Multi-Robot Complete Coverage

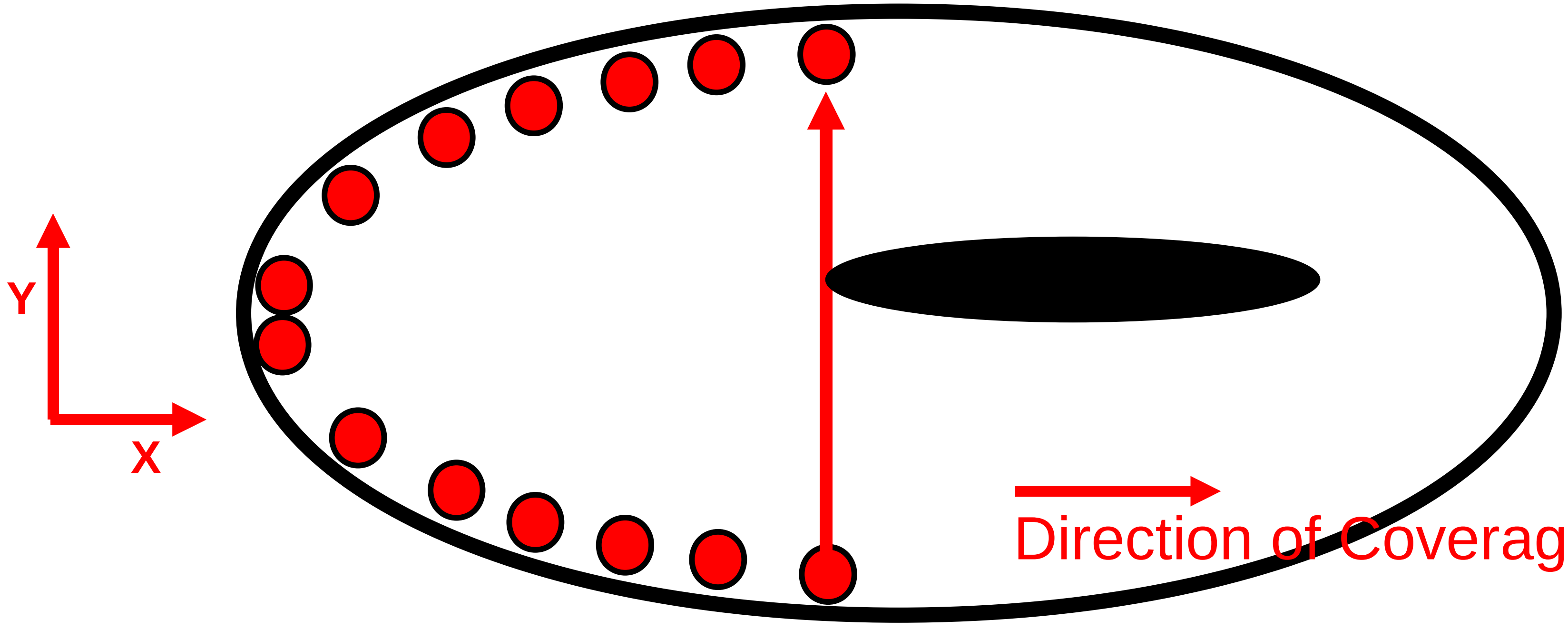
- Multiple Robots:
  - Efficiency
  - Robustness
  - Higher Complexity
- Inter-Robot Communication Abilities
- Guarantee of Complete Coverage

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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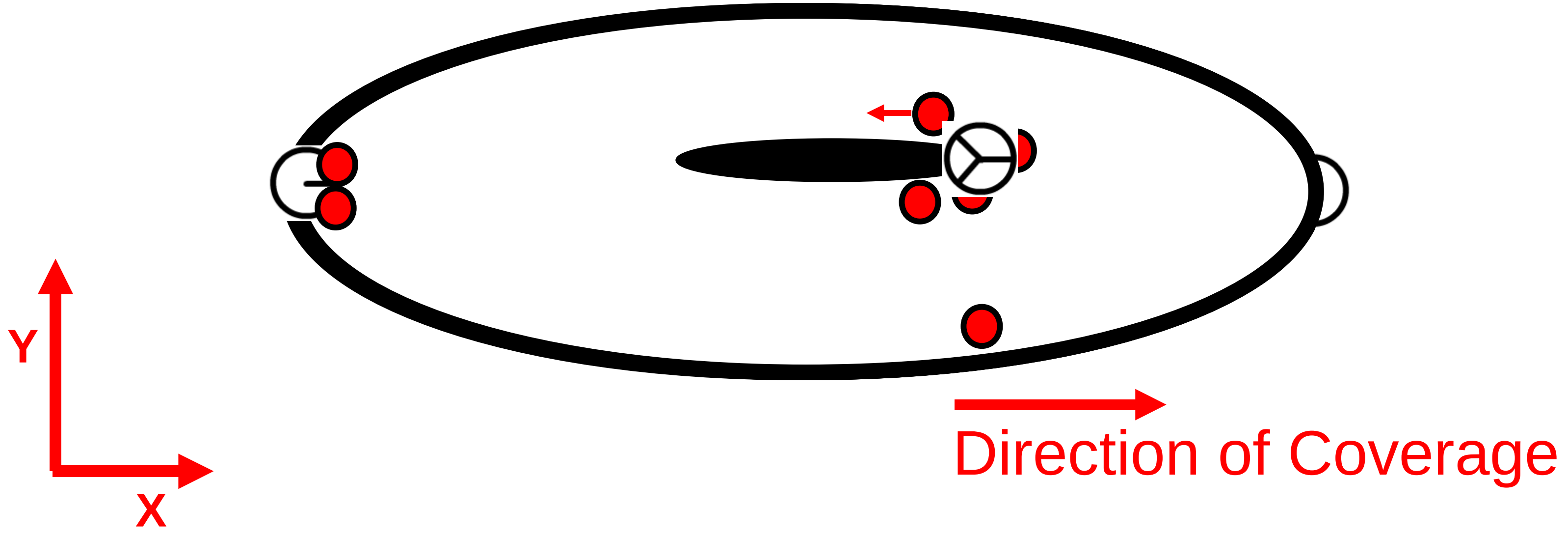
- The explorers trace the top and bottom border of the Cell maintaining the same X-coordinate until the Line of Sight is broken (i.e. a critical point is detected)
- The coverers use an up-and-down motion to cover the interior of the cell

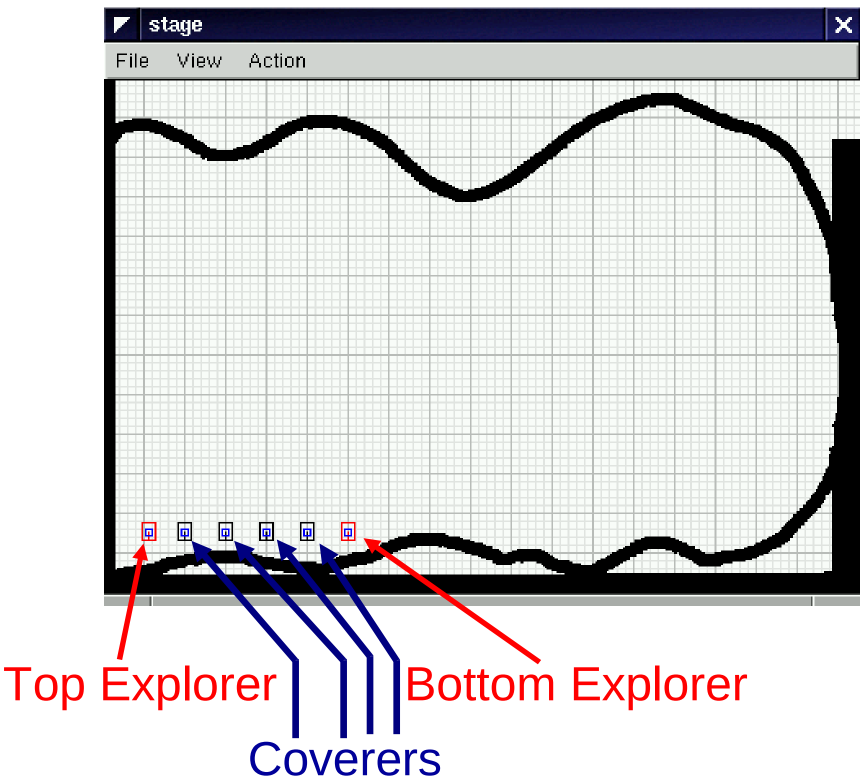
Critical Point Detection

- 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

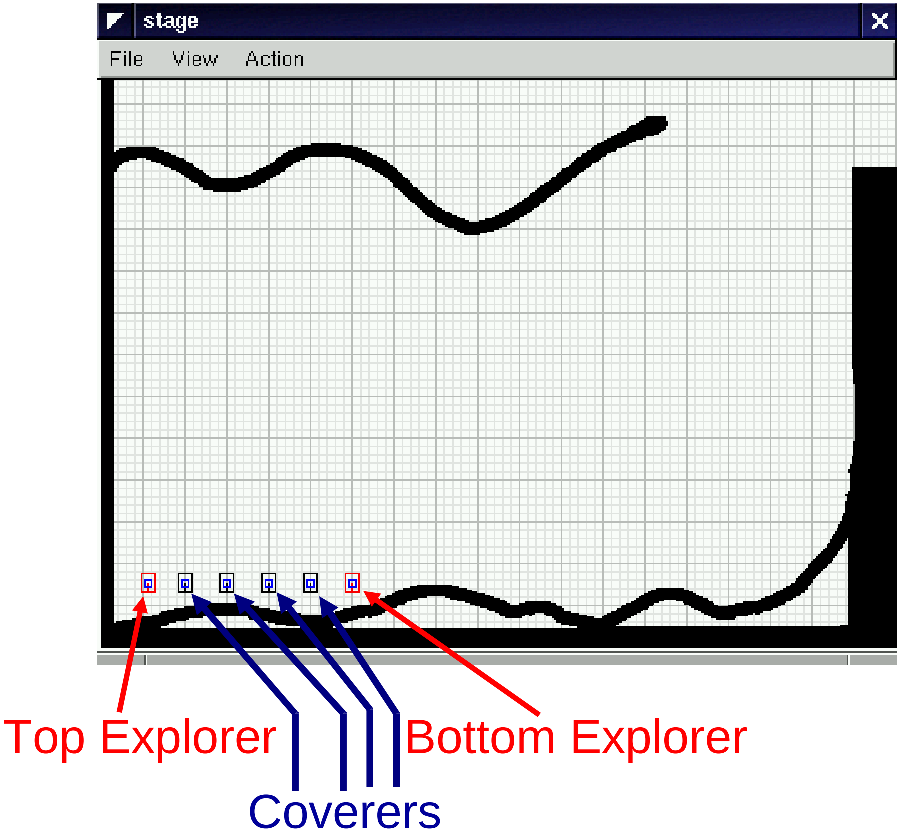
Reverse Concave Critical Point

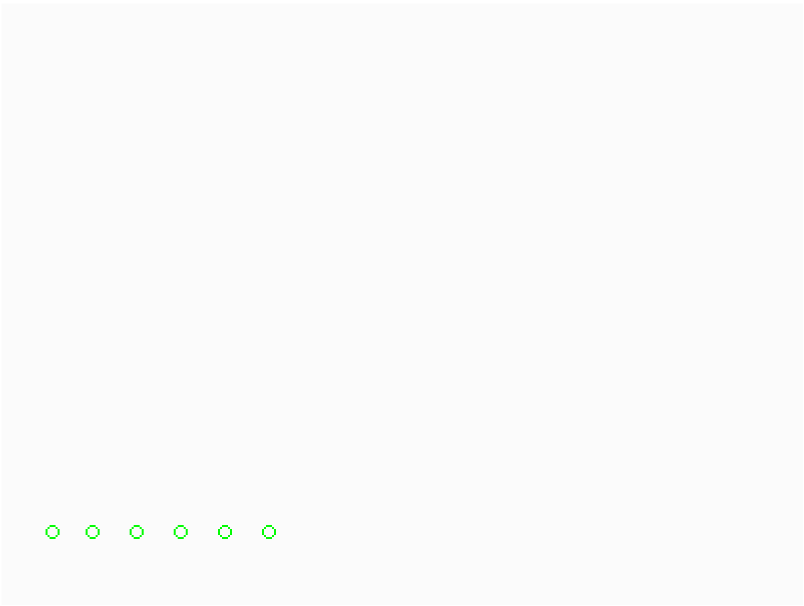


The circles represent the robot position not the sensor footprint.

Single Cell Coverage

Forward Convex Critical Point





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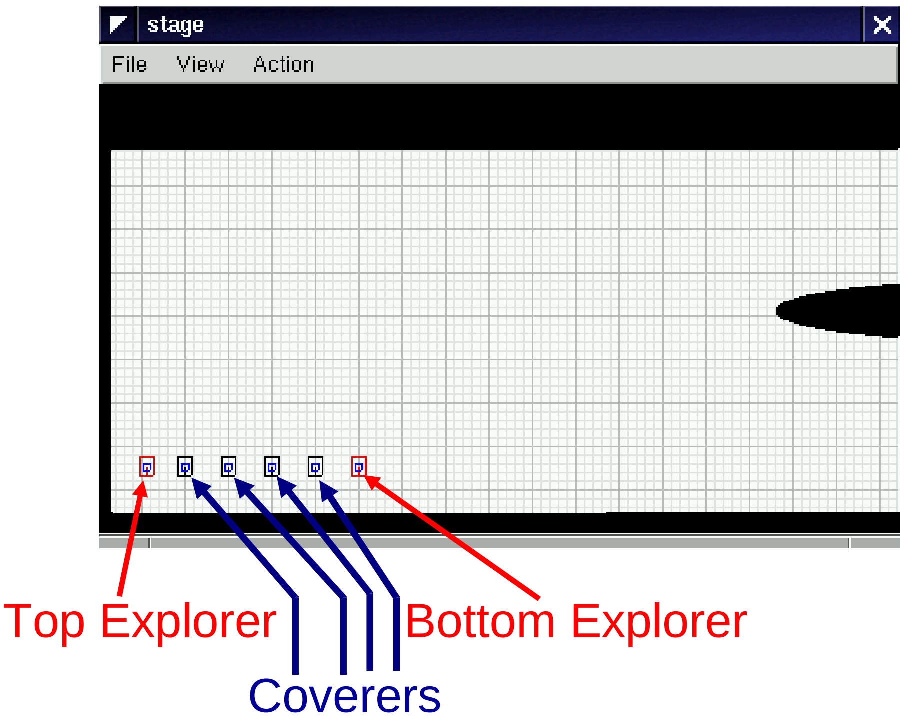
Single Cell Coverage

Reverse Convex Critical Point

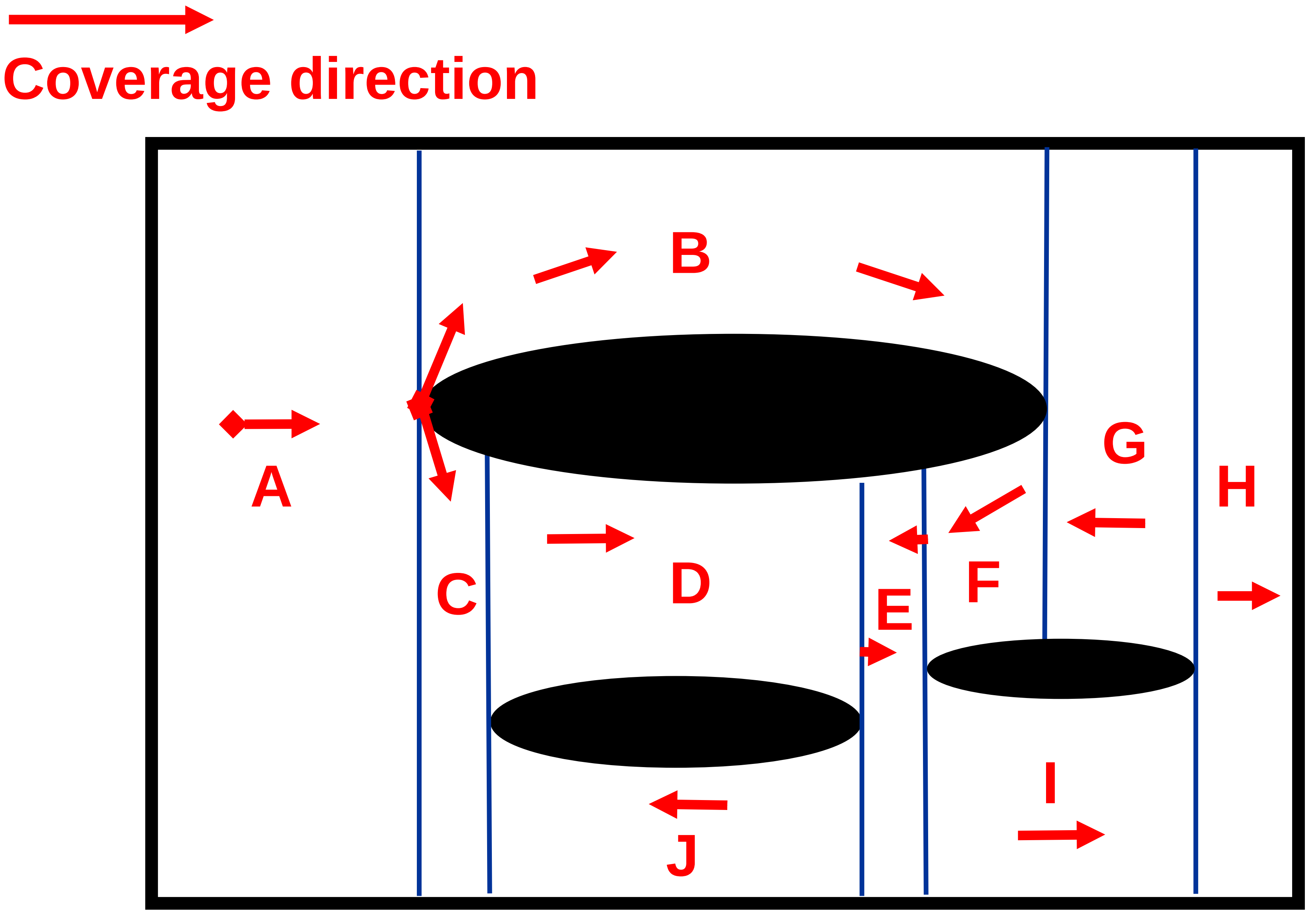


The circles represent the robot position not the sensor footprint.

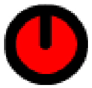
Team Coverage

- 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

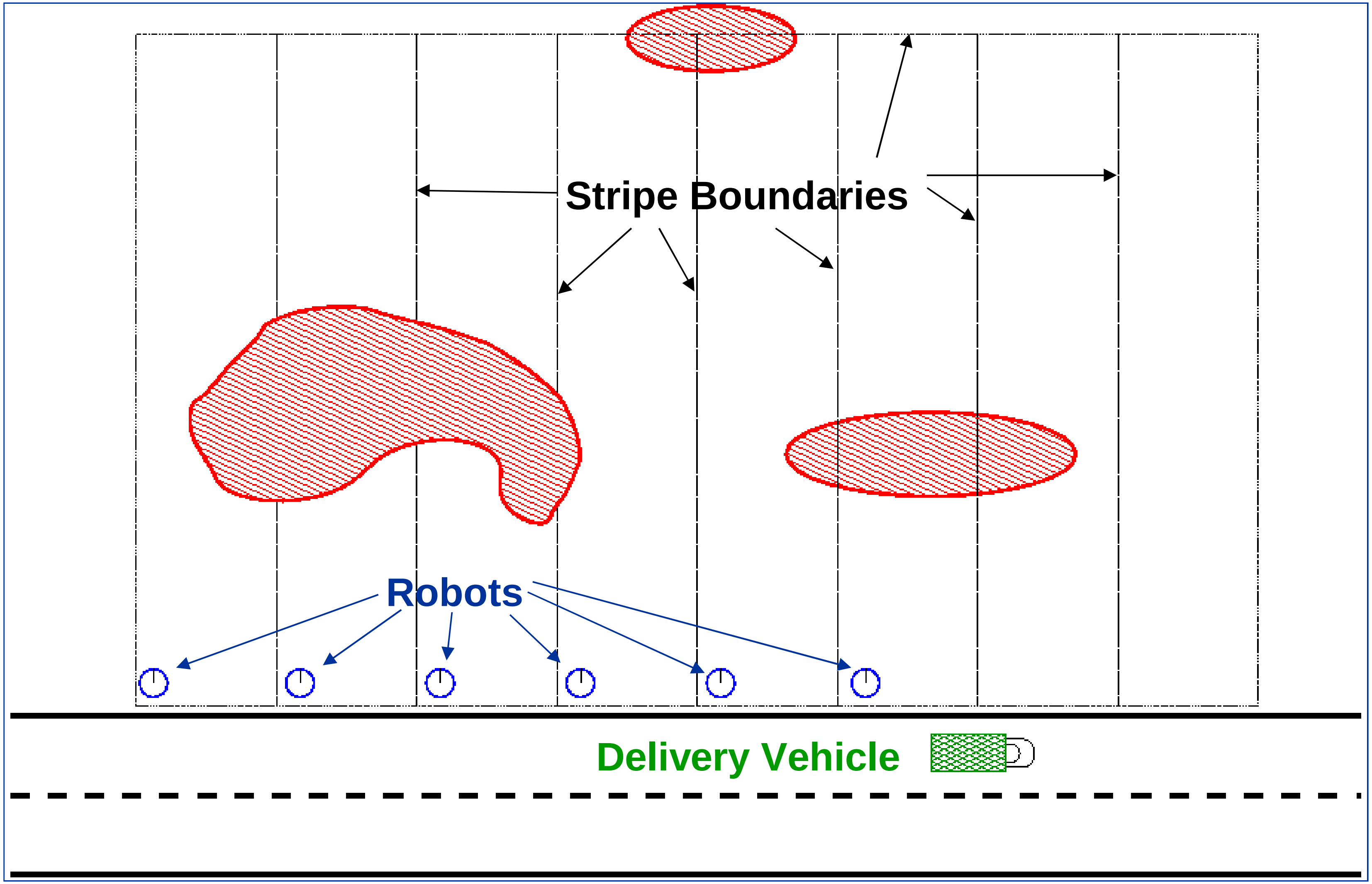
Team Splitting and Rejoining



Coverage Example



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

- See it on vlc…

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

More Multi-Robot Ideas

- Marsupial Robots

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

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

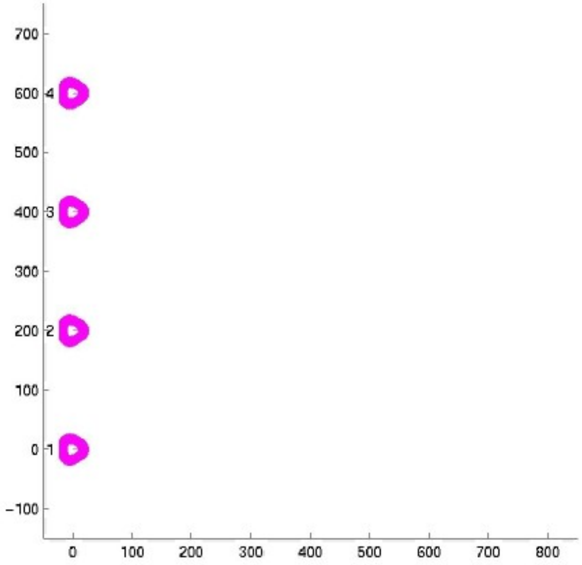
More Multi-Robot Ideas

- Marsupial Robots

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

More Multi-Robot Ideas

- Formations

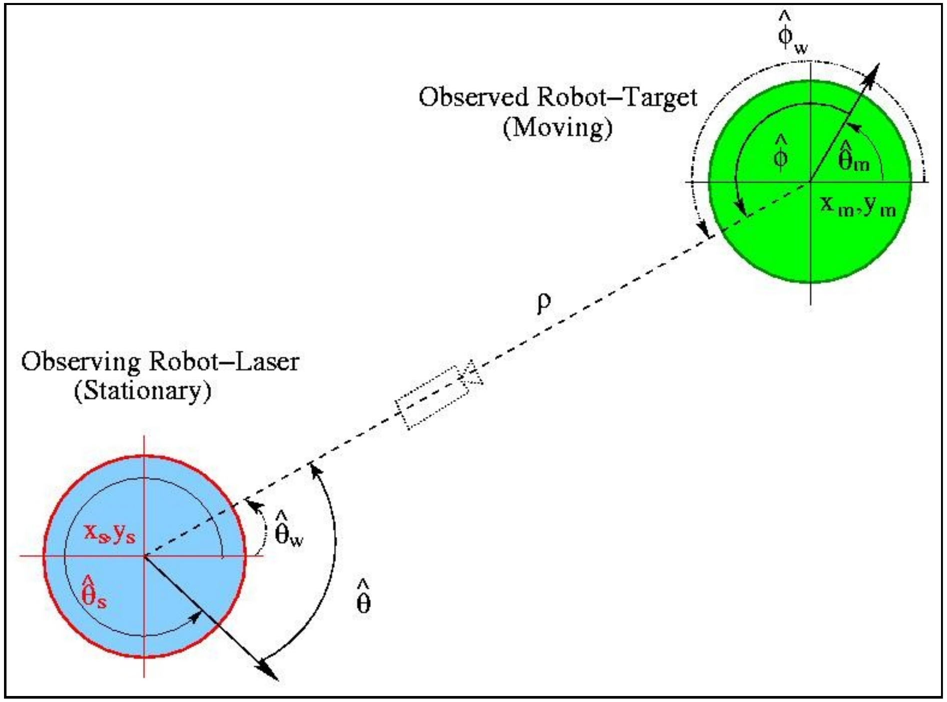


More Multi-Robot Ideas

- 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.

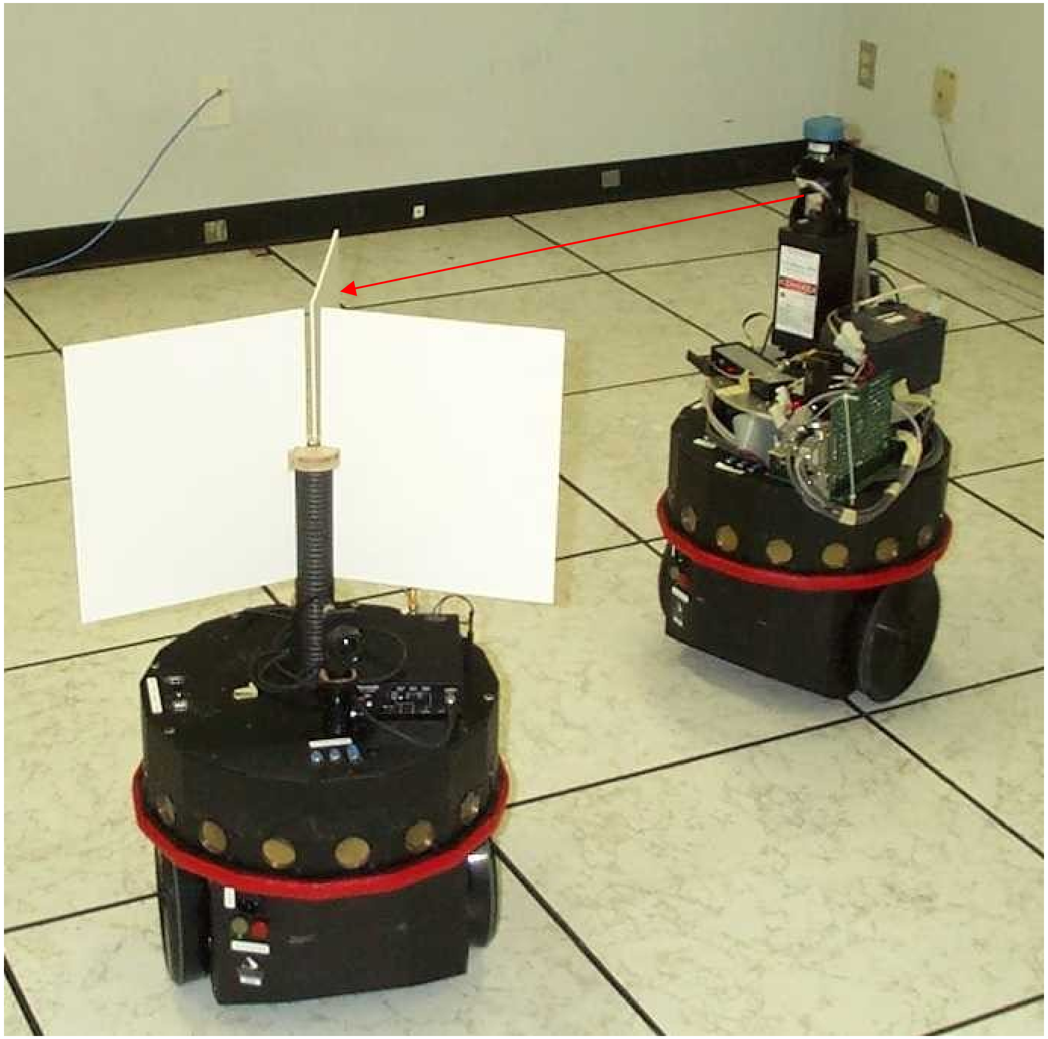


Robot Tracker Returns:

<ρ ,θ ,φ >

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

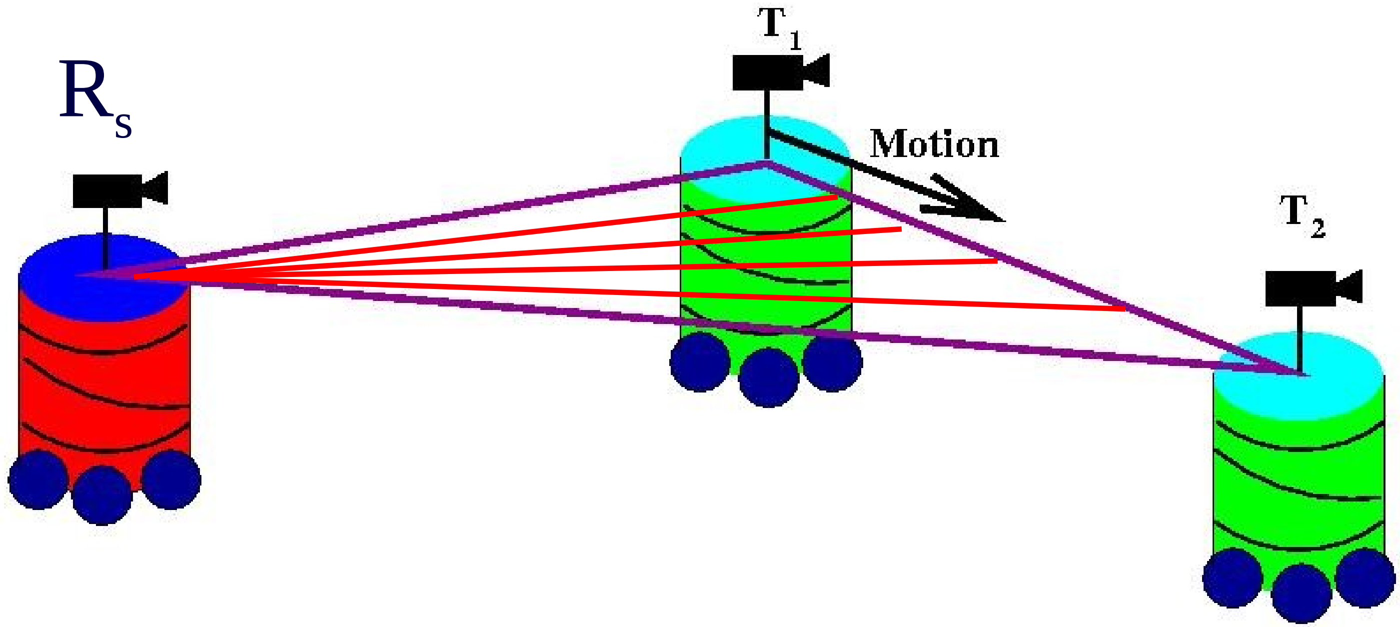
Laser Robot Tracker



Robot Tracker Returns:

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

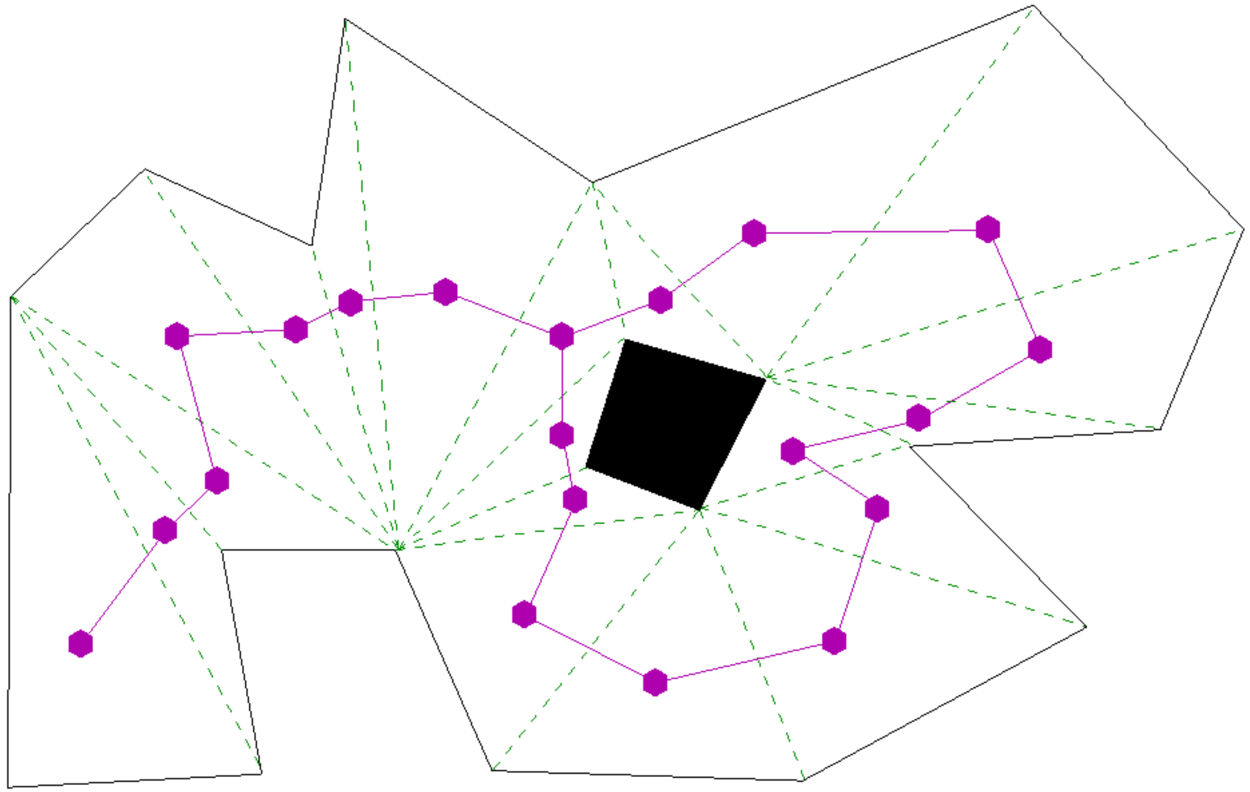
Exploration and Mapping
(Triangulation)



- 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

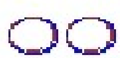


- **Bounded Area:** The range of the tracker sensor is larger than any diagonal of the environment

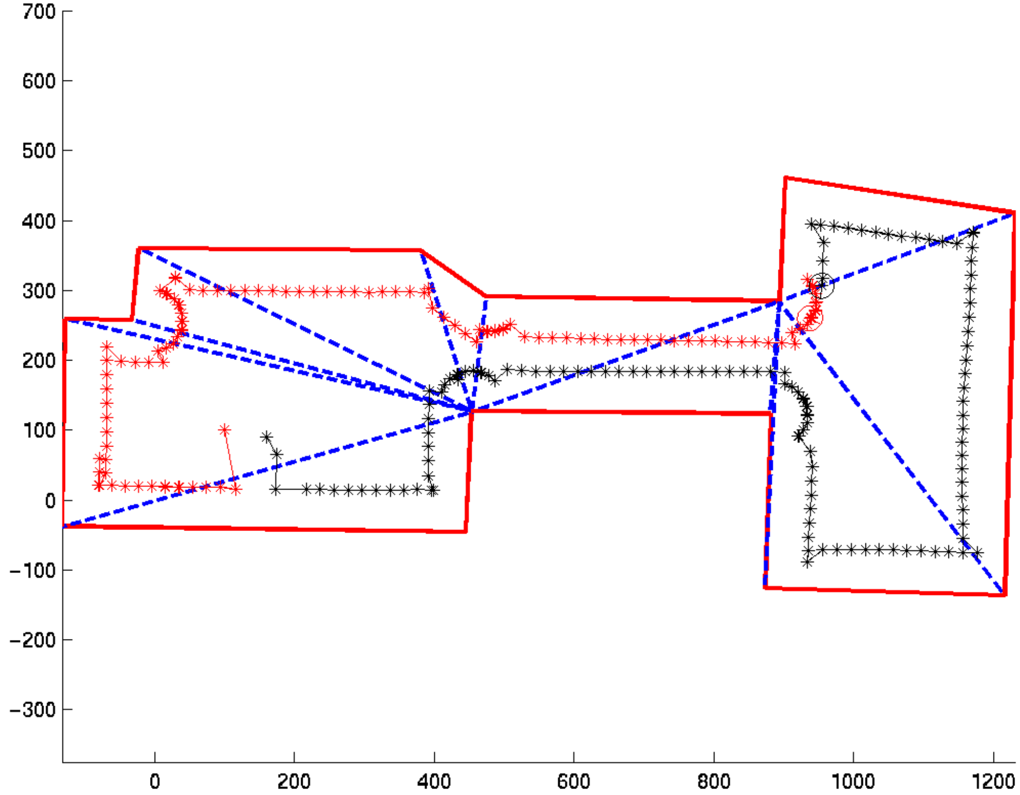
Triangulation Algorithm: Main Ideas

- **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

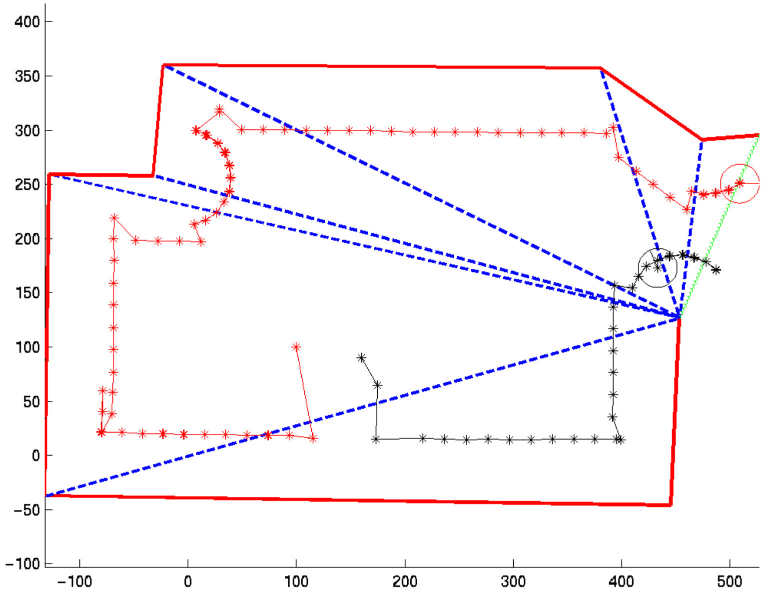


Experimental Results (Triangulation)

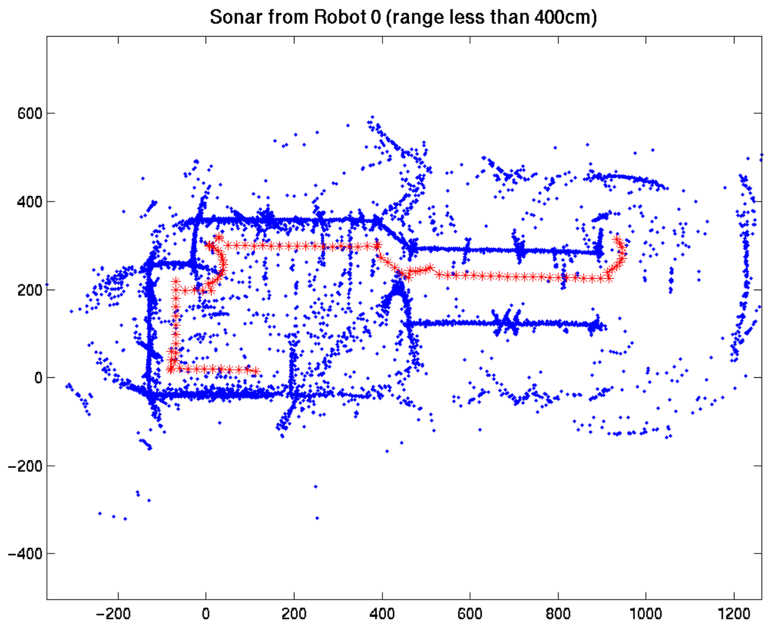


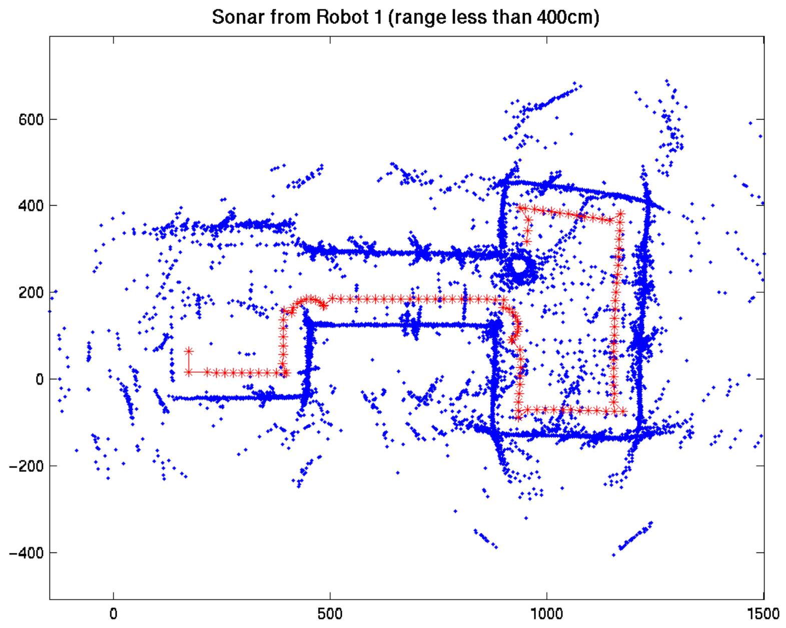
Mapping of two Laboratories

Moving out



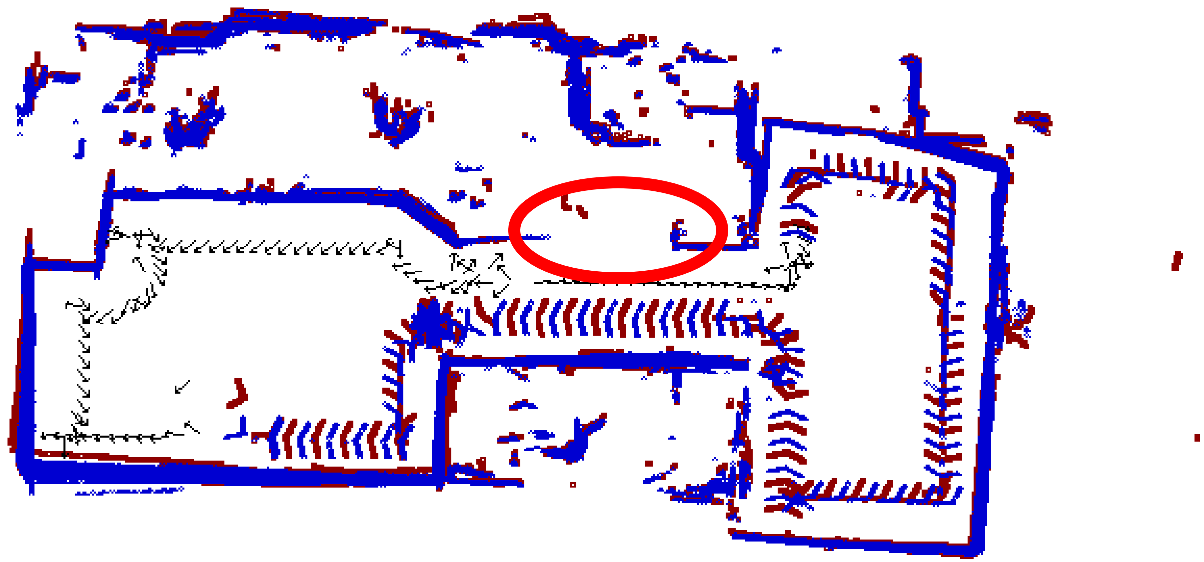
2 Laboratories, Sonar Data



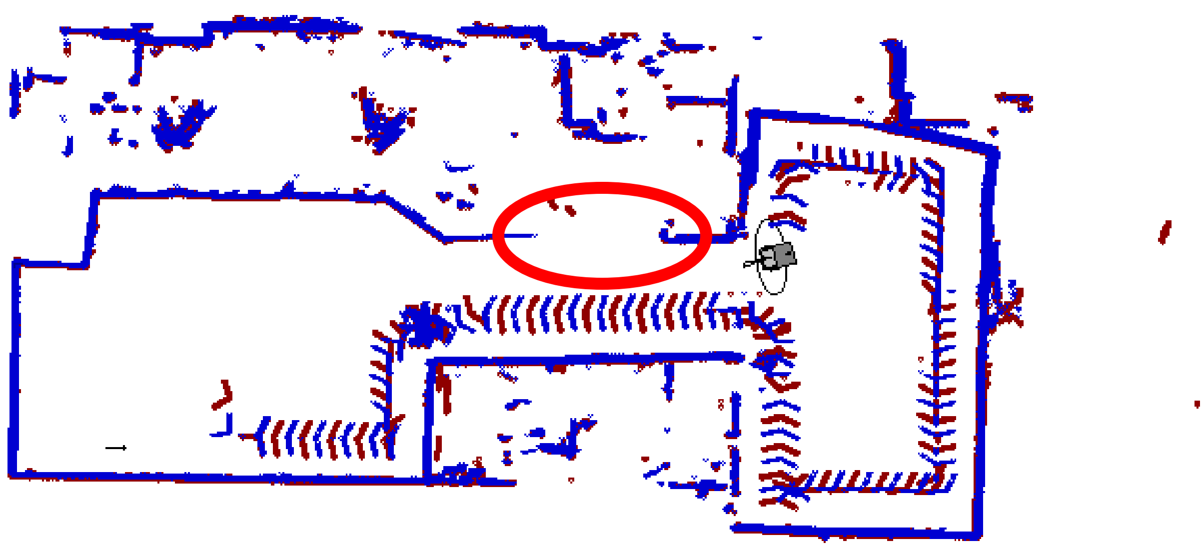


2 Laboratories, Laser Data

All Data



Scan Matched



Using S. Gutmann s/w based on Lu and Milios algorithm.

Map from Scan Match (S. Gutmann)