘startup applications’
  - Create a new startup command, give it a name, and the command is:

  -
    ```
    /usr/bin/x11vnc -auth guess -forever -loop -noxdamage -repeat
    -passwdfile /home/nvidia/.vnc/password -rfbport 5900 -shared
    ```
  - Restart

Using the VNC server

- On your laptop/phone/ipad, install a vnc client
  - Remmina (comes with Ubuntu)
  - VNCviewer
  - Connect with your car’s ip and port 5900

Race 2

Race 2 will be after spring break, on 3/18

You'll be using pure pursuit on Levine 2nd floor

Same format, with adjusted scoring criteria

References

1. https://www.ri.cmu.edu/pub_files/pub3/coulter_r_craig_1992_1/coulter_r_craig_1992_1.pdf
2. https://www.ri.cmu.edu/pub_files/2009/2/Automatic_Steering_Methods_for_Autonomous_Automobile_Path_Tracking.pdf