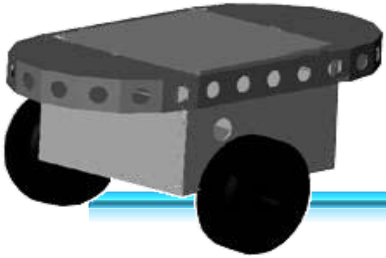
CS-417 Introduction to Robotics and Intelligent Systems

Coverage

Ioannis Rekleitis

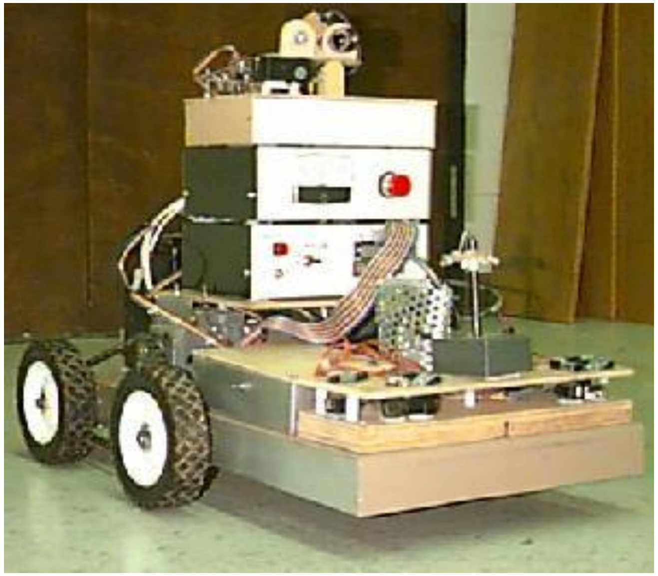


Motivation

Humanitarian Demining

Motivation

Lawn Mowing



Motivation

Vacuum Cleaning

Robotic Coverage

- More than 5 million Roombas sold!
- Automated Car Painting

Roomba Costumes

From: http://www.myroombud.com/

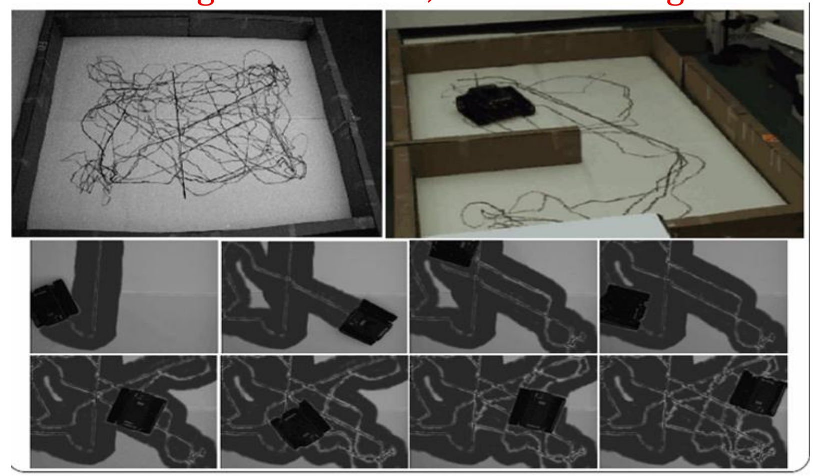
Coverage

- First Distinction
  - Deterministic **Demining**
  - Random **Vacuum Cleaning**
- Second Distinction
  - Complete
  - No Guarantee
- Third Distinction
  - Known Environment
  - Unknown Environment

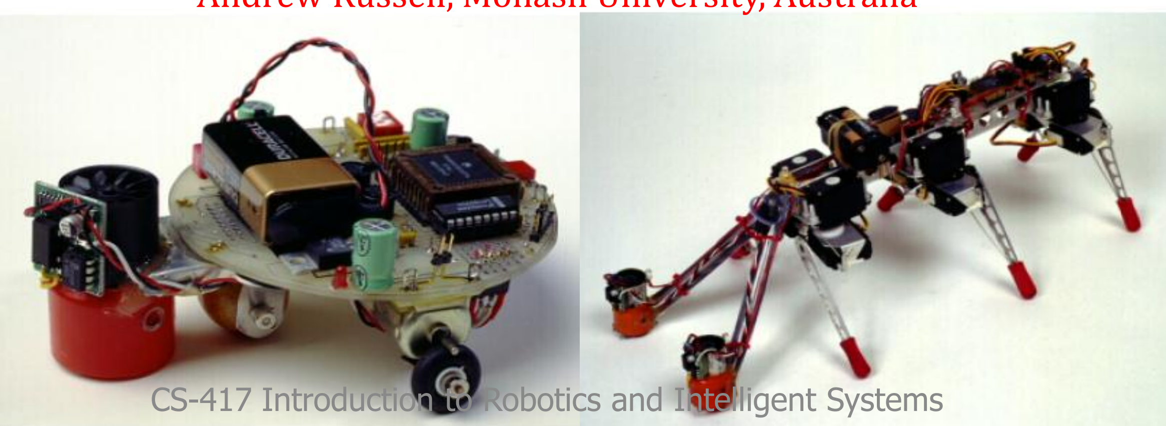
Non-Deterministic Coverage

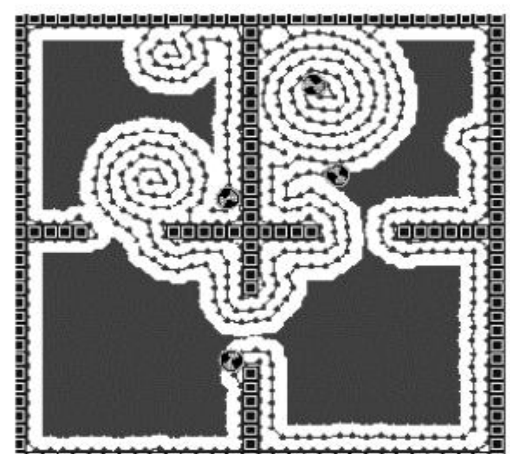
- Complete Random Walk
- Ant Robotics
  - Leave trail
  - Bias the behavior towards or away from the trails

S. Koenig Ant Robotics, terrain coverage



Andrew Russell, Monash University, Australia





Ant Robotics: I. Wagner, IBM & Technion

Deterministic Coverage

- Complete Algorithm
- Guarantees Complete Coverage

Cell-Decomposition Methods

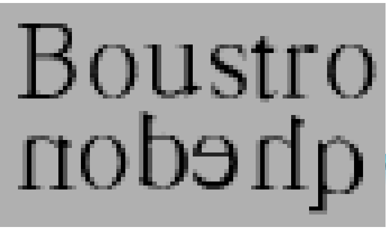
Two families of methods:

- 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

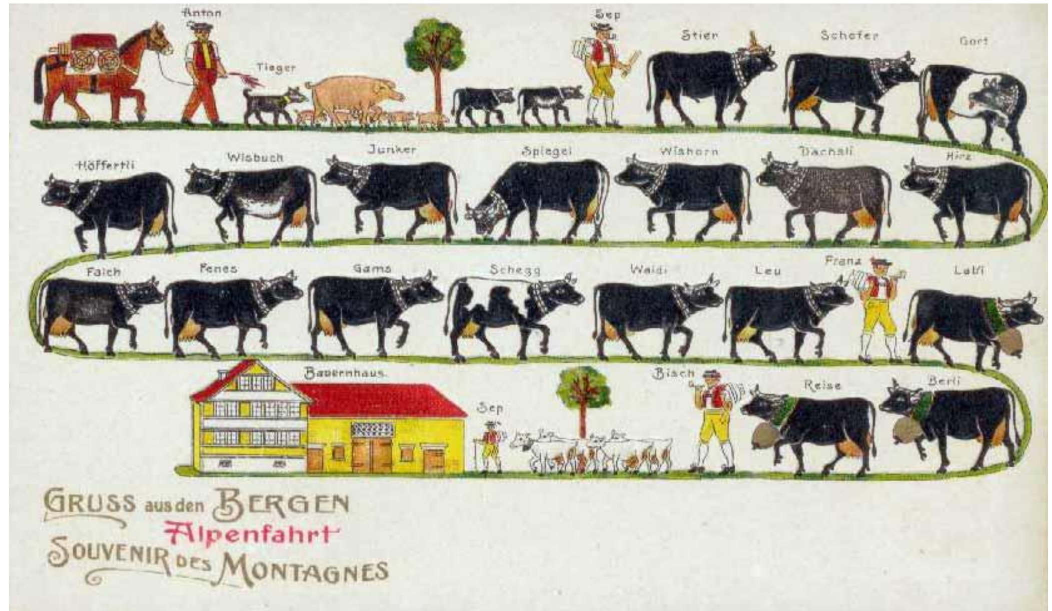
The way of the Ox!

Ioannis Rekleitis



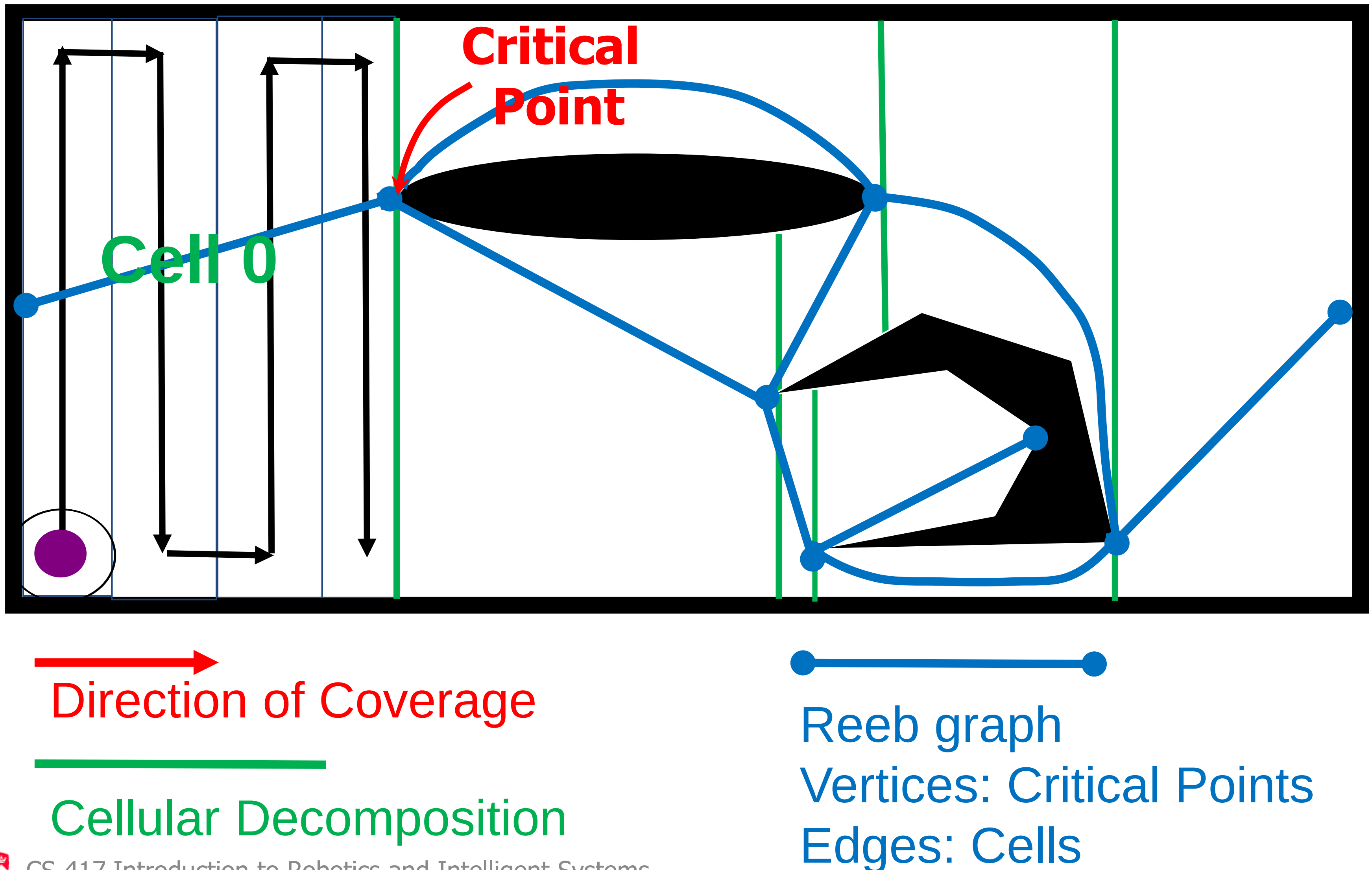
Single Robot Coverage

- Deterministic algorithm
- Guarantee of completeness
- Sensor based
- Unknown Environment



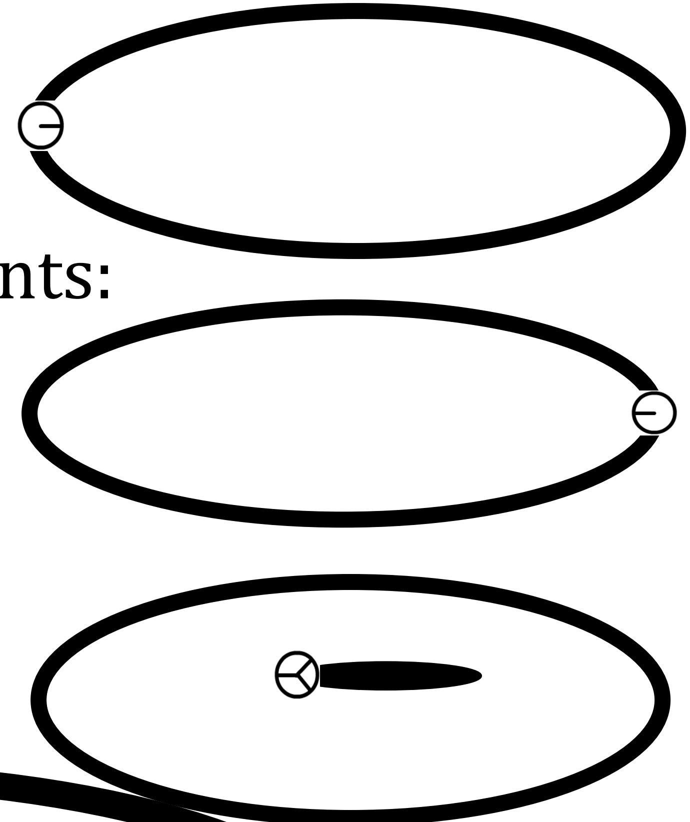
•Seed spreader algorithm: Lumelsky et al, “Dynamic path planning in sensor-based terrain acquisition”, IEEE Transactions on Robotics and Automation, August 1990.
•Boustrophedon algorithm: Choset and Pignon, “Coverage path planning: The boustrophedon cellular decomposition”, International Conference on Field and Service Robotics,1997.

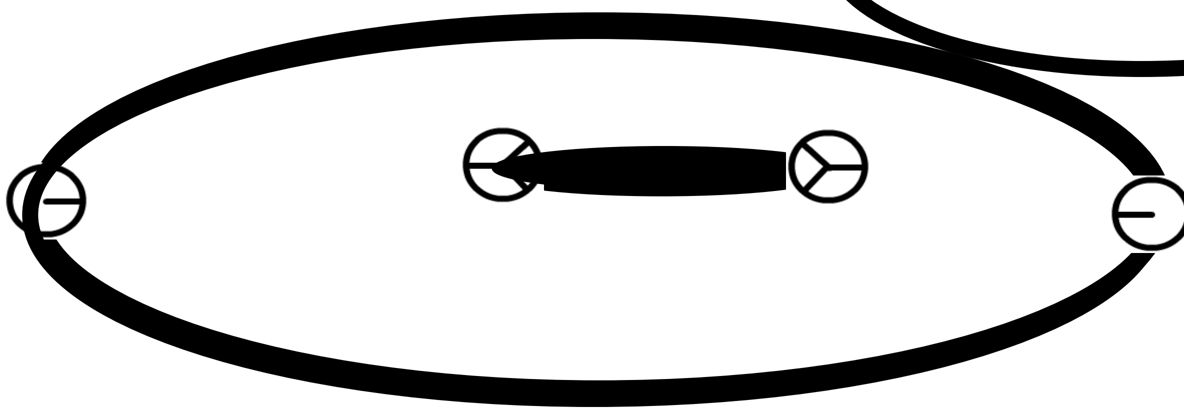
Single Robot Coverage



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

Optimal Coverage

- Find an order for traversing the Reeb graph such that the robot would not go through a cell more times than necessary

Solution

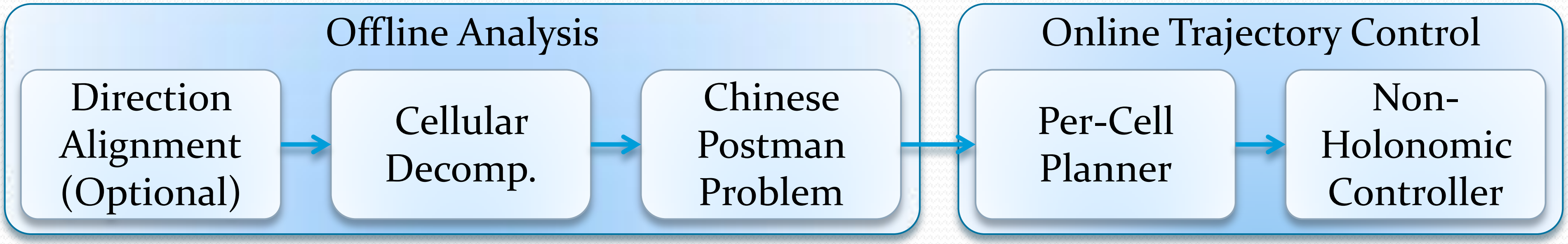
- Use the Chinese Postman Problem

Chinese Postman Problem

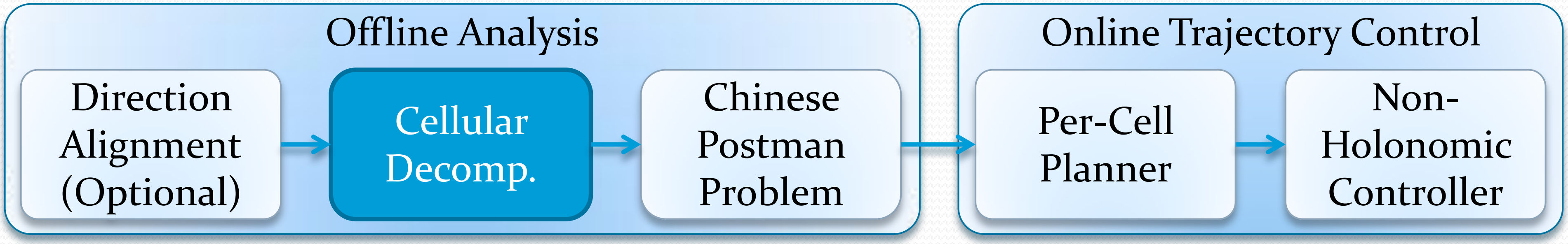
- The Chinese postman problem (CPP), is to find a shortest closed path that visits every edge of a (connected) undirected graph. When the graph has an Eulerian circuit (a closed walk that covers every edge once), that circuit is an optimal solution.

See: J. Edmonds and E.L. Johnson, Matching Euler tours and the Chinese postman problem, Math. Program. (1973).

Offline Analysis Algorithm

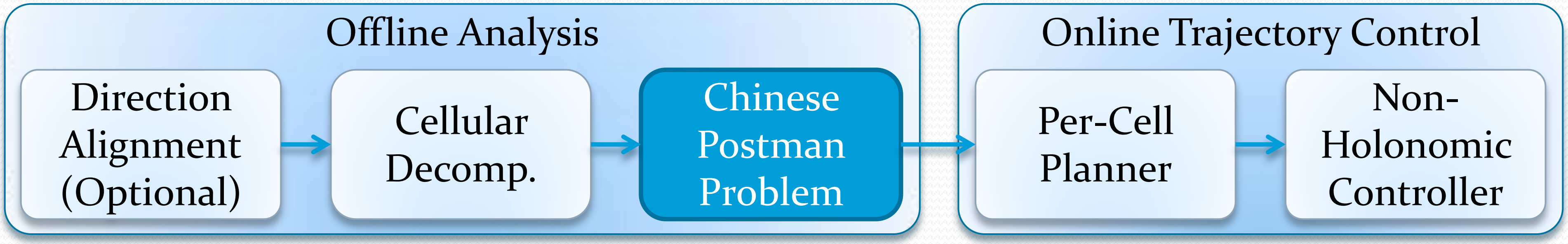


Offline Analysis Algorithm



- Input: binary map separating obstacle from free space
- Boustrophedon Cellular Decomposition (BCD)

Offline Analysis Algorithm (cont.)



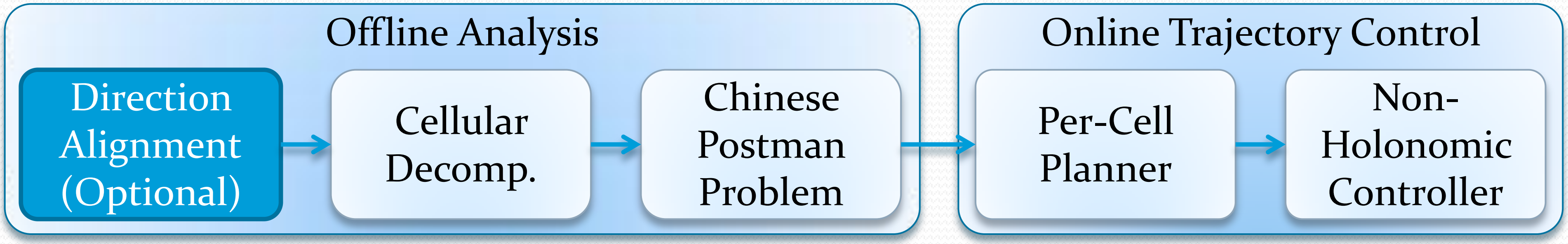
- Chinese Postman Problem
  - Eulerian circuit, i.e. *single* traversal through all cells (edges)

Per-Cell Coverage Planner

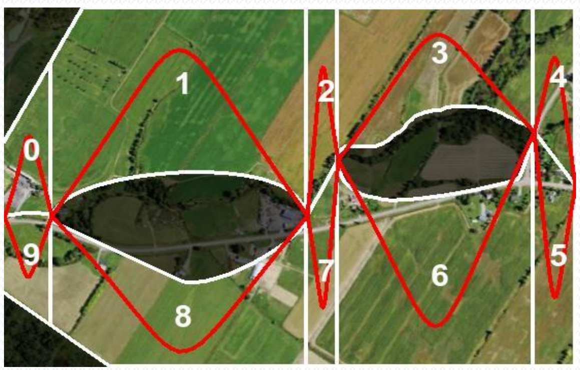
Offline Analysis: Direction Alignment (Optional) → Cellular Decomp. → Chinese Postman Problem → **Online Trajectory Control:** **Per-Cell Planner** → Non-Holonomic Controller

- Seed Spreader: piecewise linear sweep lines
- Footprint width

Coverage Direction Alignment



- Static alignment methods



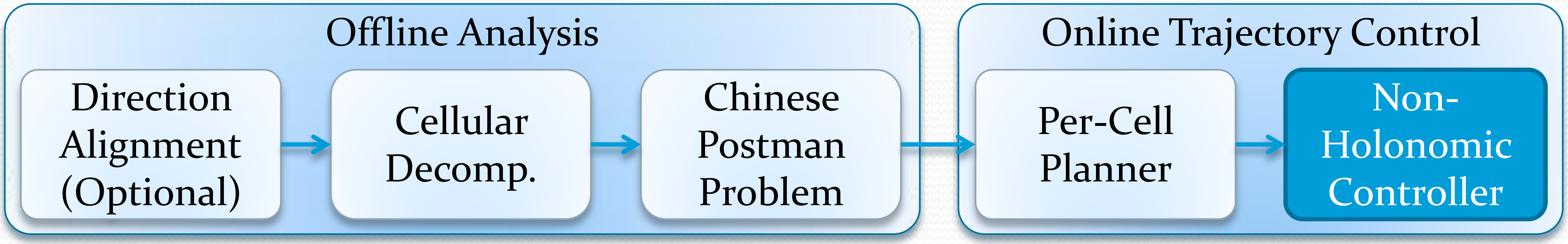
Default

Obstacle Boundaries

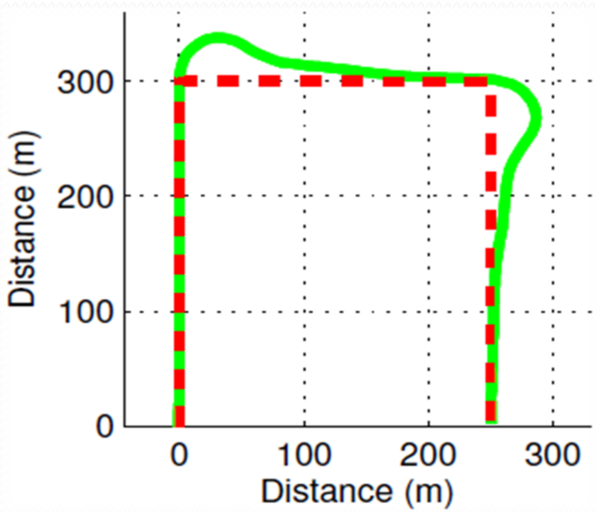
Free Space Distribution

- Alignment with average wind heading (pre-flight)

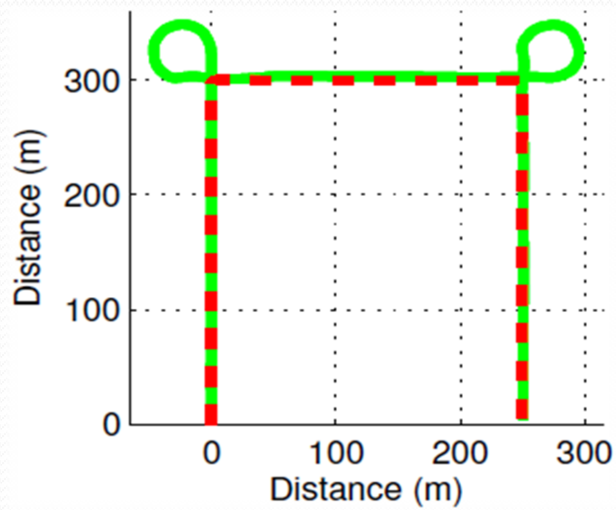
Non-Holonomic Robot Controller



- Turning strategies



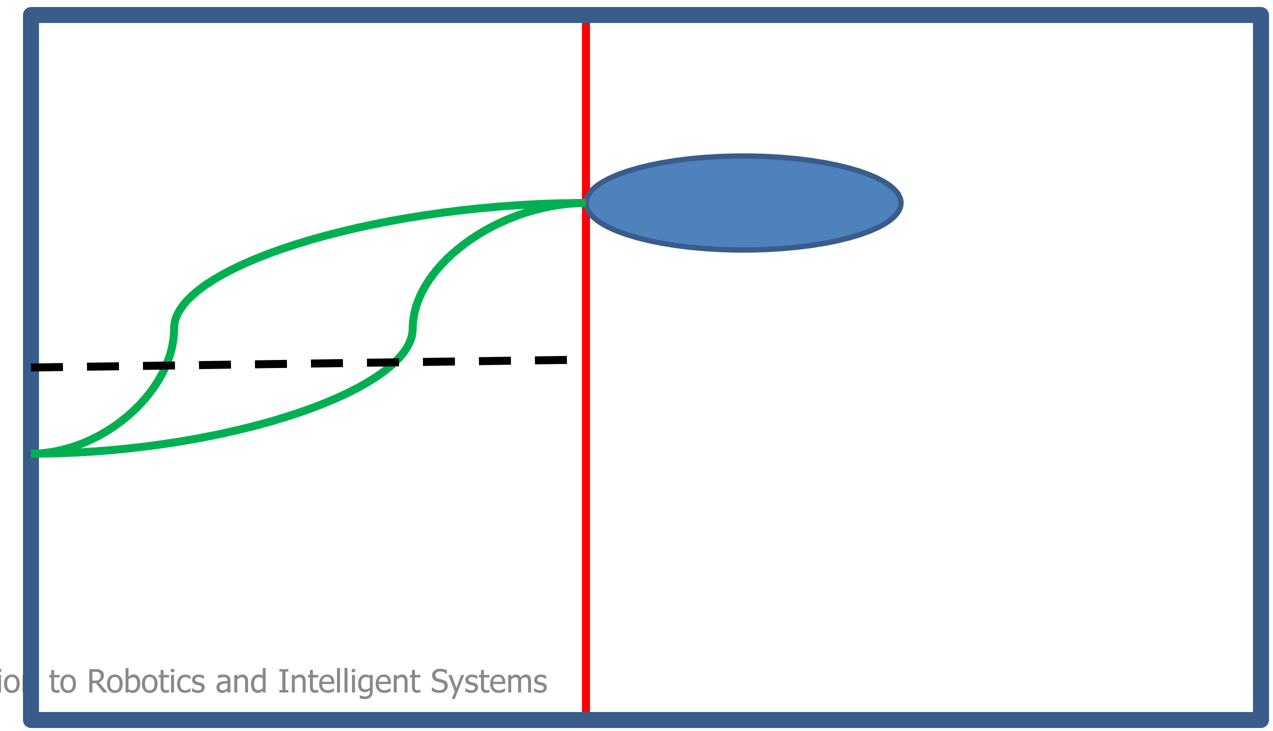
Greedy Waypoint Controller



Curlicue Controller

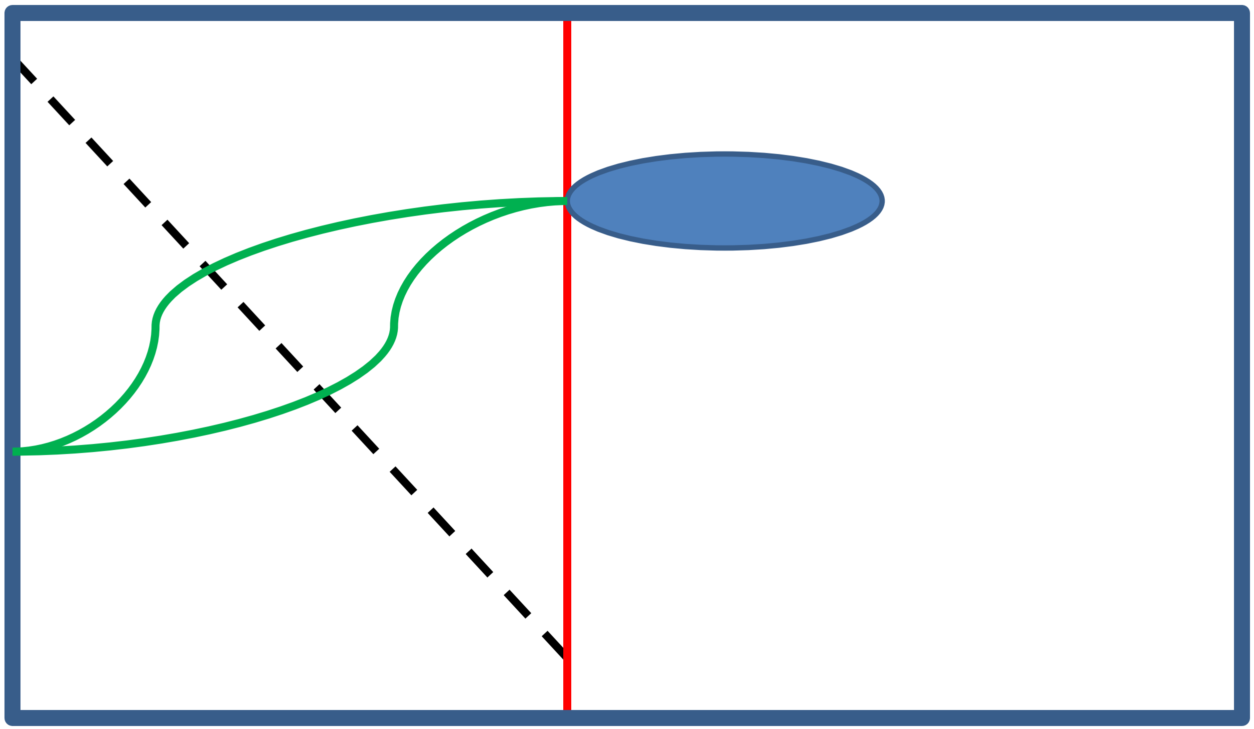
Chinese Postman Problem

- The solution of the CPP guarantees that no edge is doubled more than once
- That means some cells have to be traversed twice
- Cells that have to be traversed/covered are divided in half



Double Coverage of a Single Cell

- By dividing the cell diagonally we control the beginning and end of the coverage



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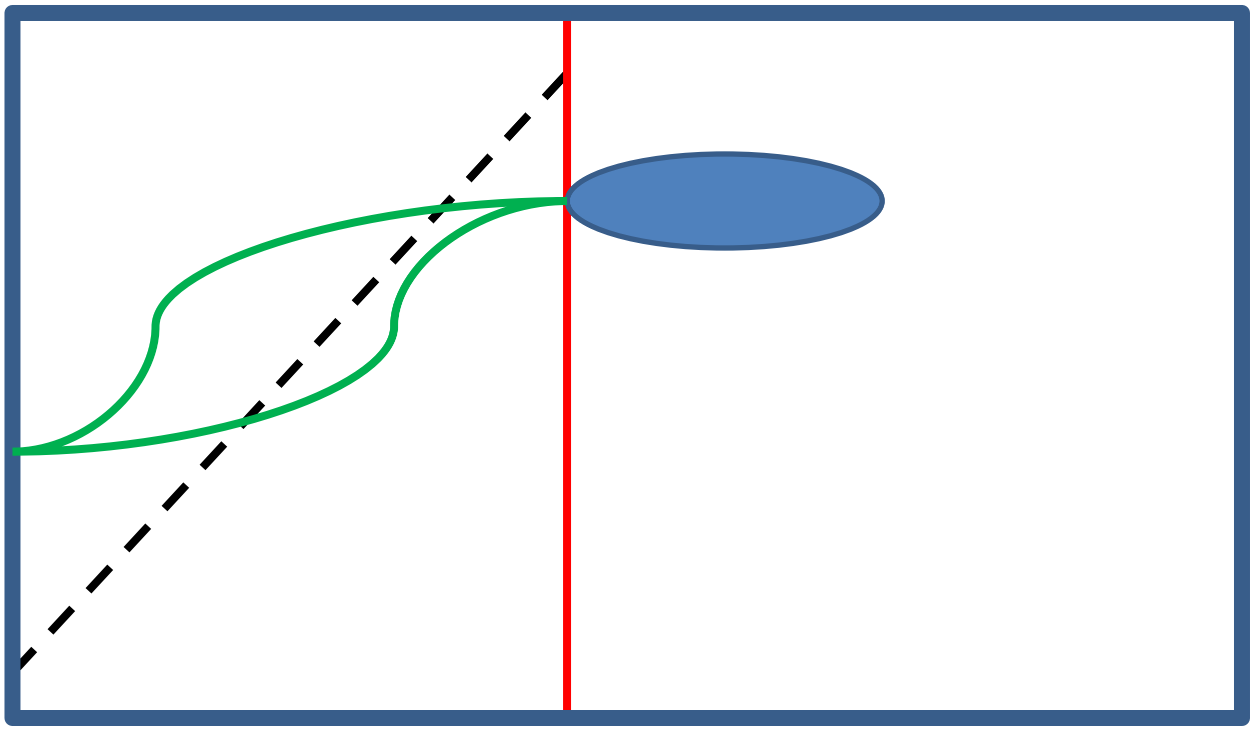
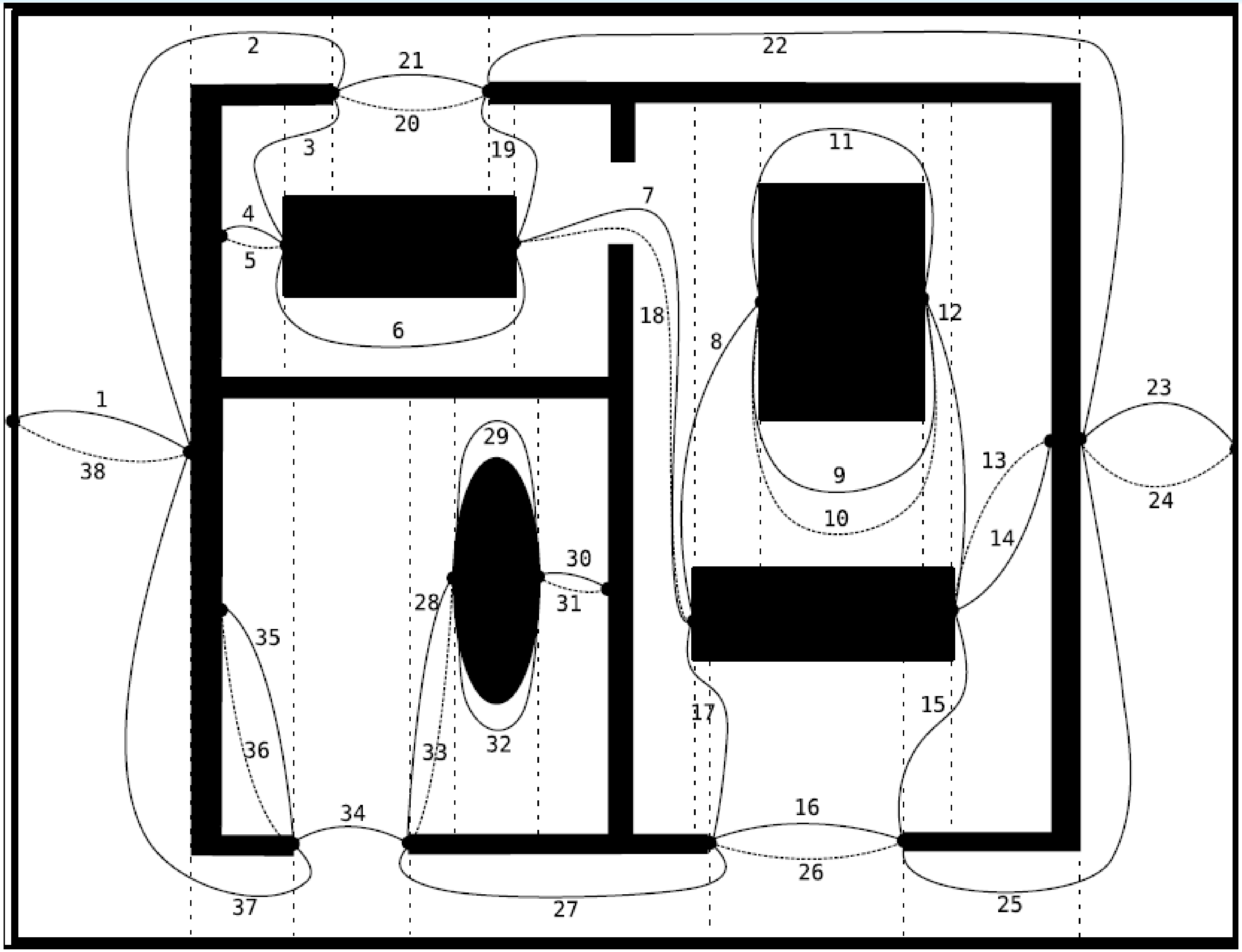


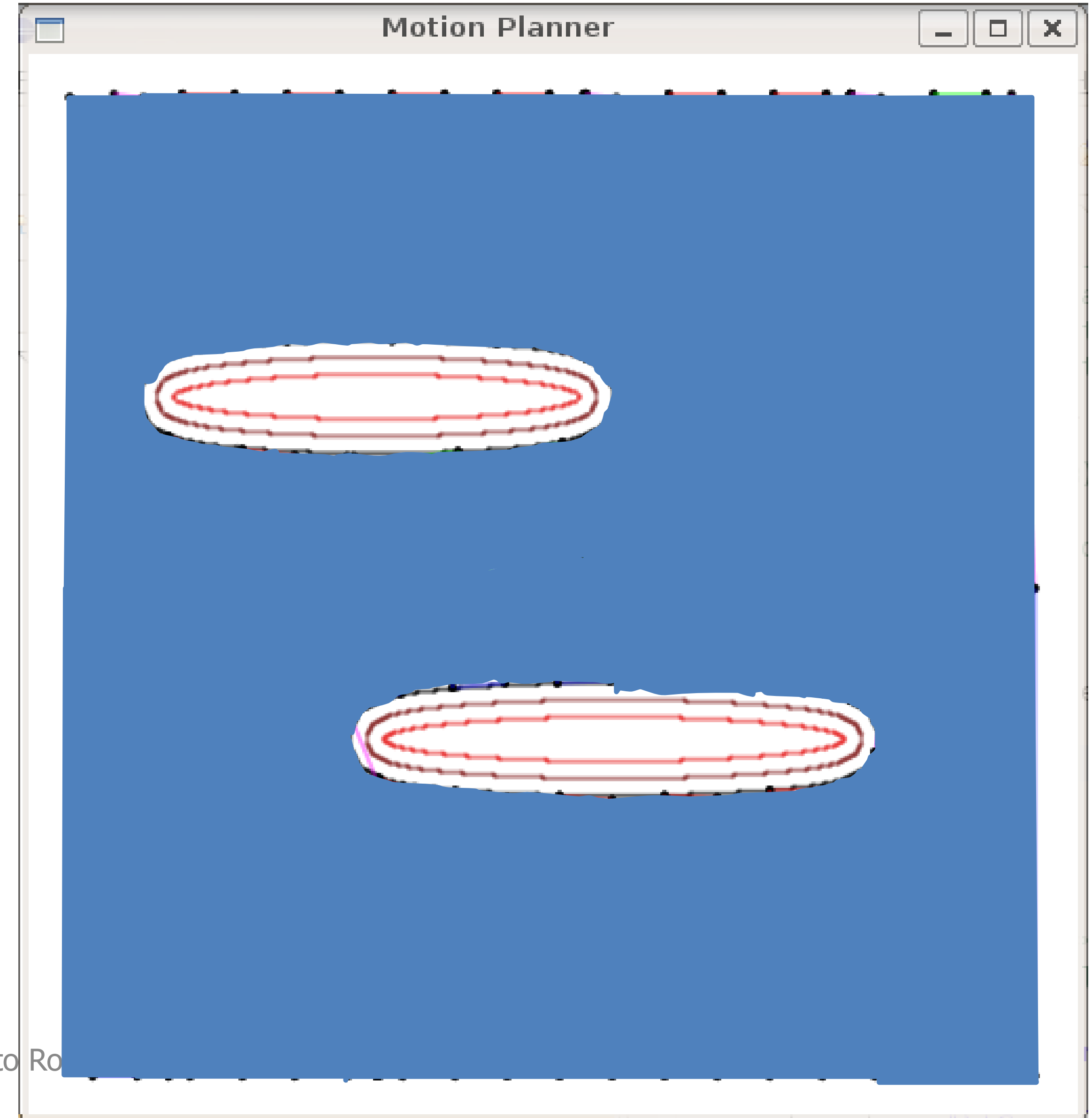
Optimal Coverage Algorithm

- Given a known environment:
  - Calculate the Boustrophedon decomposition
  - Construct the Reeb graph
  - Use the Reeb graph as input to the Chinese Postman Problem (CPP)
  - Use the solution of the CPP to find a minimum cost cycle traversing every edge of the Reeb graph
  - For every doubled edge divide the corresponding cell in half
  - Traverse the Reeb graph by covering each cell in order

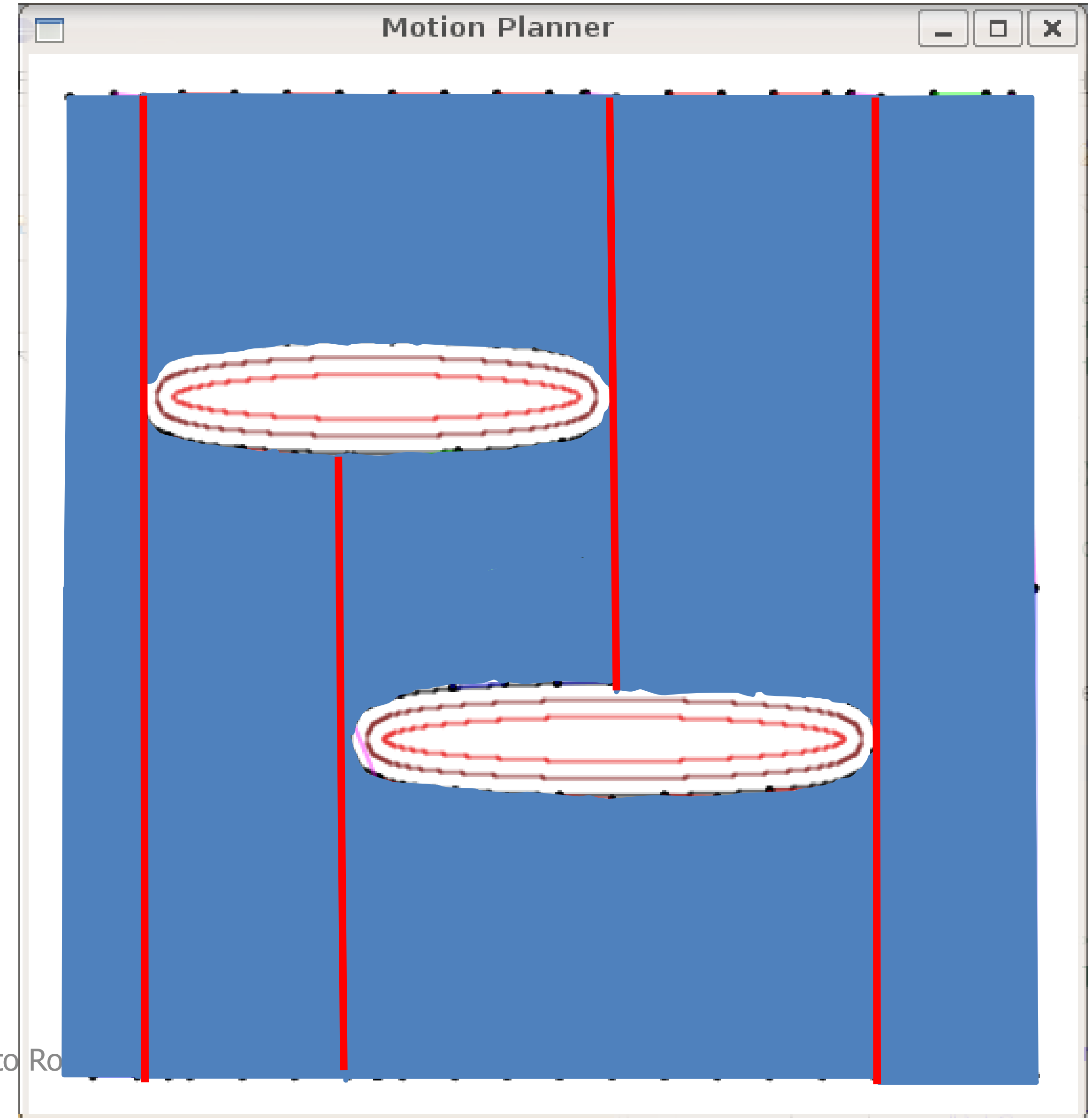
Traversal order of the Reeb graph



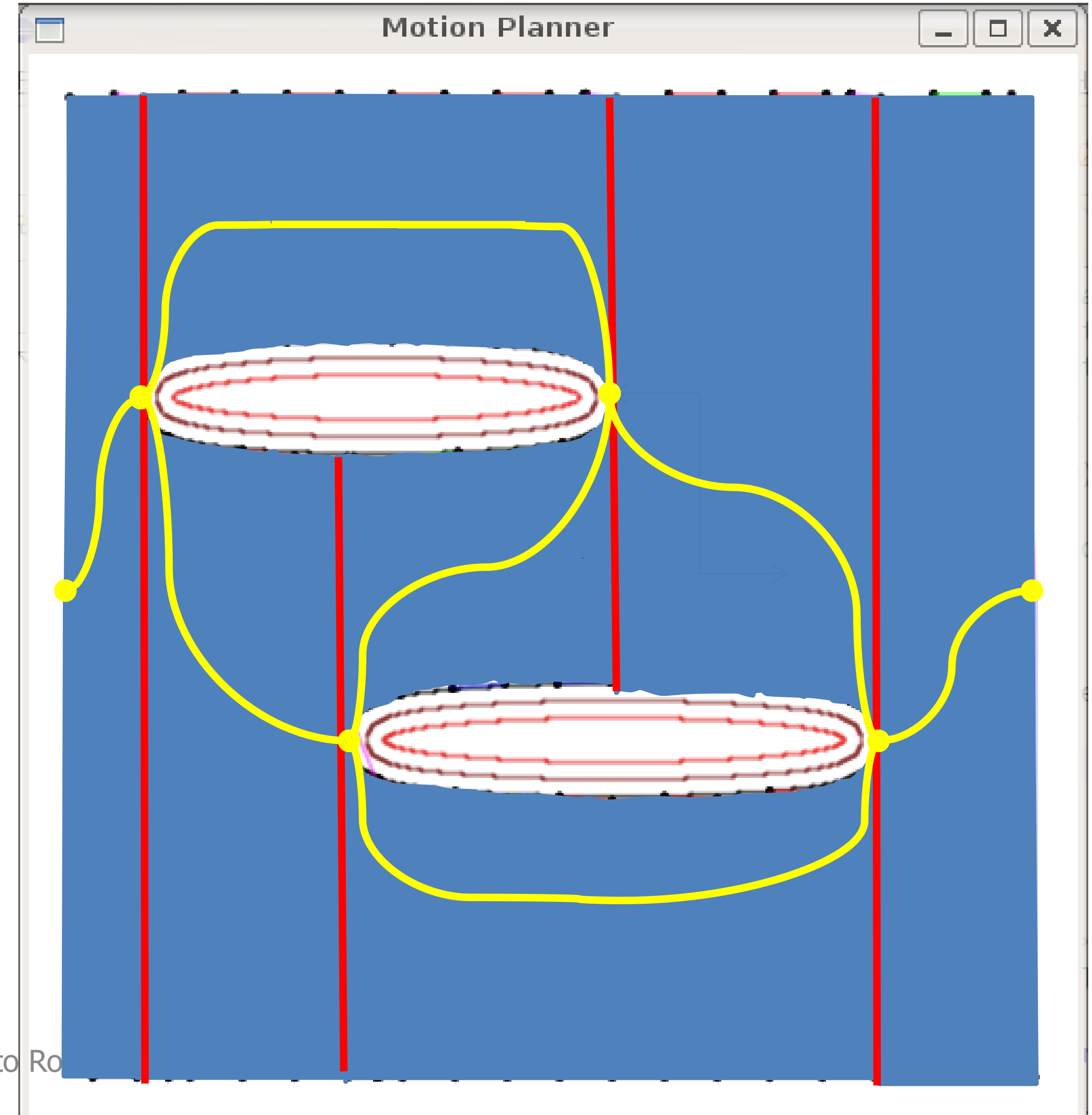
Example



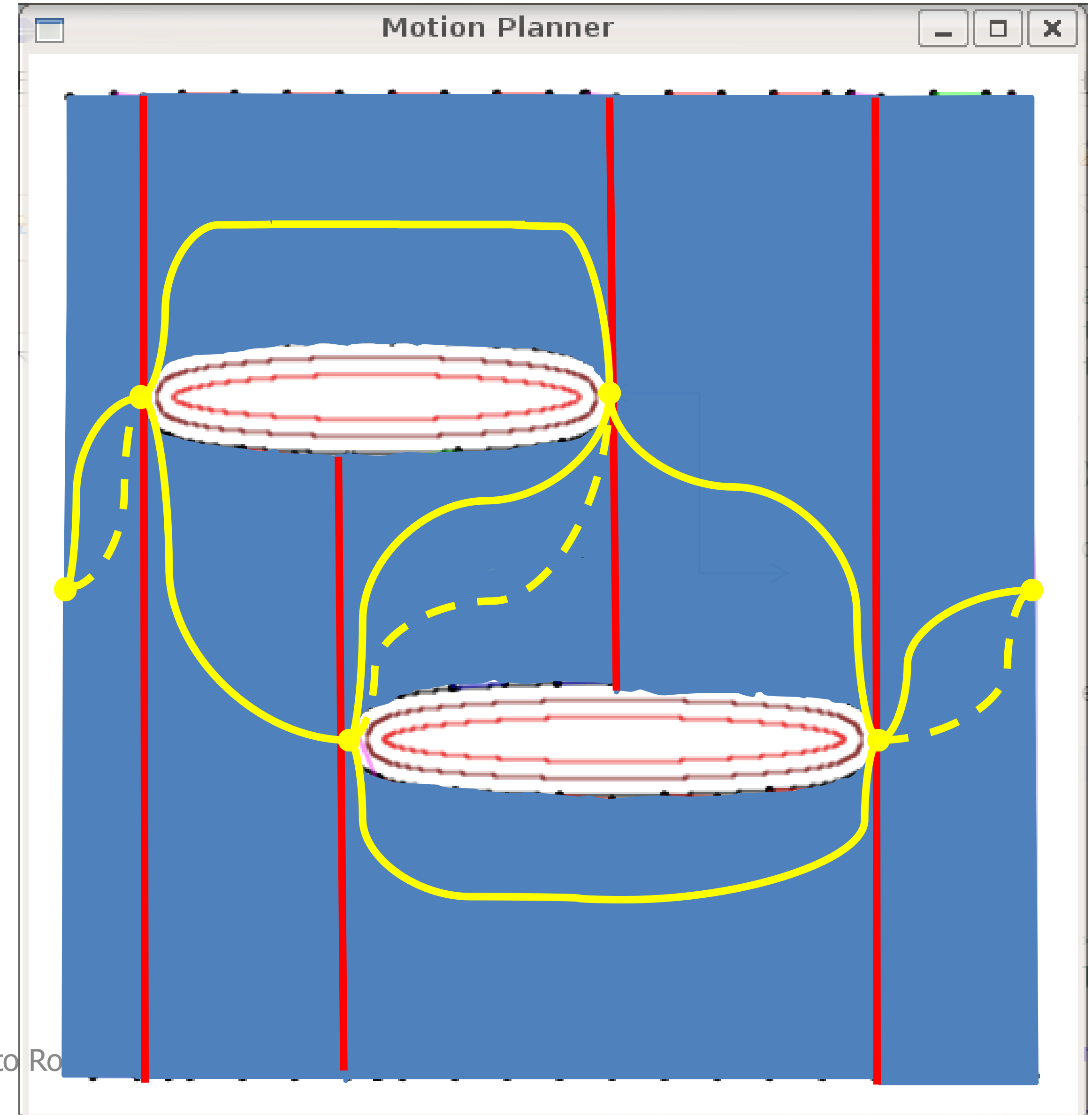
Example: Boustrophedon Decomposition



Example: Reeb Graph



Example: CPP solution



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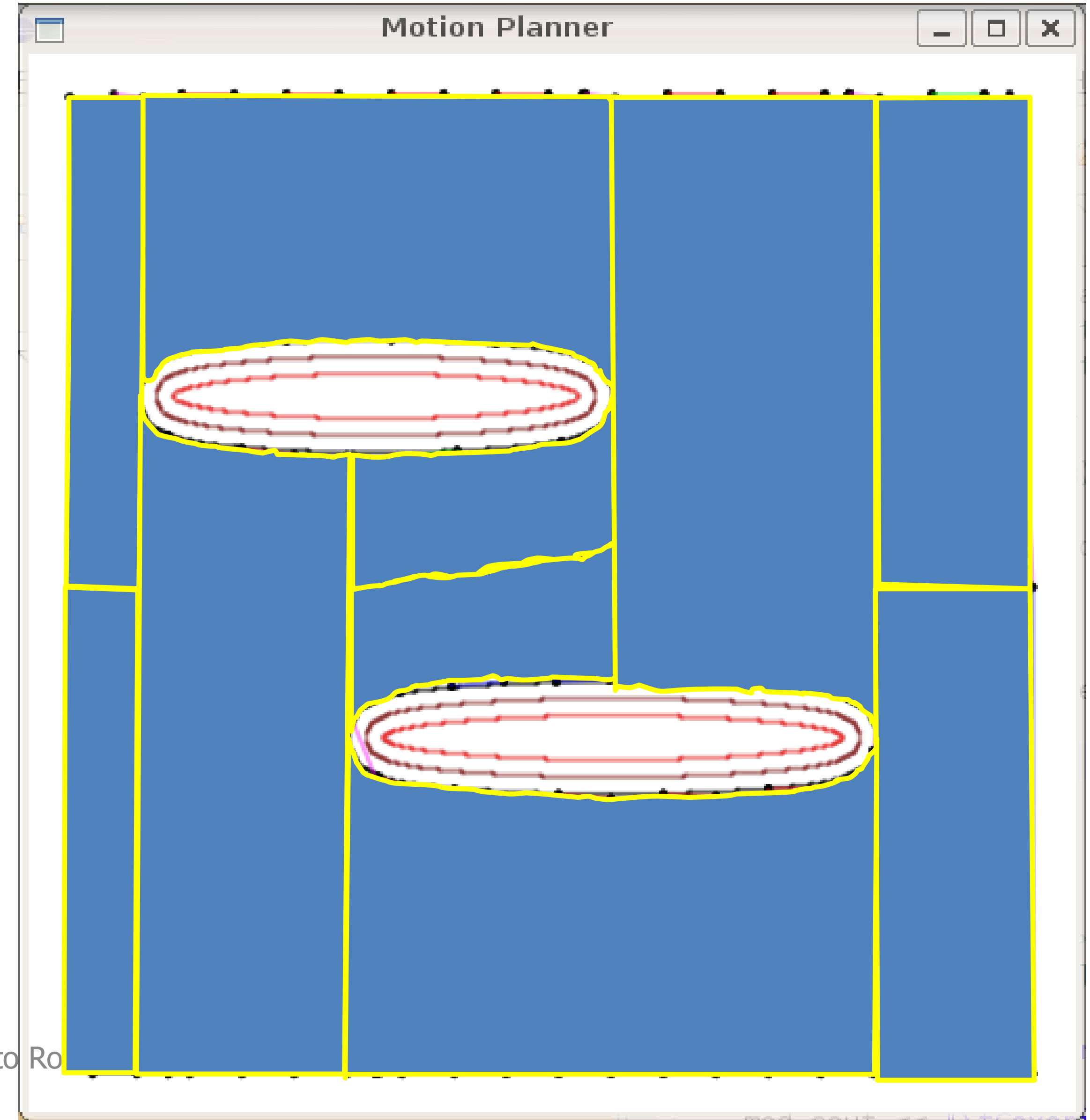

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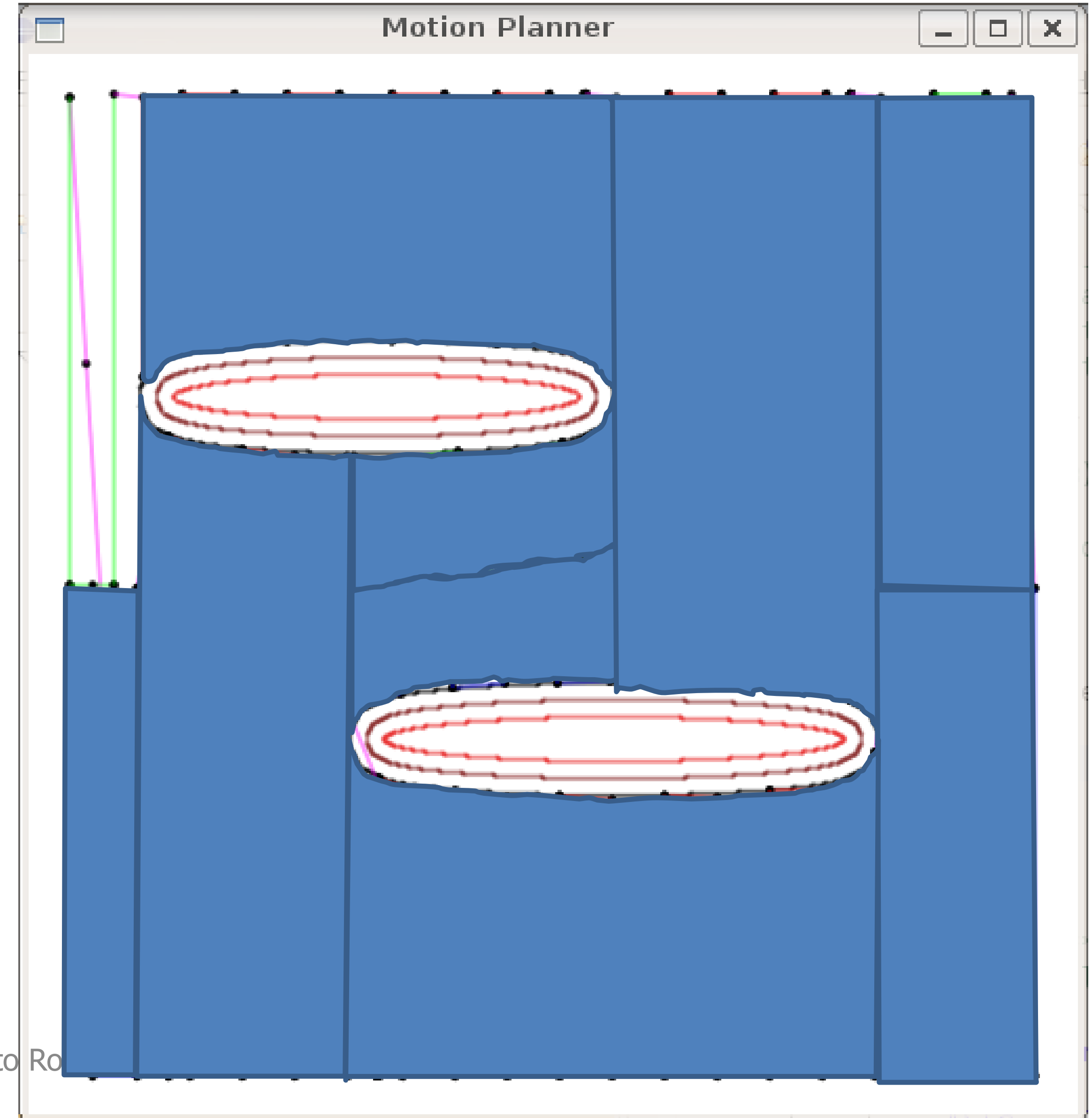

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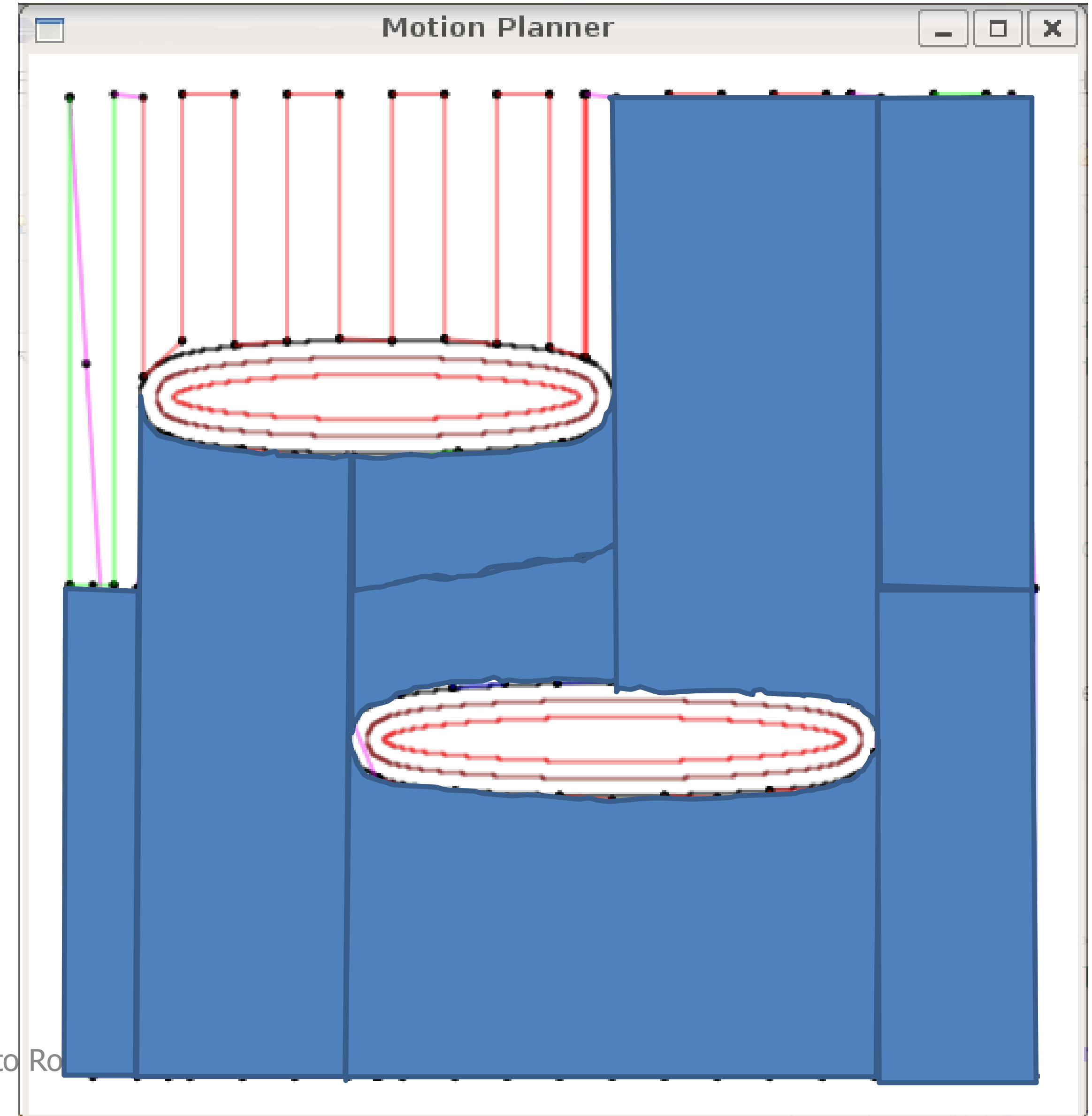

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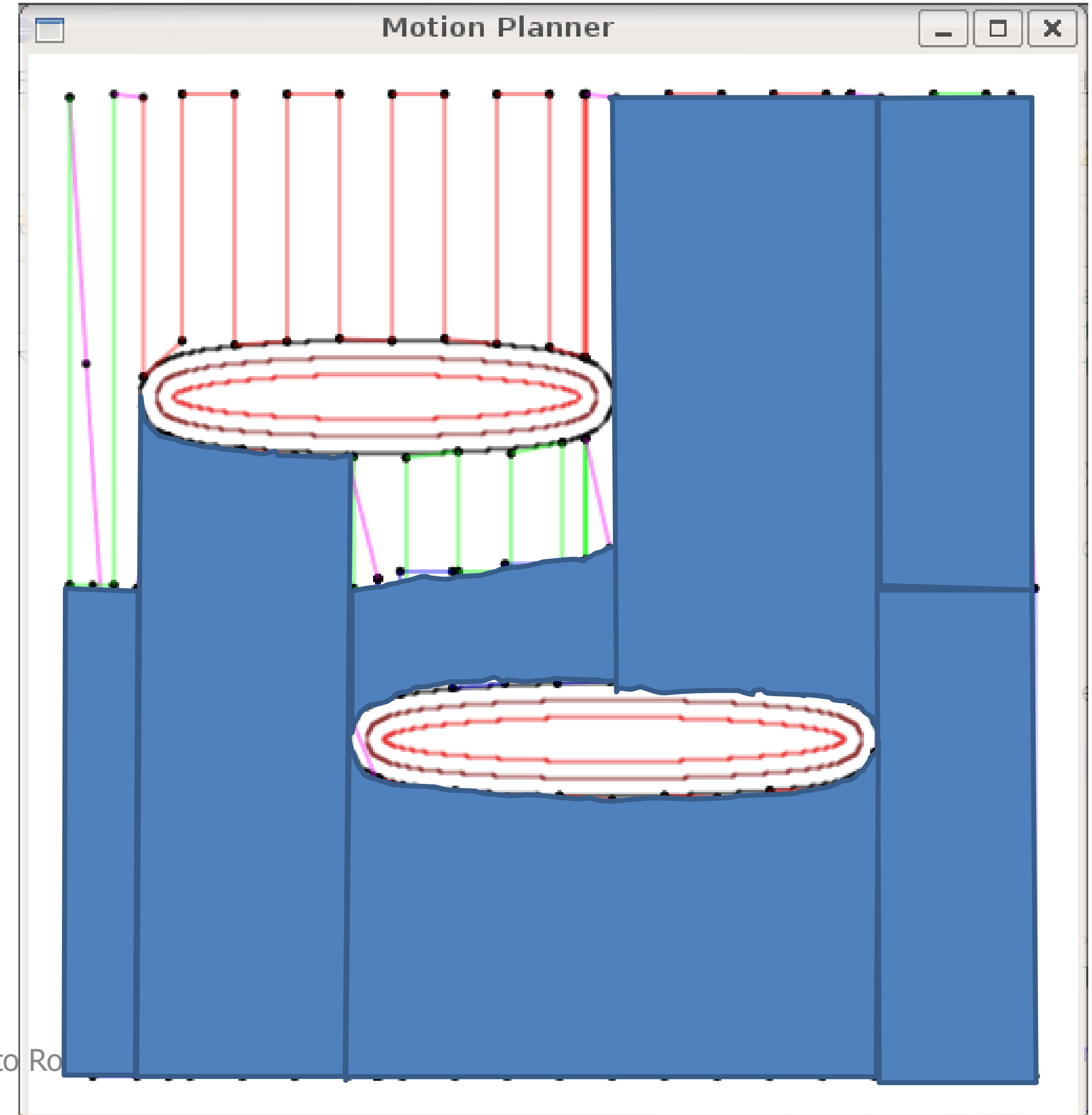

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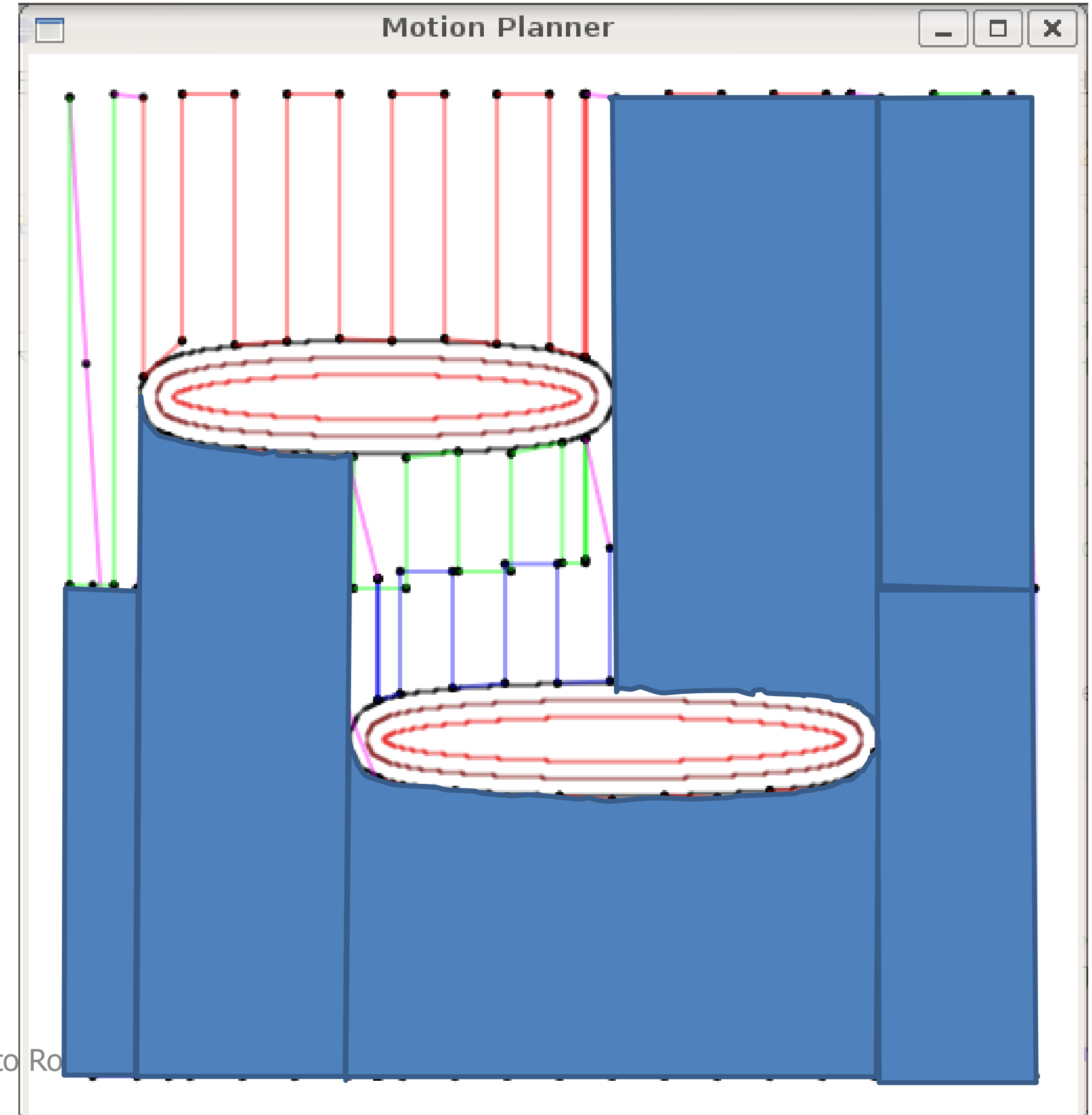

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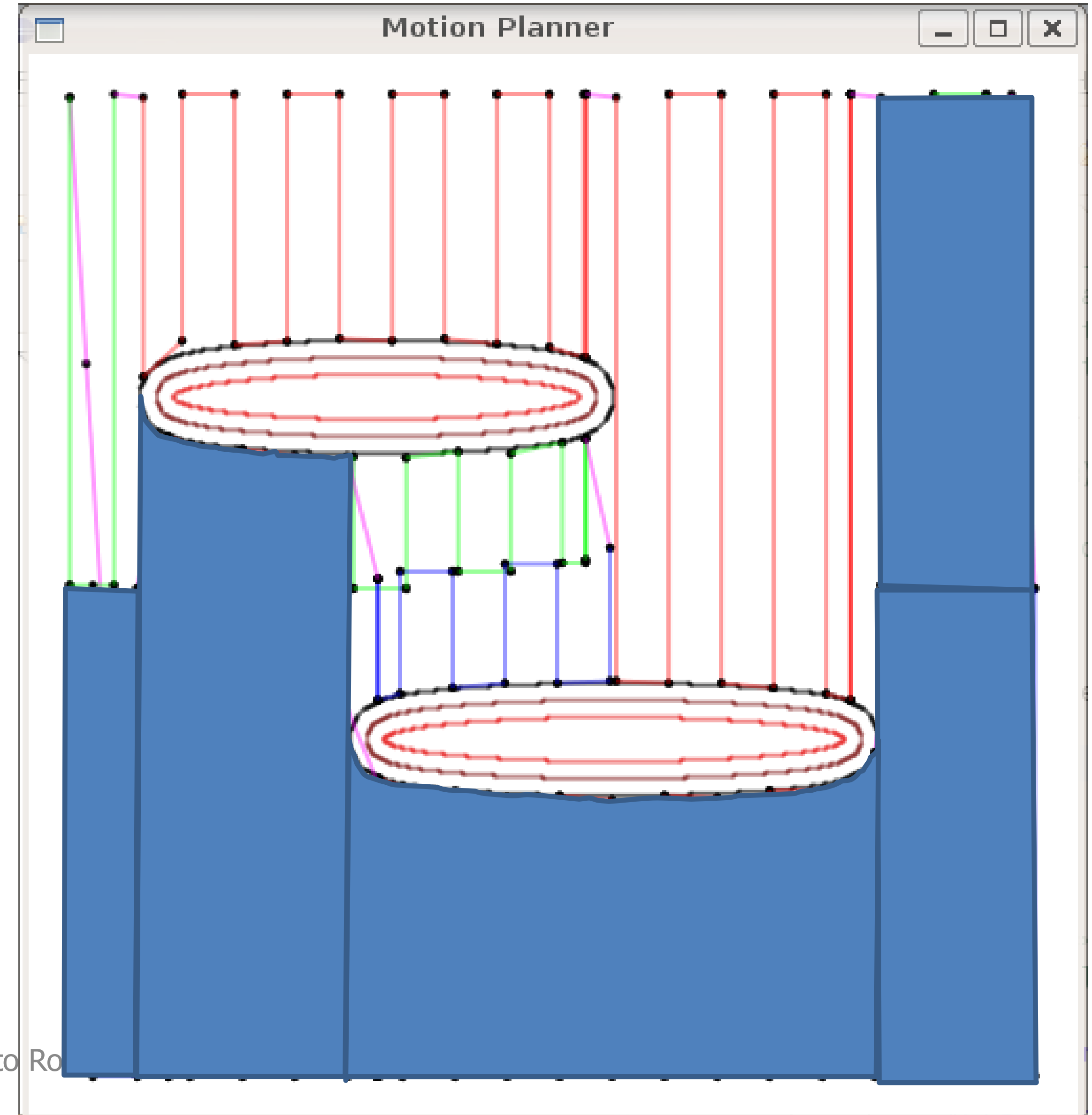

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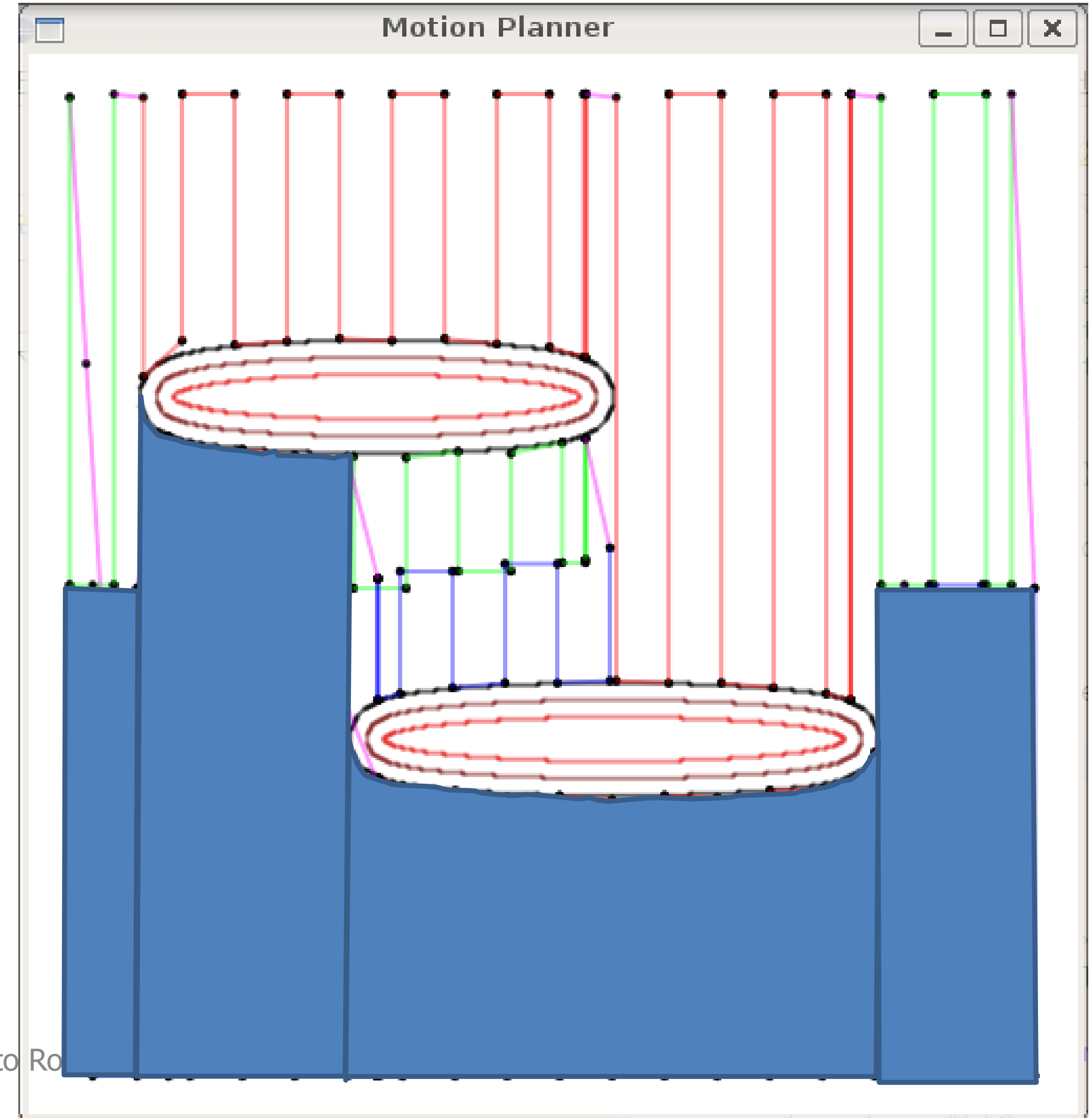

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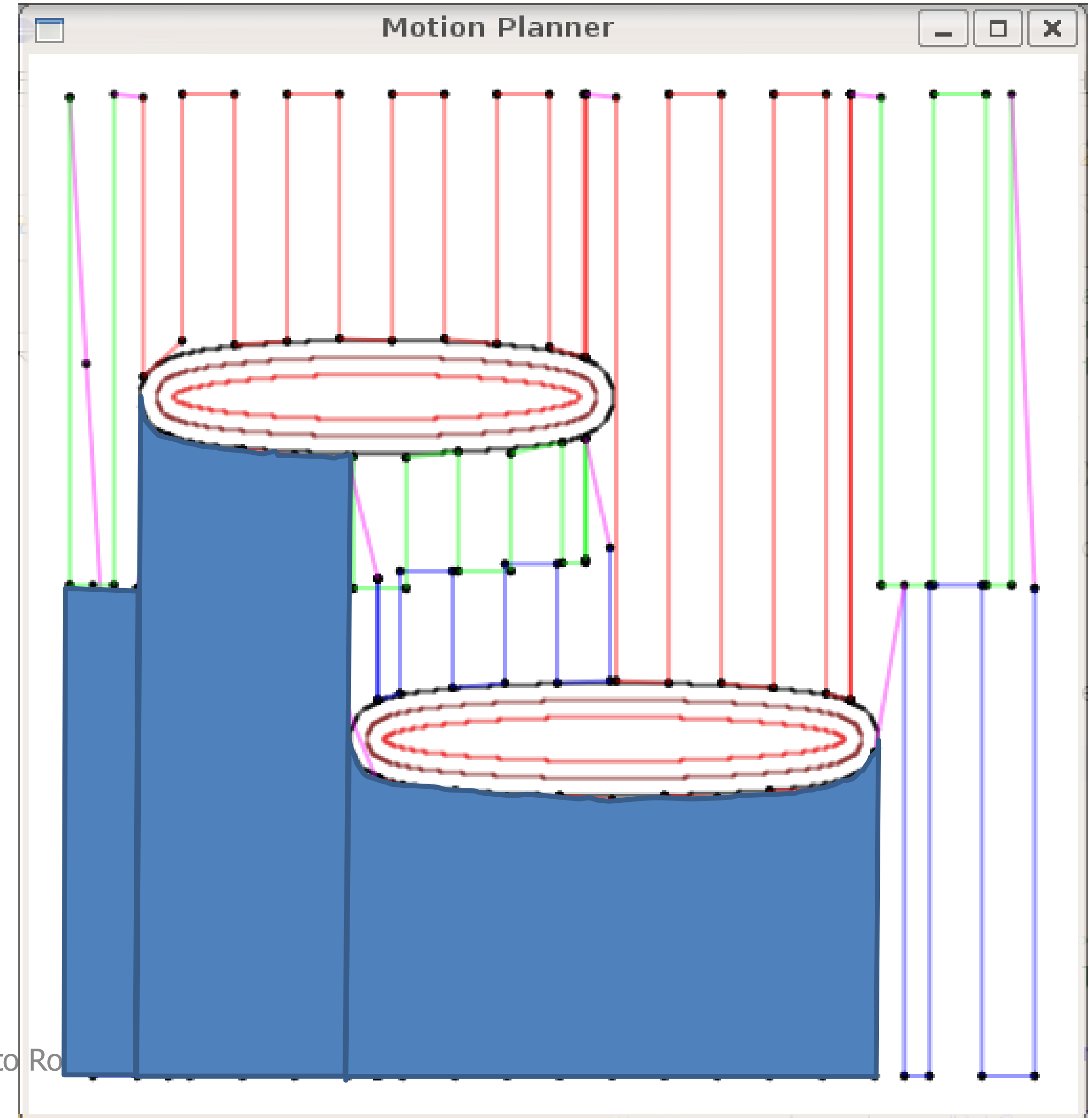

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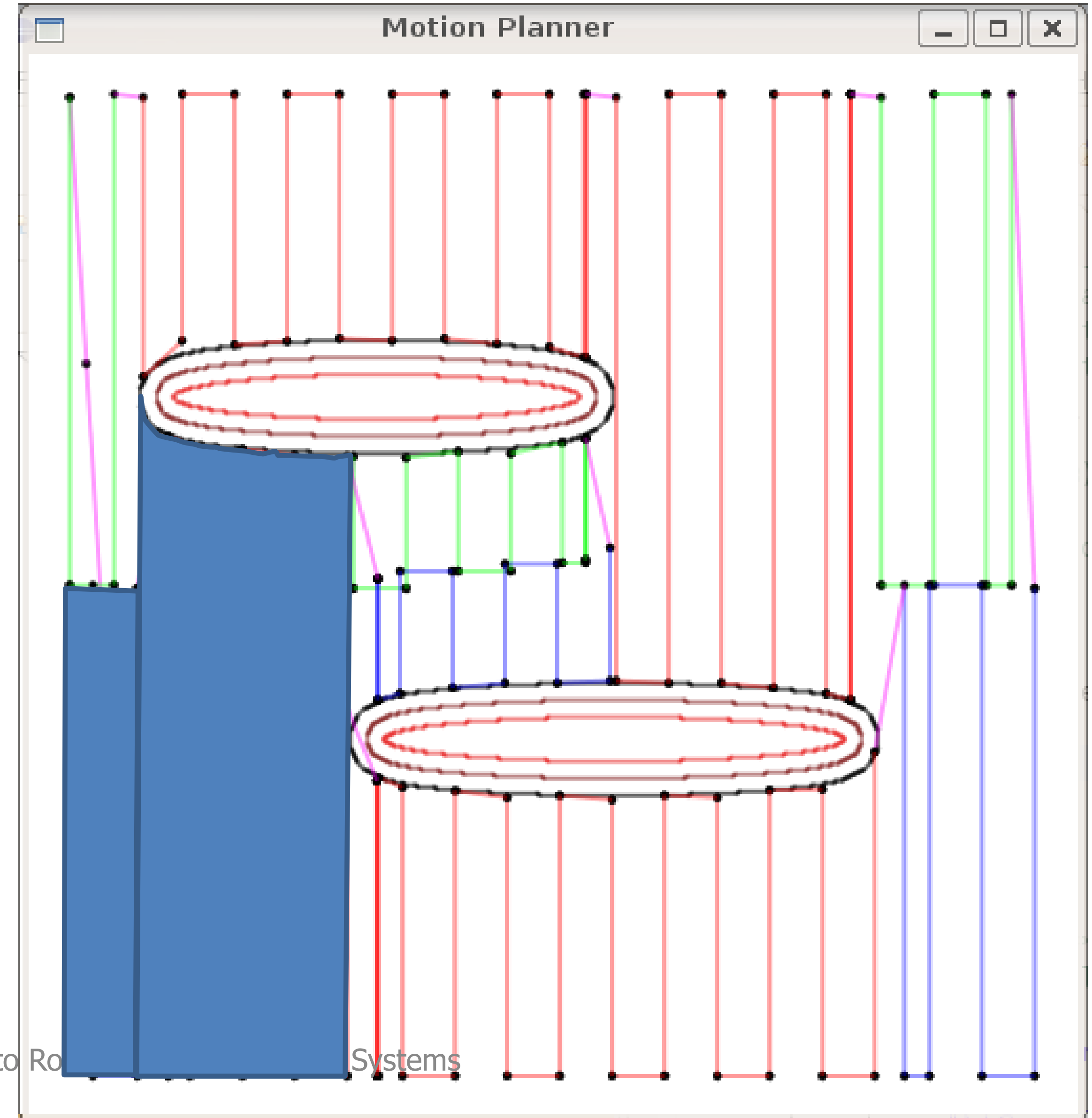

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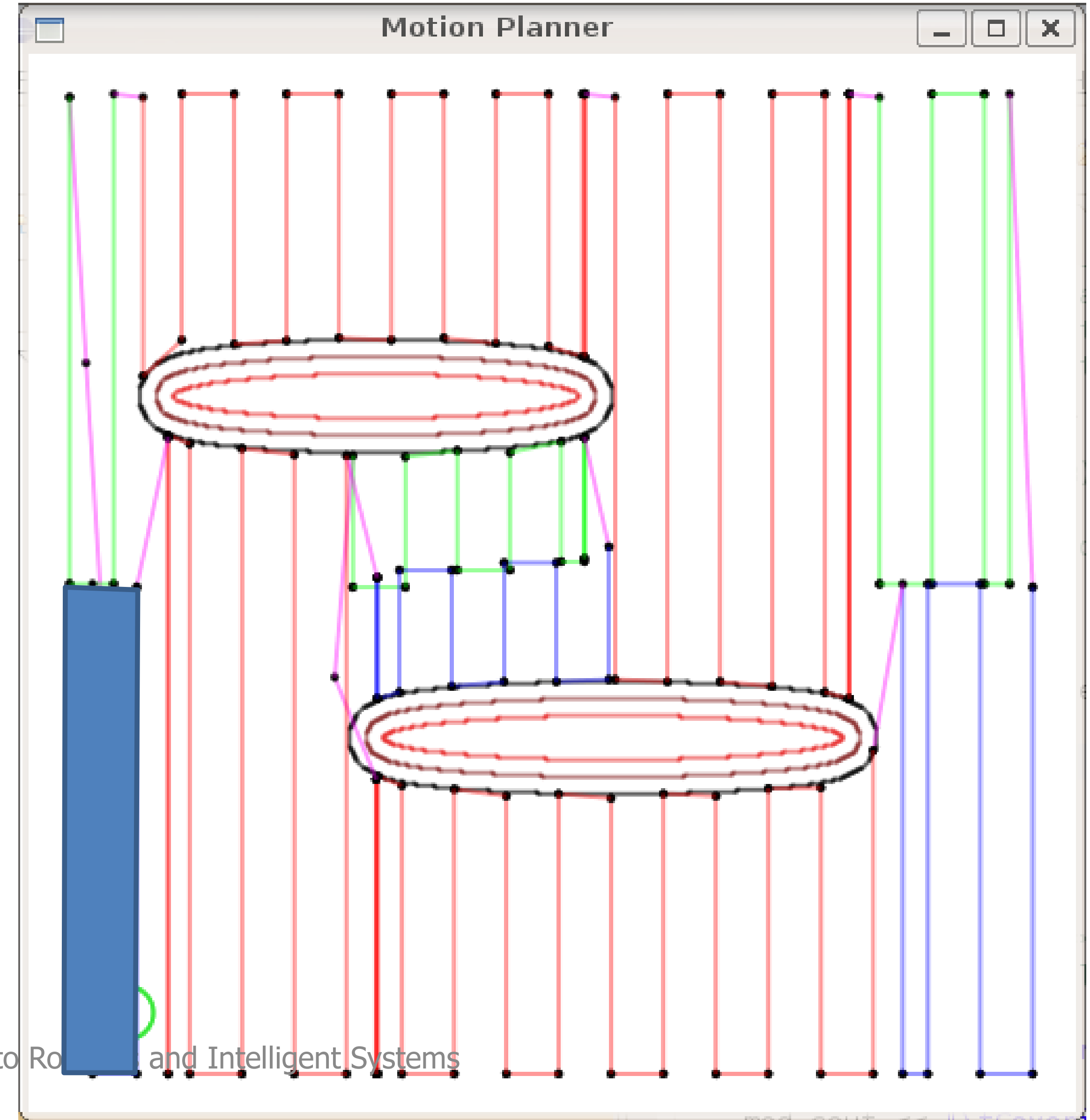

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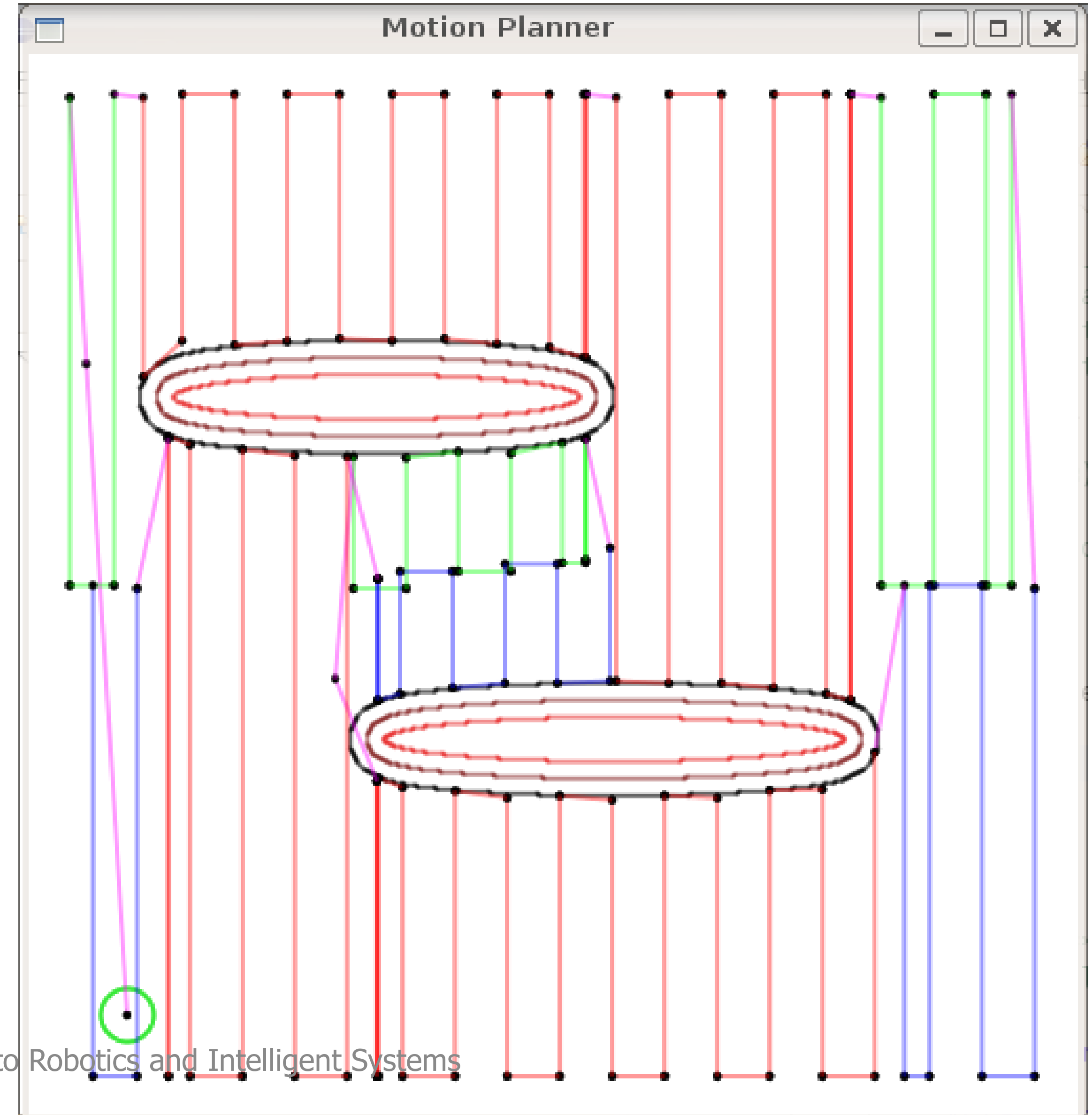

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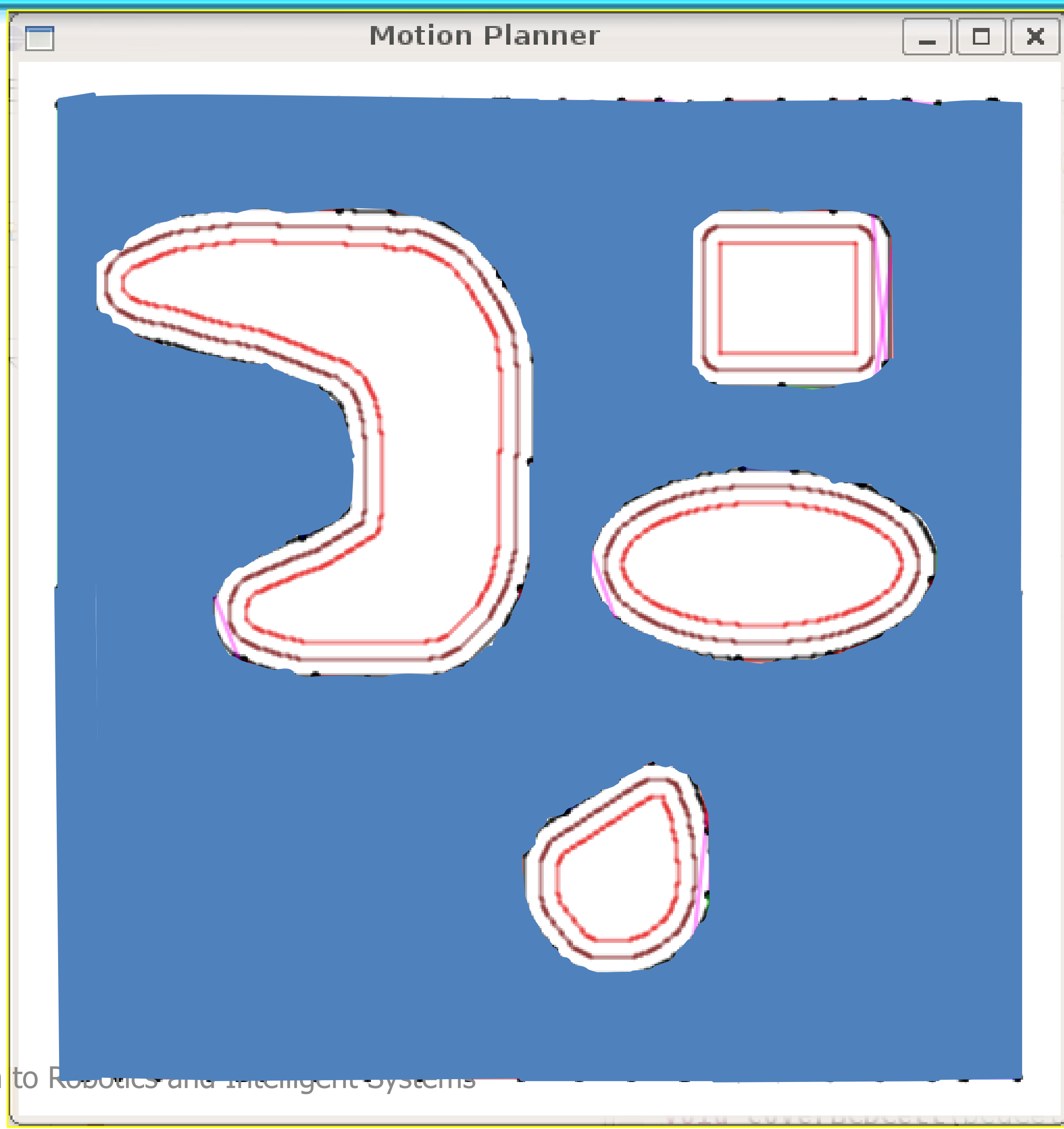
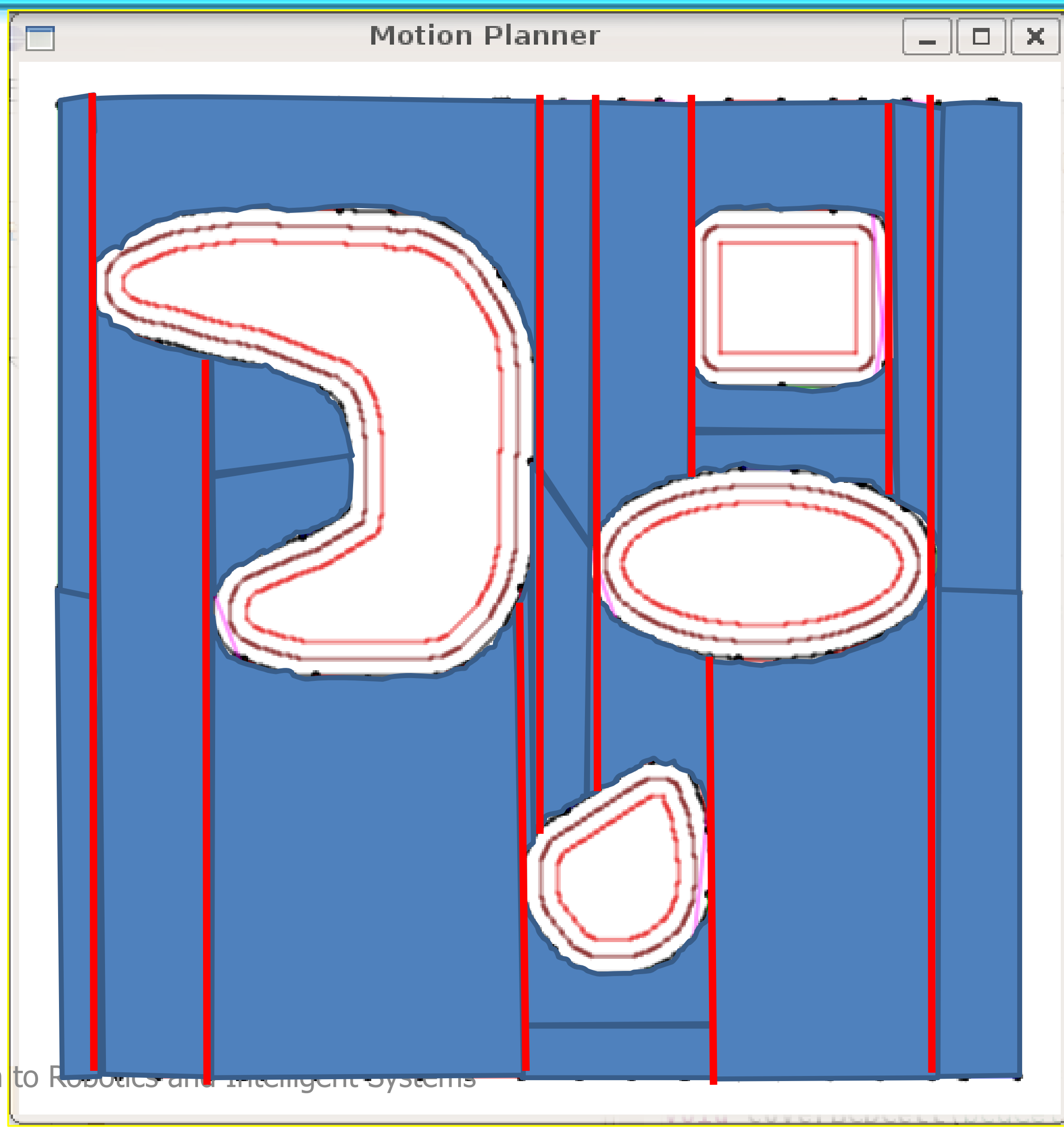


Example 2 Boustrophedon Decomp.



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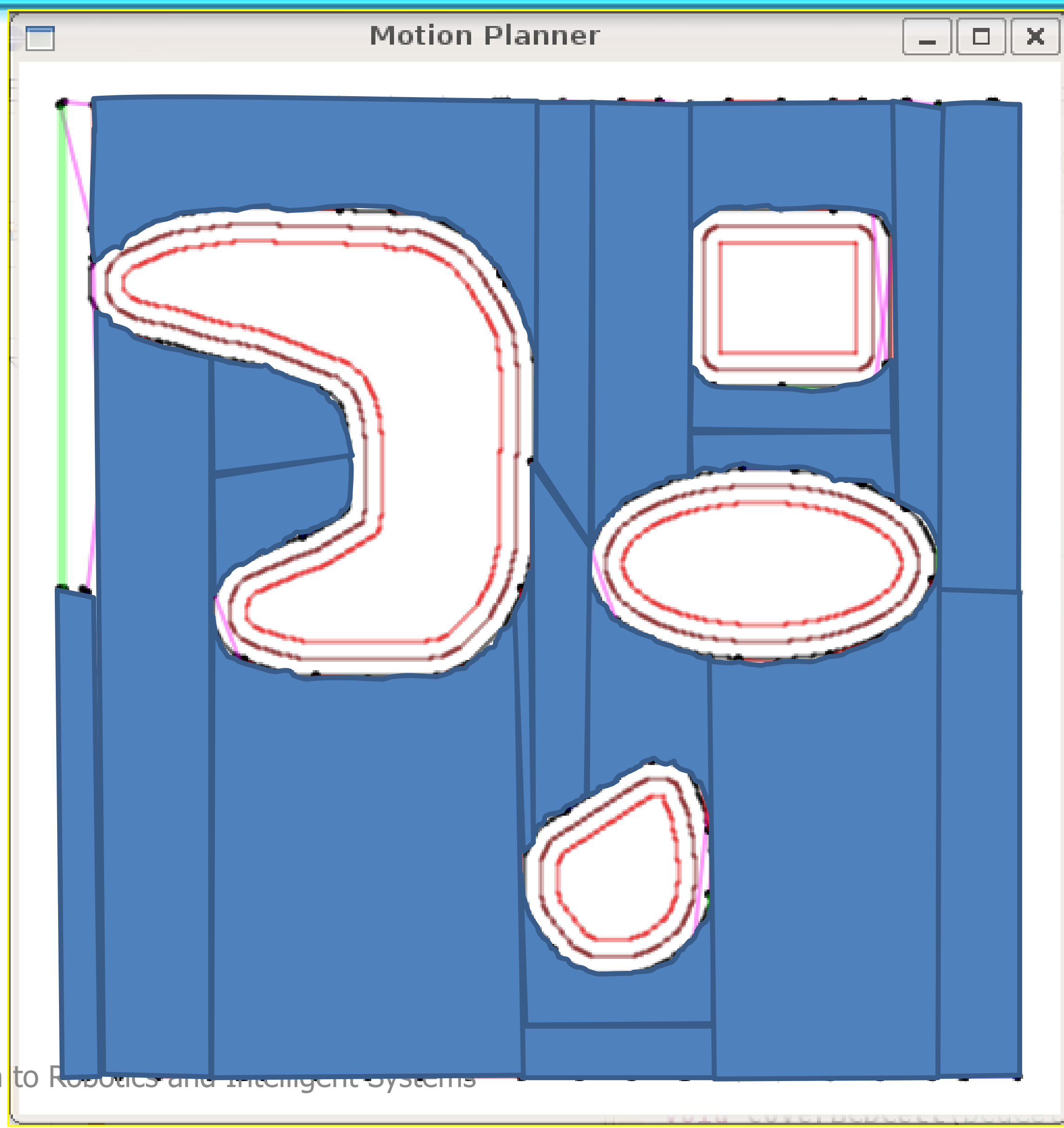

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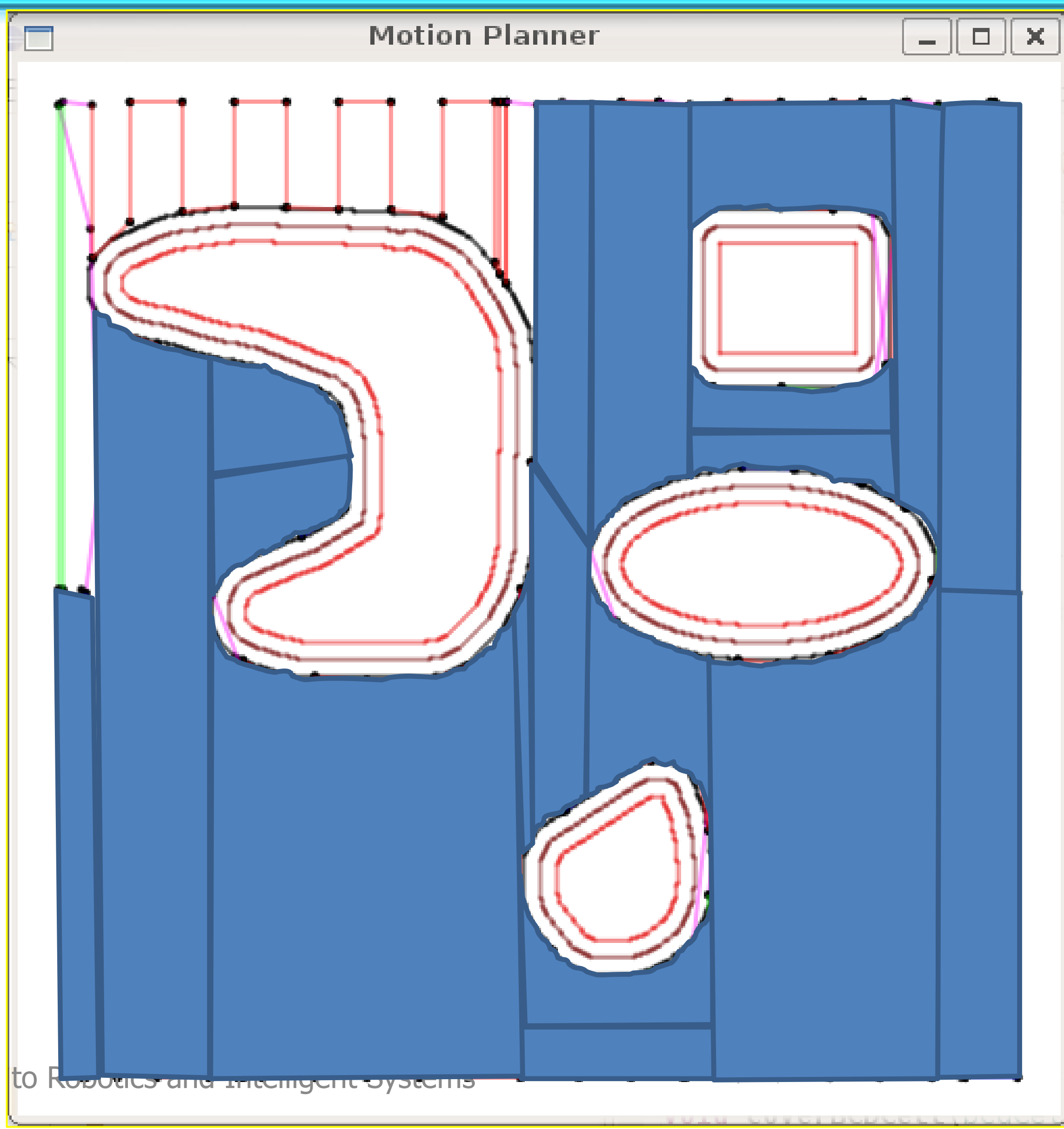

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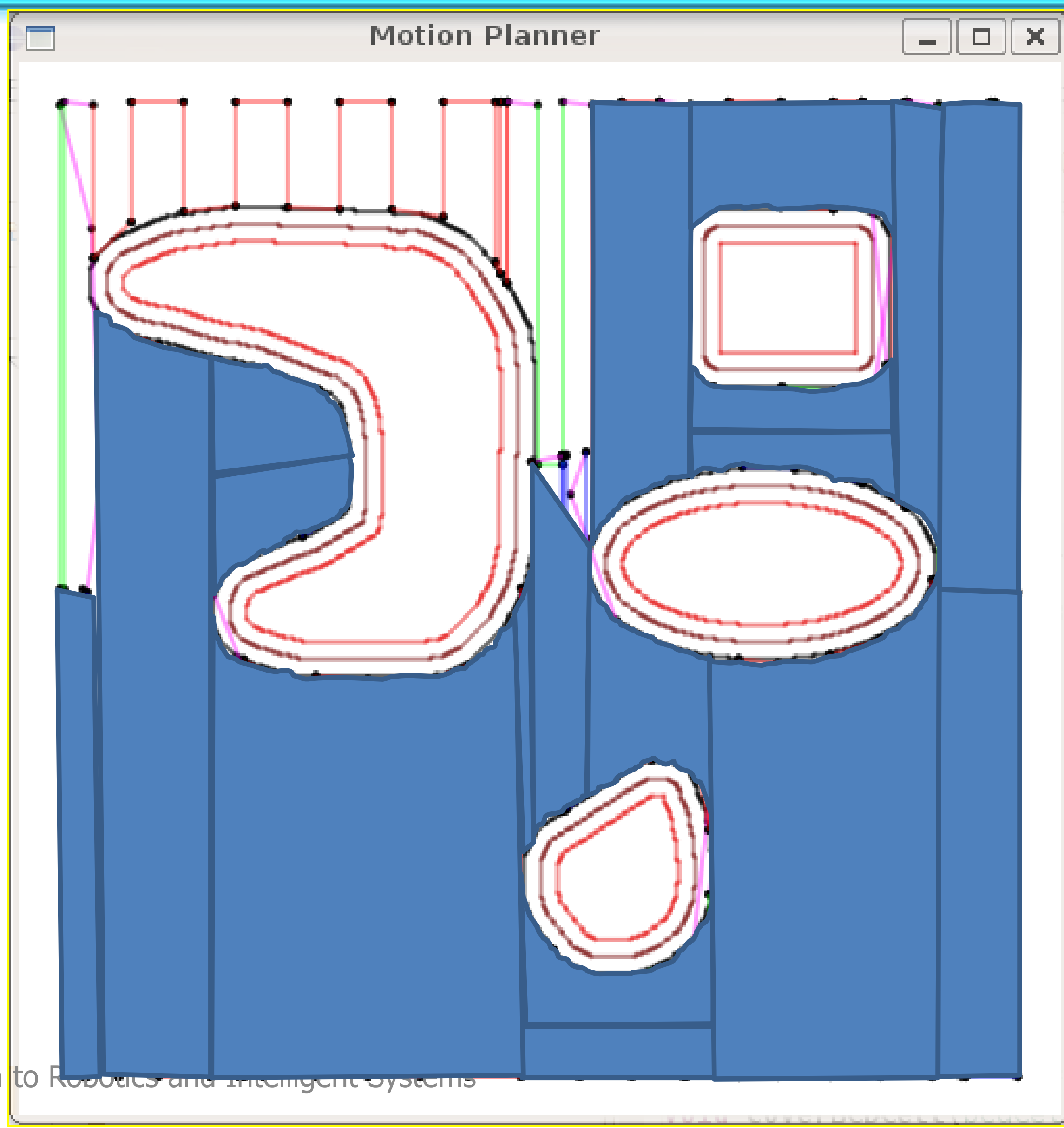

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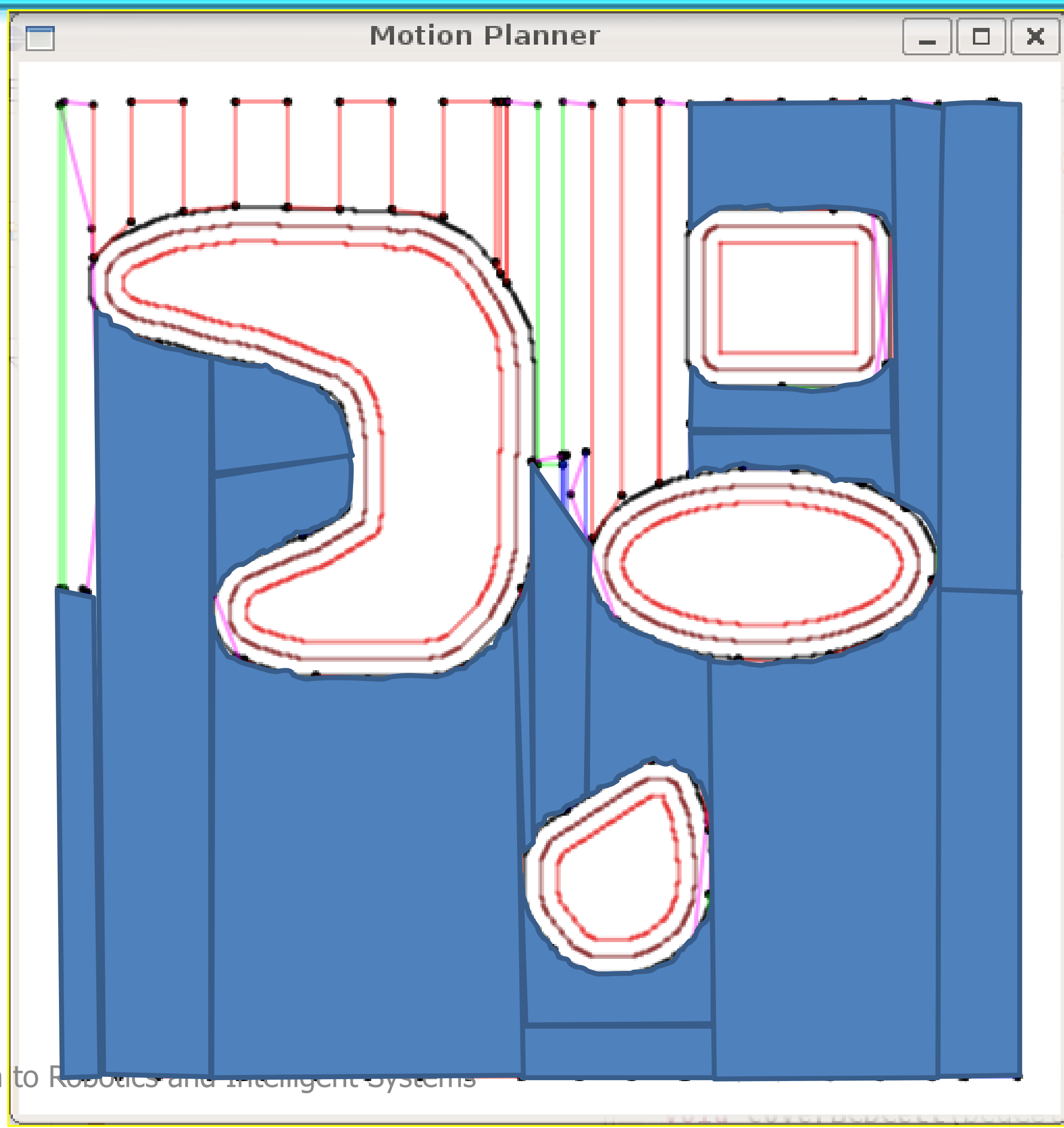

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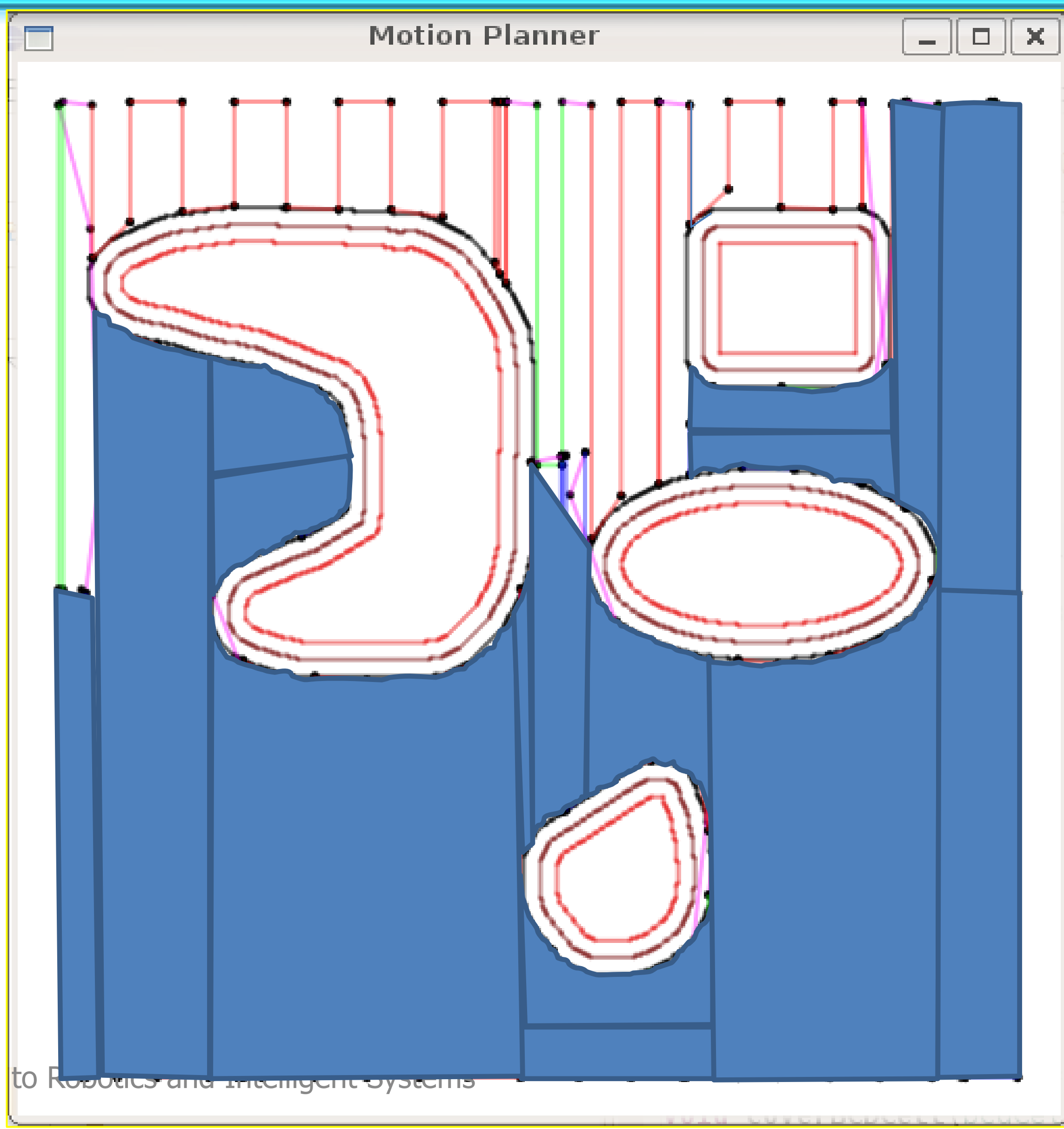

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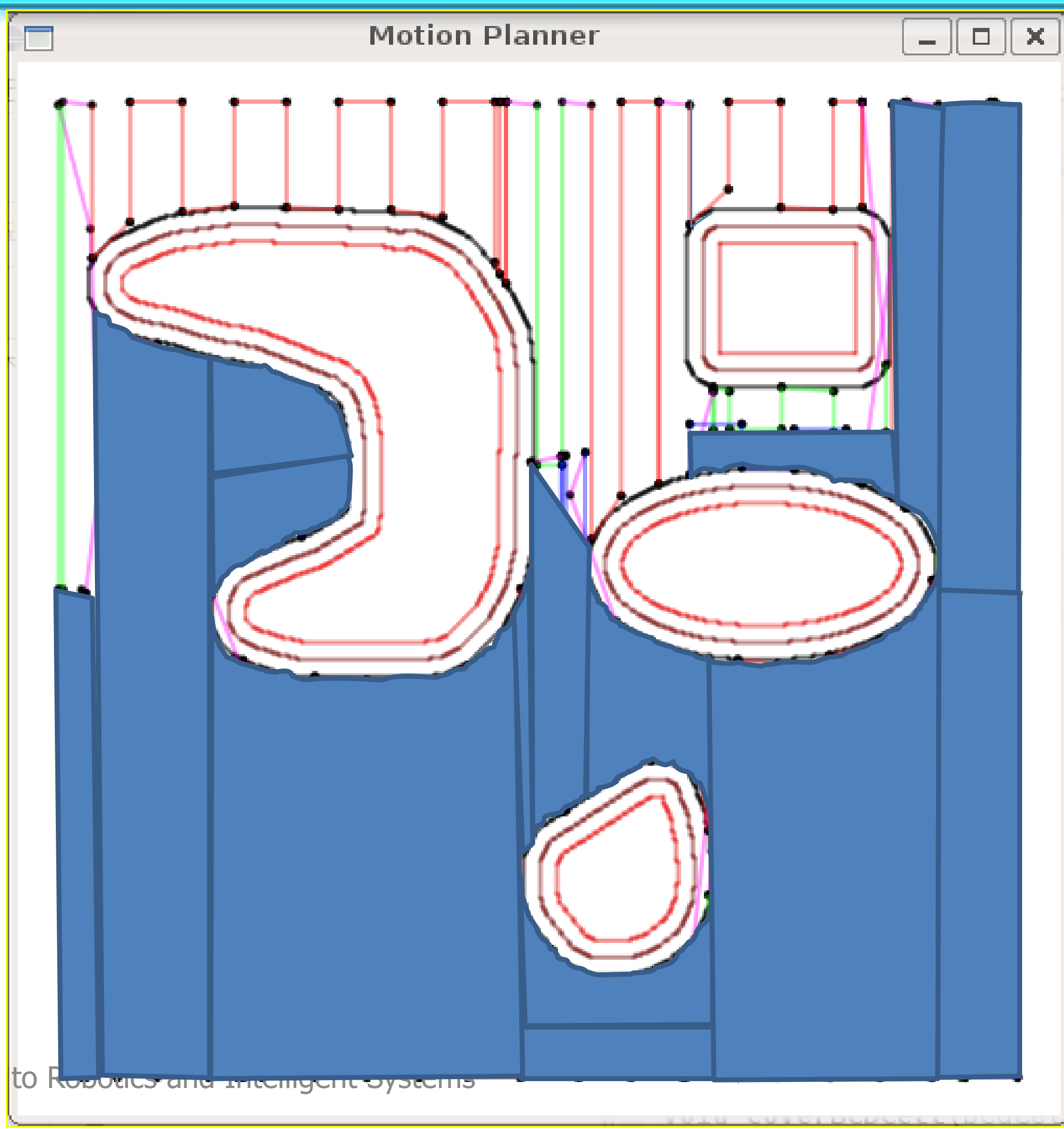

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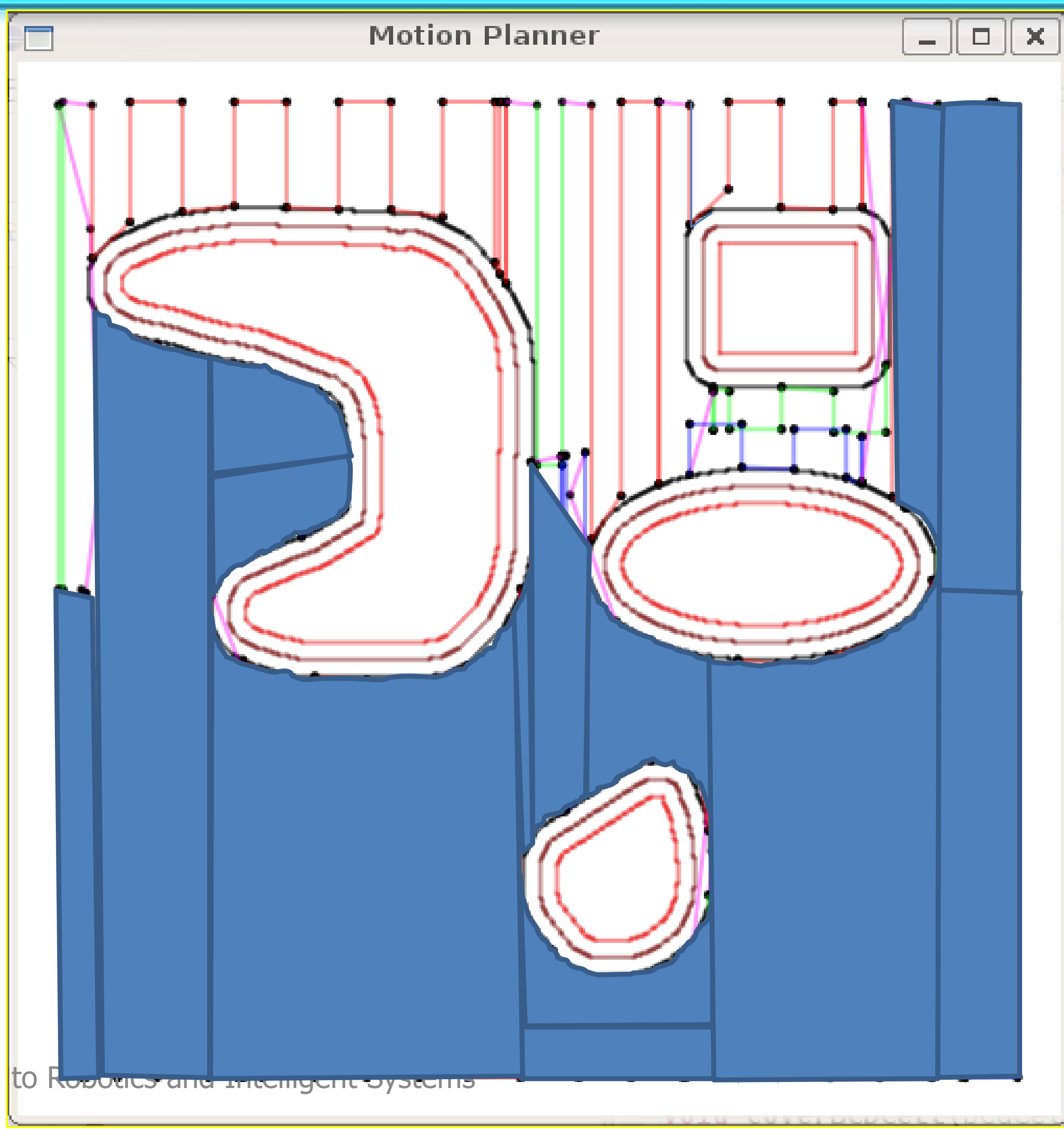

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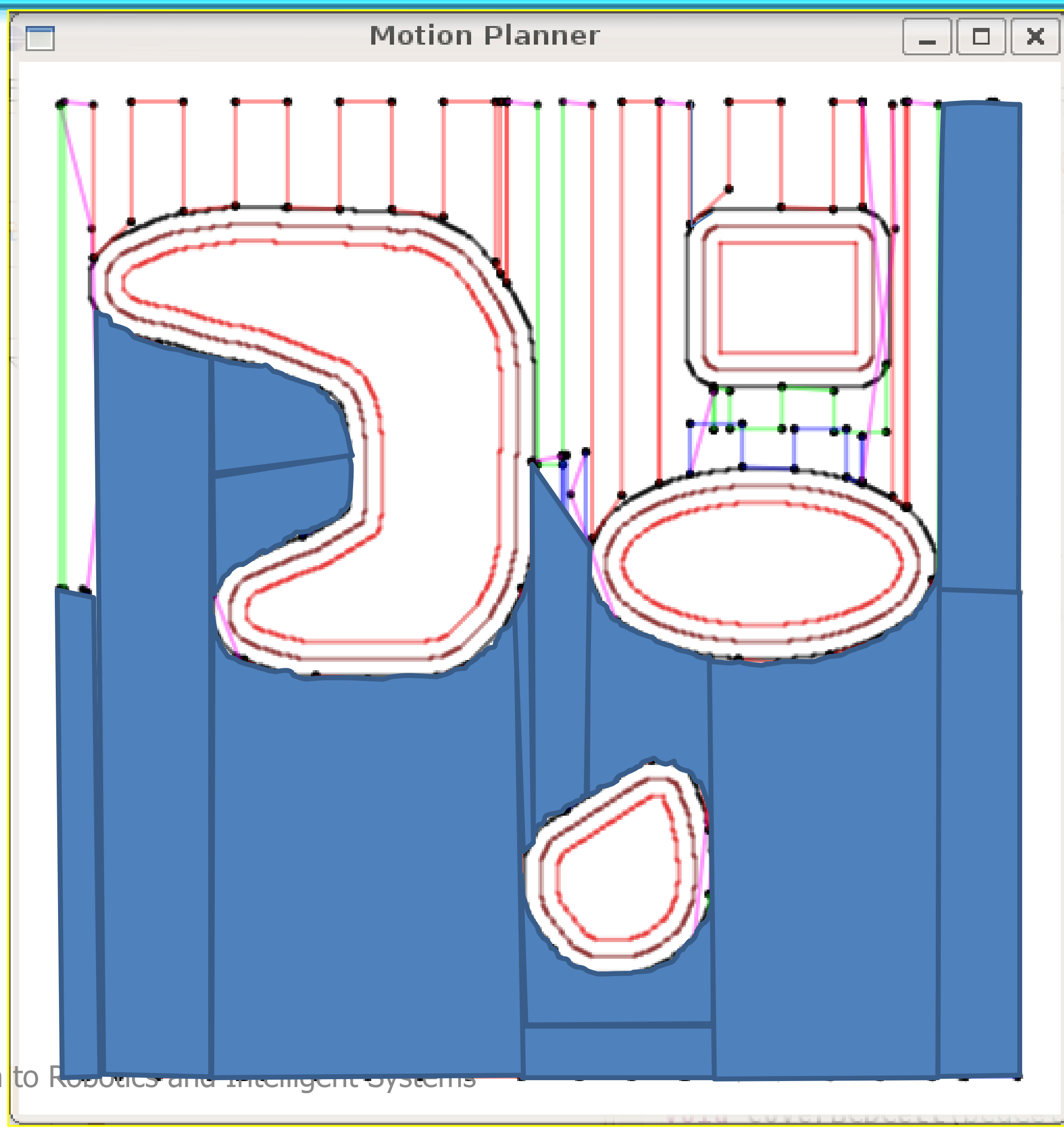

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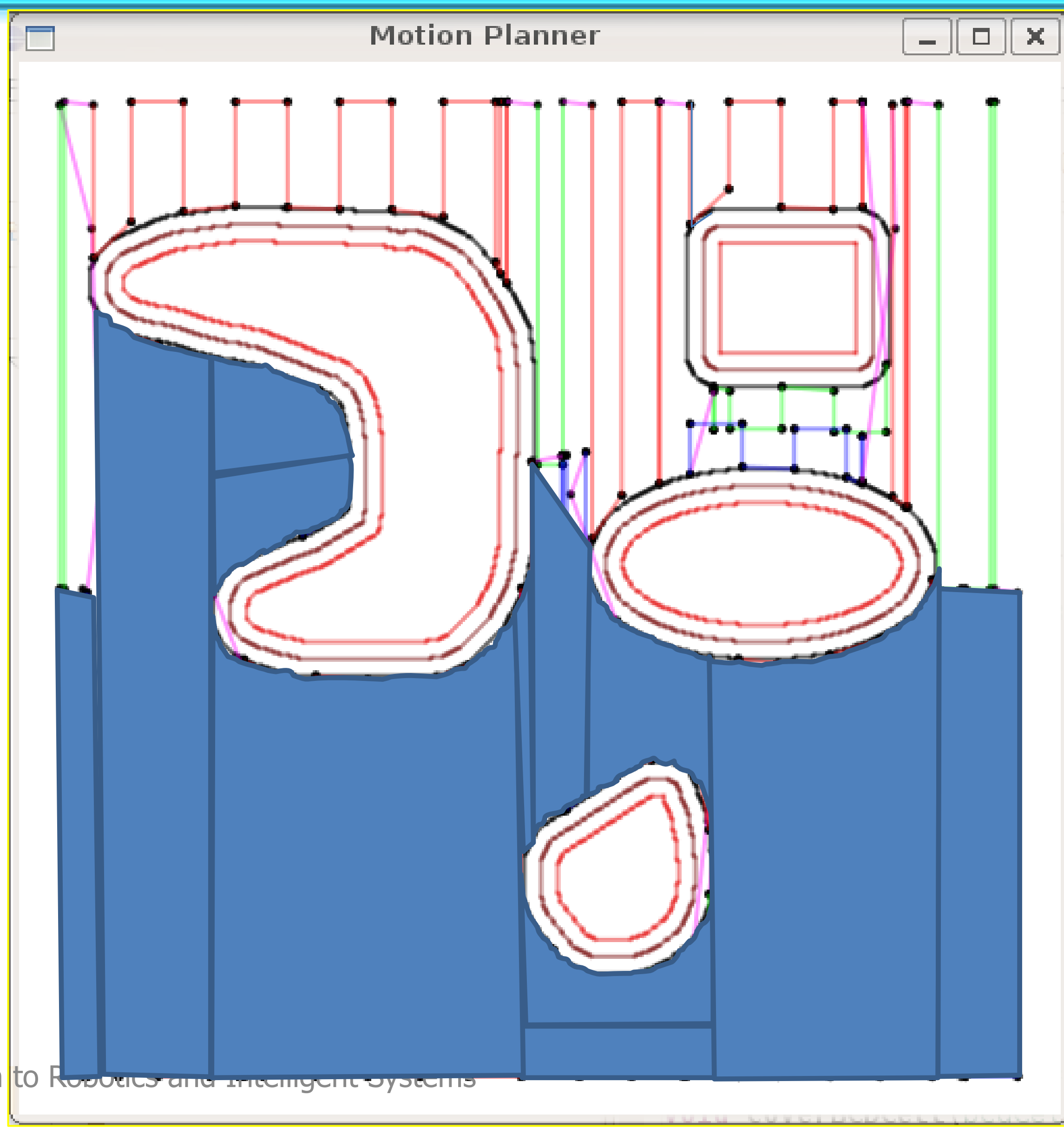

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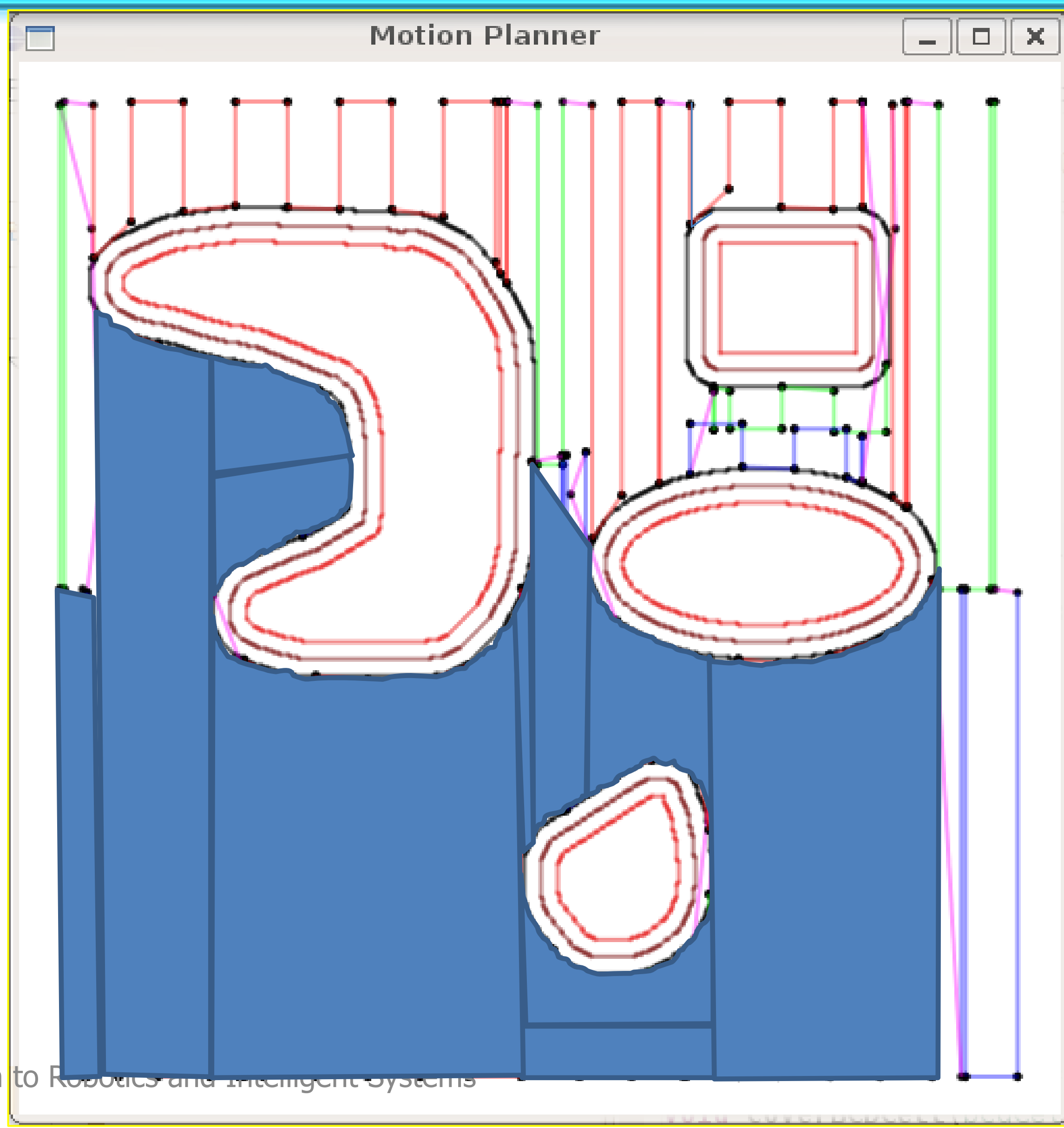

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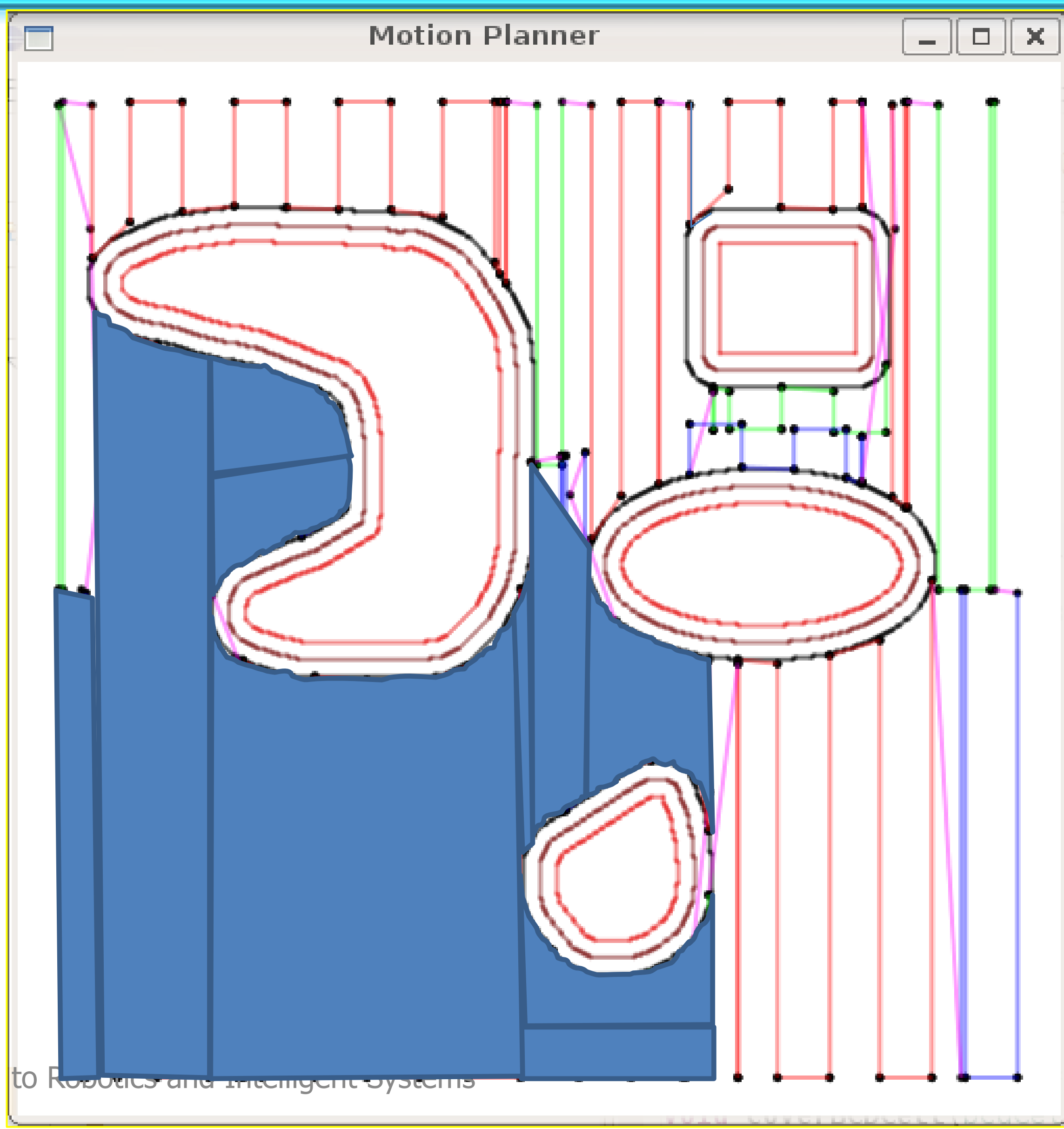

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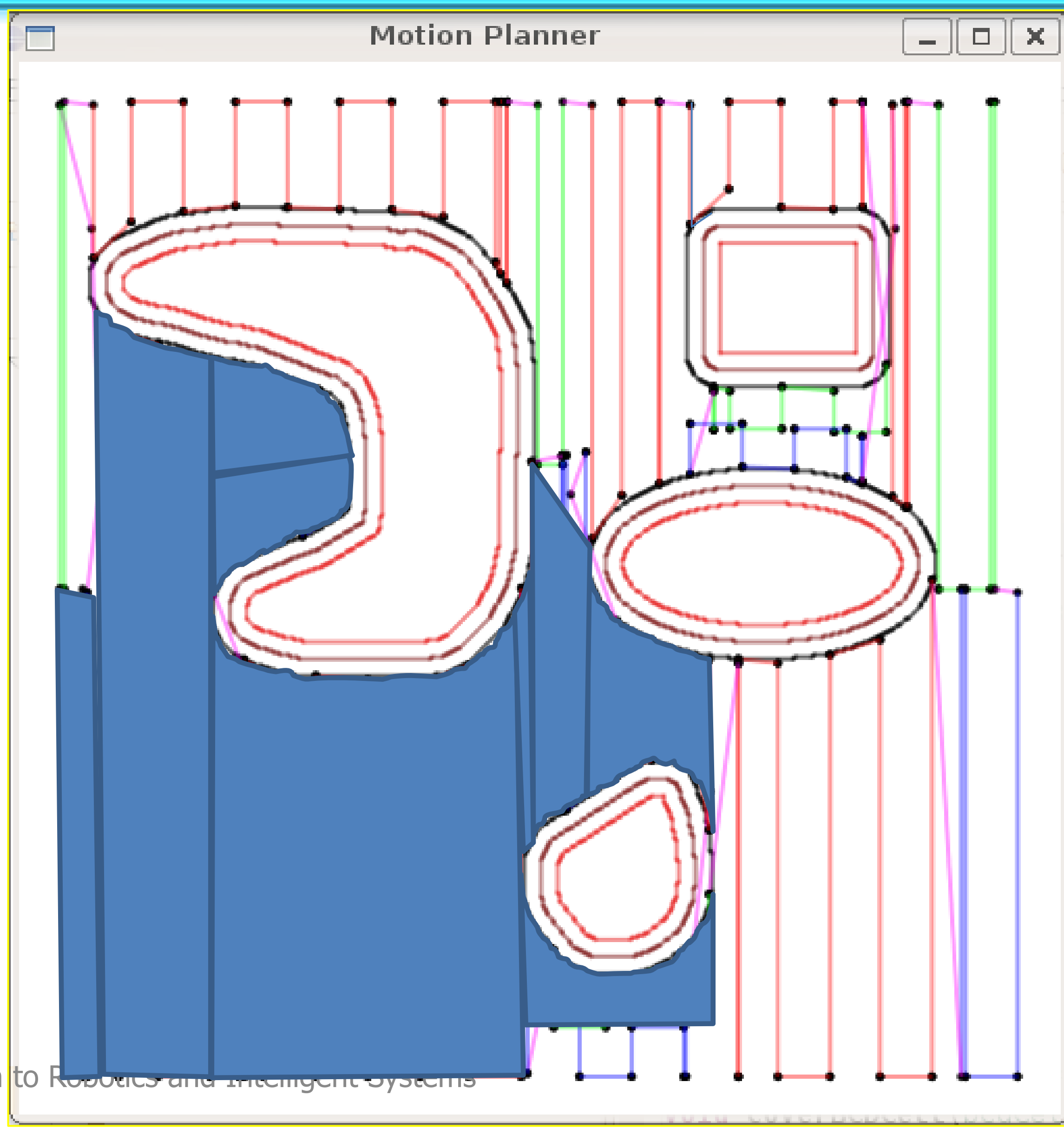

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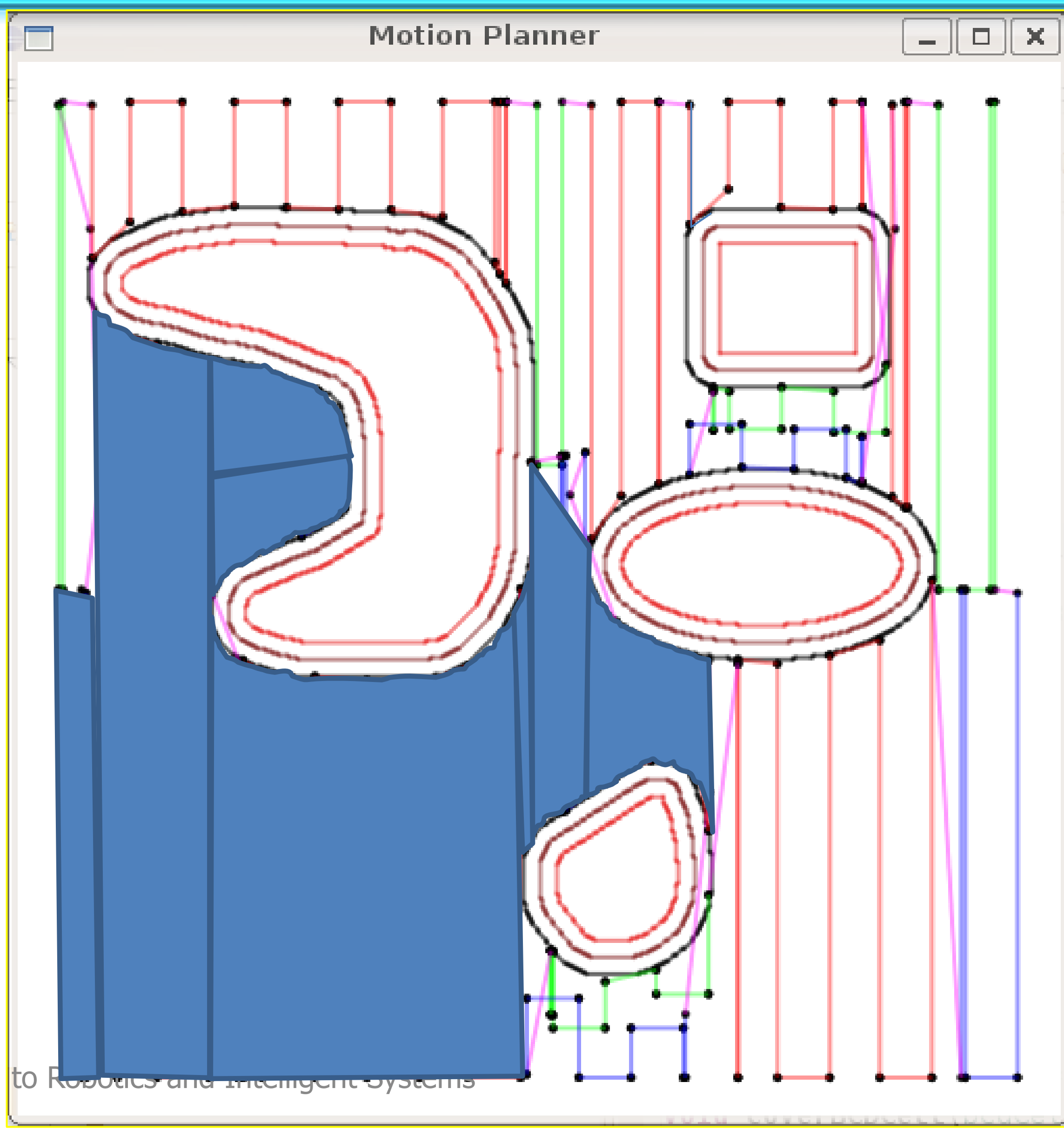

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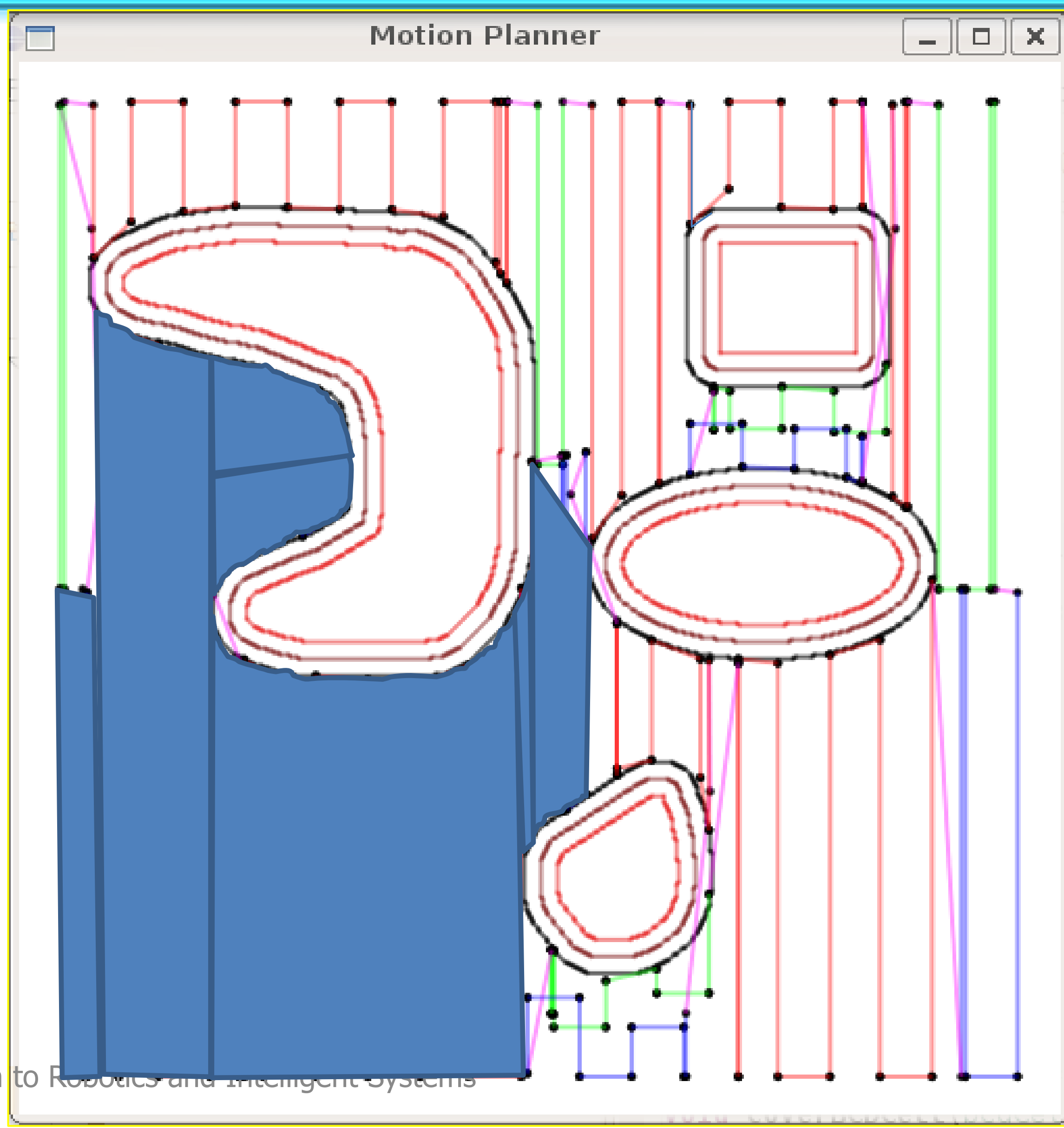

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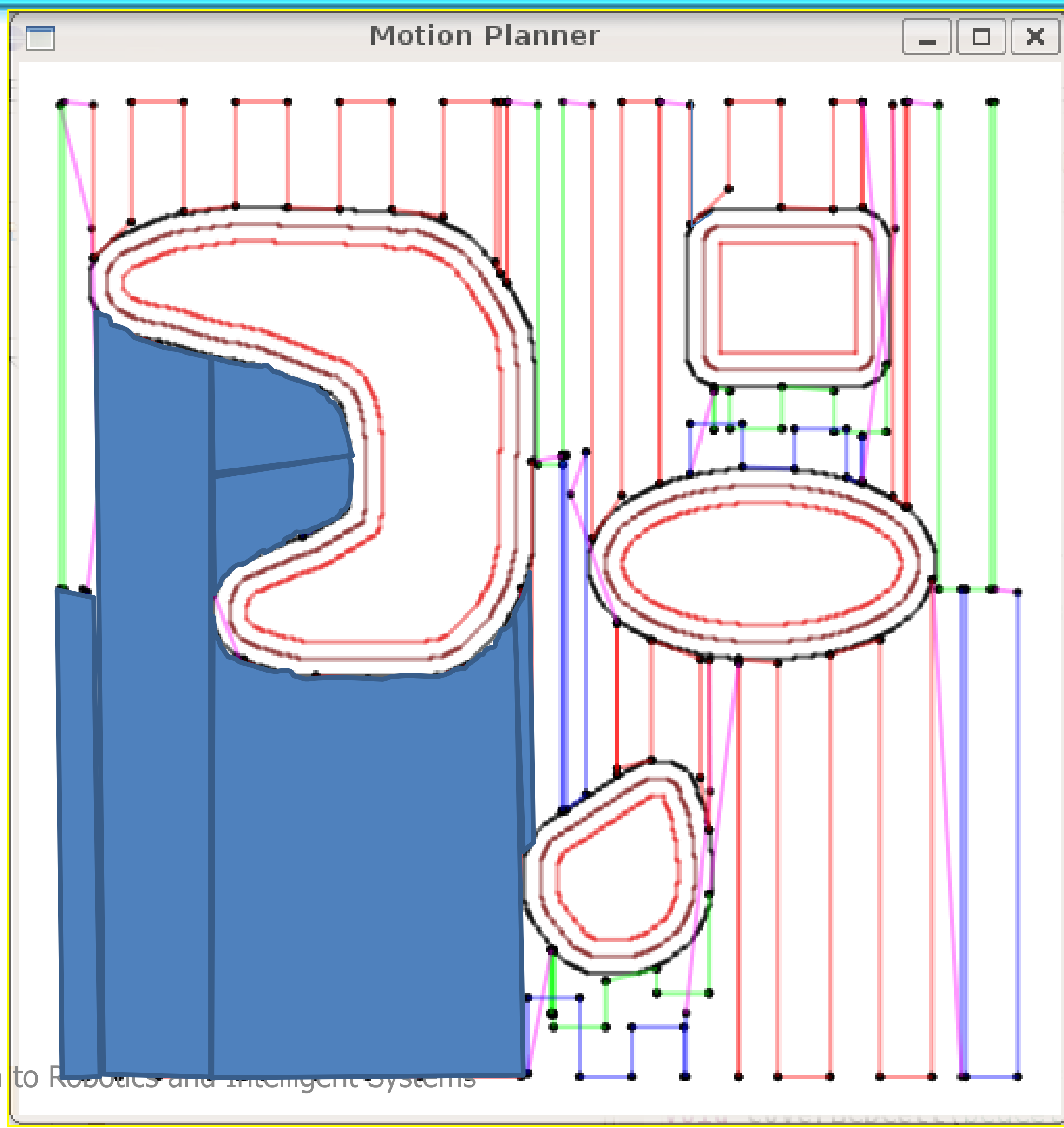

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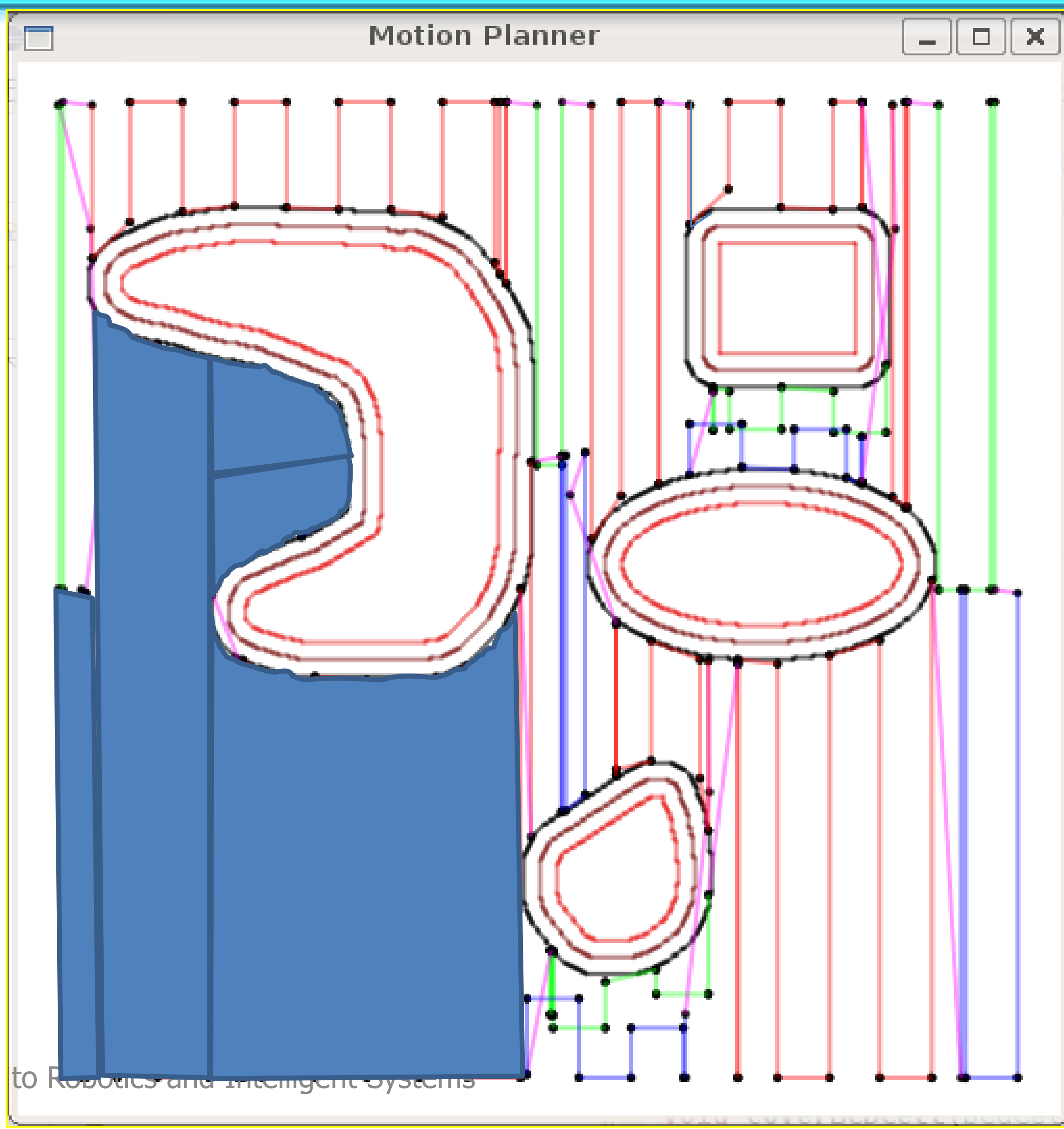

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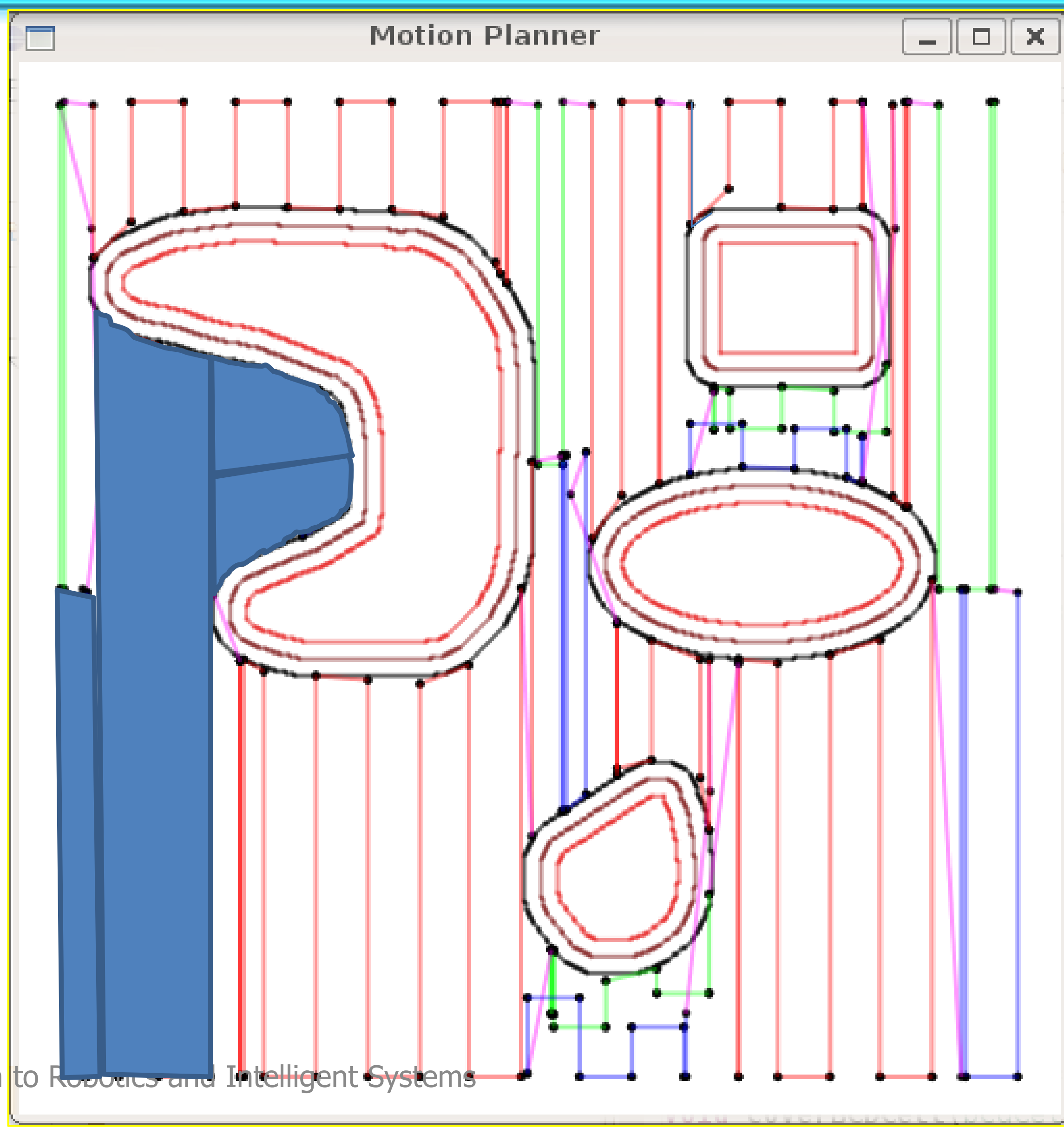

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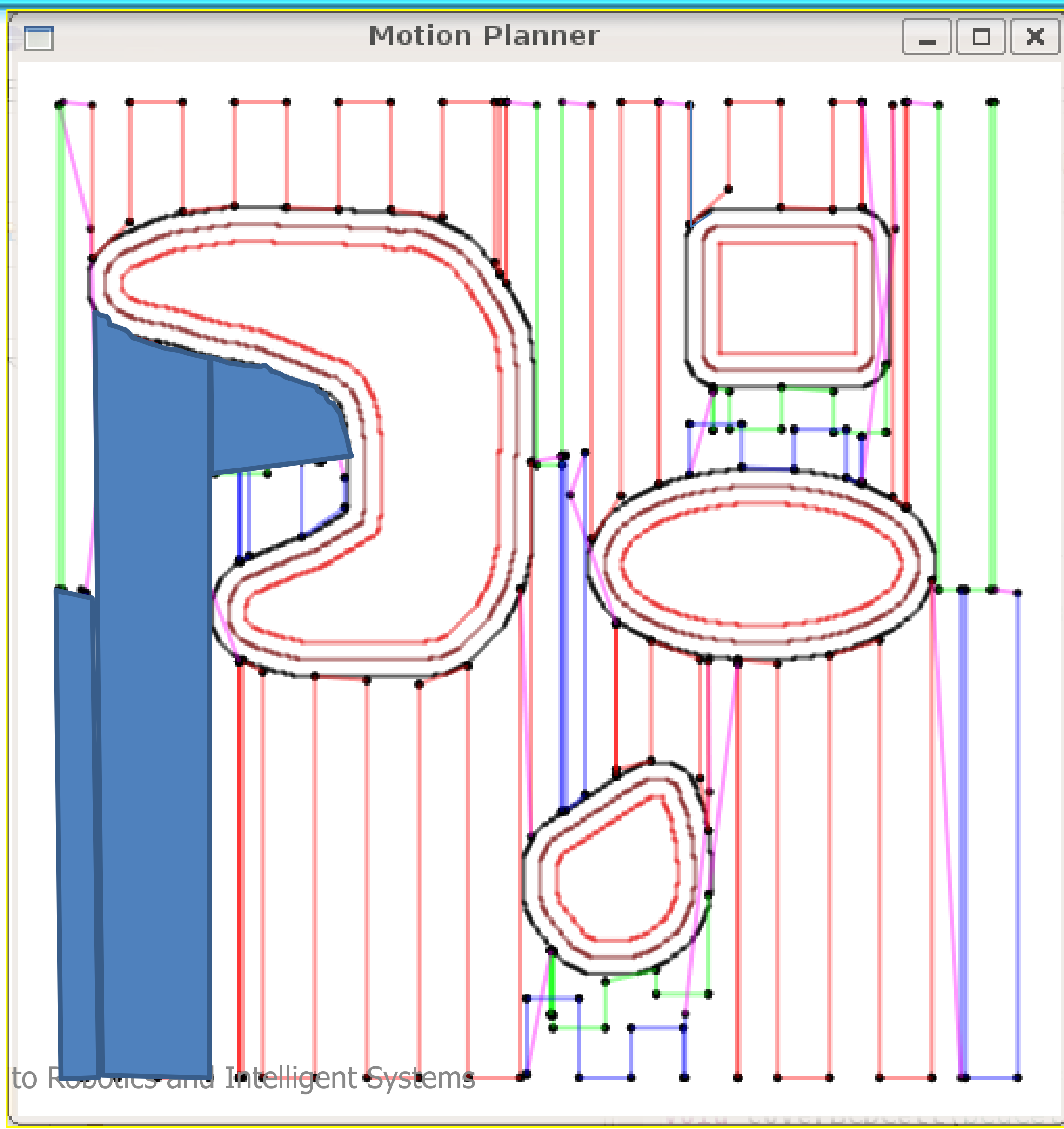

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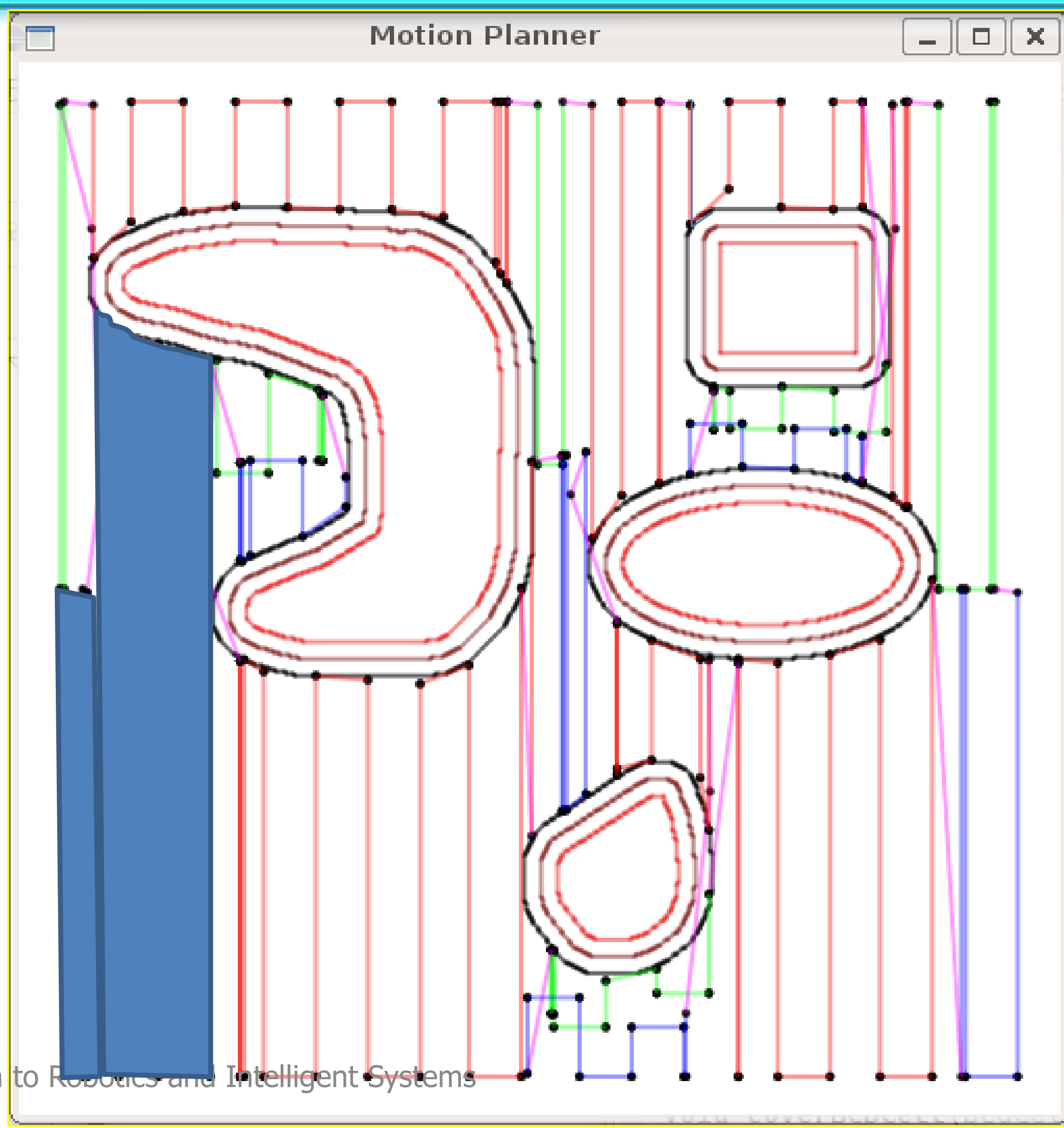

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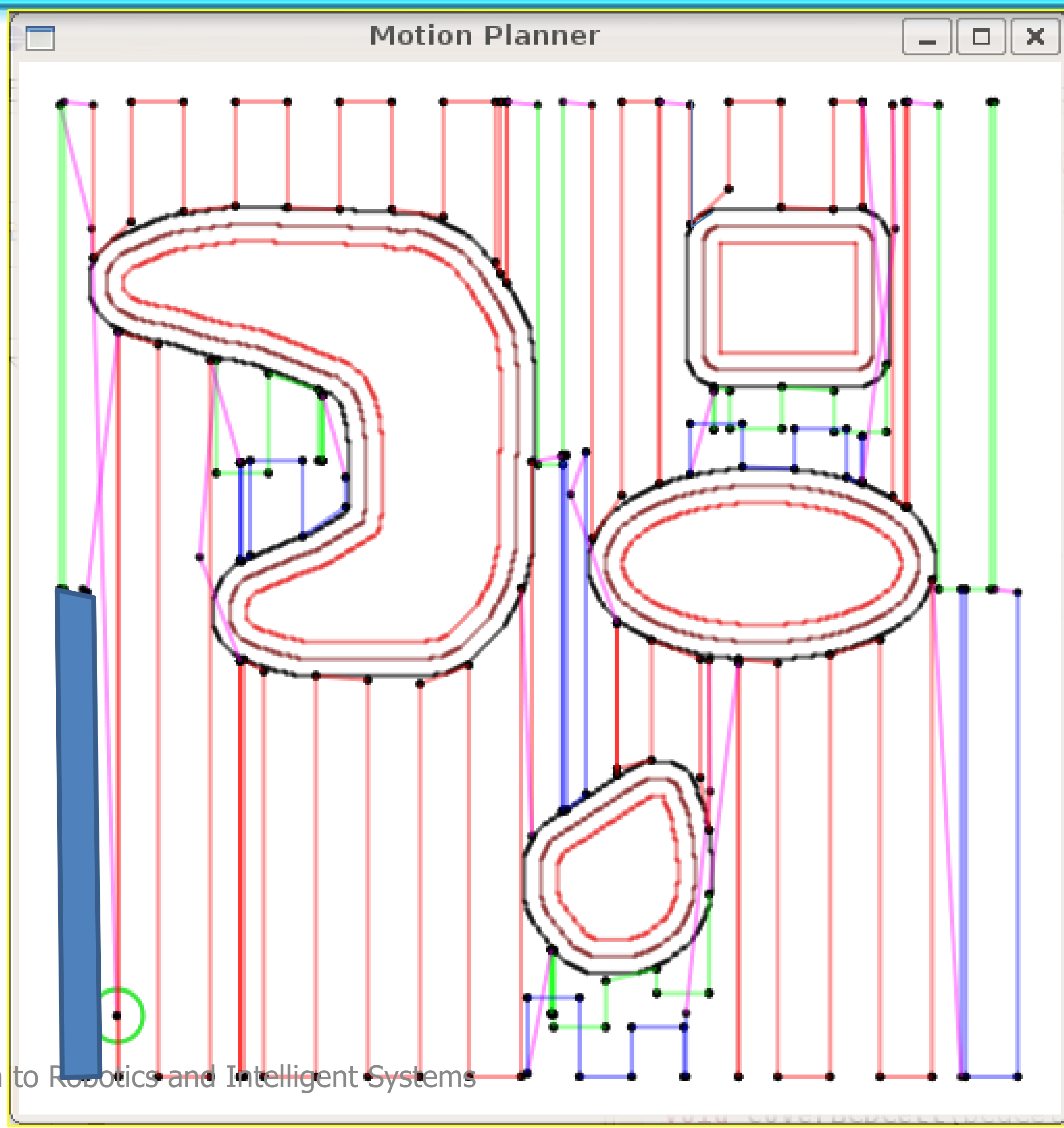

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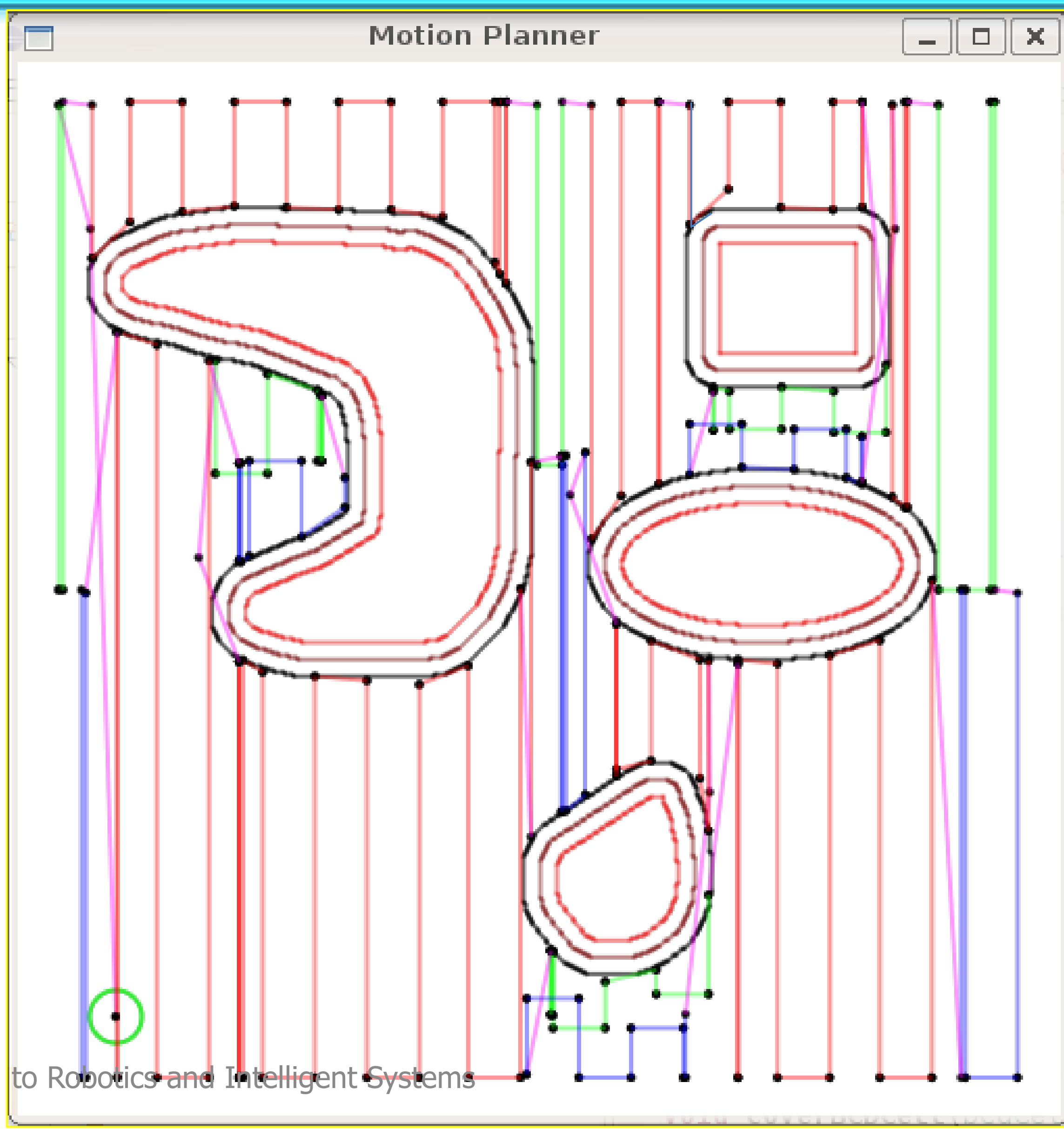
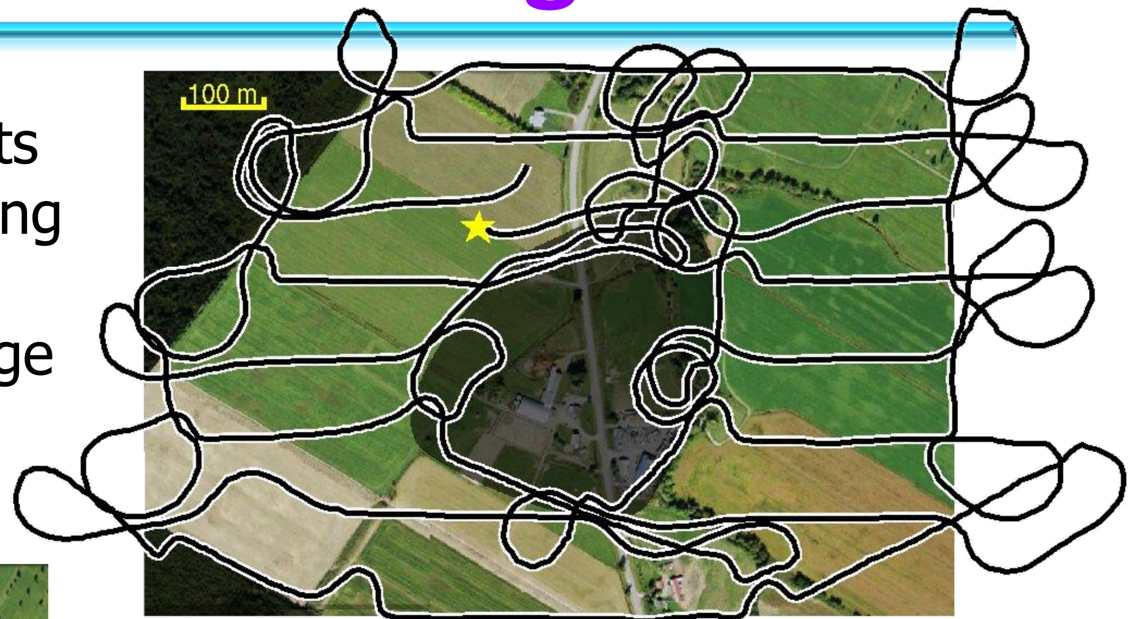


UAV-Optimal Coverage

UAV-Optimal Coverage



- UAVs non-holonomic constraints require special trajectory planning

- 120 Km of flight during coverage

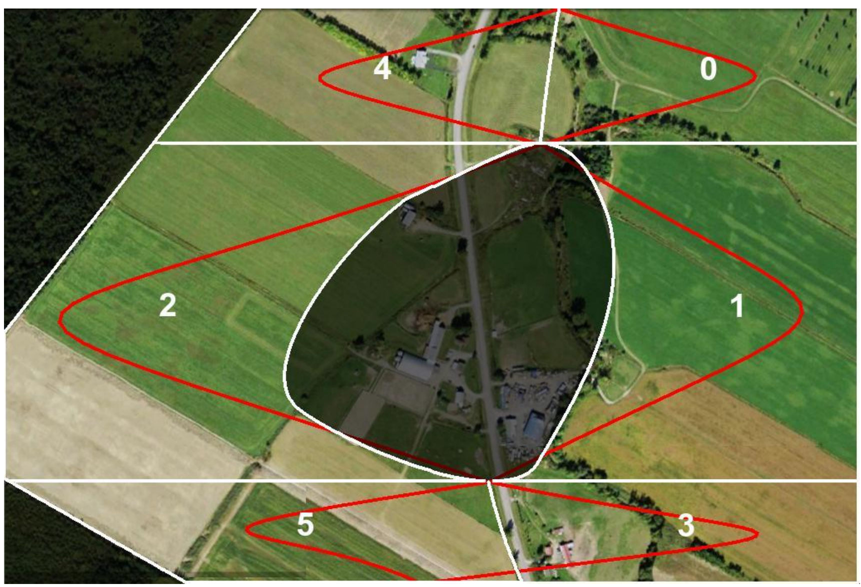
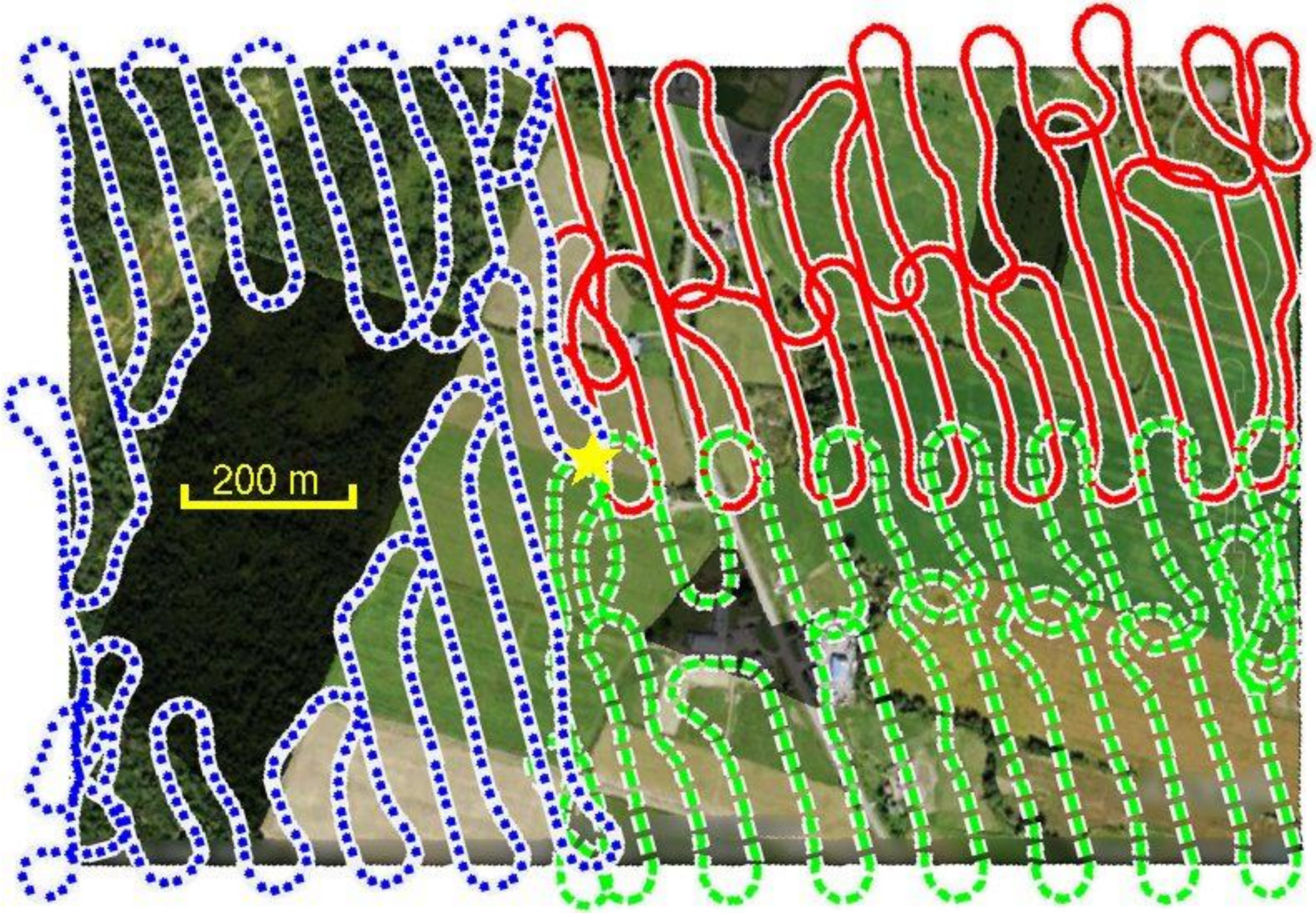


Image Mosaic

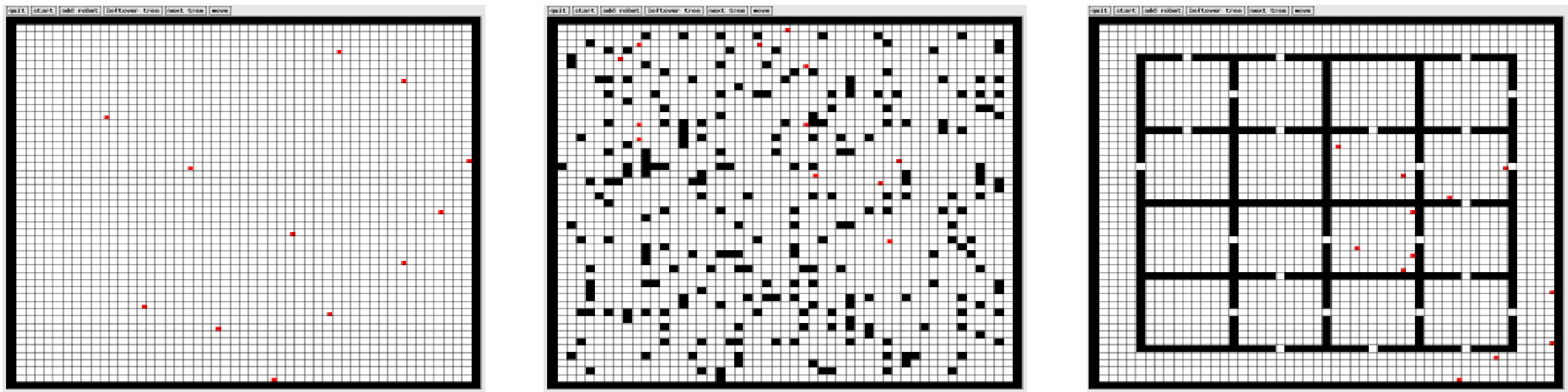
Multi-UAV



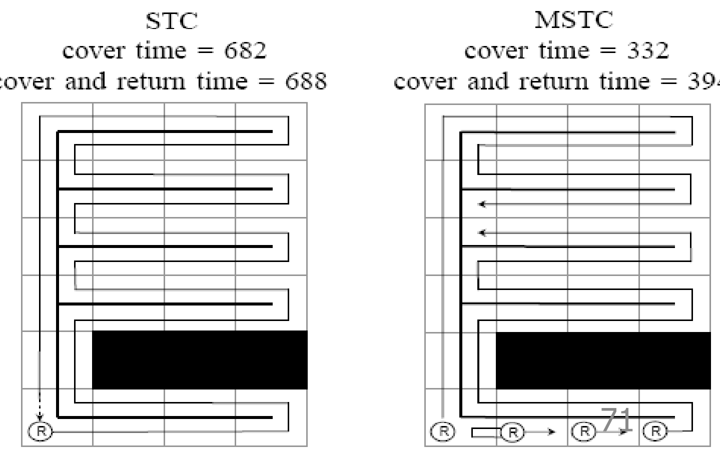
Video at ICRA 2011

Coverage of Known Worlds

Empty Terrain | Outdoor-Like Terrain | Indoor-Like Terrain



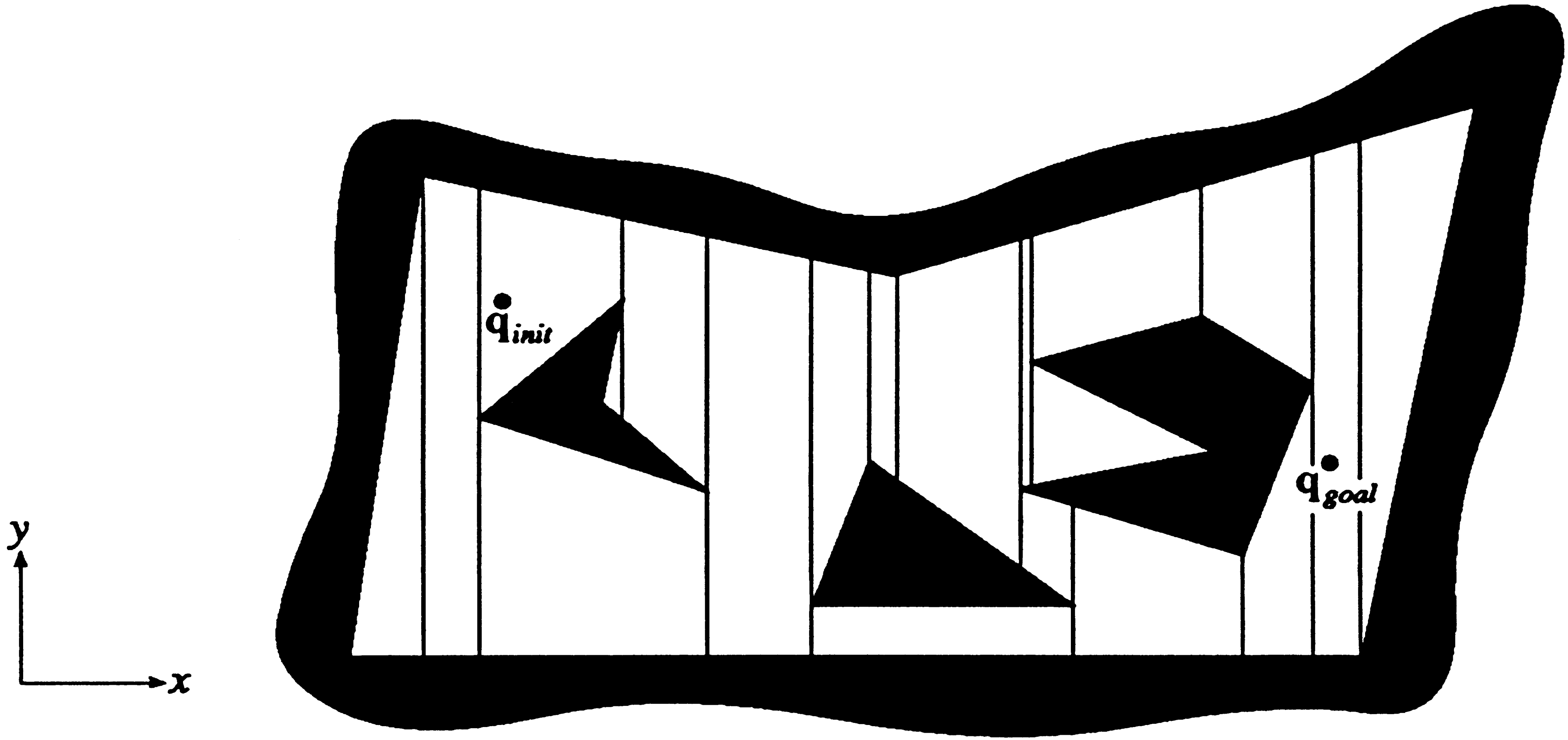
From: X. Zheng and S. Koenig. Robot Coverage of Terrain with Non-Uniform Traversability. In Proc. of the IEEE Int. Conf. on Intelligent Robots and Systems (IROS), pg. 3757-3764, 2007



Cell decomposition for Path Planning

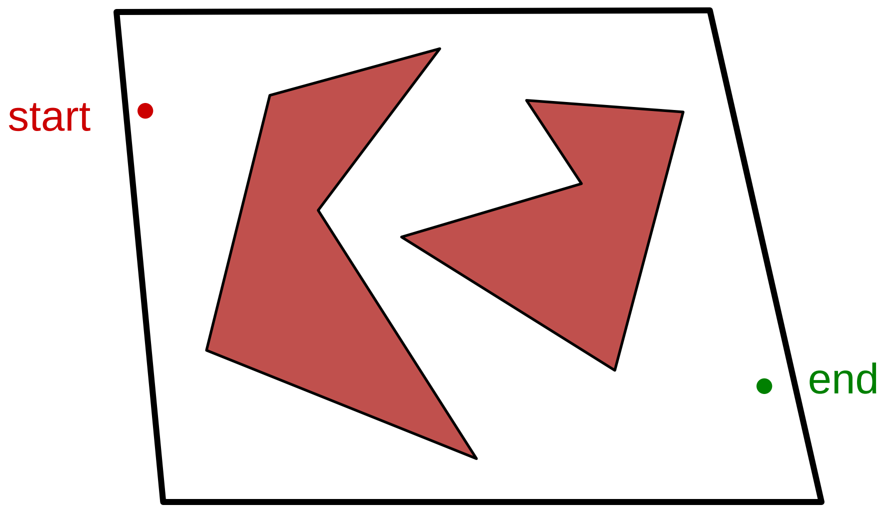
- Decompose the free space into simple cells and represent the connectivity of the free space by the adjacency graph of these cells

Trapezoidal decomposition



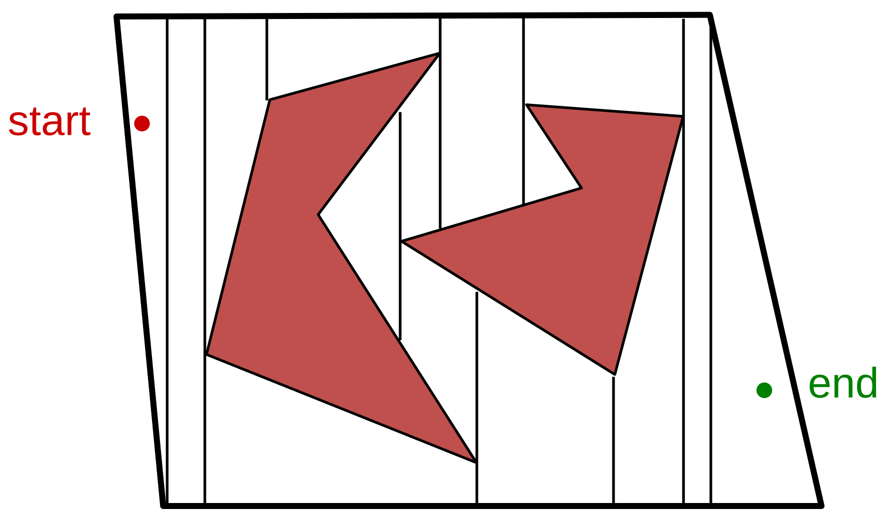
Spatial decompositions

- Dividing free space into pieces and using those...



Spatial decompositions

- Dividing free space into pieces and using those...



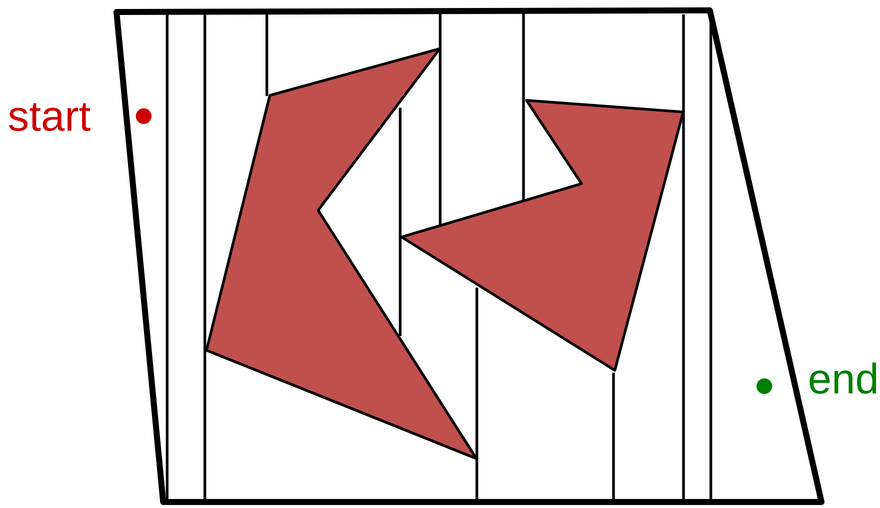
Running time?

Exact cell decomposition

sweepline algorithm

Spatial decompositions

- Dividing free space into pieces and using those...



Exact cell decomposition

sweepline algorithm

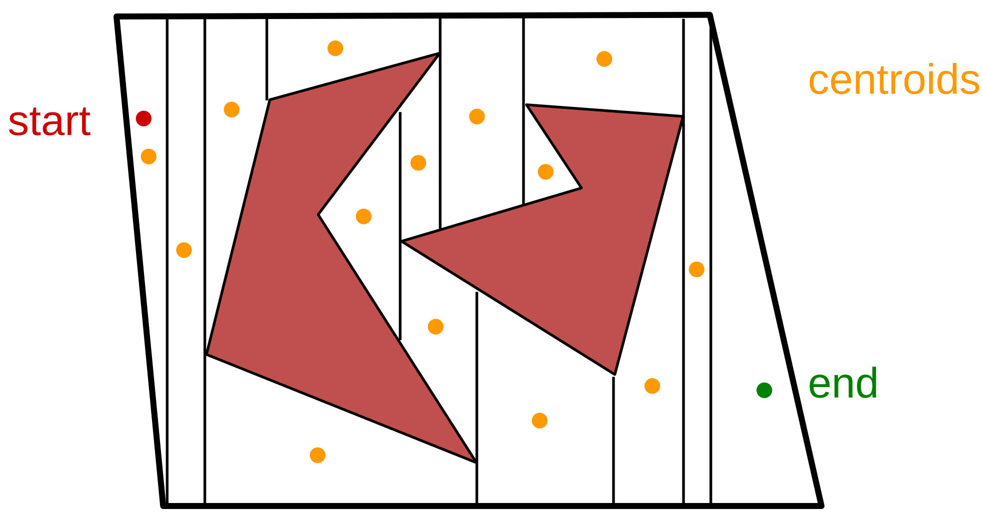
Running time?

Path?

O(N log(N))

Spatial decompositions

- Dividing free space into pieces and using those...



Exact cell decomposition
sweepline algorithm

Running time?

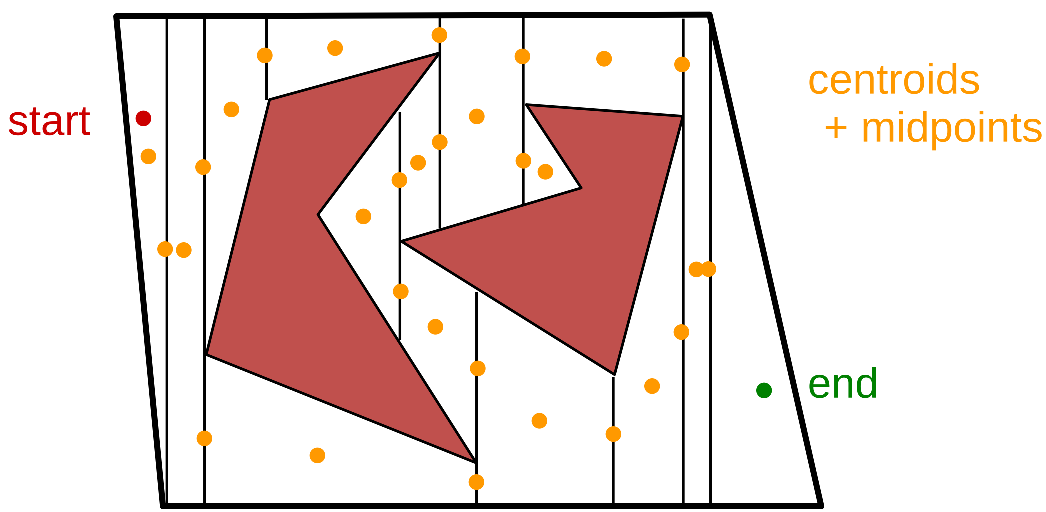
O(N log(N))

Path?

via centroids

Spatial decompositions

- Dividing free space into pieces and using those...



Exact cell decomposition
sweepline algorithm

Running time?

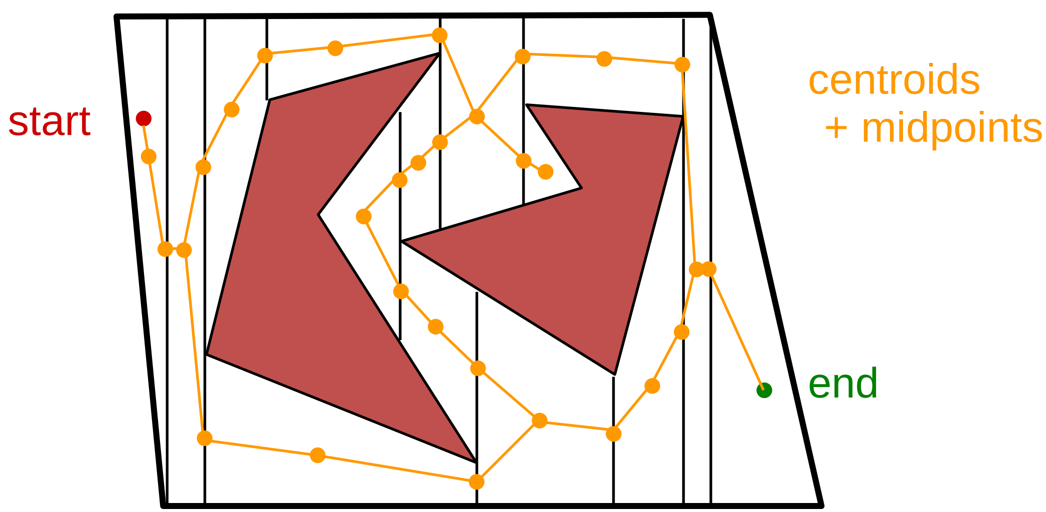
O(N log(N))

Path?

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?

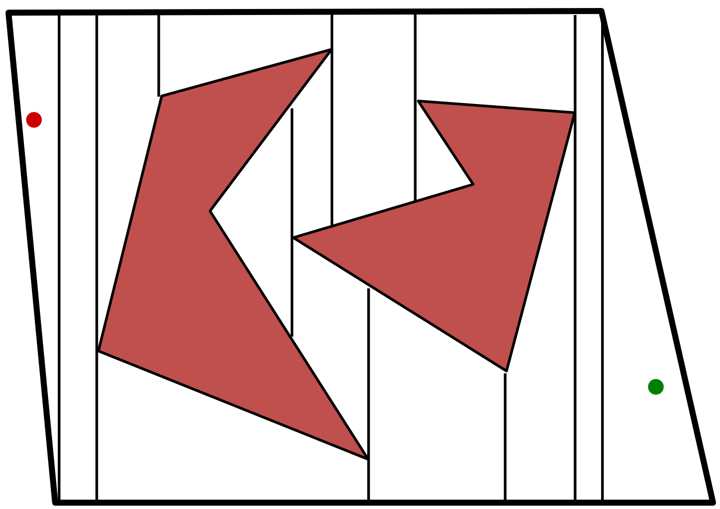
via centroids
+ edge midpoints
+ graph search

Why?

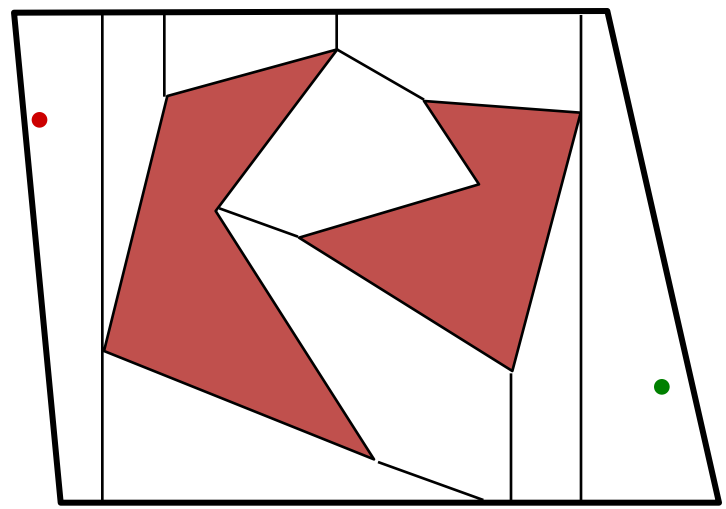
why else?

Optimality

- Obtaining the *minimum* number of convex cells is NP-complete.



15 cells



9 cells

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...

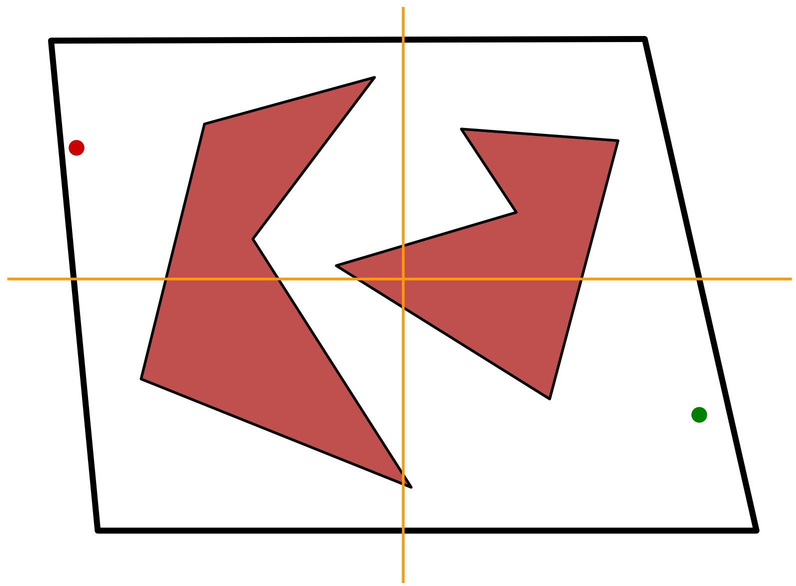
Cell-Decomposition Methods

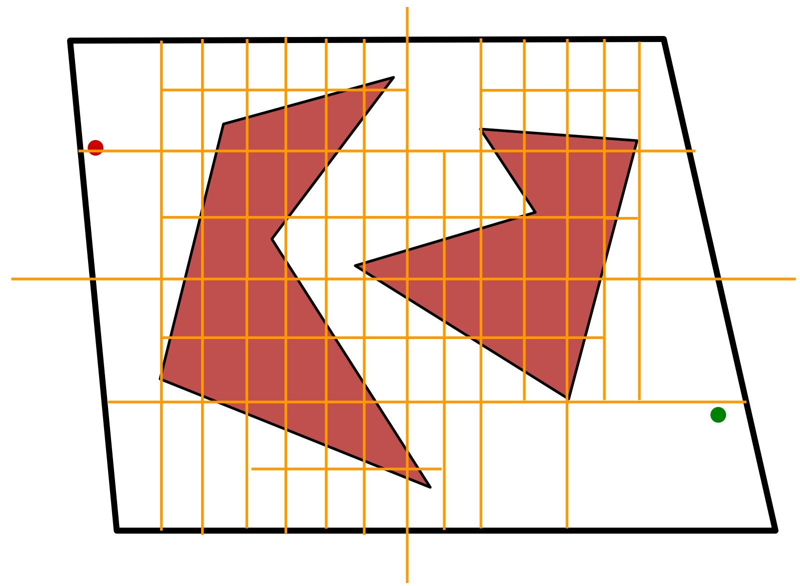
Two families of methods:

- 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

further decomposing...

- Approximate cell decomposition

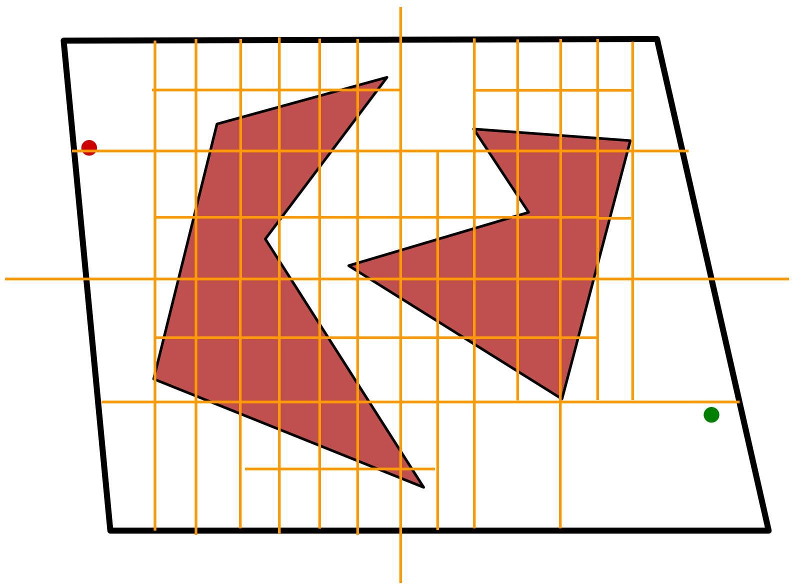




Quadtree: recursively subdivides each *mixed* obstacle/free (sub)region into four quarters...

further decomposing...

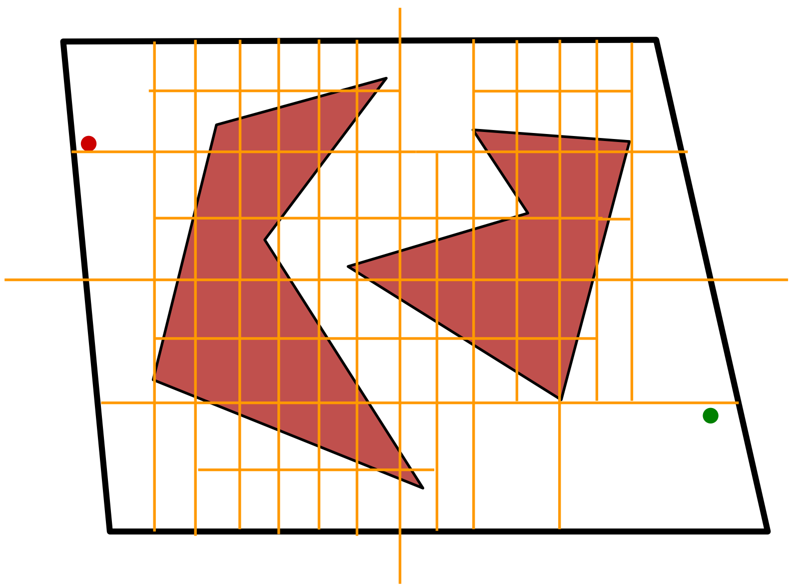
- Approximate cell decomposition



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

further decomposing...

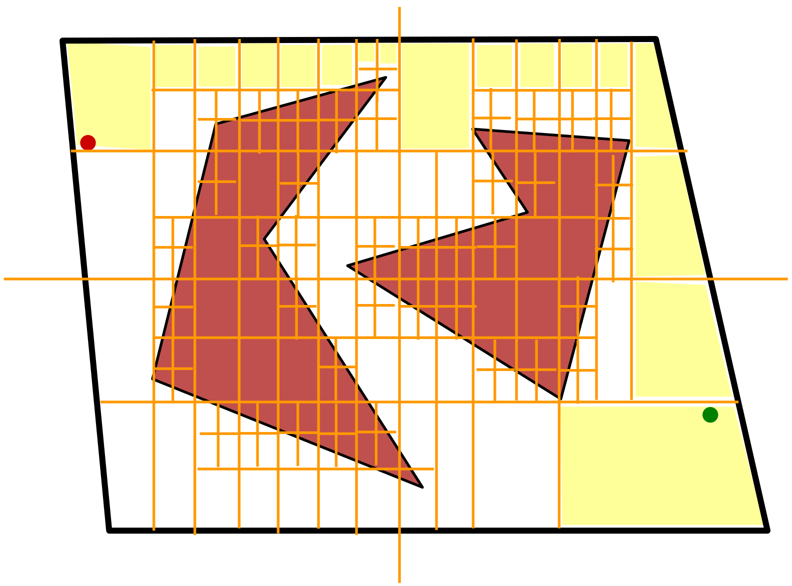
- Approximate cell decomposition



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

further decomposing...

- Approximate cell decomposition



Quadtree

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

is this a **complete** path-planning algorithm?
i.e., does it find a path when one exists ?

Octree Decomposition