UNIVERSITY OF
SOUTH CAROLINA

CSCE 774 ROBOTICS SYSTEMS

Multi-Robot Systems

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Multi-Robot Complete Coverage

- Multiple Robots:
  - Efficiency
  - Robustness
  - Higher Complexity
- Inter-Robot Communication Abilities
- Guarantee of Complete Coverage

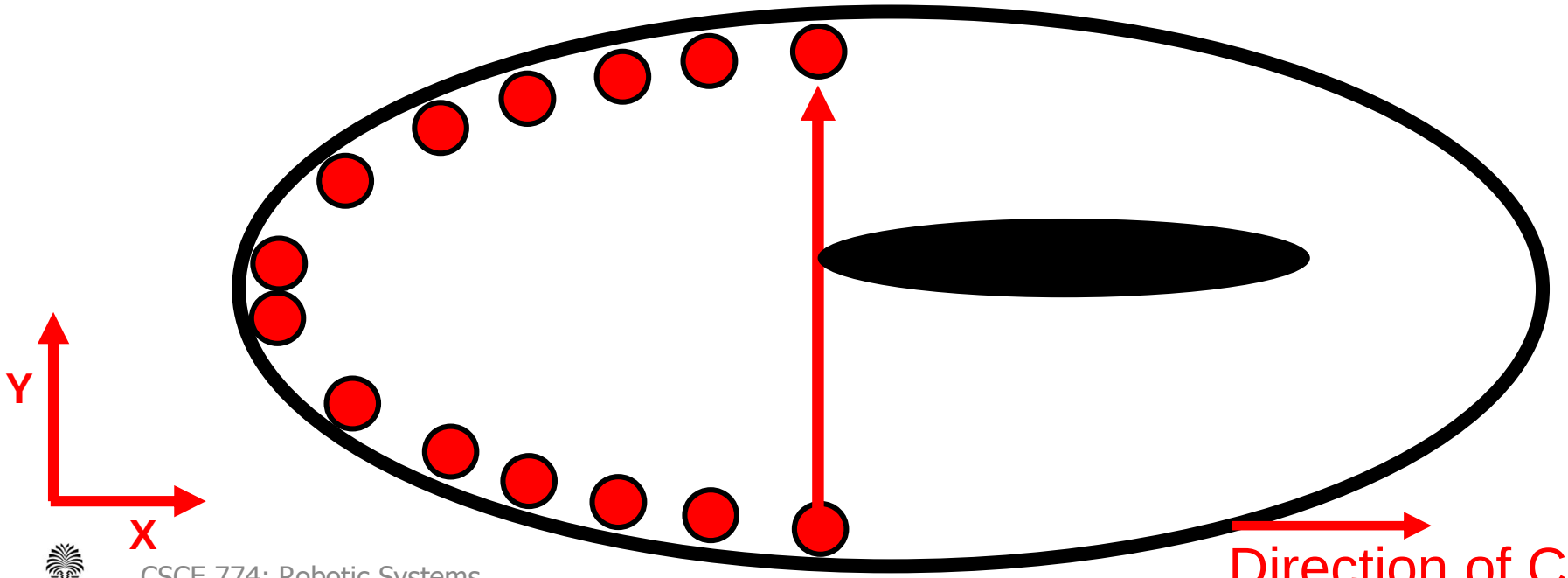
Multi Robot Complete Coverage

Limited Communication: Main Ideas

- Communication is limited to Line of Sight
- Coverage of a single cell
  - Robots have two roles:
    - Explorers
    - Coverers
- Team coordination for complete coverage of the environment
  - Limited communication
  - Deterministic approach
  - Team splits only once

Single Cell Coverage

- Each team of *N* robots has:
  - *2* explorers, *N-2* coverers
- The explorers trace the top and bottom border of the Cell maintaining the same X-coordinate until the Line of Sight is broken (i.e. a critical point is detected)



Single Cell Coverage

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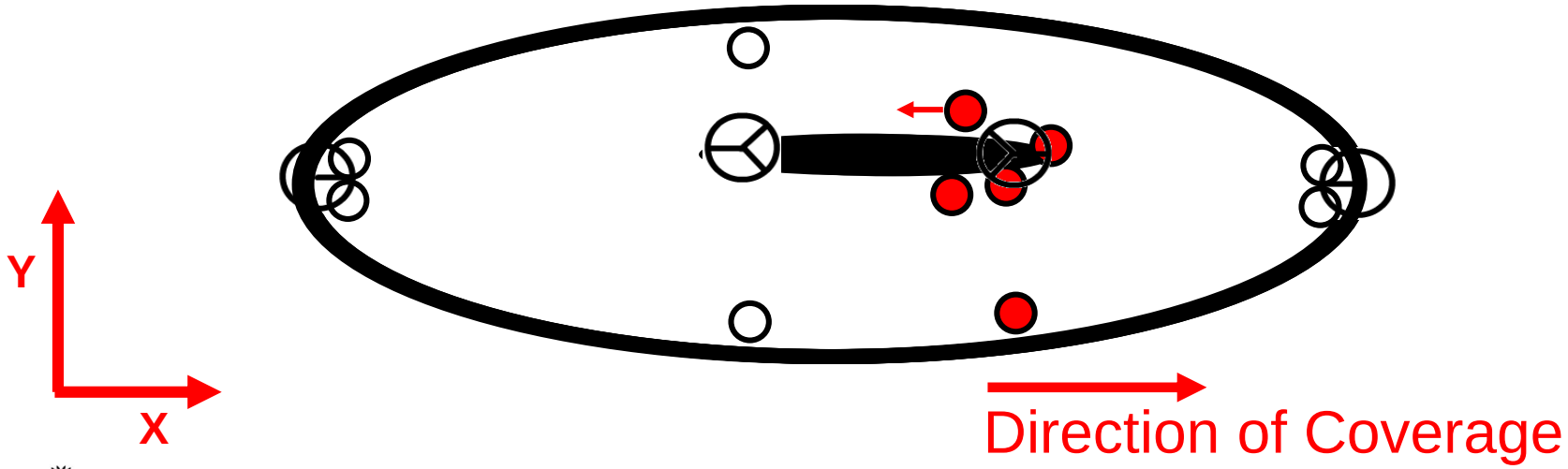
- The coverers use an up-and-down motion to cover the interior of the cell

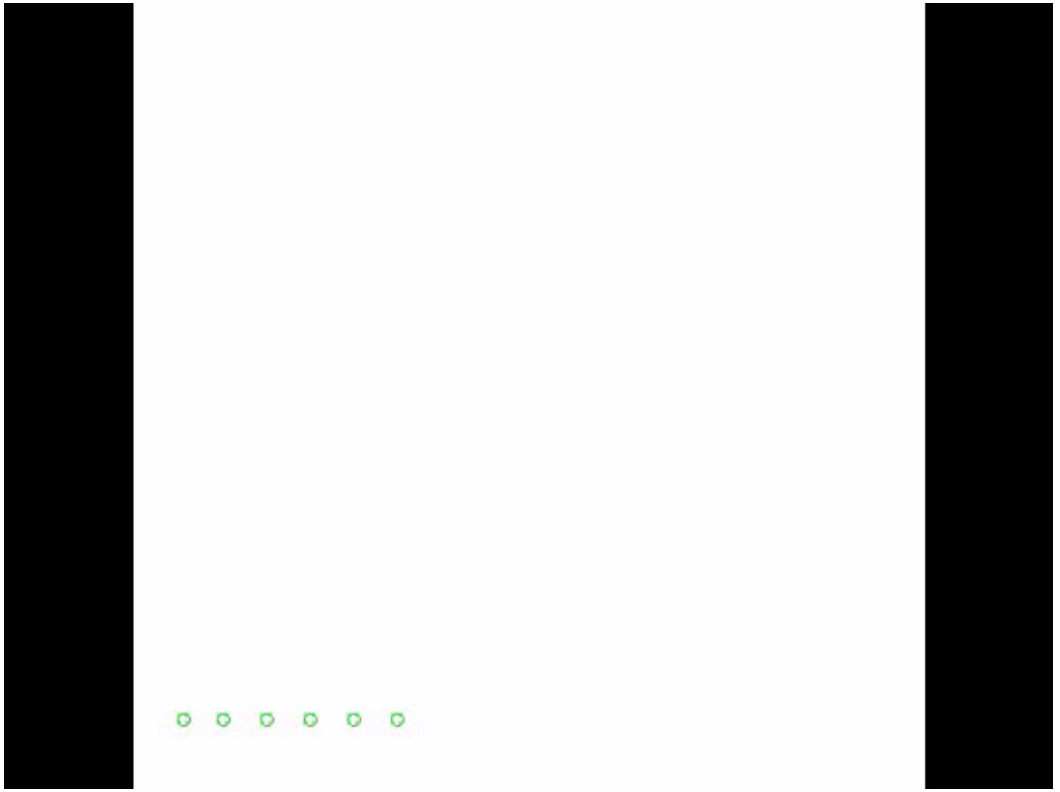
Critical Point Detection

- The explorers are able to detect all critical points:
  - Forward Concave CP (encountered only at start-up)
  - Reverse Concave CP (explorers approach each other)
  - Reverse Convex CP (Line of Sight breaks)
  - Forward Convex CP (Explorer reverses direction)



Single Cell Coverage

Reverse Concave Critical Point



Top Explorer

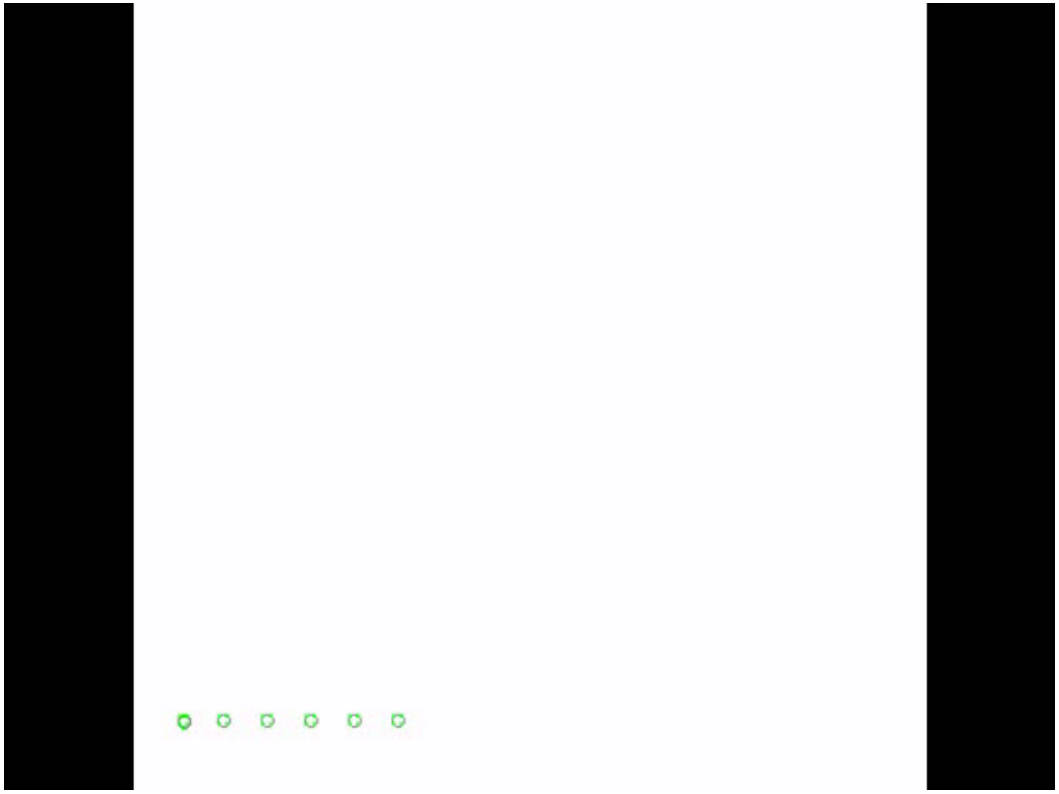
Bottom Explorer

Coverers

The circles represent the robot position not the sensor footprint.

Single Cell Coverage

Forward Convex Critical Point



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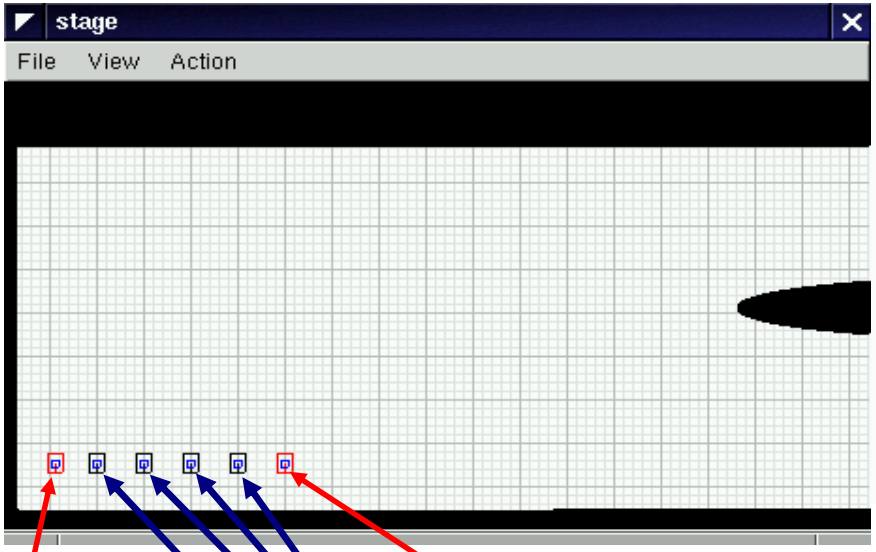
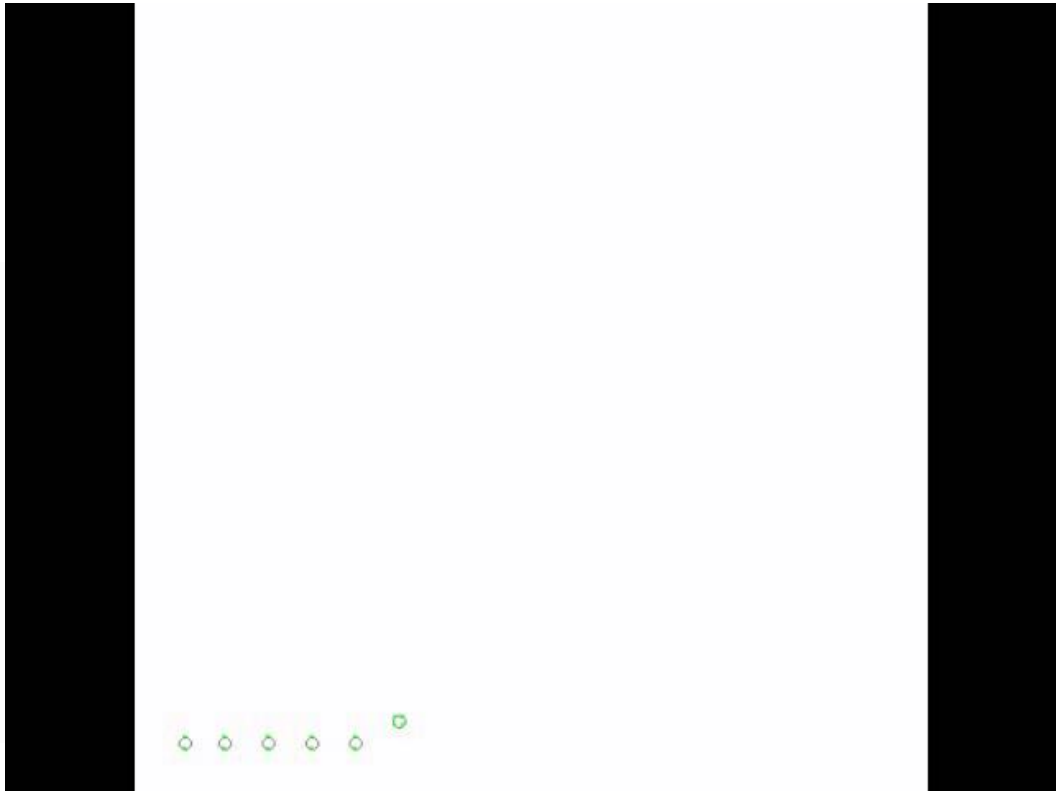
Single Cell Coverage

Reverse Convex Critical Point





Top Explorer

Bottom Explorer

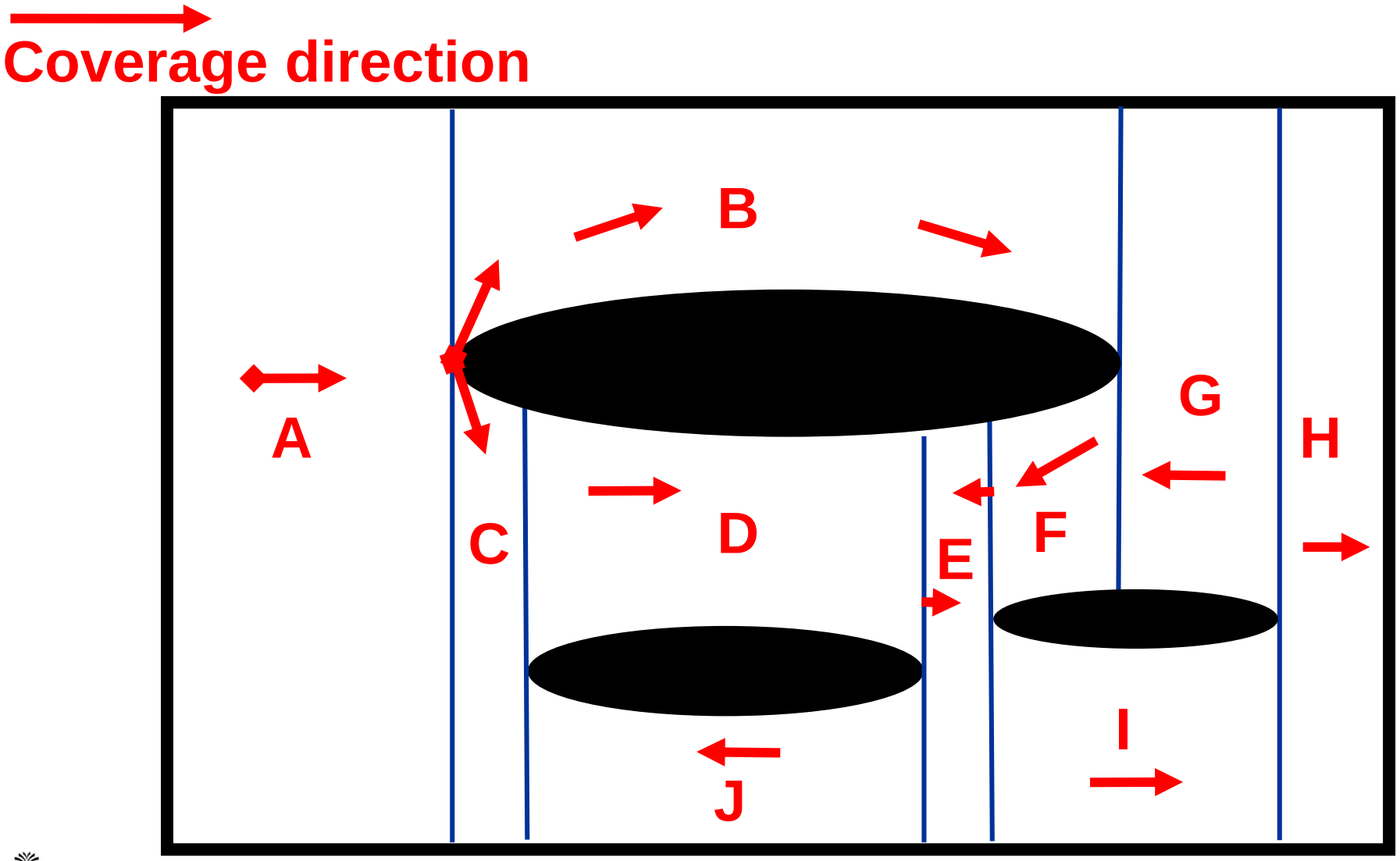
Coverers

The circles represent the robot position not the sensor footprint.

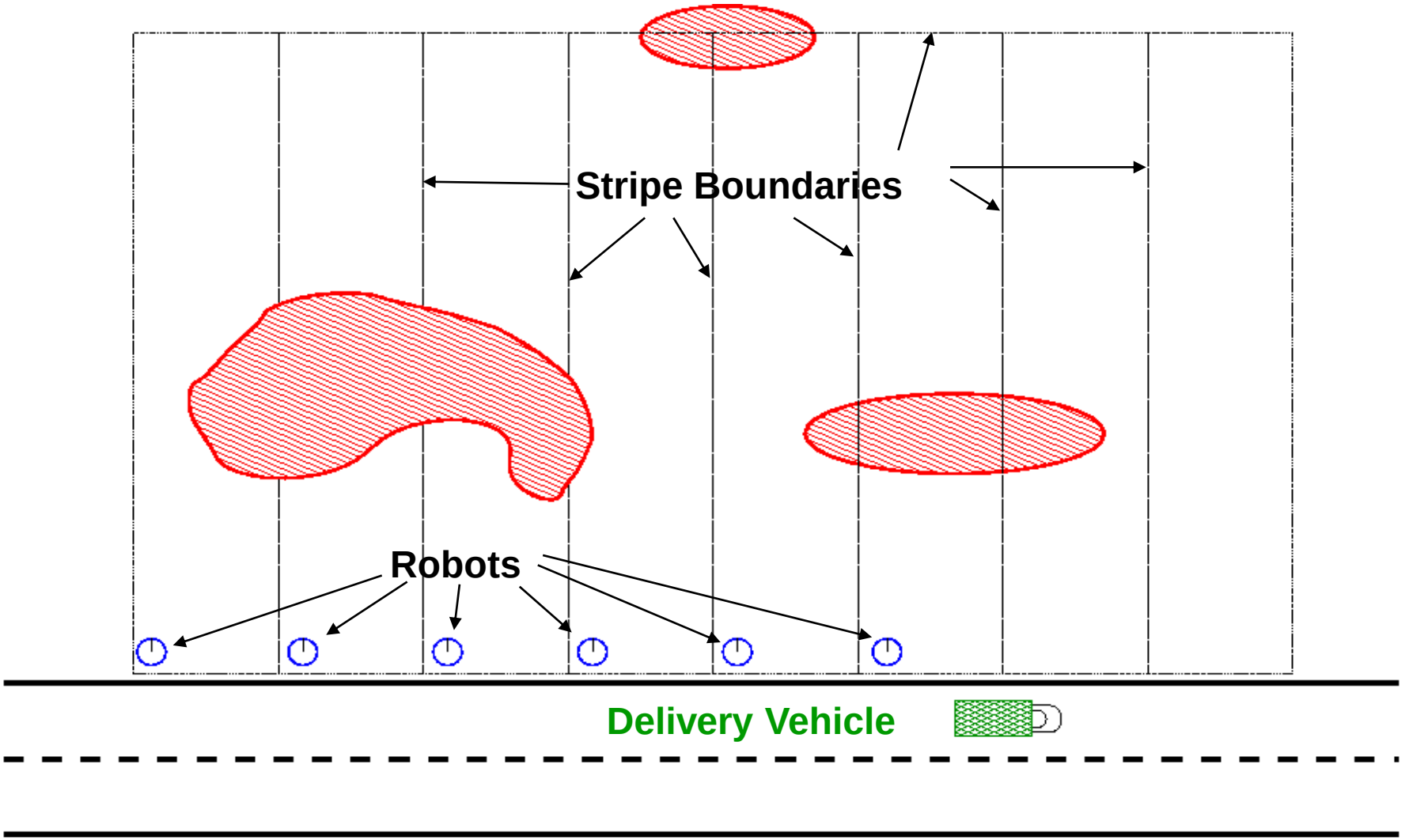
Team Coverage

- The team splits only once into two sub-teams in order to encircle an obstacle
- One sub-team moves clockwise around the obstacle, the other sub-team moves counter-clockwise
- If a sub-team encounters a dead-end it backtracks
- Guaranteed re-joining of the two sub-teams

Team Splitting and Rejoining



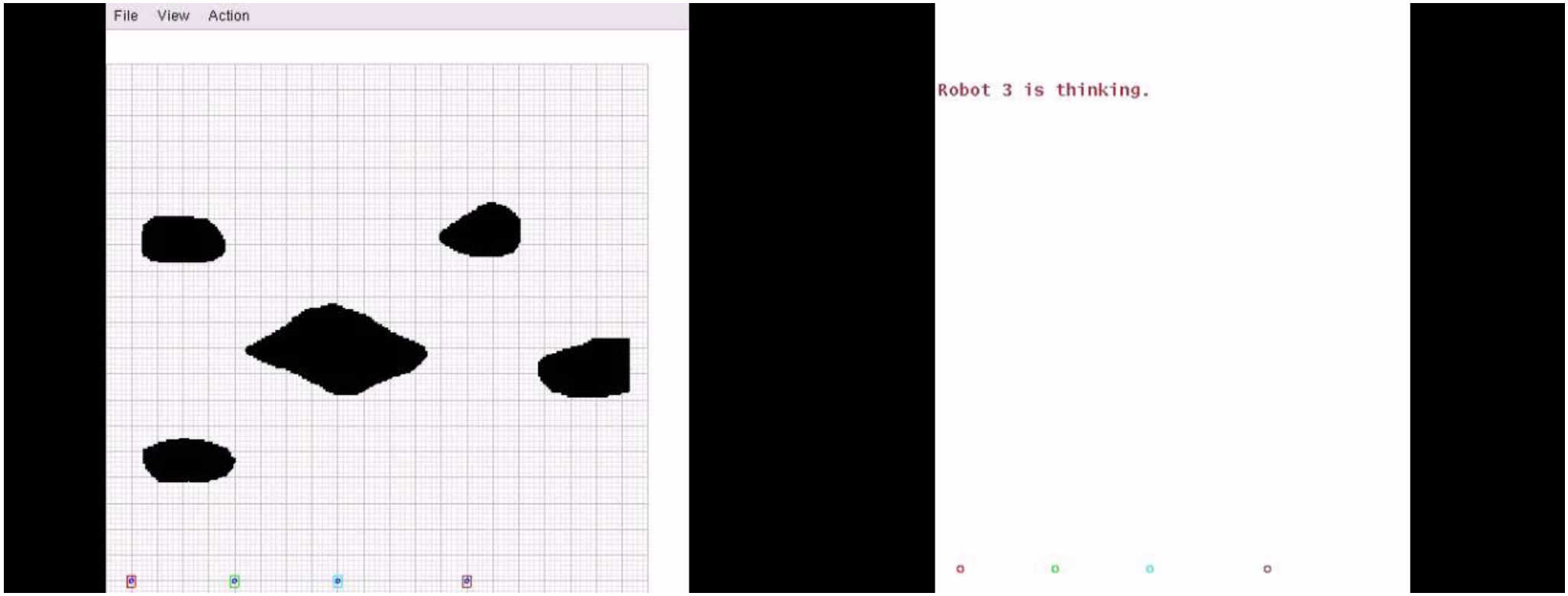
Multi-Robot Coverage Paradigm



Multi Robot Complete Coverage: Main Ideas

- Unrestricted Communication / Good Localization
- Environment is divided into as many stripes as robots
- Cooperative Exploration
  - Each robot explores the boundaries of its stripe
  - Robots Auction parts of the non reachable parts of their stripe
- Cooperative Coverage
  - Connectivity of the environment is known
  - Each robot covers the closest cell
  - Robots Auction coverage tasks

Example



Auctions!

- Used to improved performance
- A central coordinator or one team member call/administer the auction
- Robots bid for tasks based on some estimated reward/cost

Classification

- Team size
- Communication range
- Communication topology
- Communication bandwidth
- Processing ability
- Team Reconfigurability
- Team Composition

Marsupial Robots

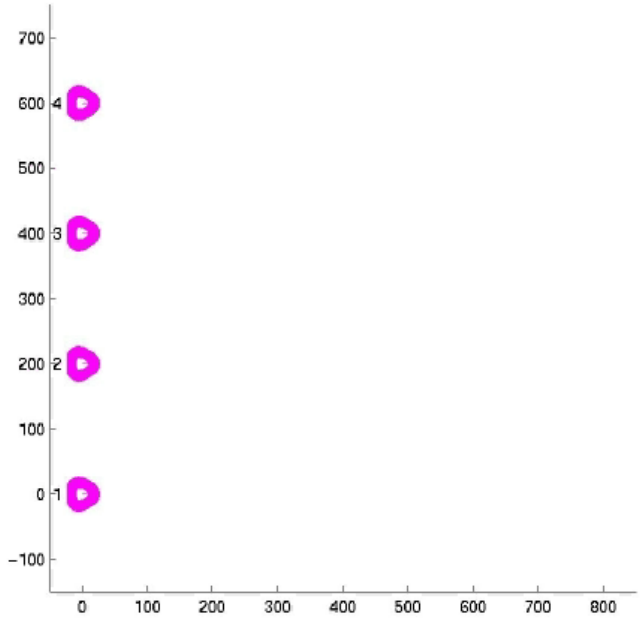
Also watch: http://www.youtube.com/watch?v=hCGgoPS91Rw

From: http://www.nosc.mil/robots/resources/marsupial/marsupial.html

Marsupial Robots

- From: http://distrob.cs.umn.edu/demos.php

Formations


700
600
500
400
300
200
100
0
−100
4
3
2
1
0
100
200
300
400
500
600
700
800

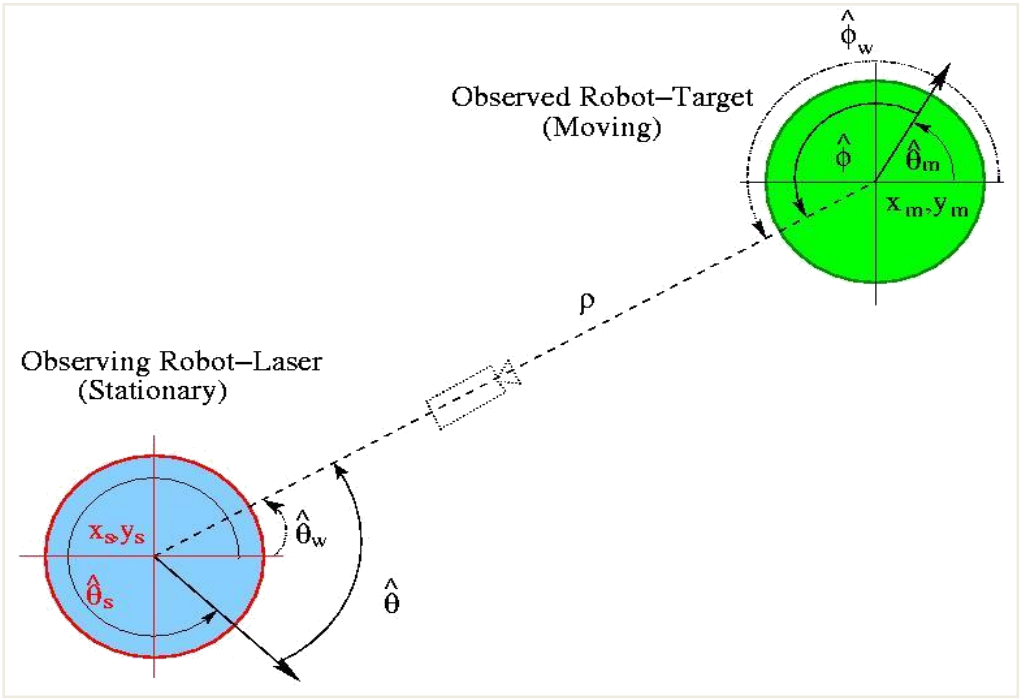
Formations

- Follow the leader
- Unit Center
- Maintain position
- Avoid Obstacles

Cooperative Localization, Mapping, and Exploration

Cooperative Localization

- Pose of the moving robot is estimated relative to the pose of the stationary robot. Stationary Robot observes the Moving Robot.



Robot Tracker Returns:

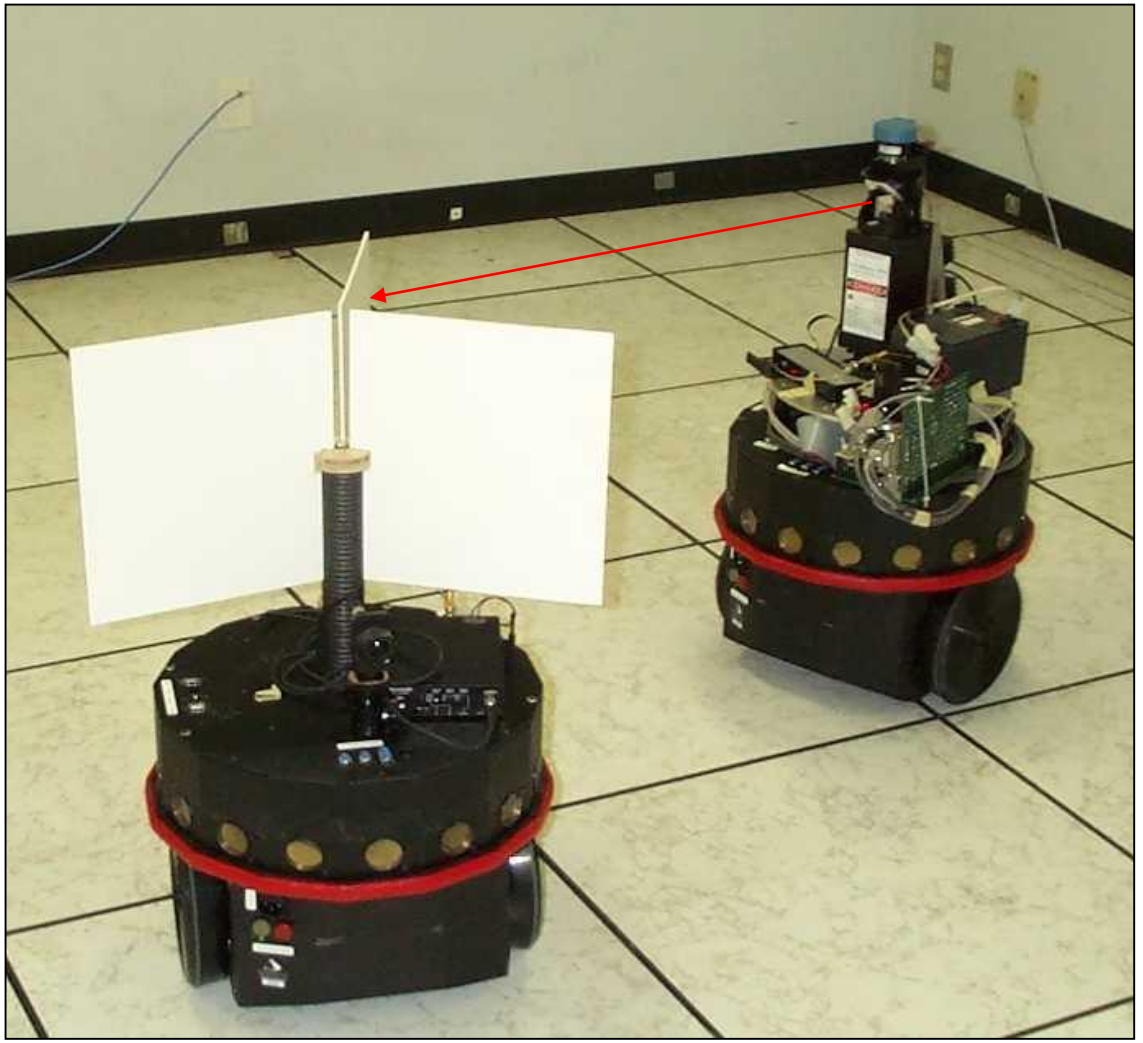
<ρ,θ,ϕ>

$$\mathbf{x}_{m_{est}}(k+1) = \begin{pmatrix} x_{m_{est}} \\ y_{m_{est}} \\ \theta_{m_{est}} \end{pmatrix} = \begin{pmatrix} x_s + \rho\cos(\theta+\theta_s) \\ y_s + \rho\sin(\theta+\theta_s) \\ \pi - (\phi - (\theta+\theta_s)) \end{pmatrix}$$

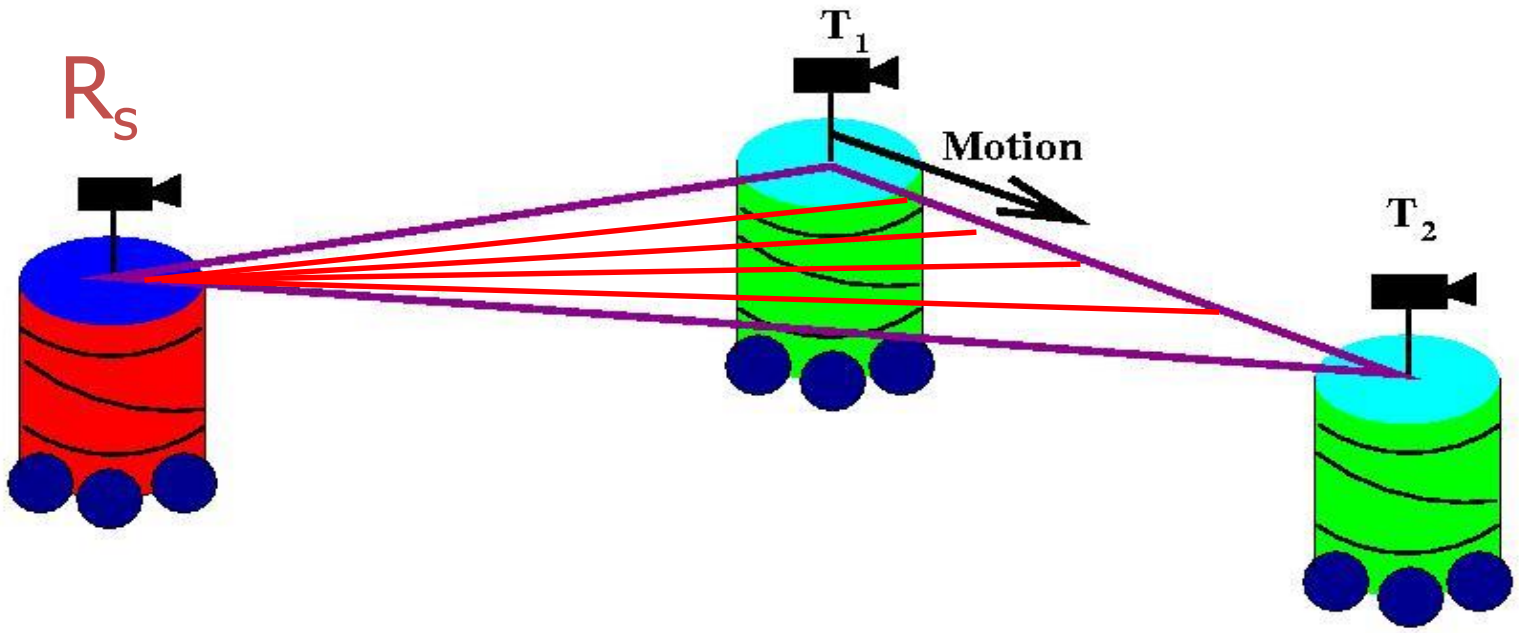
Laser Robot Tracker

Robot Tracker Returns:

$<\rho,\theta,\phi>$



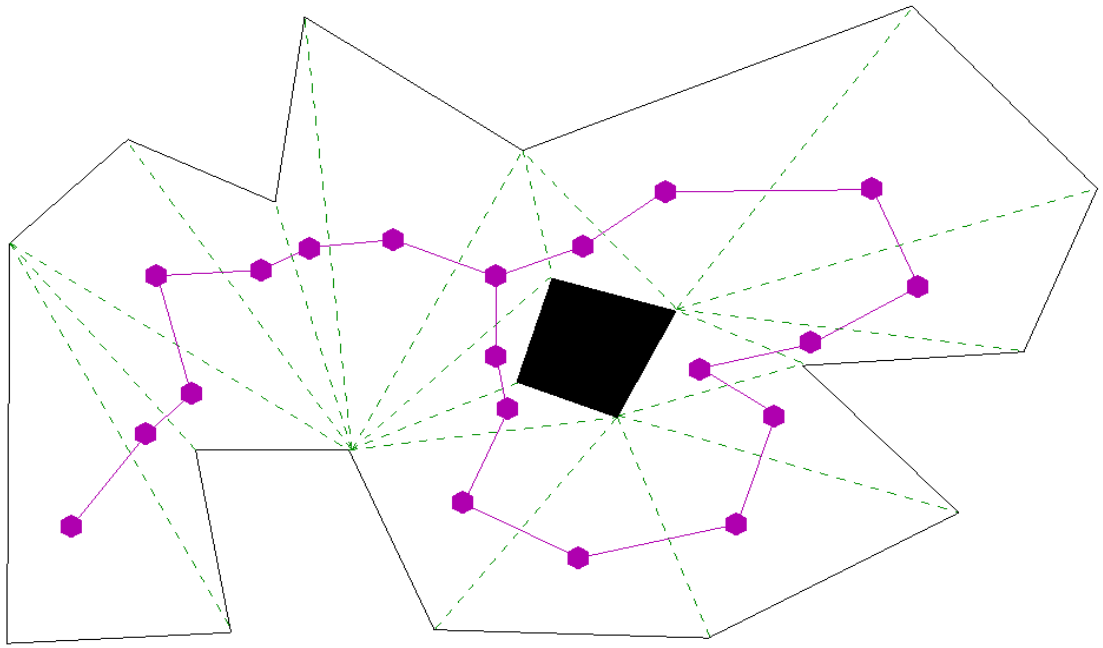
Exploration and Mapping
(Triangulation)



- If the line of visual contact is not interrupted during the motion, then the triangle $[R_S, T_1, T_2]$ is free space.
- Connect the triangles of free space in order to construct a map of the environment.

Triangulation Algorithm: Main Ideas

- **Bounded Area:** The range of the tracker sensor is larger than any diagonal of the environment

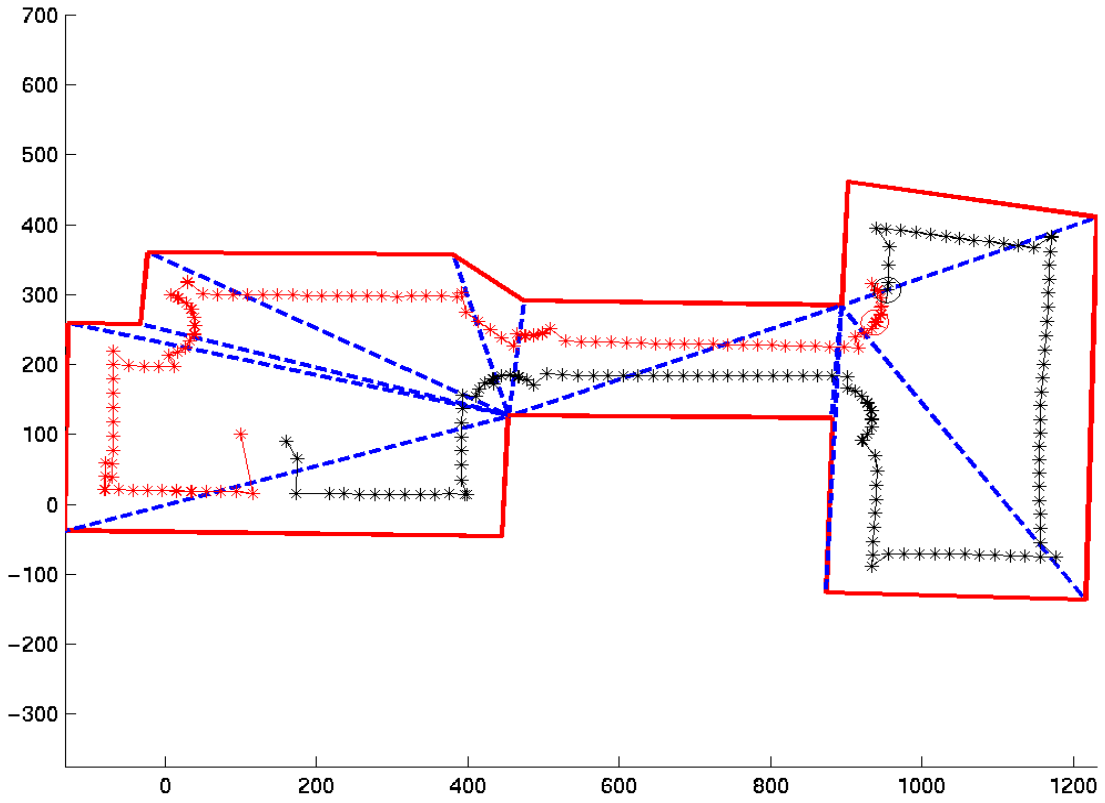


Triangulation Algorithm: Main Ideas

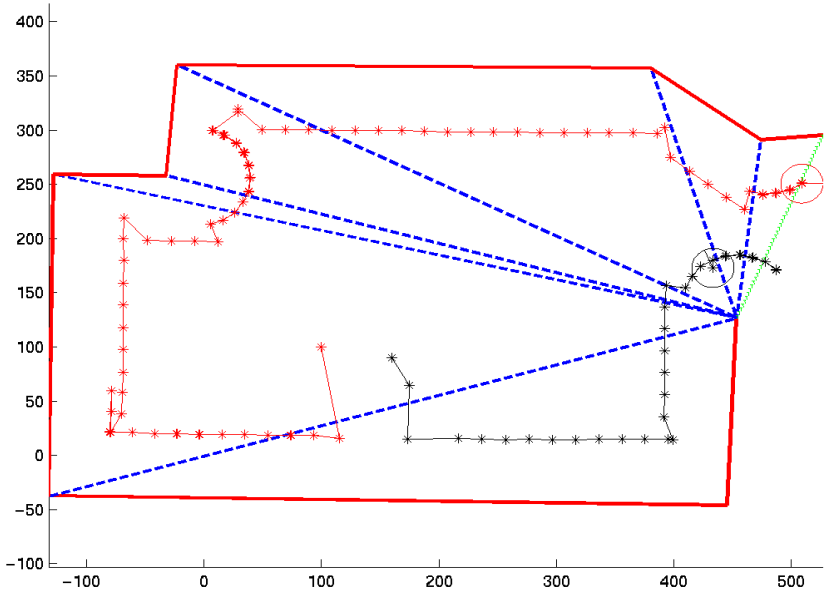
- **Robot Position:**
  - Stationary Robot: Positioned at the corners of the environment (vertices of the polygon).
  - Moving Robot: Follows the walls.
- **Exploration order:** The two robots explore the free space by following the Dual Graph of the Triangulation.
- **Decision points:** Reflex vertices.

Cooperative Exploration

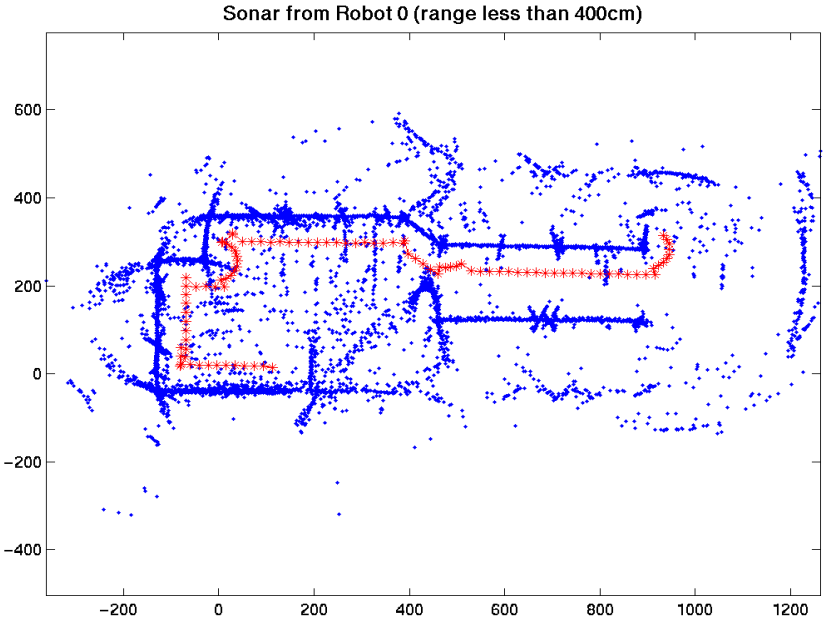
Experimental Results (Triangulation)

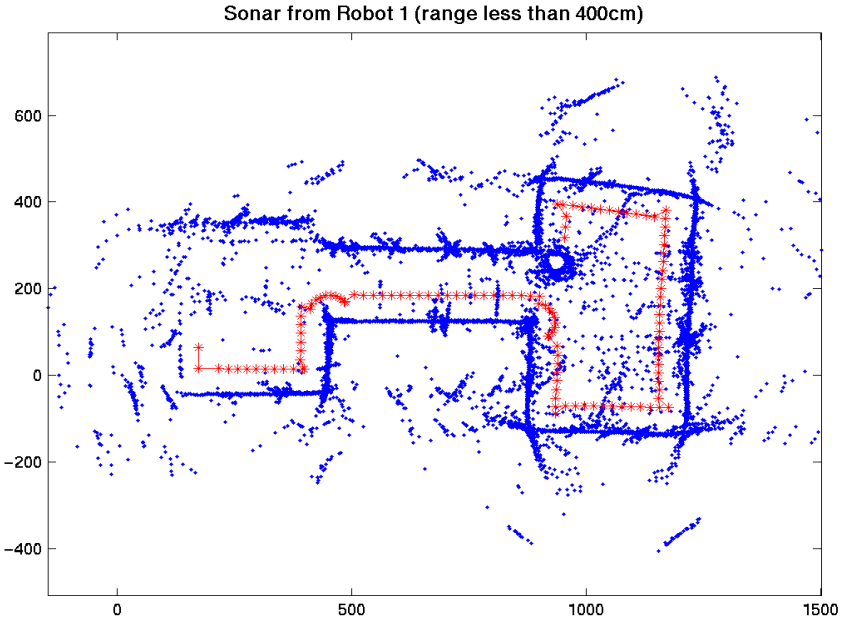


Moving out



2 Laboratories, Sonar Data

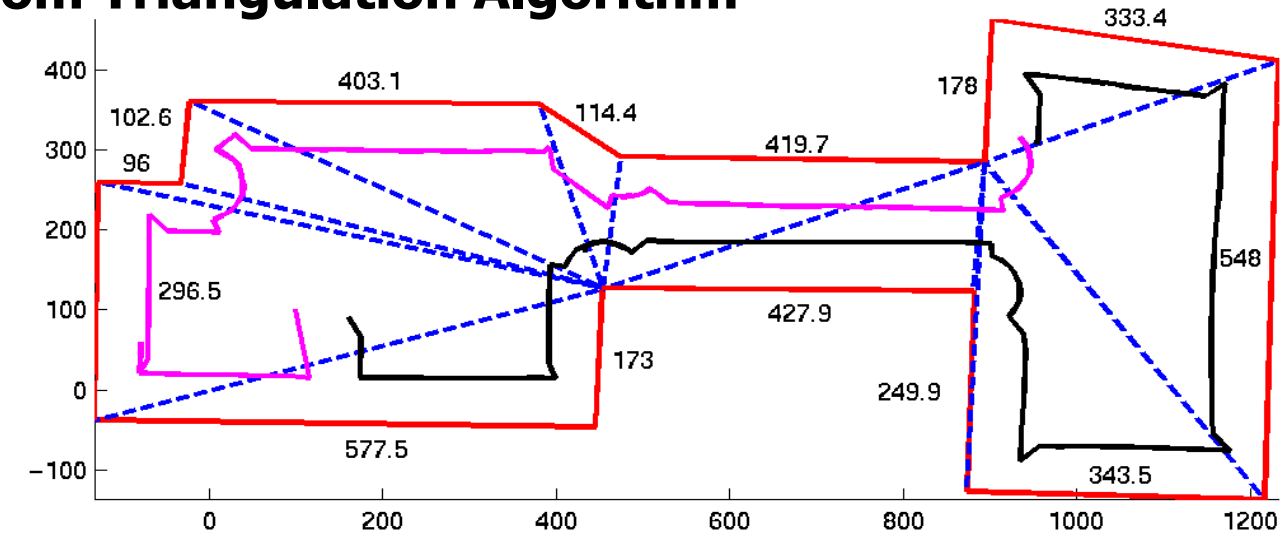




2 Laboratories, Laser Data

Map from Scan Match (S. Gutmann)

Sonar Map from Triangulation Algorithm



Perimeter: 42.71m. Mean error: 0.046m