Coverage
Motivation
Humanitarian Demining
Motivation
Lawn Mowing
Motivation
Vacuum Cleaning
Robotic Coverage

- More than 2 million Roombas sold!
- Automated Car Painting
Coverage

• First Distinction
  – Deterministic  Demining
  – Random  Vacuum Cleaning

• Second Distinction
  – Complete
  – No Guarantee

• Third Distinction
  – Known Environment
  – Unknown Environment
Non-Deterministic Coverage

• Complete Random Walk
• Ant Robotics
  – Leave trail
  – Bias the behavior towards or away from the trails

S. Koenig Ant Robotics, terrain coverage

Andrew Russell, Monash University, Australia

Ant Robotics: I. Wagner, IBM & Technion
Deterministic Coverage

- Complete Algorithm
- Guarantees Complete Coverage
Two families of methods:

- **Exact cell decomposition**
  The free space $F$ is represented by a collection of non-overlapping cells whose union is exactly $F$

**Examples:** trapezoidal and cylindrical decompositions
Boustrophedon Cellular Decomposition

The way of the Ox!
Cellular Decomposition

Critical Point (CP)

Cell 0

Direction of Coverage
Single Cell Coverage

Direction of Coverage
Cellular Decomposition

Direction of Coverage

Reeb Graph
Critical Points

There are four types of critical points:
- Forward Concave critical point
- Reverse Concave critical point
- Reverse Convex critical point
- Forward Convex critical point

Direction of Coverage
Demining in Action (almost)
Cell decomposition for Path Planning

- Decompose the free space into simple cells and represent the connectivity of the free space by the adjacency graph of these cells
Trapezoidal decomposition
Spatial decompositions

Dividing free space into pieces and using those...
Spatial decompositions

Dividing free space into pieces and using those...

Exact cell decomposition
sweepline algorithm

Running time?
Spatial decompositions

Dividing free space into pieces and using those...

Exact cell decomposition
sweepline algorithm

Running time?
Path?

O( N log(N) )
Spatial decompositions

Dividing free space into pieces and using those...

Exact cell decomposition
sweepline algorithm

Running time? \( O( N \log(N) ) \)
Path? via centroids
Spatial decompositions

Dividing free space into pieces and using those...

Exact cell decomposition

sweepline algorithm

Running time?

Path?

$O( N \log(N) )$

via centroids
+ edge midpoints
Spatial decompositions

Dividing free space into pieces and using those...

Exact cell decomposition
  sweepline algorithm

Running time?
  $O( N \log(N) )$

Path?
  via centroids + edge midpoints + graph search

Why?
  why else?
Obtaining the *minimum* number of convex cells is NP-complete.

Trapezoidal decomposition is exact and complete, but not optimal -- even among convex subdivisions.

there may be more detail in the world than the task needs to worry about...
Cell-Decomposition Methods

Two families of methods:

- **Exact cell decomposition**
- **Approximate cell decomposition**

F is represented by a collection of non-overlapping cells whose union is contained in F

**Examples:** quadtree, octree, $2^n$-tree
Approximate cell decomposition

Quadtree: recursively subdivides each *mixed* obstacle/free (sub)region into four quarters...
further decomposing...

Approximate cell decomposition

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further decomposing...

Approximate cell decomposition

Again, use a graph-search algorithm to find a path from the start to goal

Quadtree

is this a complete path-planning algorithm? i.e., does it find a path when one exists?
Octree Decomposition
Coverage of Known Worlds

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)
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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

The circles represent the robot position not the sensor footprint.
Single Cell Coverage

Forward Convex Critical Point

The circles represent the robot position not the sensor footprint.
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 direction
Coverage Example
Multi-Robot Coverage Paradigm

Delivery Vehicle

Robots

Stripe Boundaries
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 improve 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

More Multi-Robot Ideas

- Marsupial Robots

From: http://distrob.cs.umn.edu/demos.php
More Multi-Robot Ideas

• Formations