



UNIVERSITY OF
SOUTH CAROLINA

CSCE 574 ROBOTICS

Multi-Robot Systems





Multi-Robot Complete Coverage

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



Multi Robot Complete Coverage

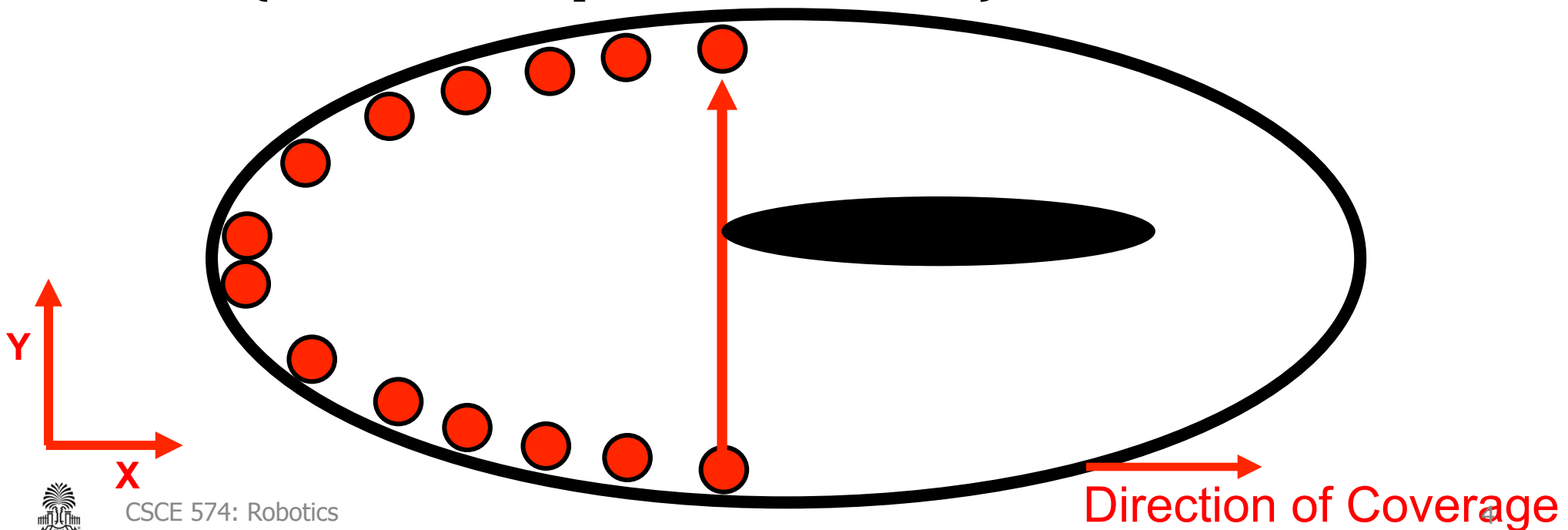
Limited Communication: Main Ideas

- 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)



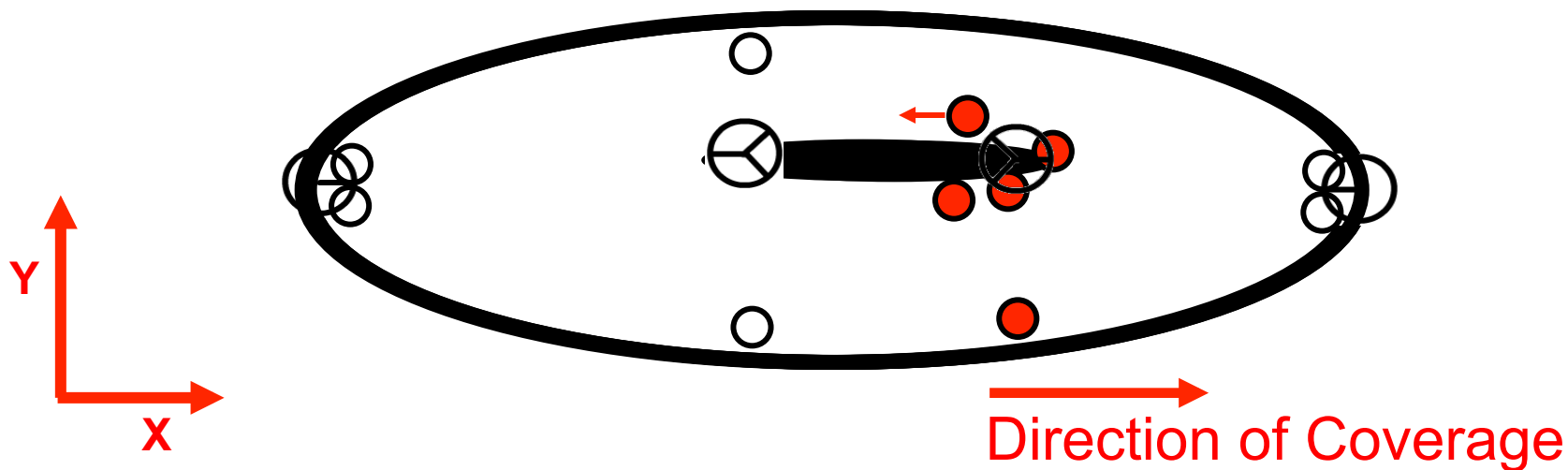
Single Cell Coverage

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



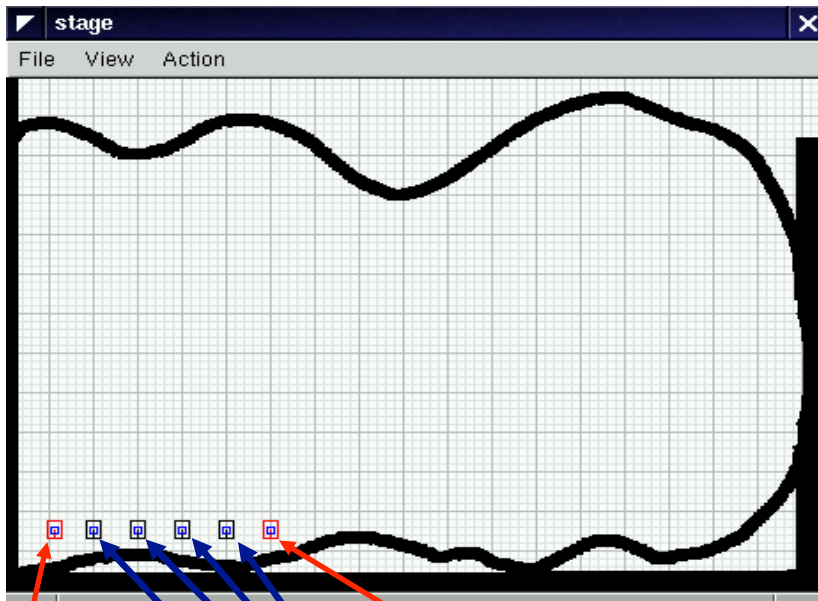
Critical Point Detection

- 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

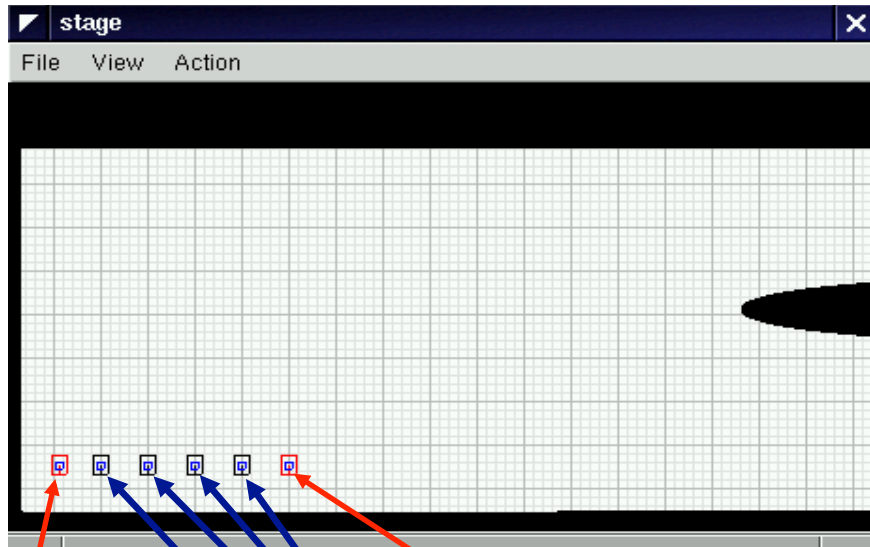


The circles represent the robot position not the sensor footprint.



Single Cell Coverage

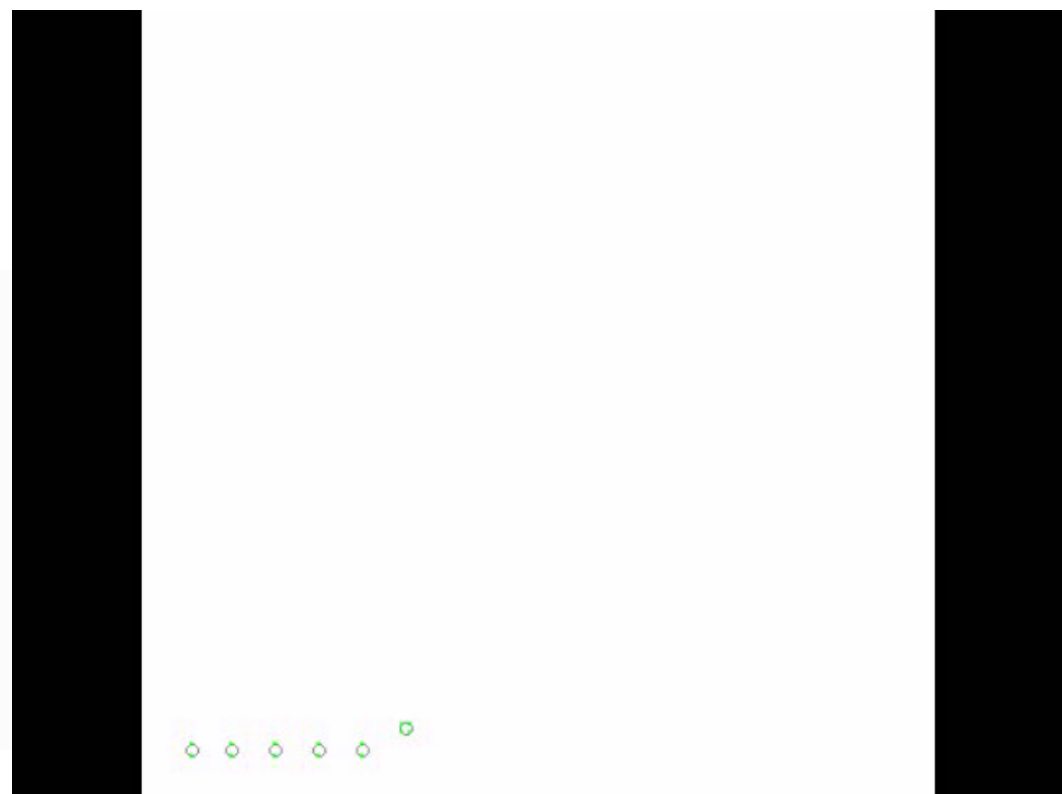
Reverse Convex Critical Point



Top Explorer

Bottom Explorer

Coverers



The circles represent the robot position not the sensor footprint.



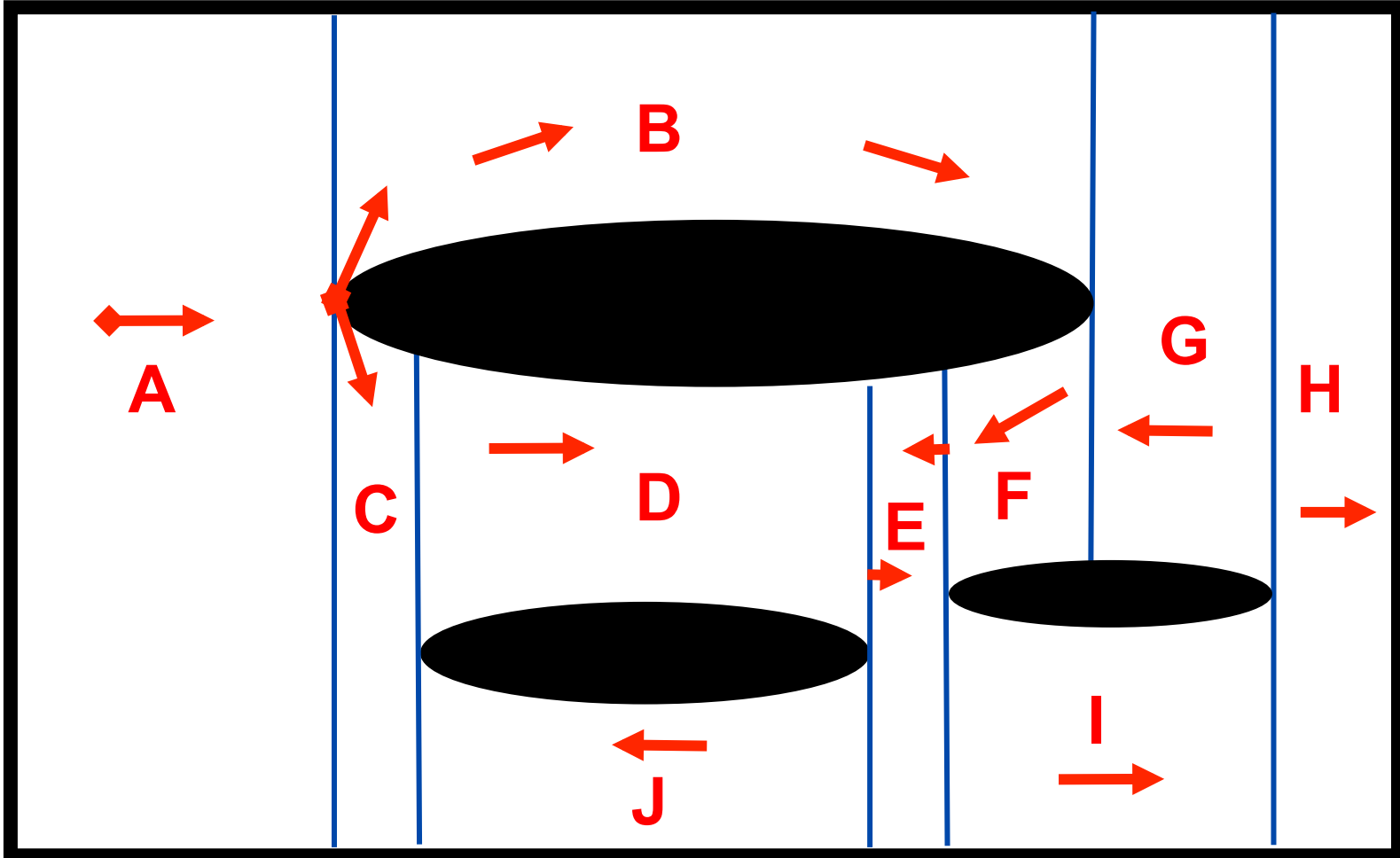
Team Coverage

- 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

→
Coverage direction



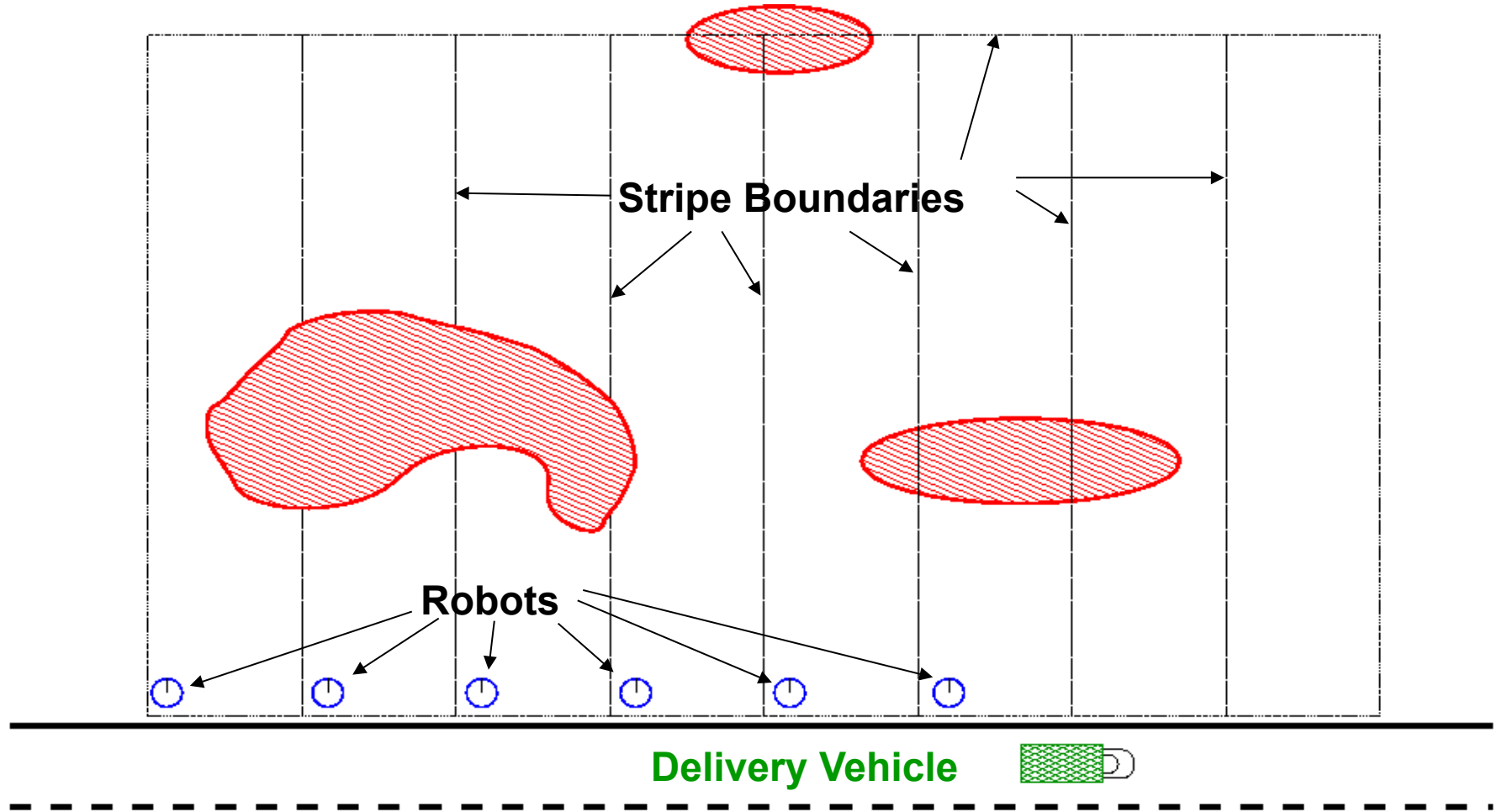
Coverage Example



See: <http://www.cs.cmu.edu/~biorobotics//multi/flashcover.html>



Multi-Robot Coverage Paradigm



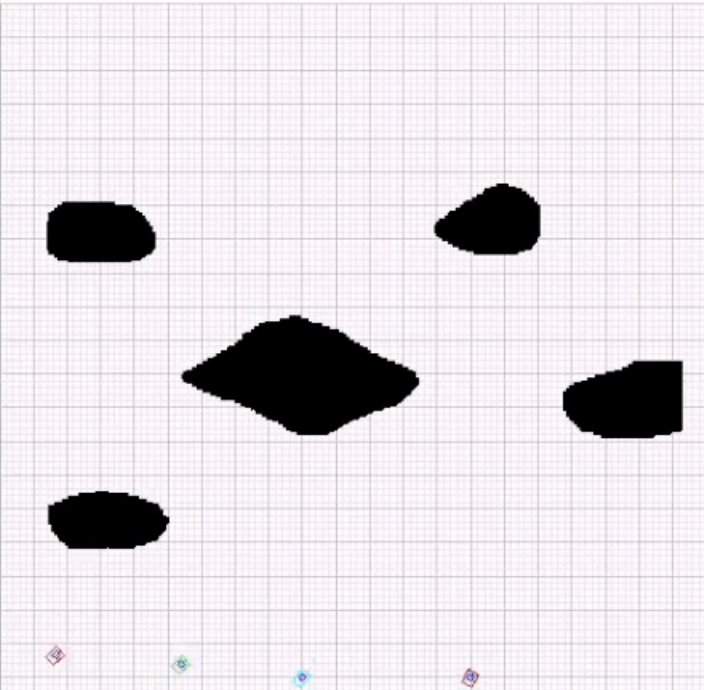
Multi Robot Complete Coverage: Main Ideas

- 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

File View Action



Robot 3 is thinking.



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>

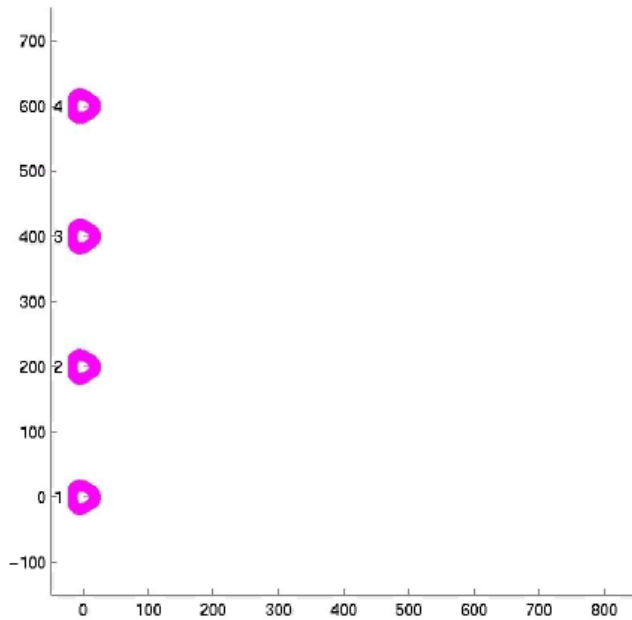


Marsupial Robots

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



Formations



Formations

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



Aerial Formations



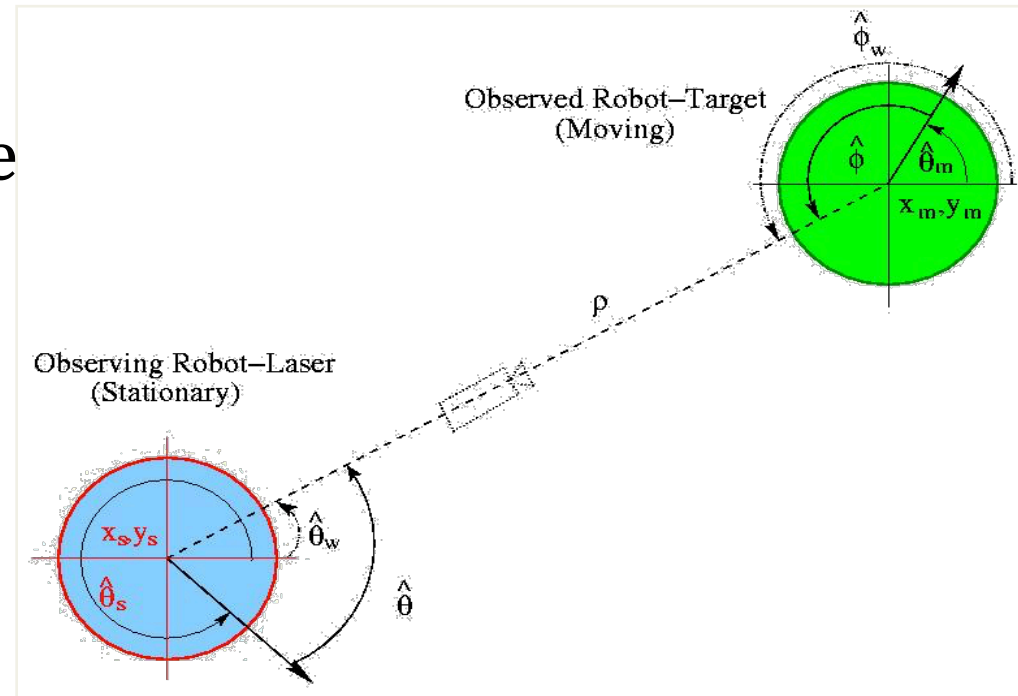


Cooperative Localization, Mapping, and Exploration



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:

$$\langle \rho, \theta, \phi \rangle$$

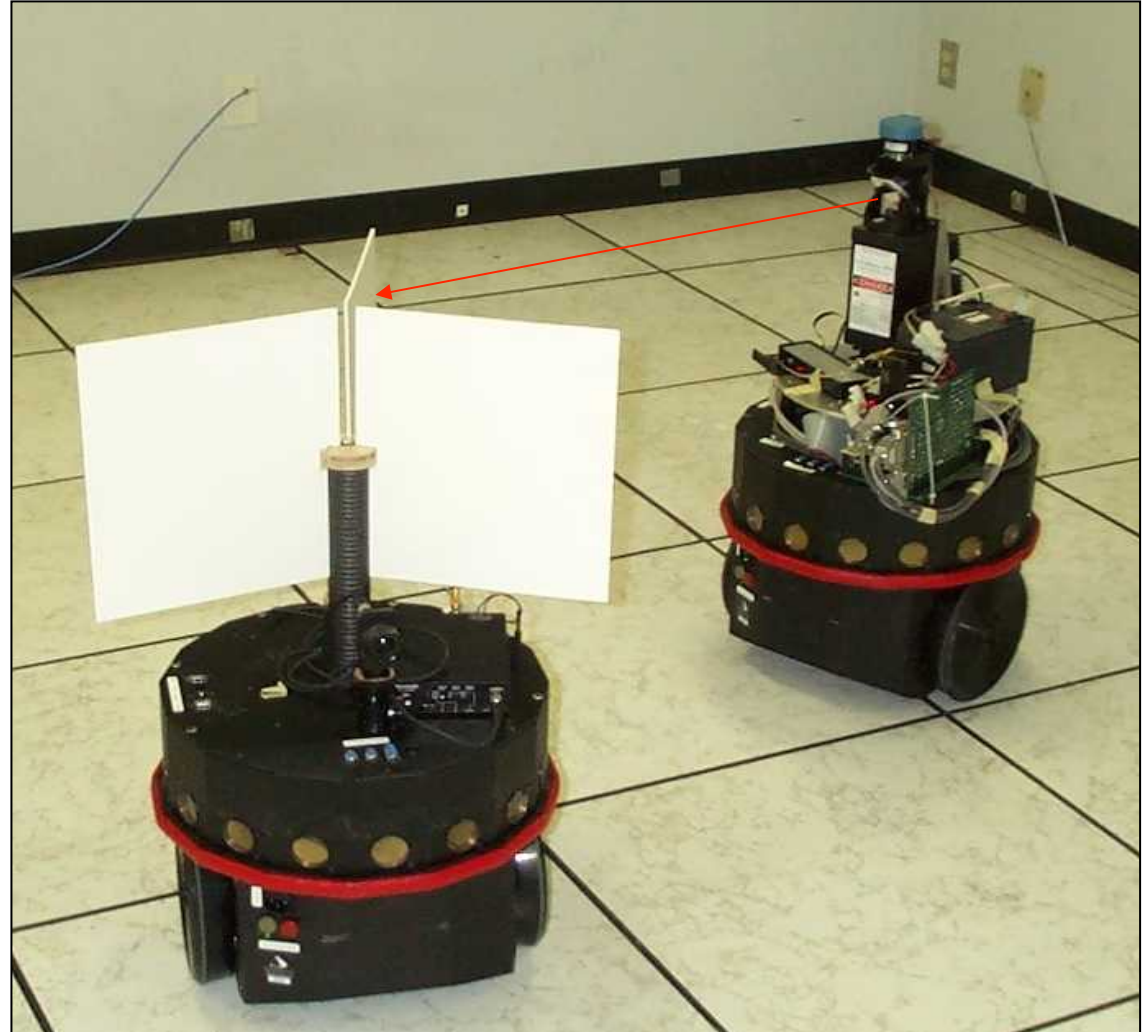
$$\mathbf{x}_{m_{est}}(k+1) = \begin{pmatrix} x_{m_{est}} \\ y_{m_{est}} \\ \theta_{m_{est}} \end{pmatrix} = \begin{pmatrix} x_s + \rho \cos(\theta + \theta_s) \\ y_s + \rho \sin(\theta + \theta_s) \\ \pi - (\phi - (\theta + \theta_s)) \end{pmatrix}$$

Laser Robot Tracker

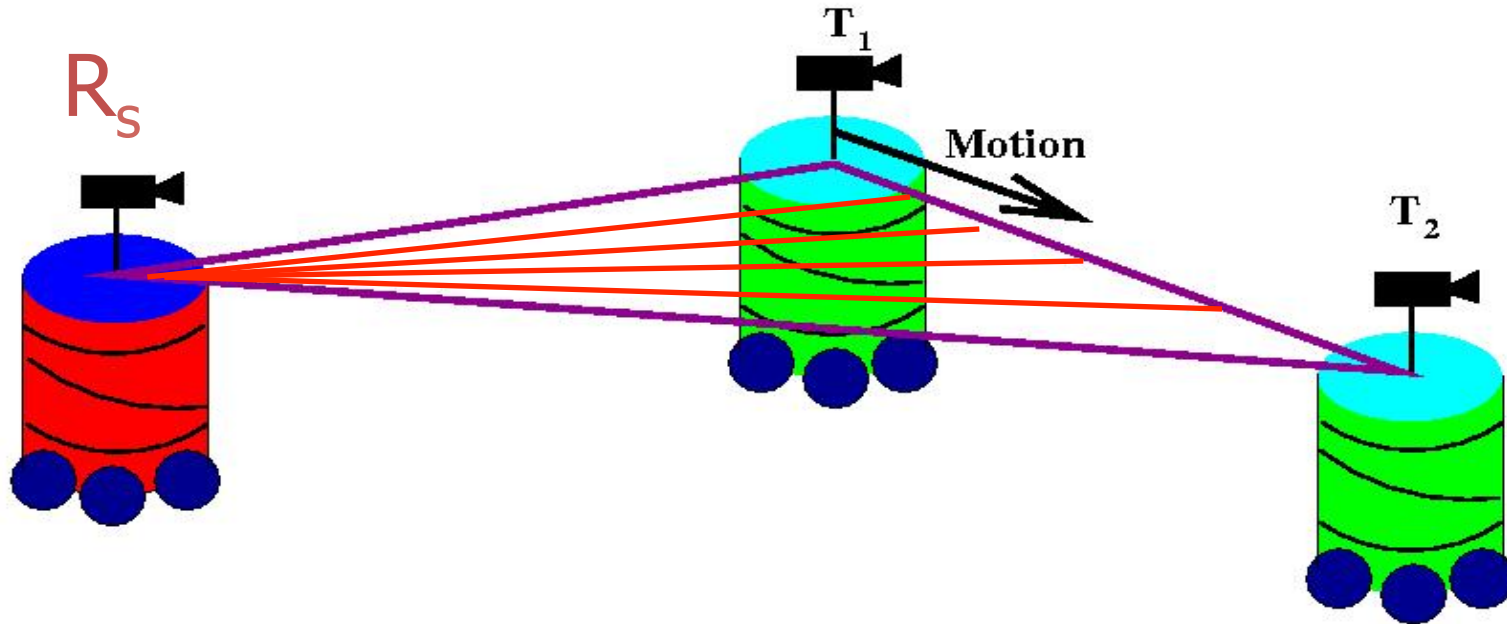


Robot Tracker Returns:

$$\langle \rho, \theta, \phi \rangle$$



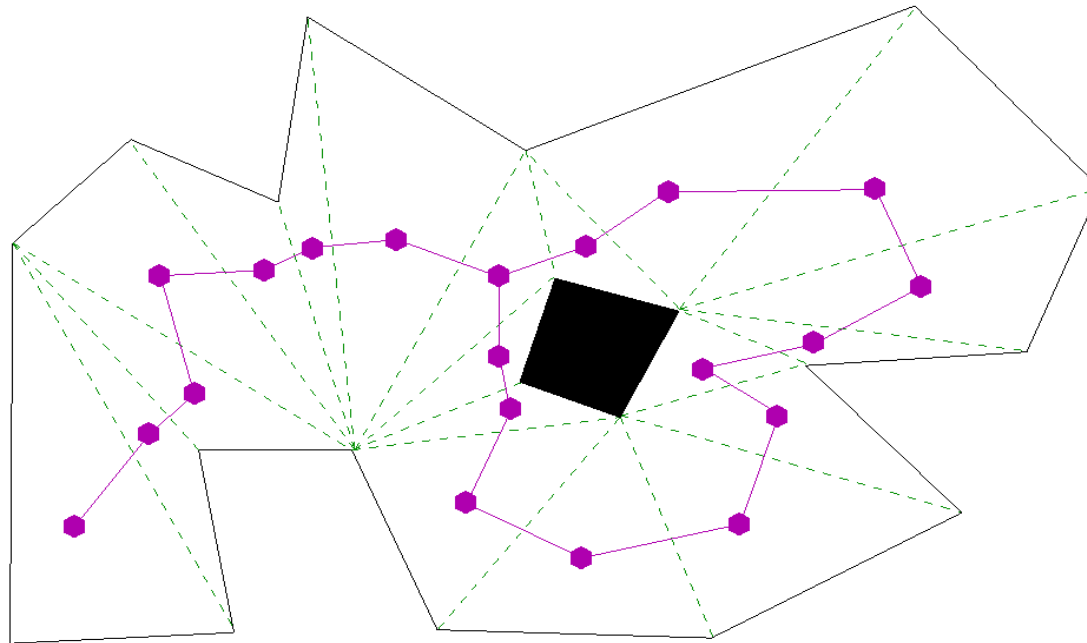
Exploration and Mapping (Triangulation)



- 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

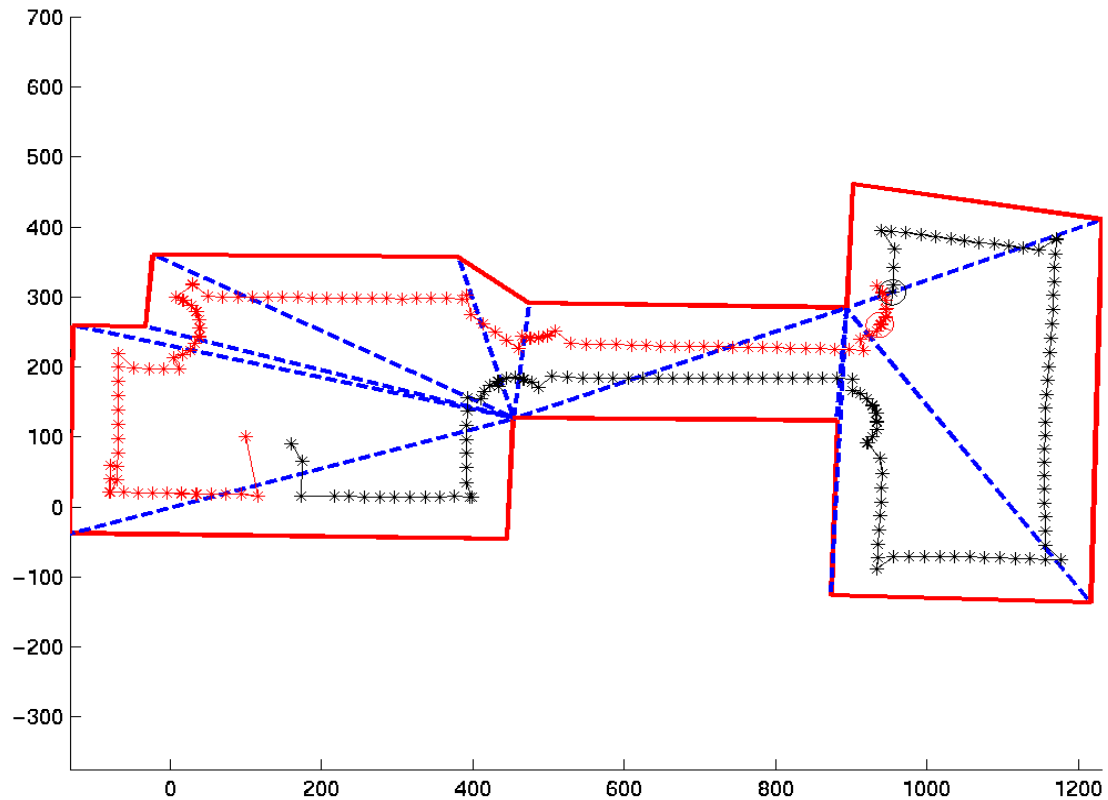
- **Robot Position:**
 - Stationary Robot: Positioned at the corners of the environment (vertices of the polygon).
 - Moving Robot: Follows the walls.
- **Exploration order:** The two robots explore the free space by following the Dual Graph of the Triangulation.
- **Decision points:** Reflex vertices.



Cooperative Exploration

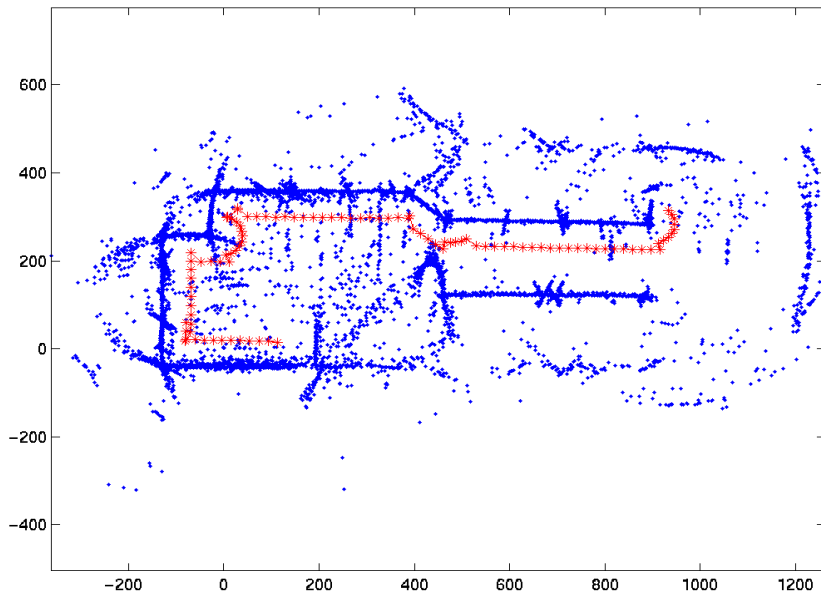


Experimental Results (Triangulation)

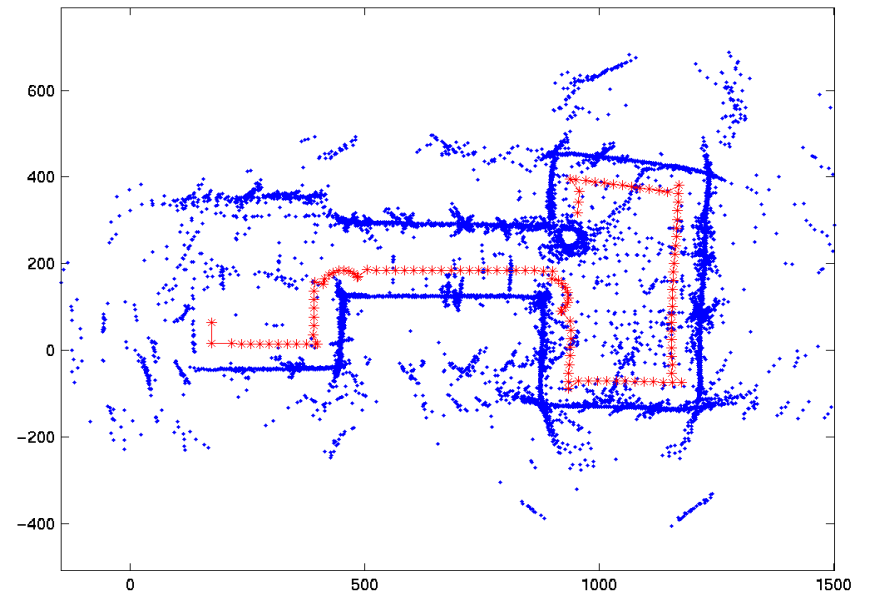


2 Laboratories, Sonar Data

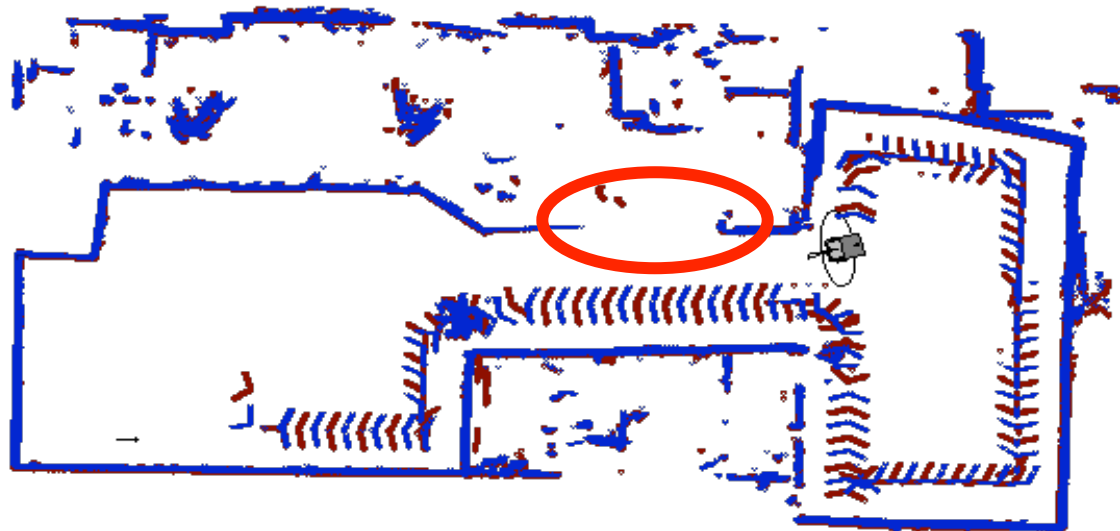
Sonar from Robot 0 (range less than 400cm)



Sonar from Robot 1 (range less than 400cm)



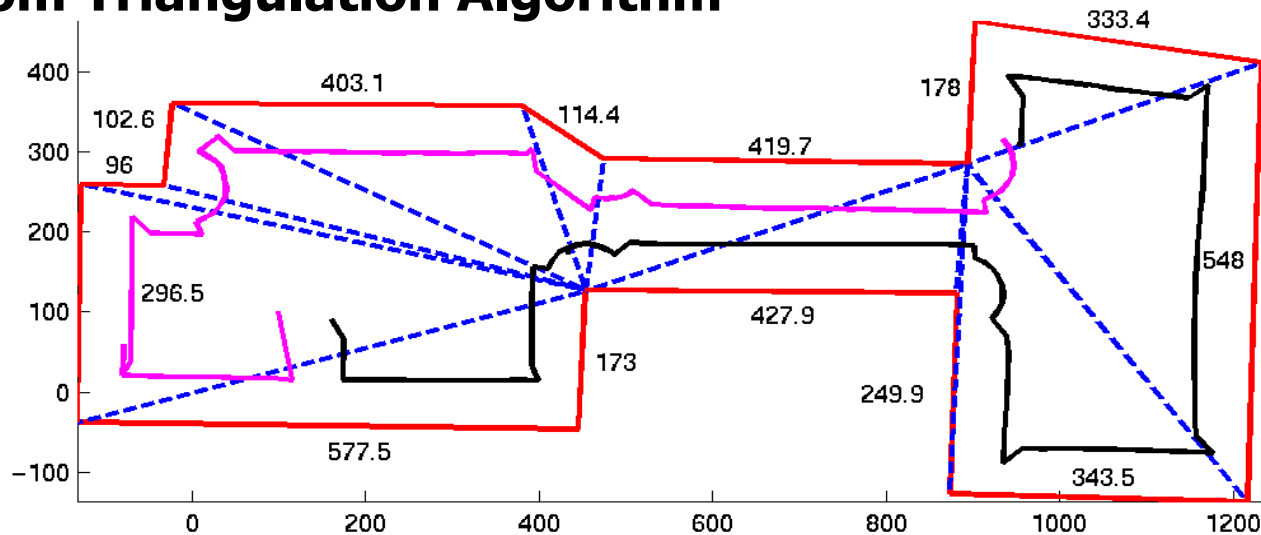
2 Laboratories, Laser Data



Map from Scan Match (S. Gutmann)



Sonar Map from Triangulation Algorithm



Perimeter: 42.71m. Mean error: 0.046m