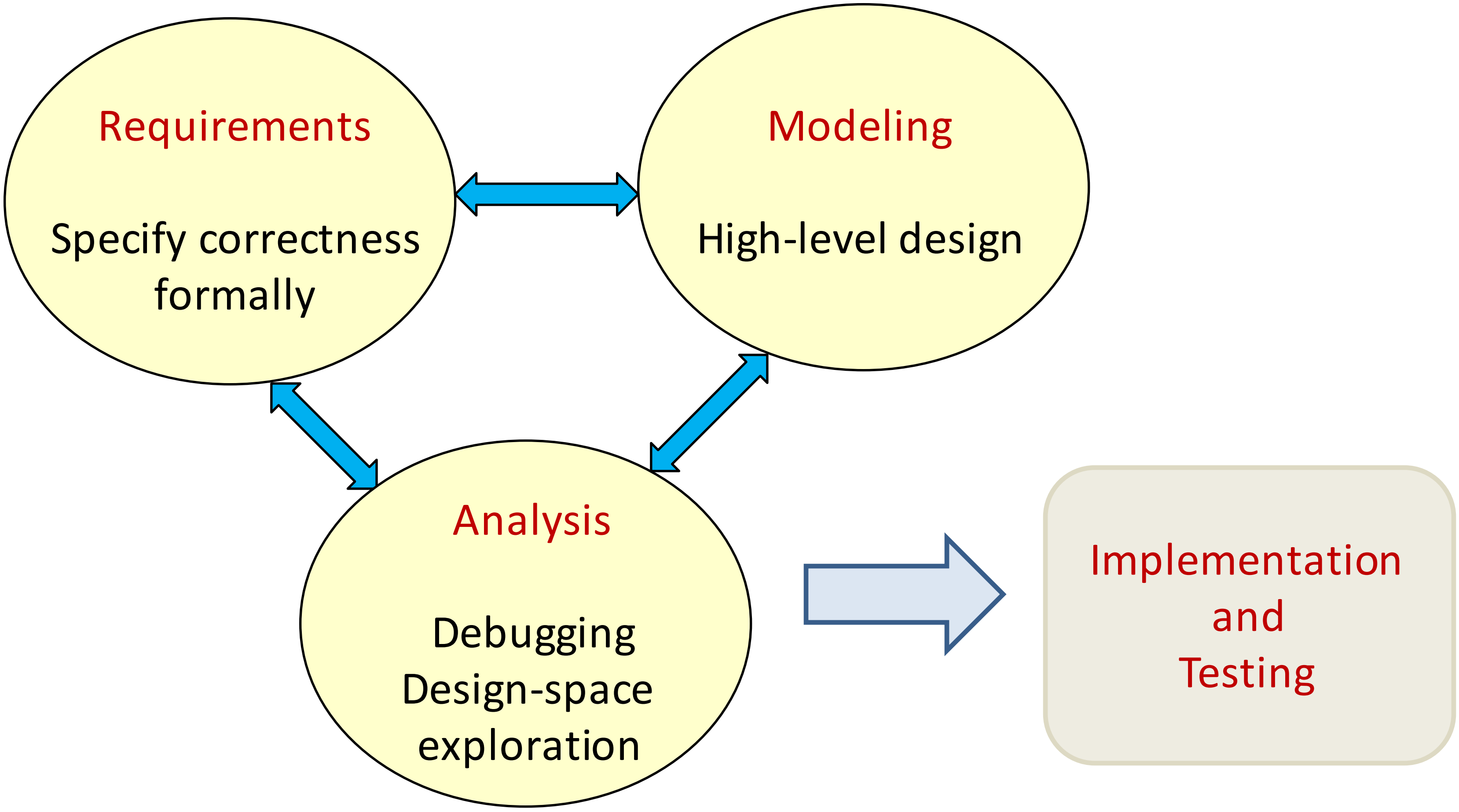
CS:4980
Foundations of Embedded Systems

Hybrid Systems

Part II

Model-Based Design and Analysis



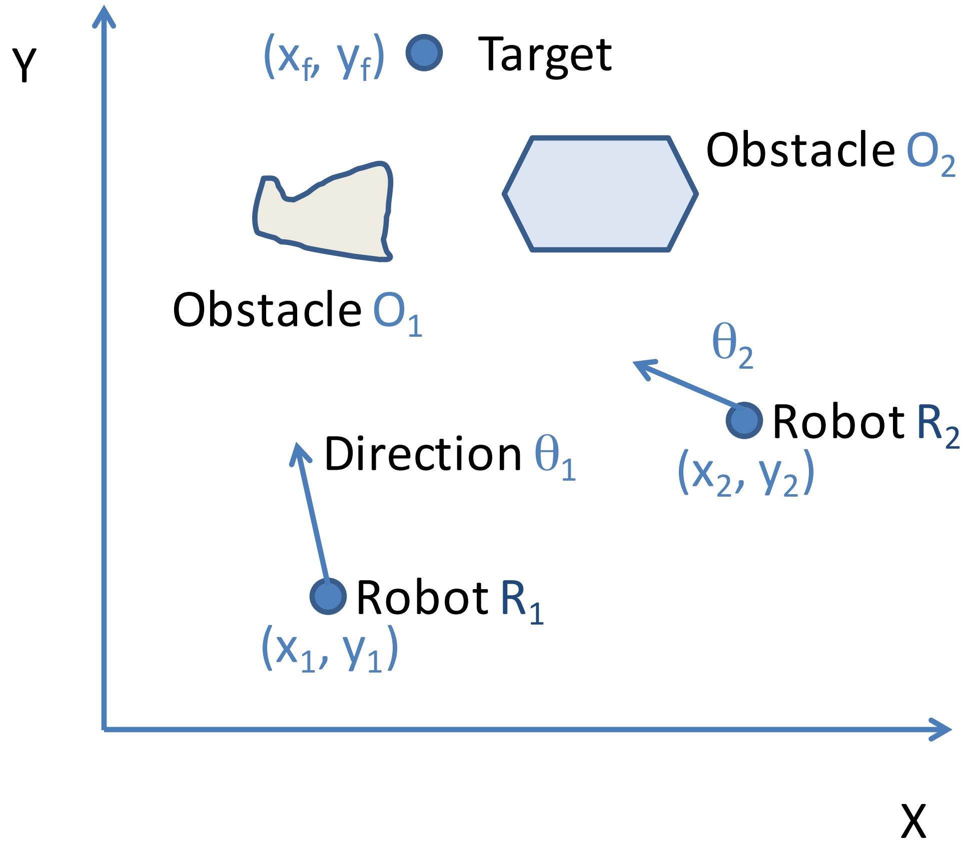
Multi-Robot Coordination

- Autonomous mobile robots in a room
- Goal of each robot:
  - Reach a target at a known location
  - Avoid obstacles (positions of obstacles not known in advance)
  - Minimize distance travelled
- Cameras and vision processing algorithms allow each robot to estimate obstacle positions
  - Estimates are only approximate, and depend on relative position of obstacles with respect to a robot's position
  - How often should robot update these estimates ?

Multi-Robot Coordination

- Each robot can communicate with others using wireless links
  - How often and what information?
  - How does communication help?
- High-level motion control (path planning)
  - Decide on speed and direction

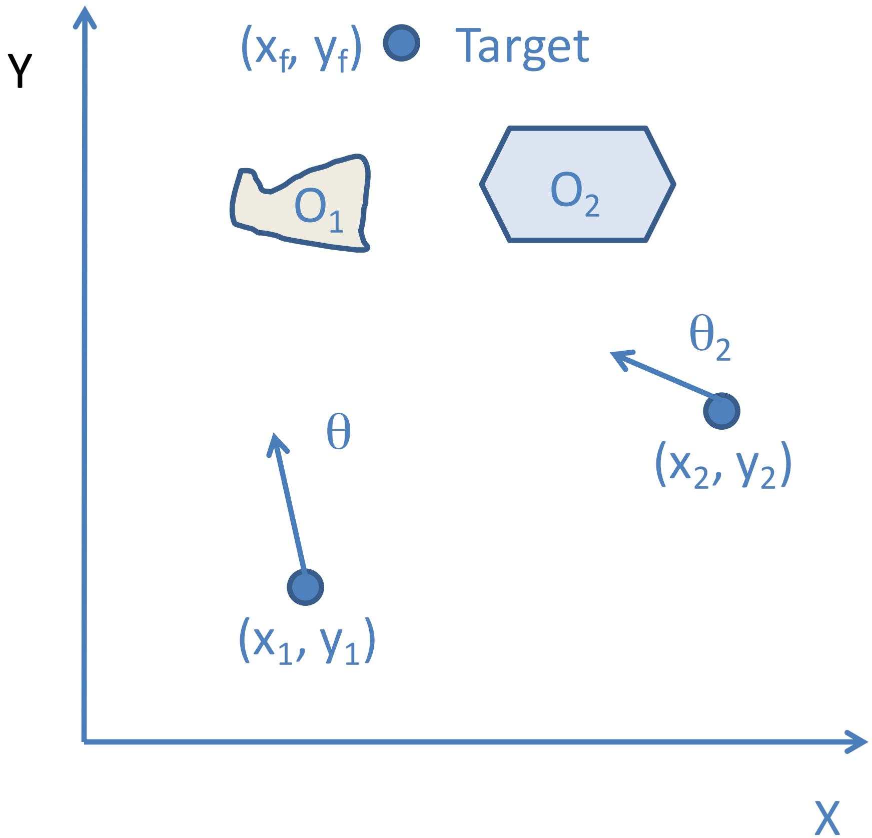
Path Planning with Obstacle Avoidance



Assumptions:

- Two dimensional world
- Point robots
- Fixed speed v

Path Planning with Obstacle Avoidance



State variables: (x_1, y_1), (x_2, y_2)

Initialization:

$(x_1, y_1) := (x_{10}, y_{10})$
$(x_2, y_2) := (x_{20}, y_{20})$

Dynamics:

$dx_1 = v \cos \theta$ $dx_2 = v \cos \theta_2$
$dy_1 = v \sin \theta$ $dy_2 = v \sin \theta_2$

Safety requirement:

$(x_1, y_1), (x_2, y_2) \notin O_1 \cup O_2$

Liveness requirement:

Eventually $(x_1, y_1) = (x_f, y_f)$ and
Eventually $(x_2, y_2) = (x_f, y_f)$

Performance: Reduce distance travelled!

Abstractions

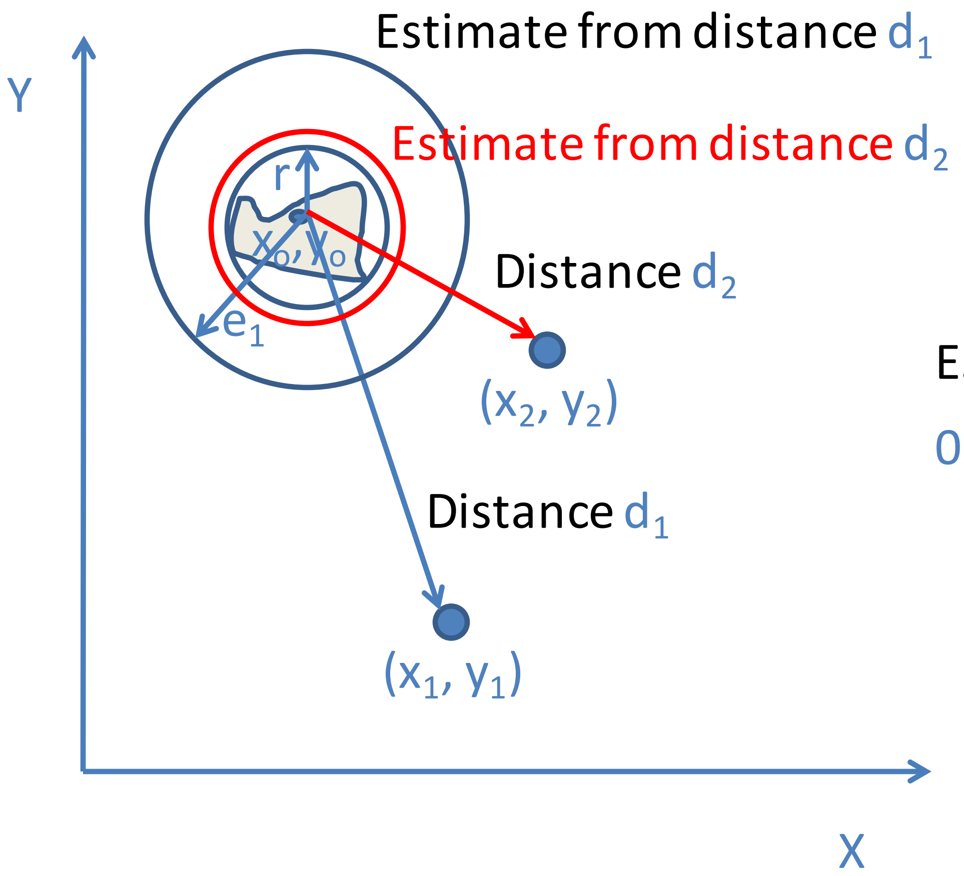
- For modeling and analysis for motion planning, we need to simplify obstacle shapes and complexity of image processing algorithms
  - Simplicity and abstraction: key to modeling
- Assume each robot is a point
  - Can be described by coordinates of point
- Assume each obstacle/estimate is a circle
  - Can be described by coordinates of center and radius
  - Assumption: real obstacle is always contained in estimated circle
  - Alternative: ellipses (more accurate)

Modeling Obstacles

- Consider an obstacle with center (x_o, y_o) and radius r
  - Radius of smallest circle that envelopes the actual obstacle

- Estimate of the obstacle as computed by a robot using image processing algorithms of a robot
  - A circle with center (x_o, y_o) and radius $e > r$
  - The closer the robot to the obstacle, the better the estimate
  - Estimate e decreases with distance of robot from obstacle, and converges to r

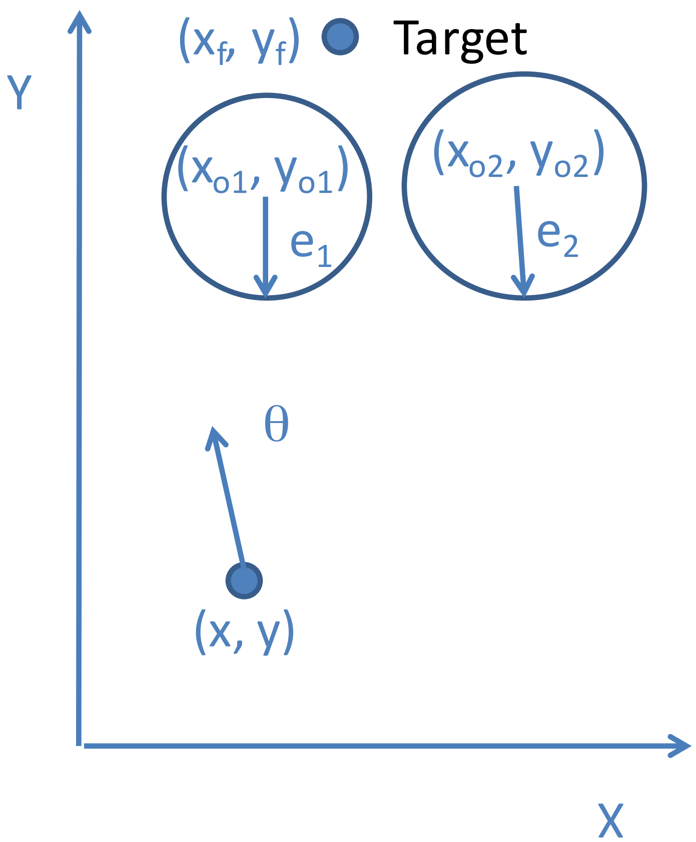
Obstacle Estimation



Estimated radius: $e_1 = r + a\,(d_1 - r)$

$0 < a < 1$ is a constant

Rule for Obstacle Estimation



Robot R_1 maintains radii e_1 and e_2 that are estimates of the obstacles

Obstacle estimation is computationally expensive

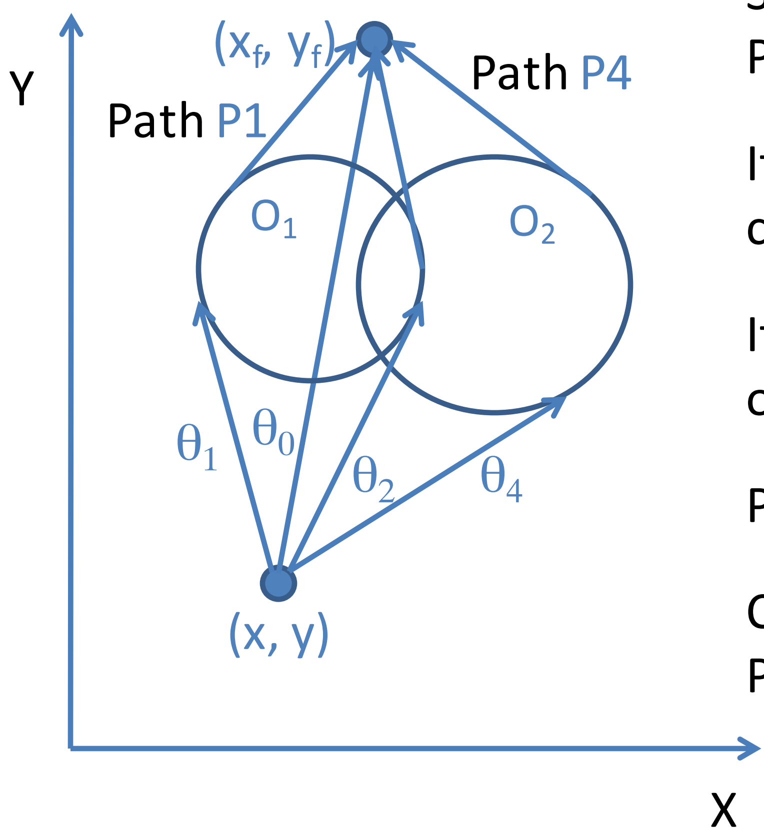
Every t_e seconds, robot executes discrete update:

$e_1 := \min(e_1, r_1 + a(\mathrm{dist}((x, y), (x_{o1}, y_{o1})) - r_1)$;

$e_2 := \min(e_2, r_2 + a(\mathrm{dist}((x, y), (x_{o2}, y_{o2})) - r_2)$

Computation for robot R_2 is symmetric

Path Planning



Shortest path: straight line to target
Preferred direction: θ_0

If estimate of obstacle O_1 intersects straight path, calculate two paths that are tangents to obstacle

If estimate of obstacle O_2 intersects straight path, or obstacle O_1, calculate tangent paths

Plausible paths: P1 and P4

Calculate which one is shorter:
Planning algorithm returns either θ_1 or θ_4

Path Planning

- Function plan with inputs:
  - current position of robot R_i
  - target position
  - obstacle O_1 position (center and radius estimate)
  - obstacle O_2 position (center and radius estimate)
- Output: Direction for motion
  - Best possible path to target while avoiding obstacles and assuming estimates are correct
- Function plan written in C code (can be embedded in model)
- Does it help to rerun planning algorithm again as robot moves?
  - Yes! Estimates may improve, suggesting shorter paths
  - Invoke planning algorithm every t_p seconds

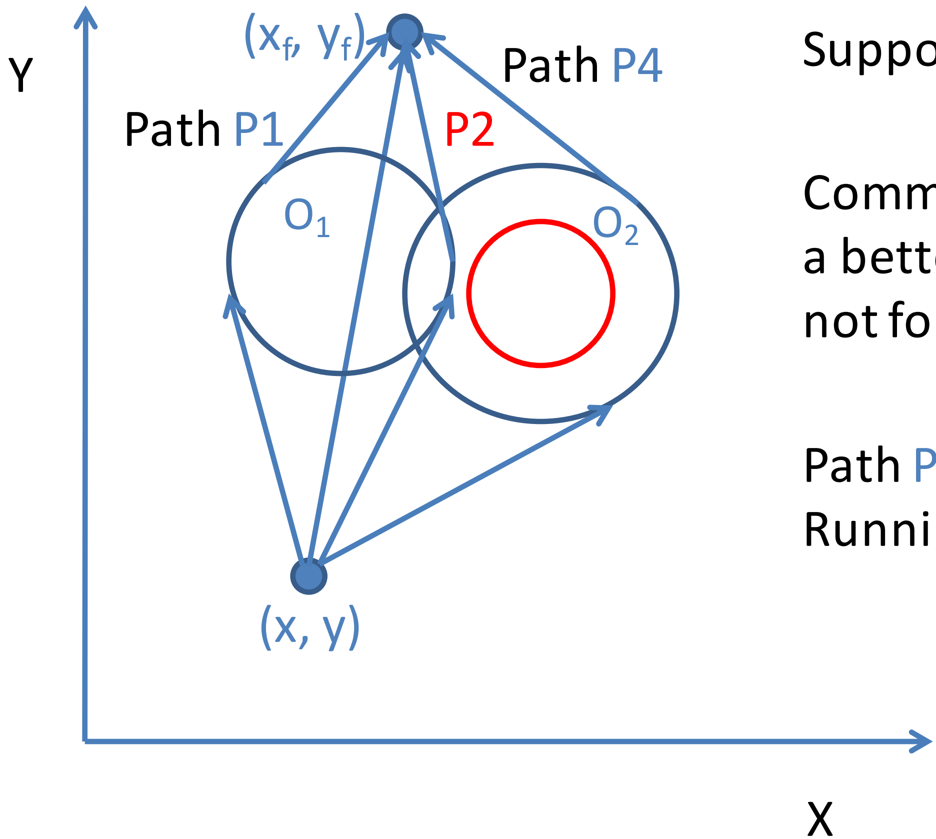
Communication

- Each robot has its own estimate of each obstacle
- Robot R_2's estimates may be better than R_1's own estimates
- Strategy: Every t_c seconds, send your own estimates to the other robot, and receive estimates from it
- If your own estimates are e_{i1} and e_{i2}, and you receive estimates e_{j1} and e_{j2}, set

  $e_{i1} := \min(e_{i1}, e_{j1})$

  $e_{i2} := \min(e_{i2}, e_{j2})$

Effect of Coordination

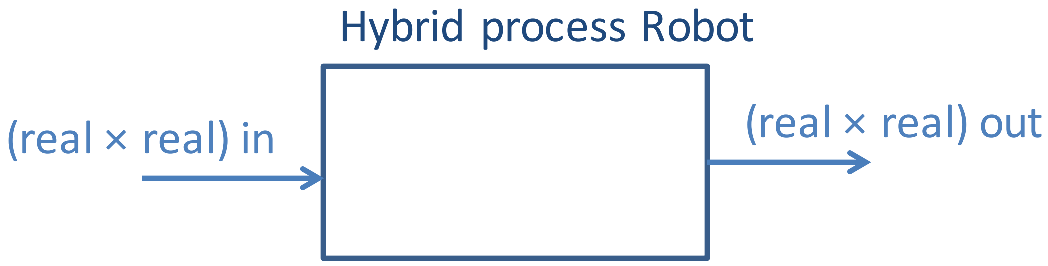


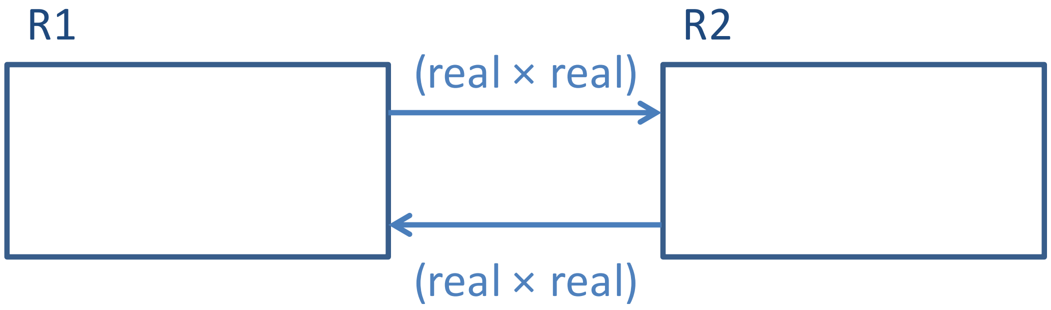
Suppose Path P1 was preferred

Communication with other robot gives a better estimate of obstacle O_2, but not for obstacle O_1

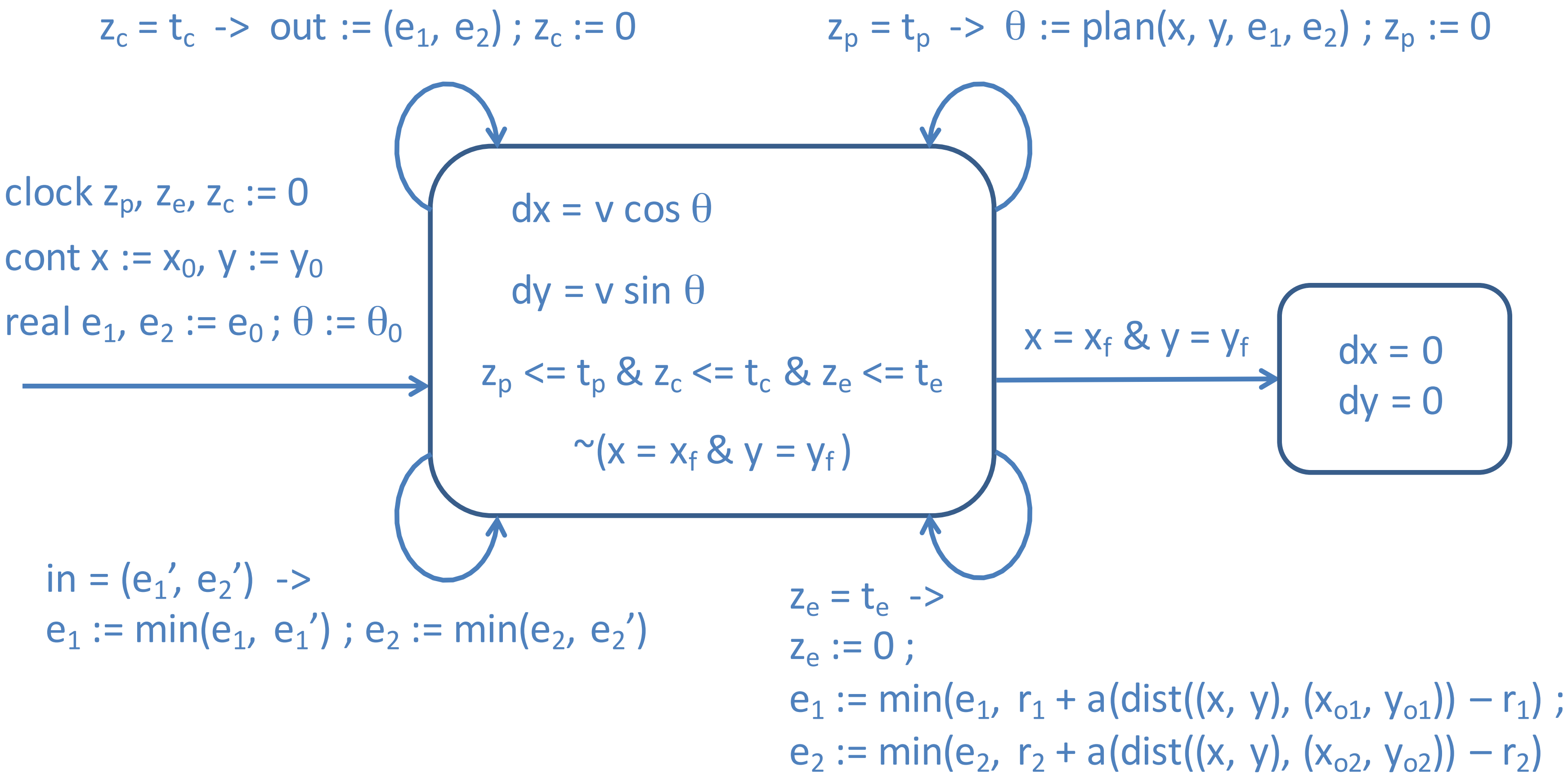
Path P2 is now viable.
Running planner again could choose path P2

System of Robots





Robot Model



$z_c = t_c$ -> out := (e_1, e_2) ; z_c := 0
$z_p = t_p$ -> θ := plan(x, y, e_1, e_2) ; z_p := 0
clock z_p, z_e, z_c := 0
cont x := x_0, y := y_0
real e_1, e_2 := e_0 ; $\theta := \theta_0$
dx = v cos θ
dy = v sin θ
$z_p <= t_p$ & $z_c <= t_c$ & $z_e <= t_e$
~(x = x_f & y = y_f)
x = x_f & y = y_f
dx = 0
dy = 0
in = (e_1', e_2') ->
e_1 := min(e_1, e_1') ; e_2 := min(e_2, e_2')
$z_e = t_e$ ->
z_e := 0 ;
e_1 := min(e_1, r_1 + a(dist((x, y), (x_{o1}, y_{o1})) – r_1) ;
e_2 := min(e_2, r_2 + a(dist((x, y), (x_{o2}, y_{o2})) – r_2)

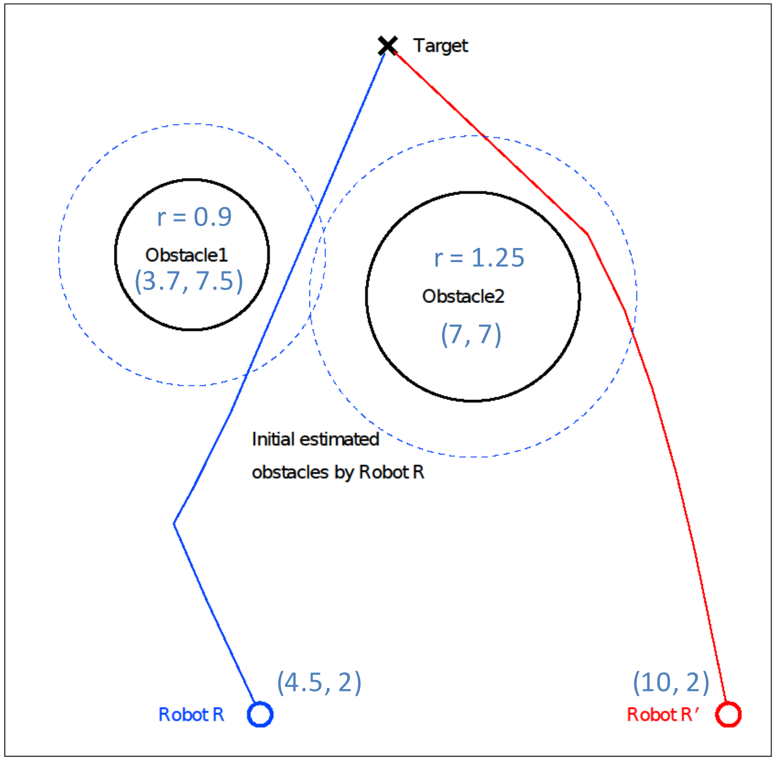
Analysis

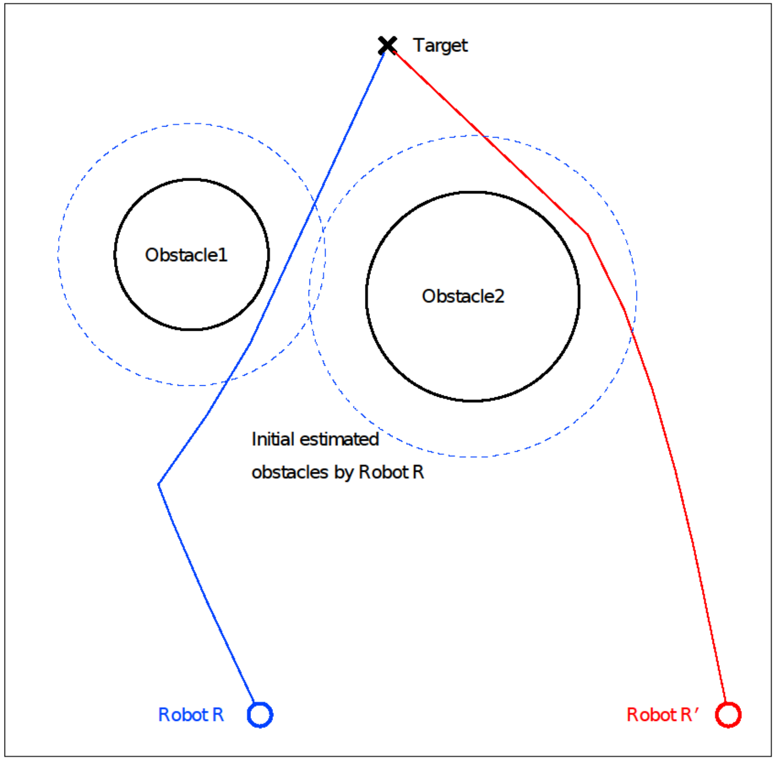
- Key system parameters
  - How often should a robot communicate?
  - How often should a robot execute planning algorithm
  - How often should a robot execute image processing algorithm to update obstacle estimates?

- Design-space exploration: Choose values of t_c, t_p, t_e
  - Reduce distance travelled, but also account for costs of communication/computation

- Symbolic analysis beyond the scope of current tools, so need to run multiple simulations

Illustrative Execution

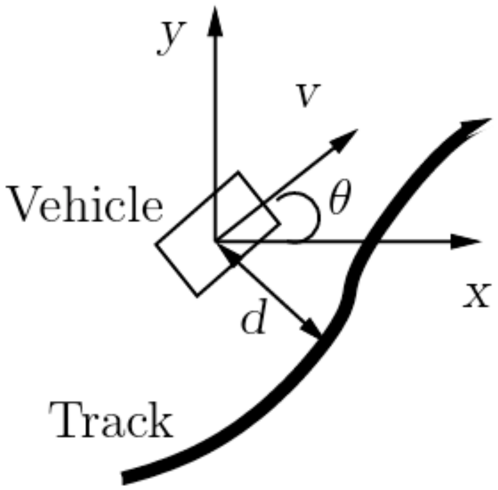




- Speed v : 0.5 u/s
- Planning rate t_p : 2 s
- Obstacle estimation rate t_p : 2 s
- Communication rate t_c : **4 s**
- Distance travelled by R' : 9.15 u
- Distance travelled by R : **8.65** u

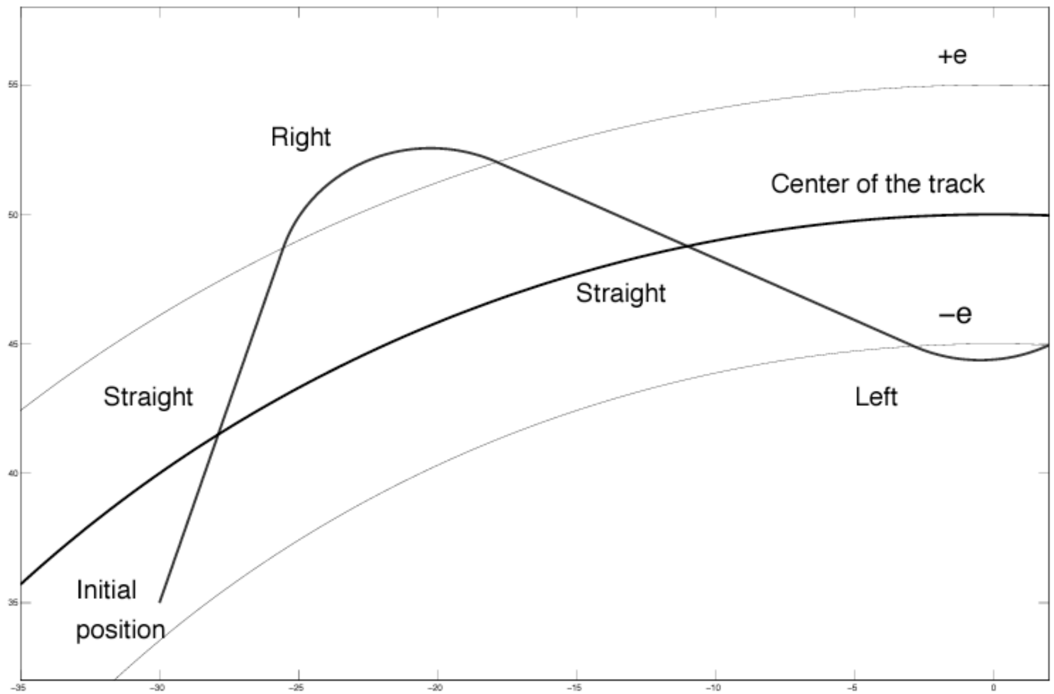
- Speed v : 0.5 u/s
- Planning rate t_p : 2 s
- Obstacle estimation rate t_p : 2 s
- Communication rate t_c : **>> 4 s**
- Distance travelled by R' : 9.15 u
- Distance travelled by R : **8.81** u

Automated Guided Vehicle



- Autonomous vehicle on a flat surface, following a visual track
- Goal of each robot:
  - Move along a track (i.e., center line of a road)
  - Follow track as close as possible
- Cameras and vision processing algorithms allow vehicle to sense track and measure (signed) distance d from center of the track
- Two degrees of freedom: move forward and rotate
- Two velocities: (regular) velocity (v, θ) and angular velocity ω

Automated Guided Vehicle Controller



Inputs: {start, stop} command c, distance d from center of track

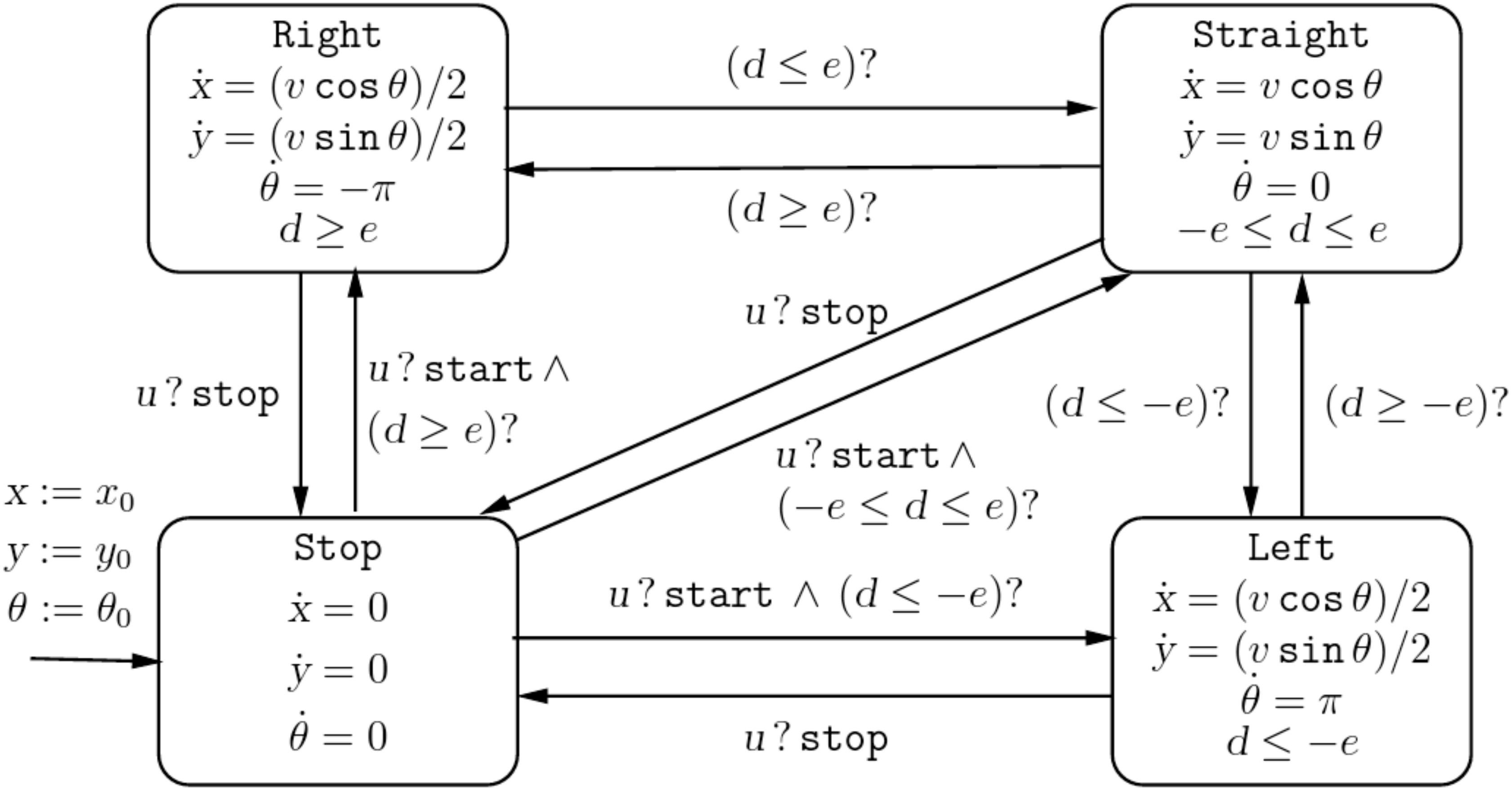
Outputs: speed v, angular speed ω

State: coordinates x, y; angle θ

Modes: Stop, Straight, Left, Right

Simplifications: $v \in \{v_c/2, v_c\}$ and $\omega \in \{-\pi, 0, \pi\}$

Automated Guided Vehicle Controller



Credits

Notes based on Chapter 9 of

Principles of Cyber-Physical Systems
by Rajeev Alur
MIT Press, 2015