Cooperative Robotics

Literature Survey

Presented to the ISRG

October 24, 2002

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Presented Research

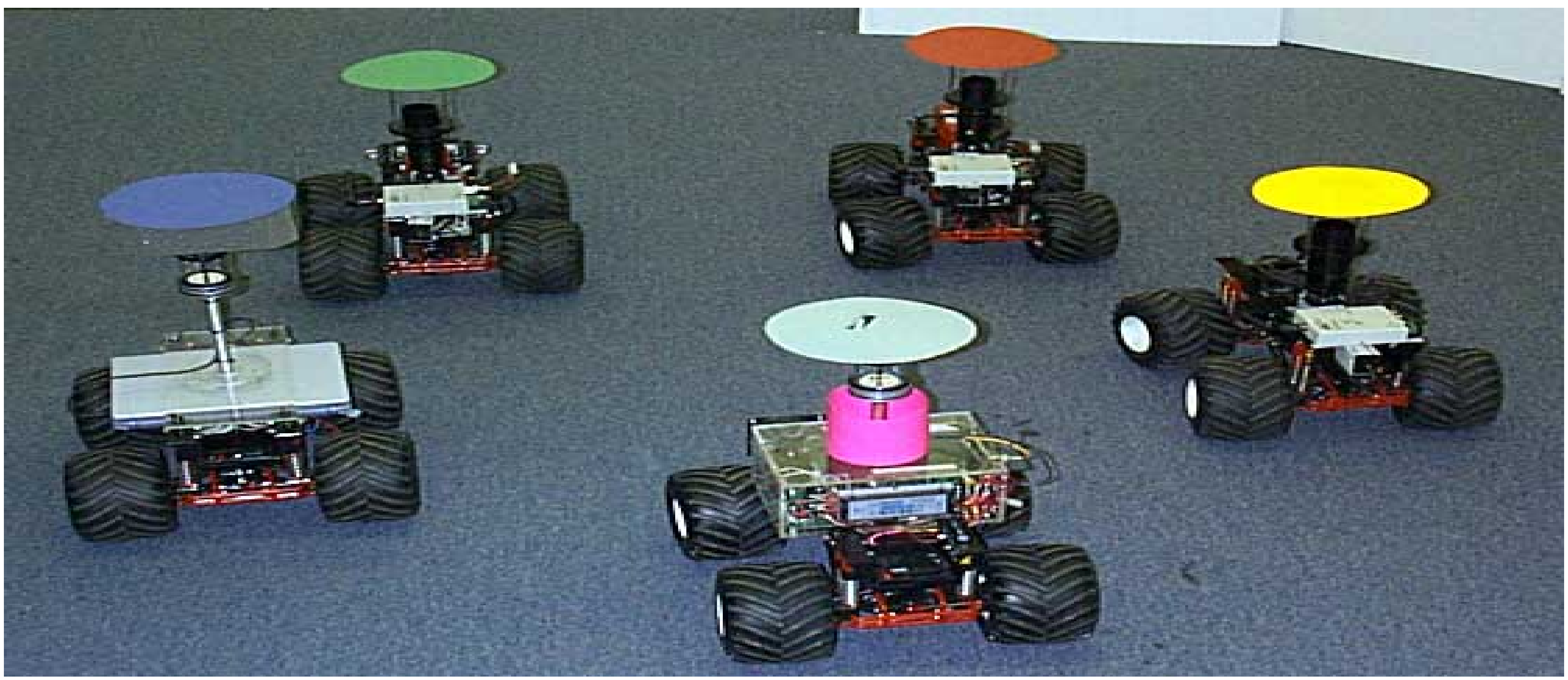
- Multiple Autonomous Robots (MARS)
- Supervising Multiple Autonomous Mobile Robots
- Swarm Intelligence
- Cooperative Control of Distributed Multi-Agent Systems
- Multi Robot Coordination for Robust Exploration

MARS: Multiple Autonomous Robots

University of Pennsylvania

GRASP Laboratory

Philadelphia, Pennsylvania



Current Projects

1. Cooperative Control and Localization of Multiple Robots

- Autonomous robots to maintain a formation
- Develop a set of graph-based algorithms including:
  - Discovery
  - Cooperative Localization
  - Cooperative Control

2. Network of Autonomous Robots for Fire-fighting

- Cooperative localization and tracking
- Conduct search and rescue operations

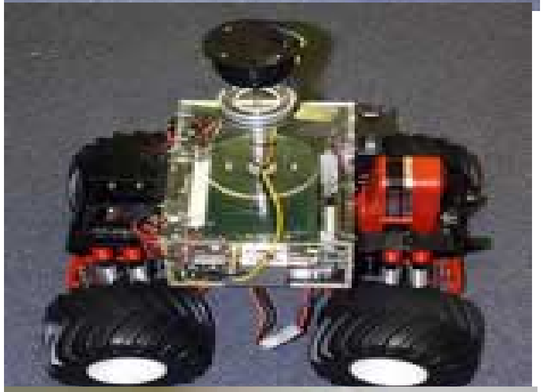
Robotic Platforms

ClodBuster™ I :

1. **Camera**
2. **Wireless Video**
3. **Micro-controller**

ClodBuster™ II :

1. **Camera**
2. **On-board PC**



ClodBuster™ III :

1. **Camera**
2. **Laptop**

Cooperative Localization and Control for Multi-Robot Manipulation

J. Spletzer, A. K. Das, R. Fierro, C. J. Taylor,V. Kumar, and J. P. Ostrowski

GRASP Laboratory
University of Pennsylvania
Philadelphia, PA

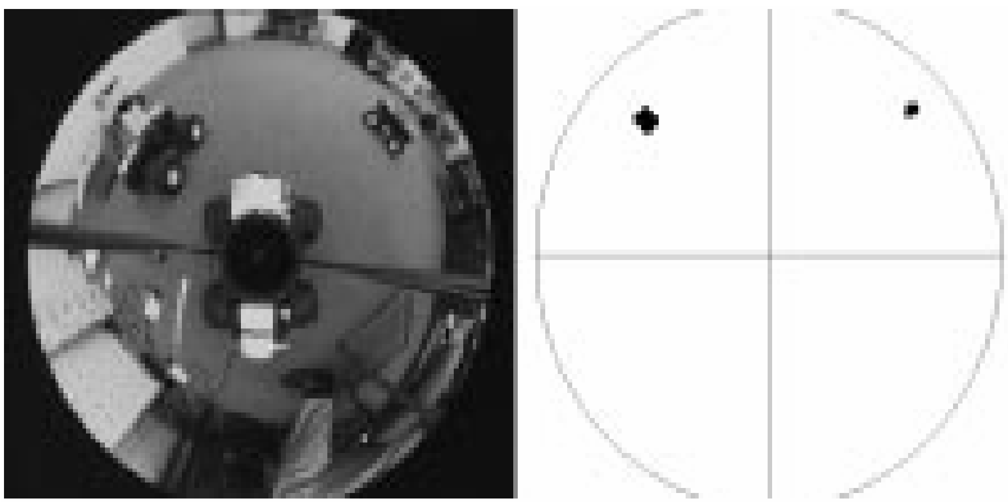
Summary:

1. Localization based on visual sensors
2. Control algorithms to maintain a formation
3. A framework for coordinated behavior

Localization by Visualization

Hardware:

•**3 Clodbuster™** robots with Omni-directional cameras.



Actual Image and “blob” used to estimate direction vectors.

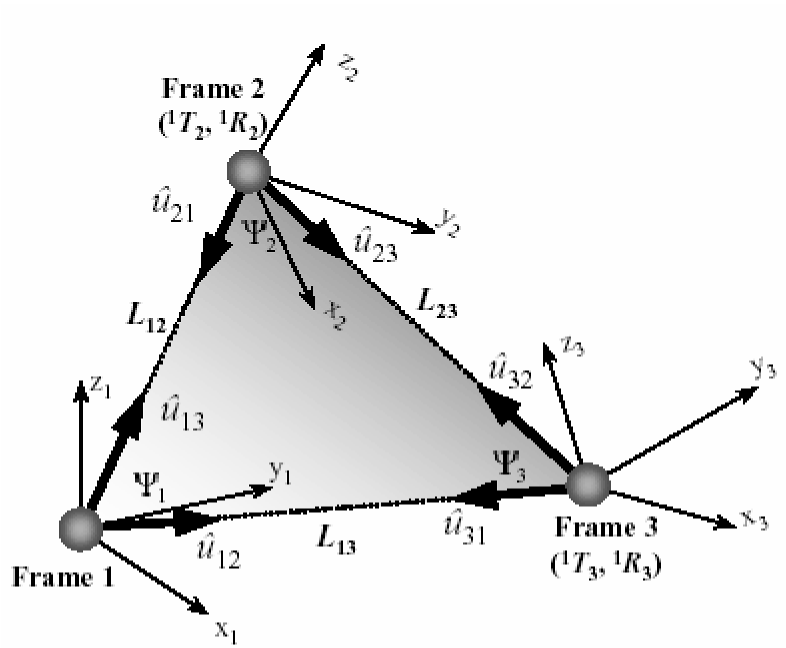
The camera on each robot uses resulting “blobs” from pictures to estimate direction vectors.

Formation Models

•Internal Angles are found by using a scalar product.

For Example: $\psi_2 = \cos^{-1}(\hat{u}_{21} \cdot \hat{u}_{23})$

•The sine rule can be applied, giving the position relative to a single robot.



A vector model with Frame 1 as reference.

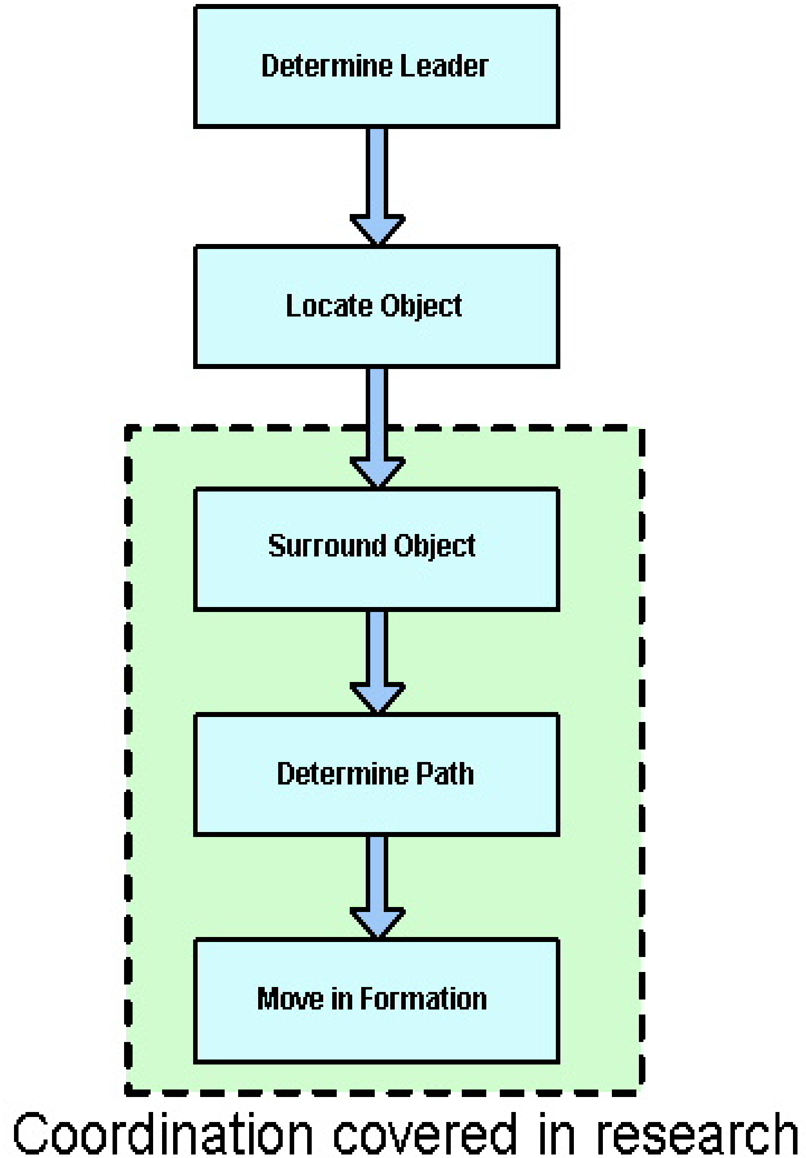
Formations to Coordinate Behavior

Coordinated manipulation :

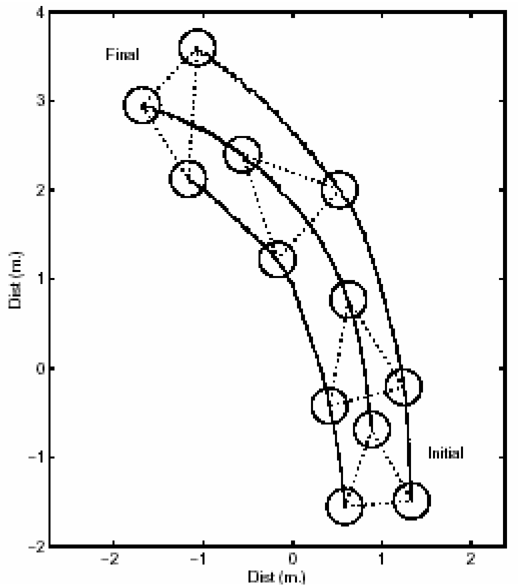
- Robots surround an object
- Leader determines trajectory
- Maintain formation

Coordinated Behavior by Formation

Coordination Process



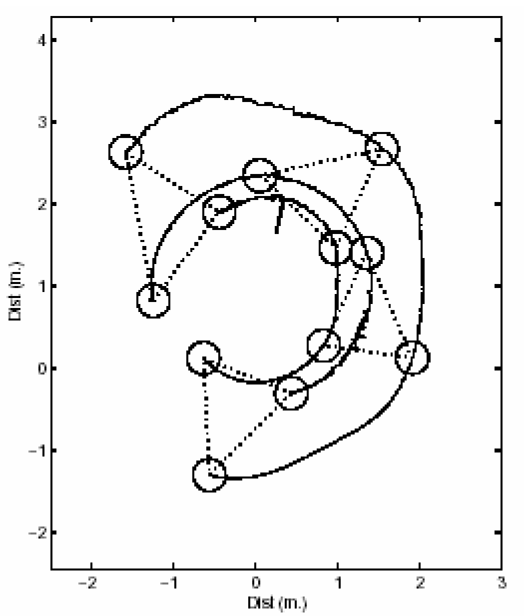
Formation Tests and Results



•Trajectories included both an arc and a circular path. *(Left)*

•Objects were placed in the center.

•Robots moved an object in “tight” or “loose” formations. *(Below)*



Applicable Research

- Dynamically centralized control
- Non-global relative localization
- Controlled formation methods

A Hybrid Approach to Supervising Multiple Co-operant Autonomous Mobile Robots

D P Barnes, R S Aylett, A M Coddington,
R A Ghanea-Hercock

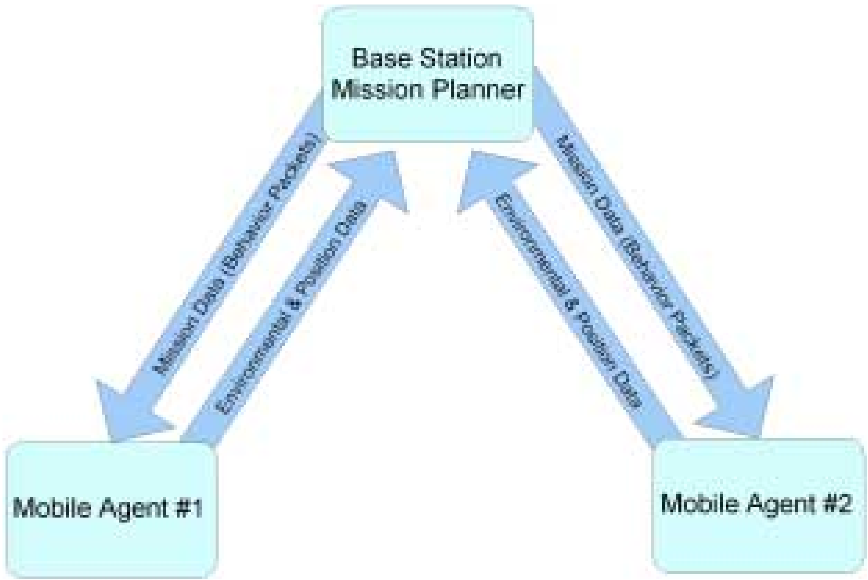
UK Robotics Ltd., Manchester, UK

Project Goals

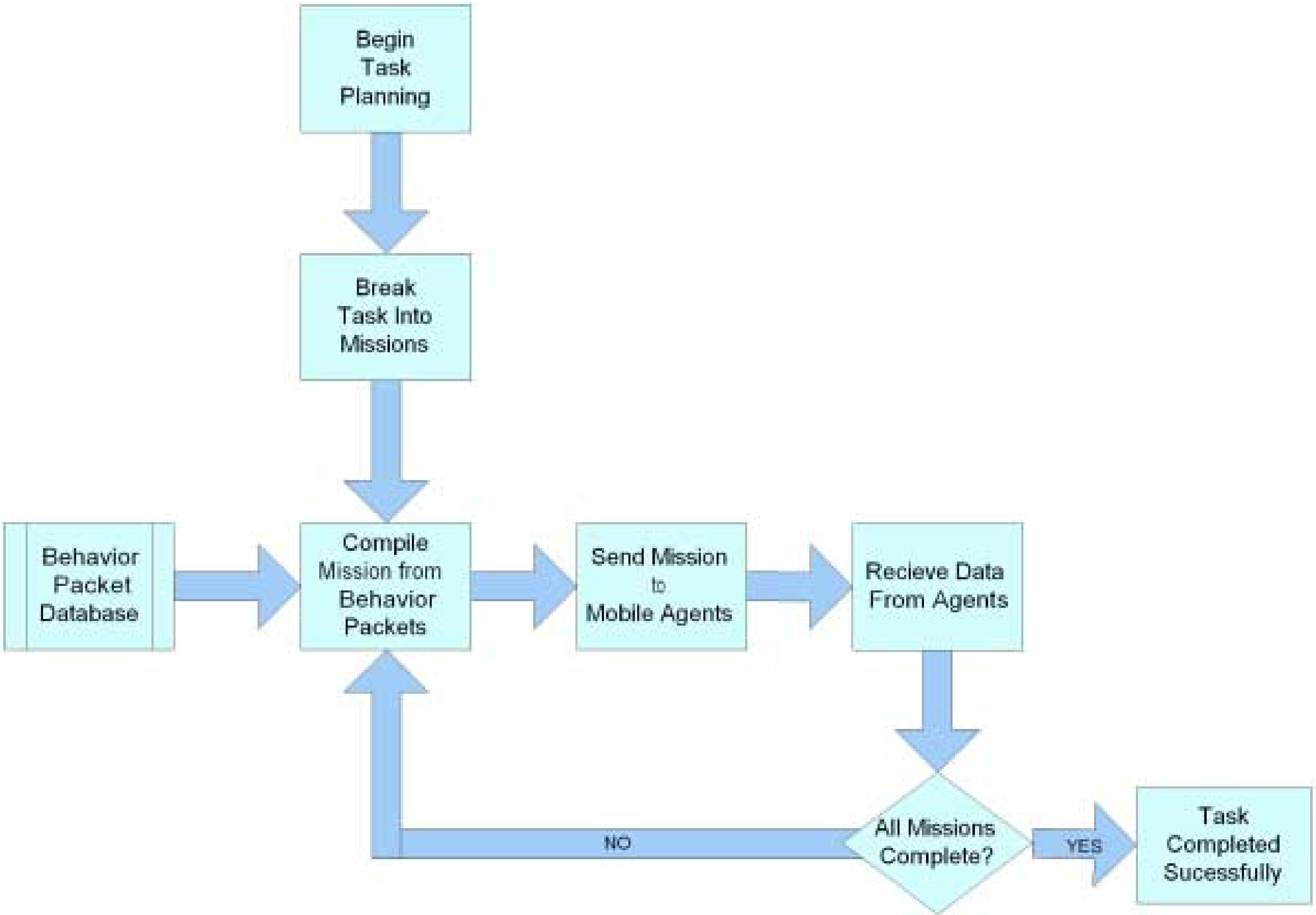
- Control the interaction of robots working together in hazardous conditions.
- Ability to work together to accomplish a specific task.
- Plan, prioritize and coordinate robotic actions to accomplish a task.

System Architecture

- Base station controls planning & organization
- Agents work without low level instructions
- Agents transmit mission status and collected data



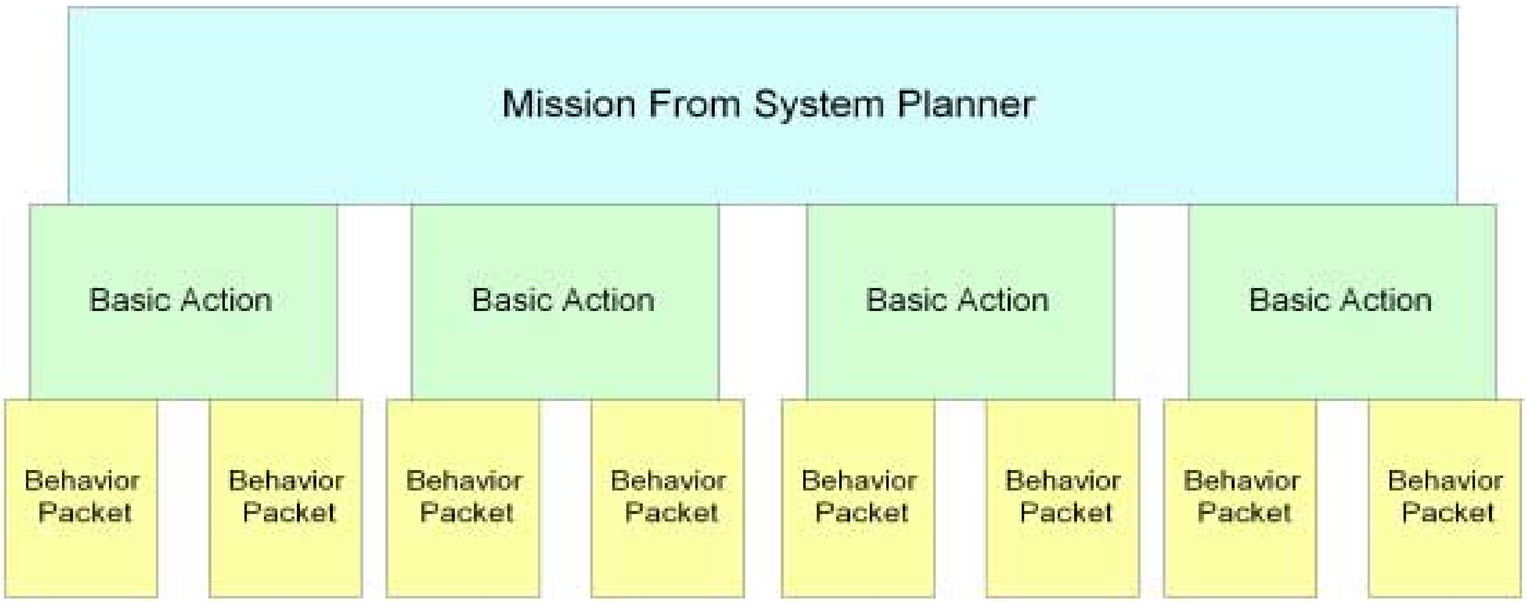
Mission Planning Process



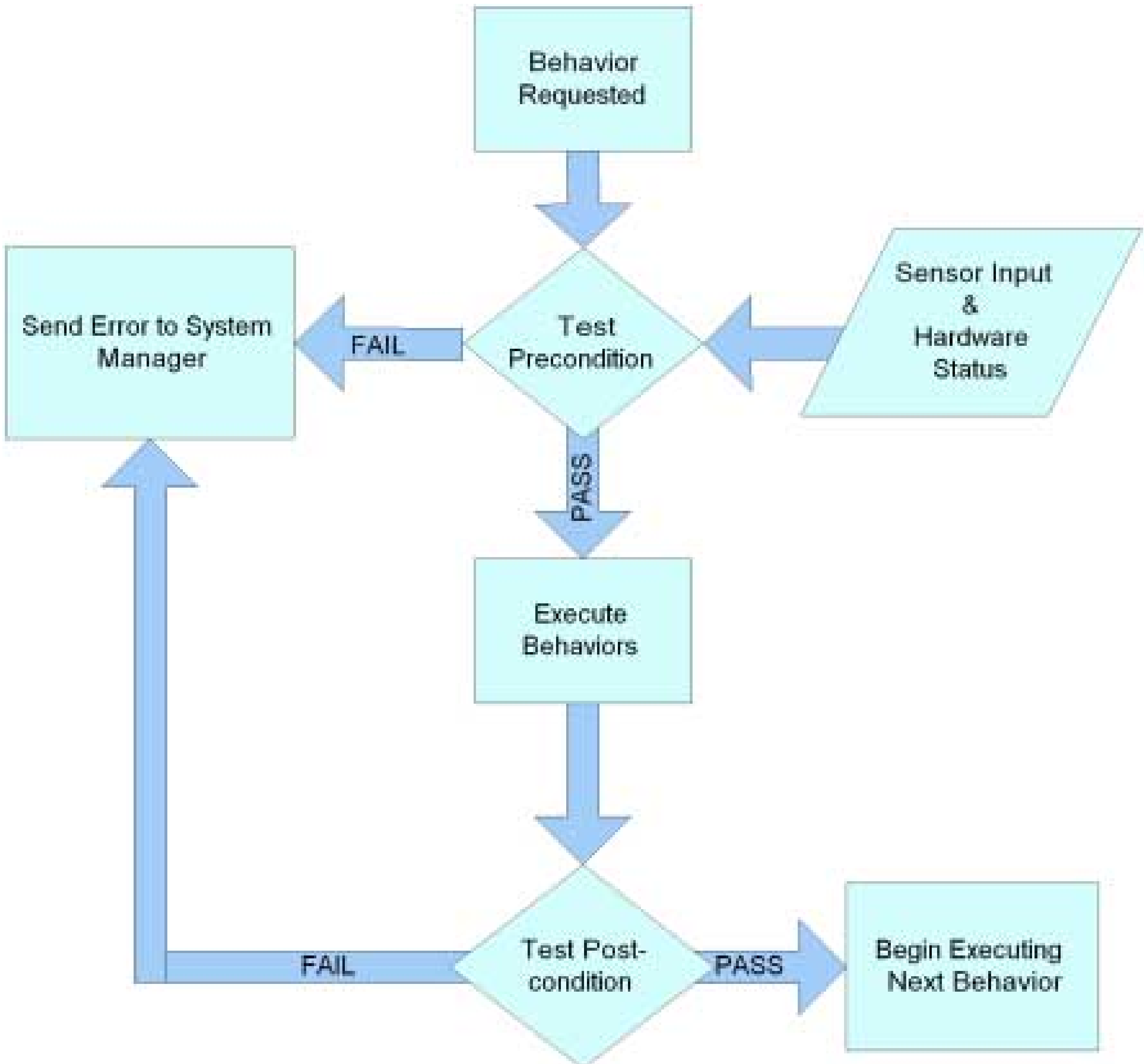
Breaking Down Missions

- System Planner Utilizes:
  - Shape & Dimension of Search Area
  - Database of each agents capabilities
  - Algorithms to optimize agent use

Mission Hierarchy



Executing a Behavior



Task Hierarchy

- Agents prioritize their own behaviors
- Behaviors are divided into:
  - Self Preservation
  - Environmental Adaptation
  - Teamwork with other Agents
  - Action/Task completion

Project Status

- Algorithms tested on 2 mobile robots
- The system planner compiles & transmits missions
- Transport, Navigate, Dock, and Track actions implemented

Useful Information

- System architecture useful for coordinating two or more independent robots
- Defined level of command abstraction
- Modular approach to generating instructions
- Simple top level communications
  - Detailed instructions stored in agents
- Method of task prioritization in the mobile robots

Swarm Intelligence: From Natural to Artificial Systems

Eric Bonaneau, Marco Dorigo, and Guy Theraulaz

Oxford University Press, 1999

Swarm Characteristics

- Large Number of Simple Individuals
- Limited Individual Intelligence
- Complex Coordinated Behavior
- Self Organizing Algorithms

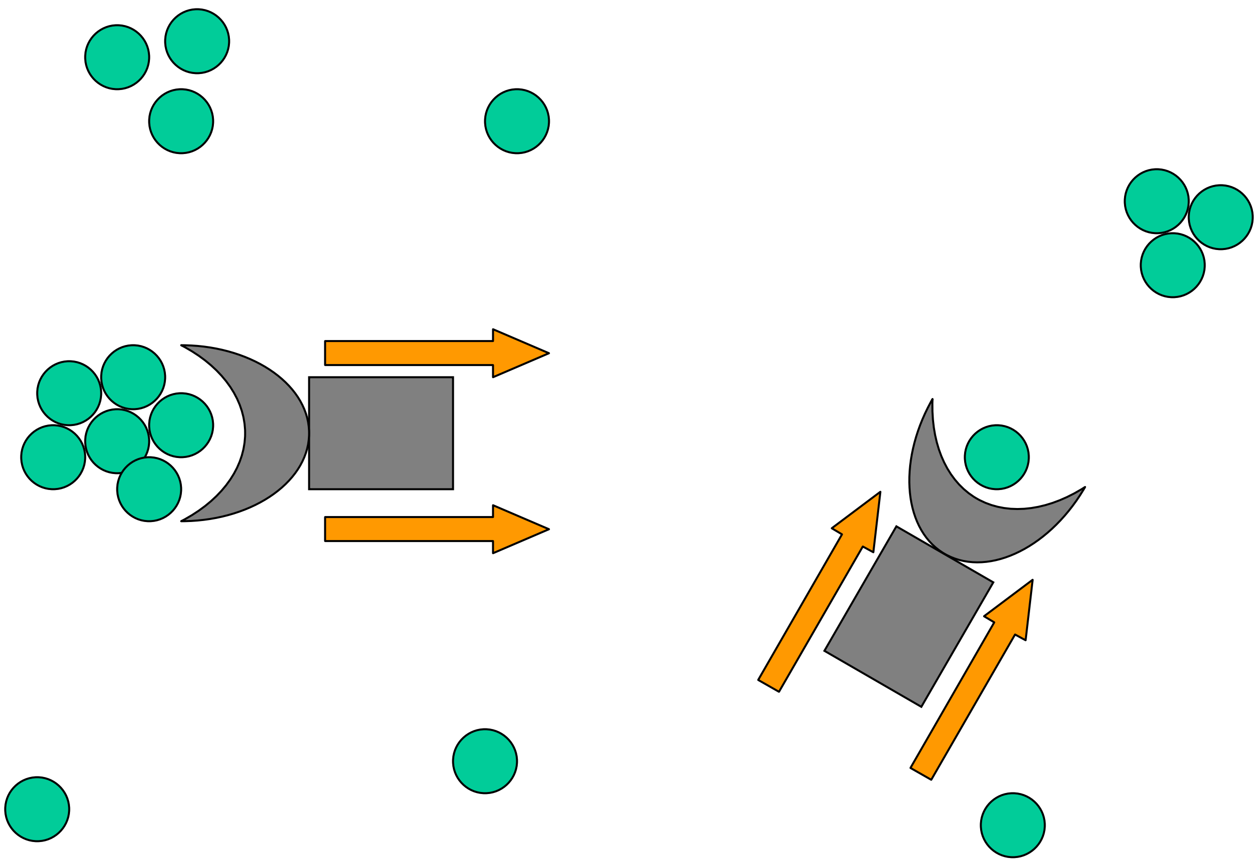
Self Organizing Algorithms

- Stigmergy
  - Indirect Interactions Through Environment
- Positive Feedback
  - Recruitment
  - Time Decay
- Probabilistic

Collection and Sorting

- 3 Rules
  - Move in Straight Line
  - Random Turn Away From Obstacle
  - Drop Object at Group, Then Random Turn Away
- Simple Implementation
- Creates Object Clusters
- Scales Moderately Well
- Efficiency Probabilistic

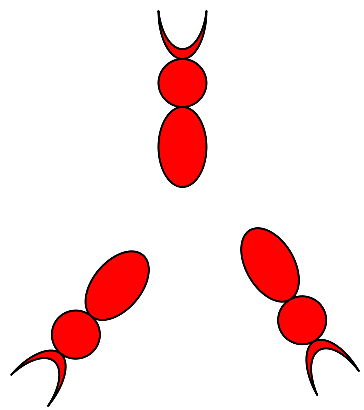
Collection Diagram



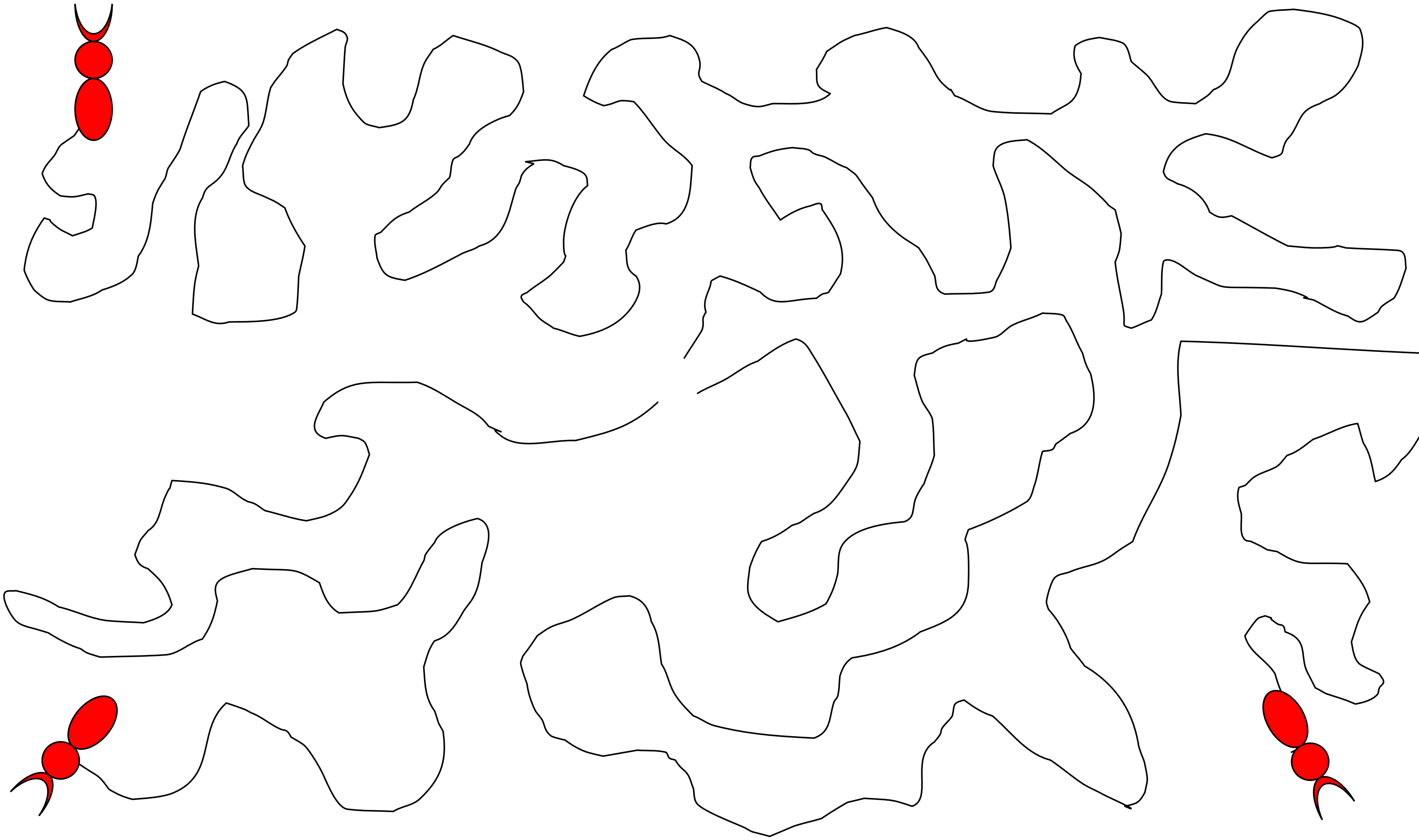
Swarm Mapping

- Rules
  - Random Path for Individual
  - Do Not Cross Others Trail
  - Trail Decays With Time
- Scales Well
- Local Optimization Possible
- Efficiency Probabilistic
- Completeness Probabilistic

Swarm Mapping Diagram



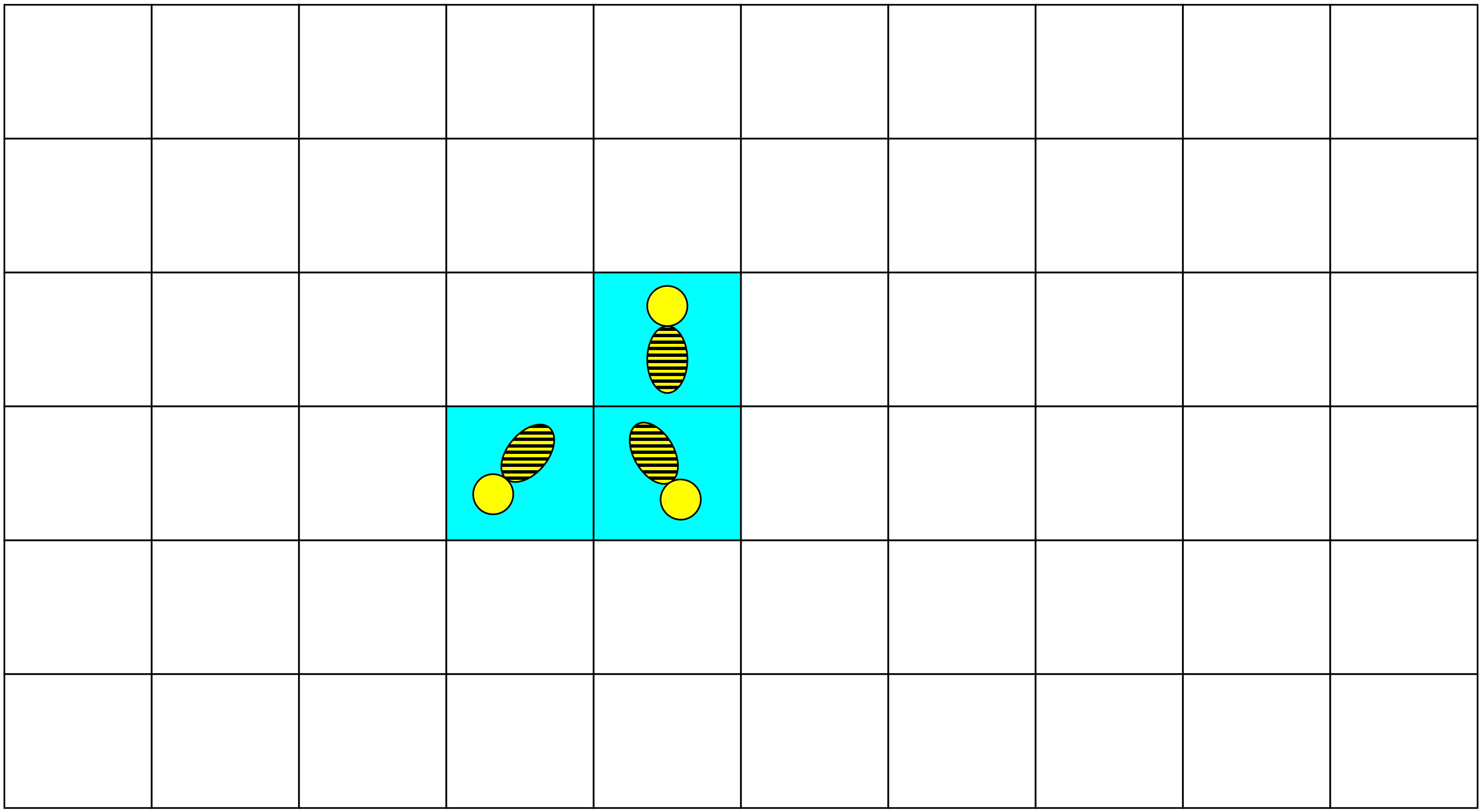
Swarm Mapping Diagram



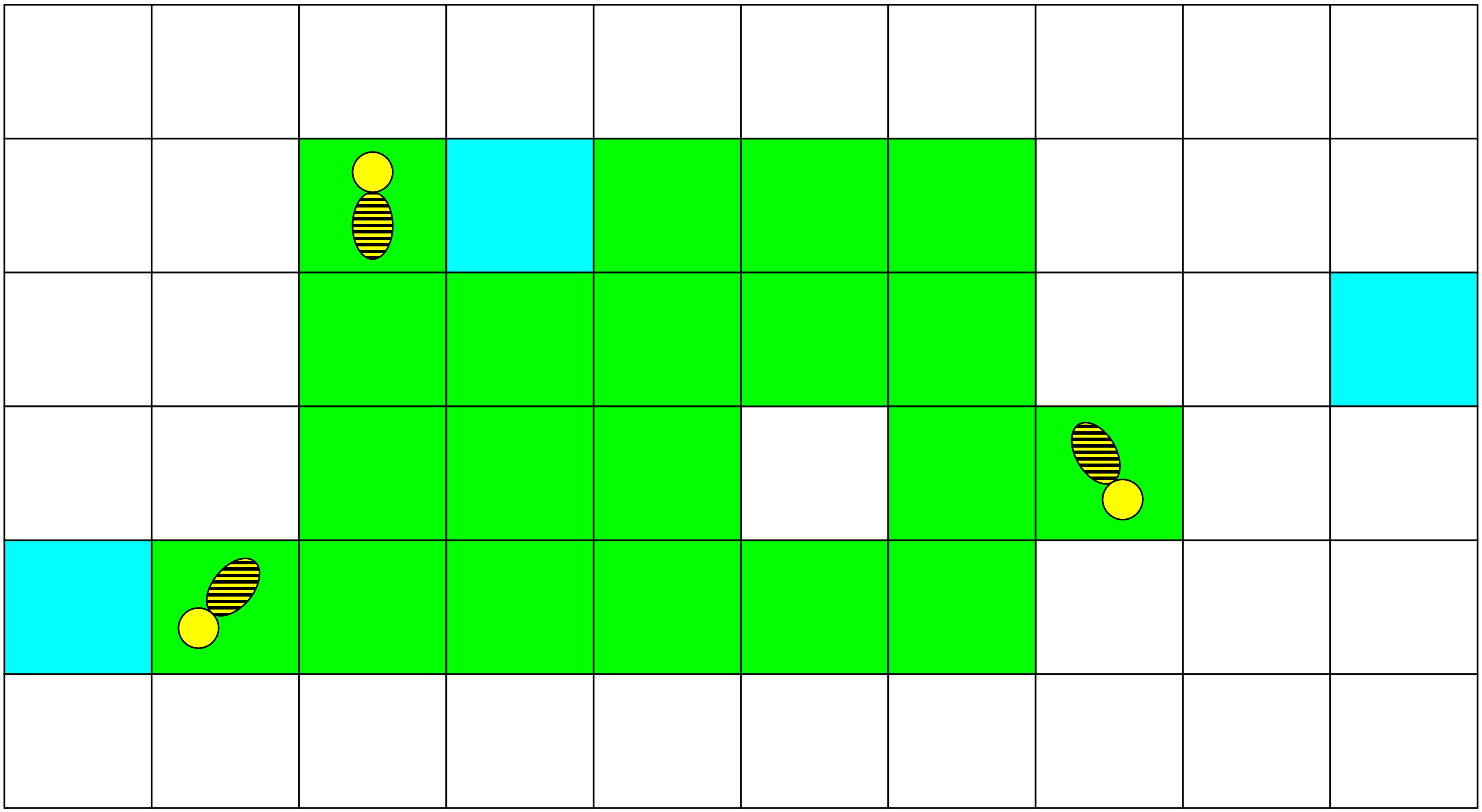
Advanced Swarm Mapping

- Rules
  - Divide Area into Subsections
  - Claim Nearby Unclaimed, Unsearched Subsection to Search
  - Search Subsection
  - Repeat Until Entire Area Searched
  - Claims Decay With Time
- Scales Well
- Efficient
- Complete

Advanced Swarm Mapping Diagram



Advanced Swarm Mapping Diagram



Advantages of Swarm Intelligence

- Robust
- Flexible
- Easily Scalable
- Simple Rules
- Decentralized
- Large Group Memory Available

Disadvantages of Swarm Intelligence

- High Communications Bandwidth
- Currently Limited to Simple Tasks
- Large Group Memory Needed

Cooperative Control of Distributed Multi-Agent Systems

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Department of Electrical Engineering, The Ohio State University
2015 Neil Avenue, Columbus, OH 43210-1272, USA

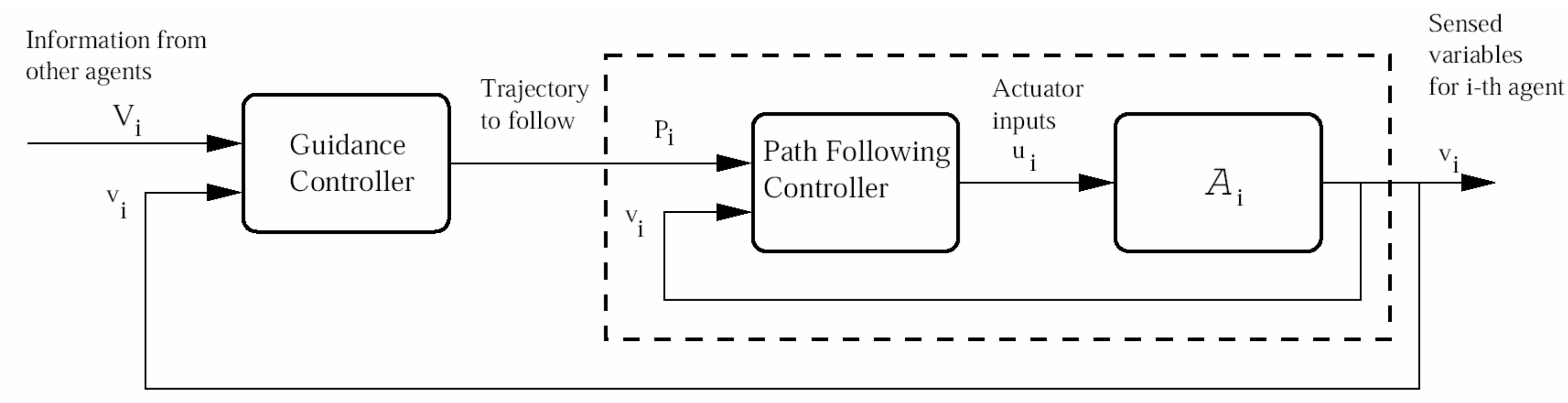
Problem

Cooperative search by a team of distributed agents

Agents:

- avoid obstacles or threats
- target sensing capabilities
- wireless inter-agent communication
- computing capabilities to make guidance decisions

Inter- and Outer-loop controllers



A_i - self
V - sensor information from other agents
v_i - sensor info from self
P - desired trajectory
u_i - commands to actuators to trace path

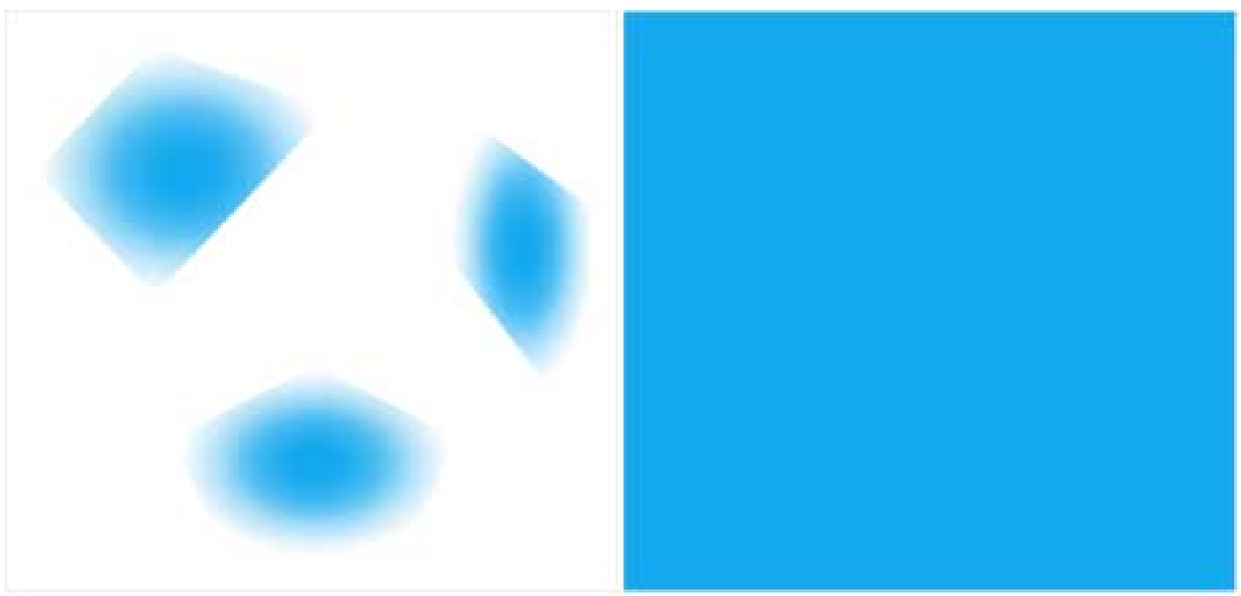
Learning

Each agent has a three-dimensional map: $z = S(x,y)$

$z = 1$ certain to exist

$z = -1$ certain not to exist

$z = 0$ total uncertainty



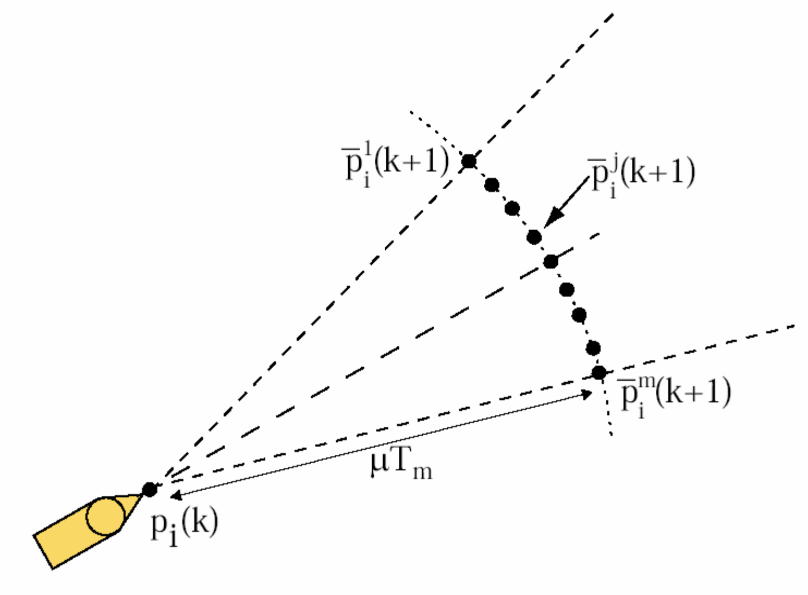
Decision Making

- Path Generation - Based on maneuverability constraints

- Path Selection - Based on cost function

- Cost function - Each agent's subgoal has an associated cost to penalize or favor a behavior

Path Generation



- A path variation due to maneuverability
- Calculate cost of all subgoals for each generated path

Path Selection

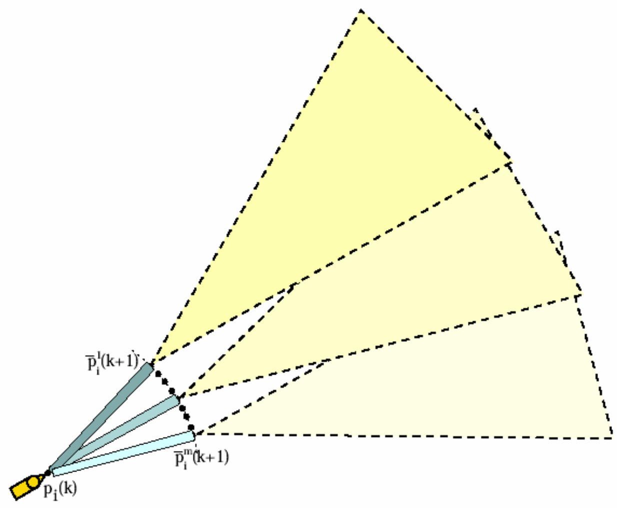
Total cost: $J = w_1 J_1 + w_2 J_2 + w_3 J_3$

w_x are weights with corresponding costs J_x for subgoal *x*

Select path with minimum total cost

Possible subgoals:

- S1 - Follow path of maximum uncertainty
- S2 - Follow path leading to region of maximum uncertainty



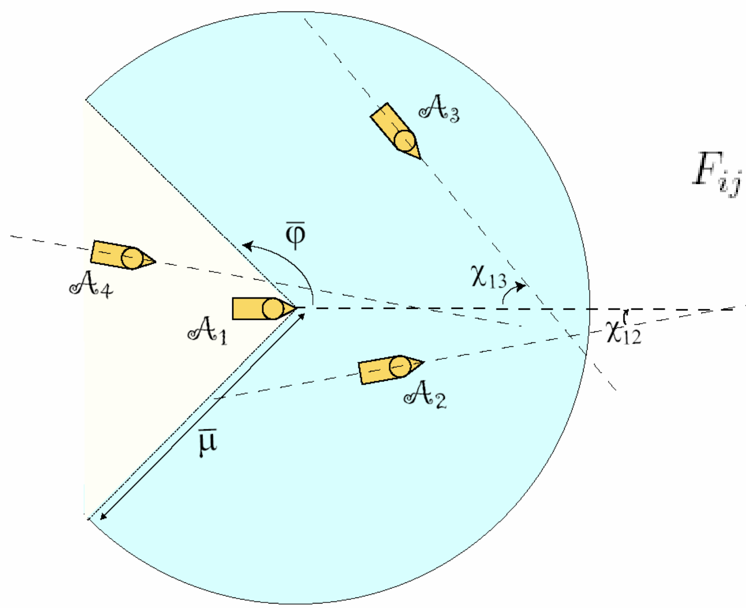
- C1 - Follow path of minimum overlap

Artificial potential field method to reduce overlap

Rivaling force is non-zero iff:

1) location of A_j is within minimum distance $\boldsymbol{\mu}$ and maximum angle $\boldsymbol{\varphi}$ from location A_i

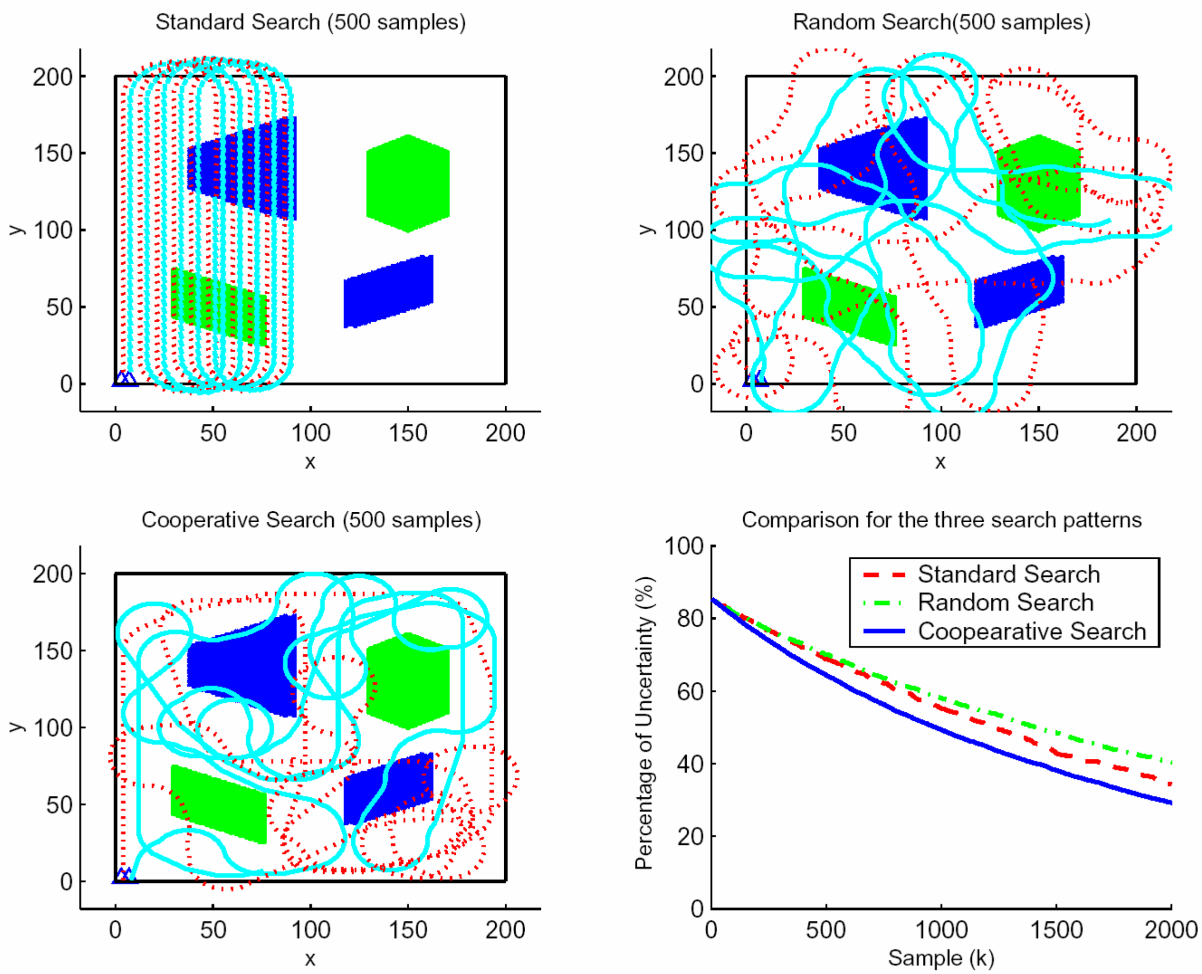
2) The difference in heading angle $x_{ij}(k)$ between A_j and agent A_i lies within (-x, +x)



$$F_{ij}(k) = \begin{cases} k_1 e^{-\alpha \rho_{ij}} \vec{\rho}_{ij} \\ 0 \end{cases}$$

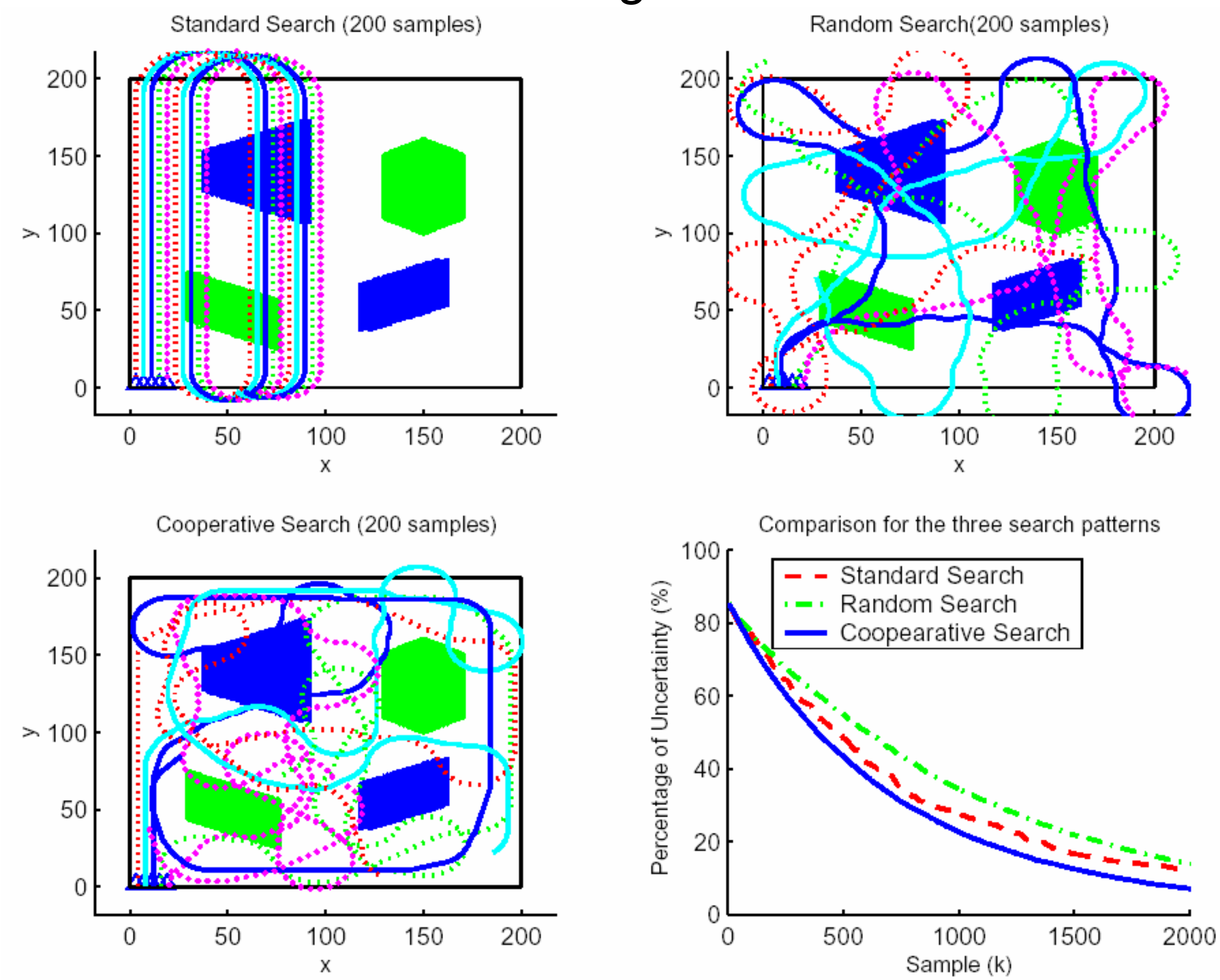
Simulation Results

2 agents



Simulation Results

5 agents



Major contributions

- Creating a straightforward cost based decision making scheme
- “Rivaling Force” to reduce search overlap
- Path generation
- Path selection

Multi-Robot Collaboration for Robust Exploration

Ioannis Rekleitis

Gregory Dudek

Evangelos Milios

Robot Tracker System

- Localization
- Obstacle/Object Finding
- Exploring
- Adding More Robots

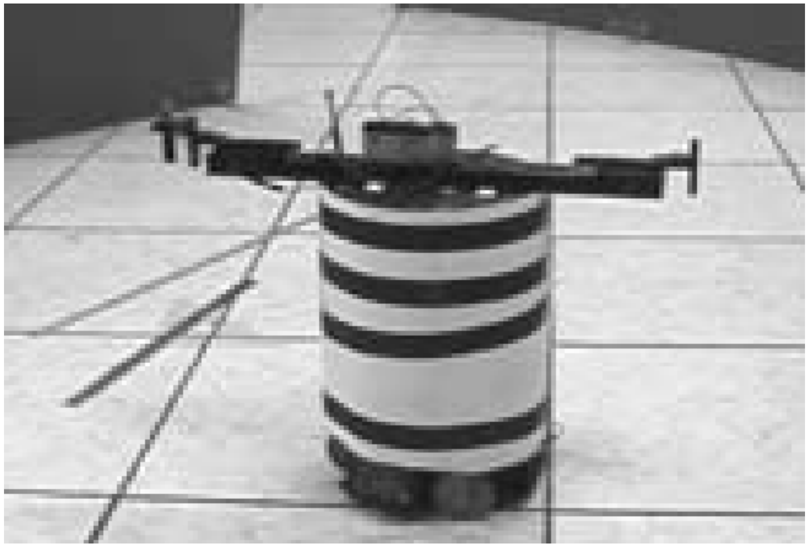
Dead Reckoning

- Odometric (Single Robot)
  - Optical Encoders
- Landmarks (Single Robot)
  - Sonar
  - Laser Range Finders
  - Assume Complete Information
  - Optimistic
- Cooperative (Multiple robots)
  - One Robot Always Stationary
  - Robot Tracker Sensor
  - Removes Uncertainty

Cooperative Localization

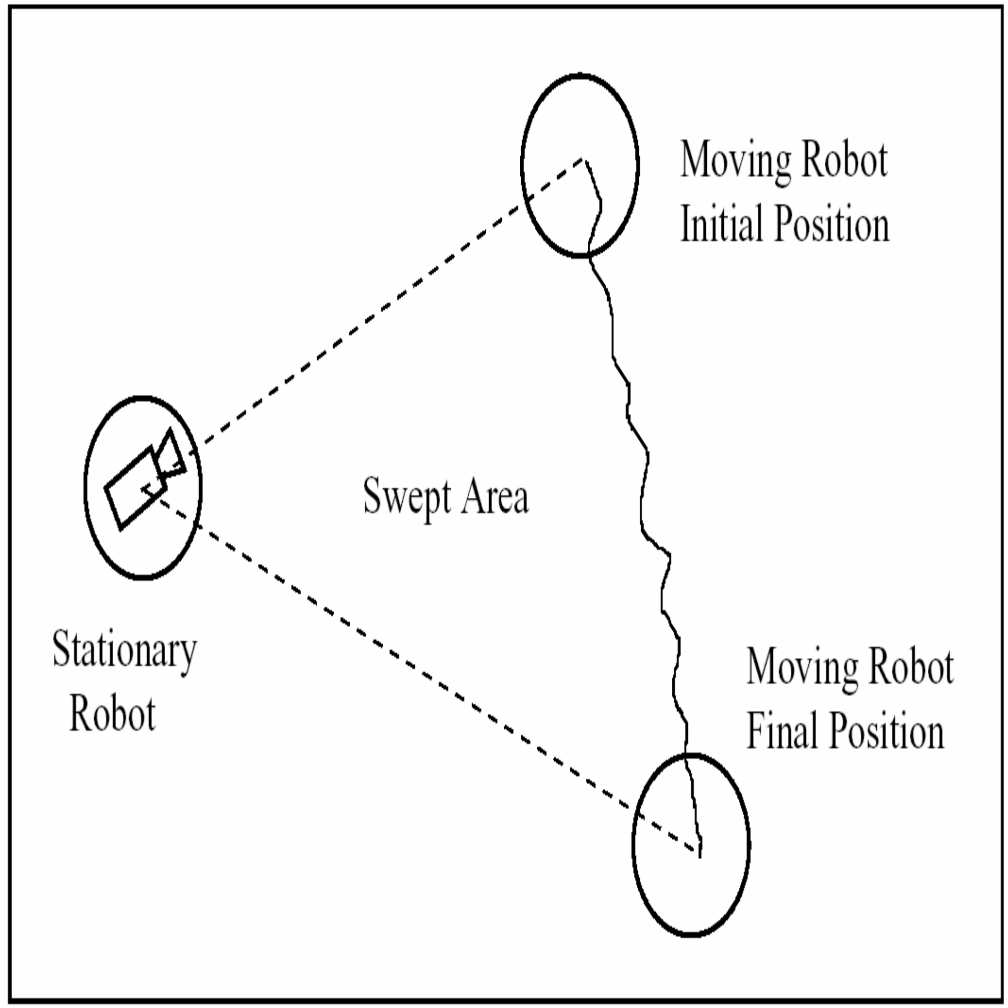
- Observing Camera

- Accuracy
  - Few Centimeters
  - 3 to 5 Degrees



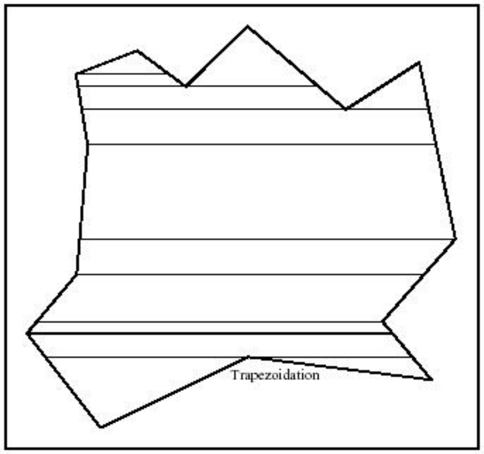
Object and Obstacle Locating

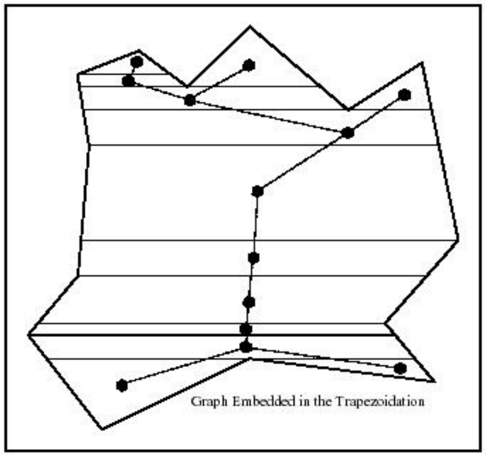
- Scans Between Robots
- Interrupted Visibility Between Robots = Object
- One Sensor type for everything

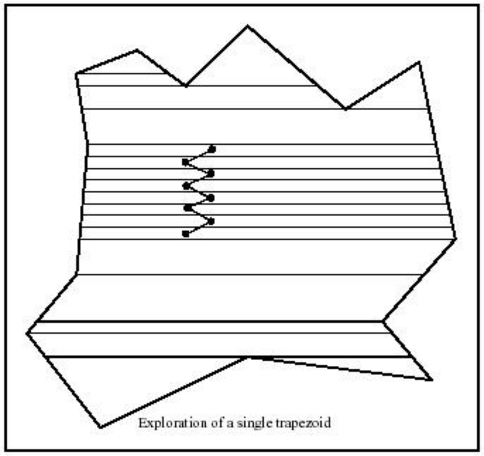


Exploring Large Areas

Trapezoidation Algorithm





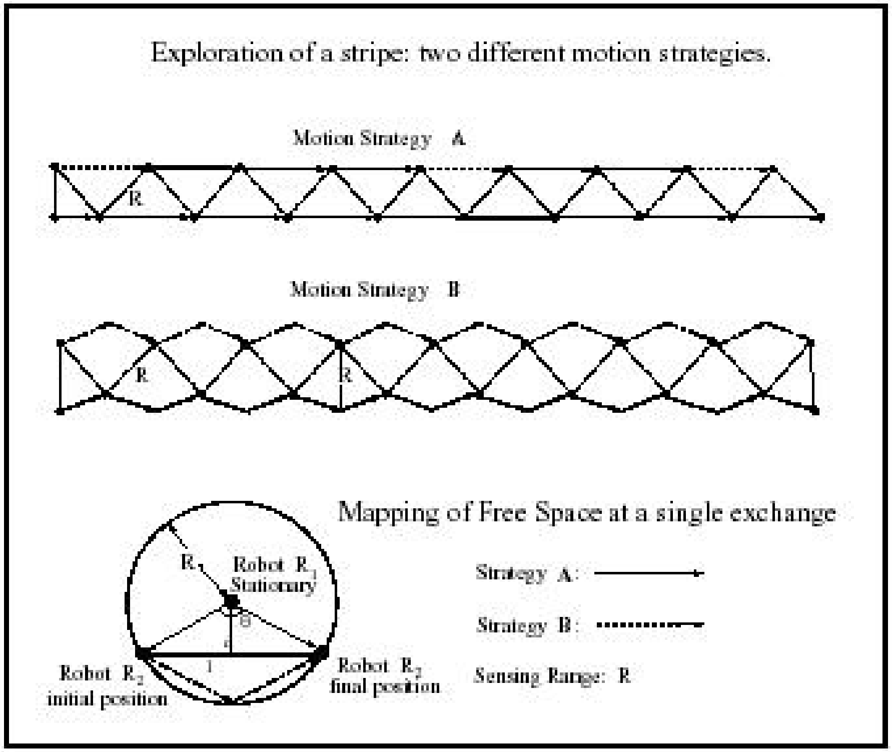


1. Break Area into Trapezoids
2. Depth-First Traversal
3. Break Trapezoid into stripes

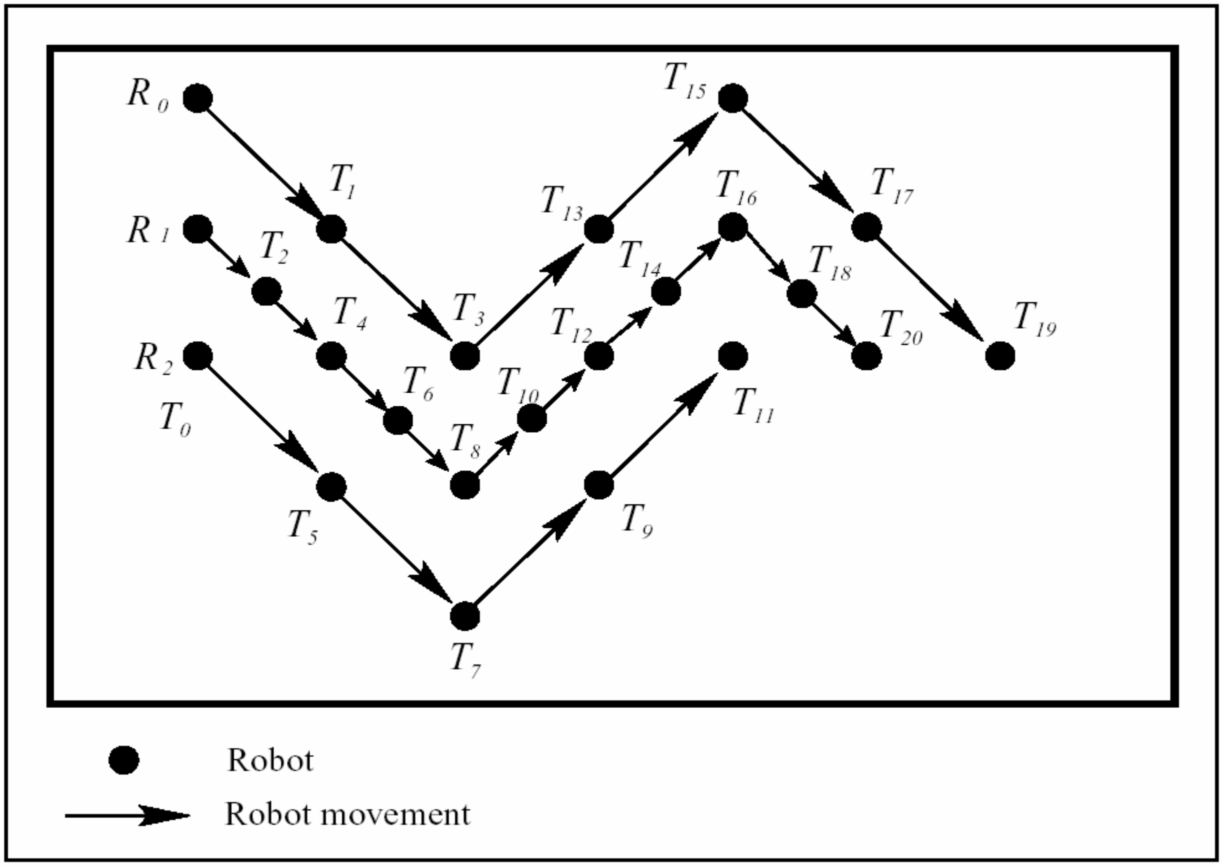
Motion Strategies

- Motion Strategy A
  - Straight Lines
  - Inefficient (D<R)

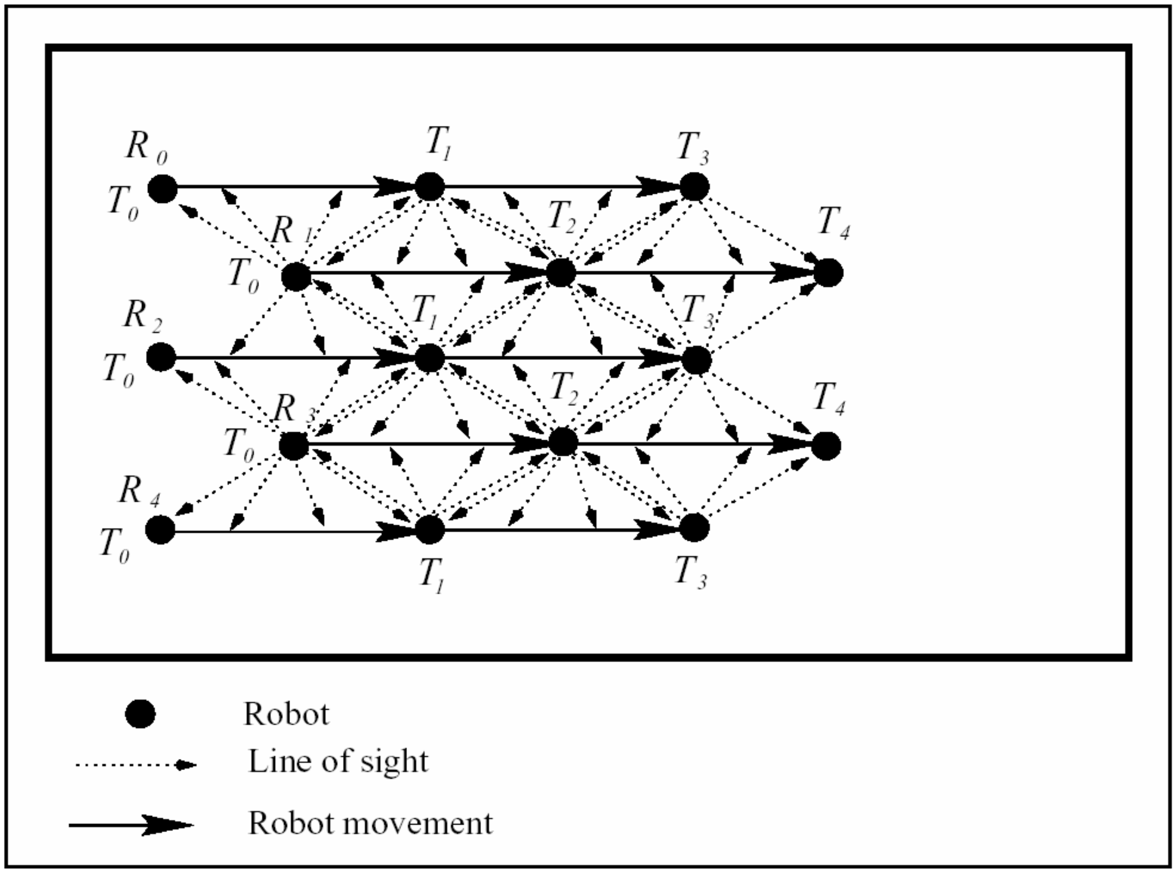
- Motion Strategy B
  - Diamond Shape
  - Optimal (D=R)



Searching With 3 Robots



Searching With 5 Robots



Research Assessment

- Advantages
  - No Sonar Beacons Required
  - Sensors Are Not Object Sensitive
  - No Uncertainties
- Disadvantages
  - Speed
  - Can Not Identify What An Object Is
  - Objects Are Relative to the Robots

Patterned Search Planning and Testing For the Robotic Antarctic Meteorite Search

Field Robotics Center

Carnegie Mellon University

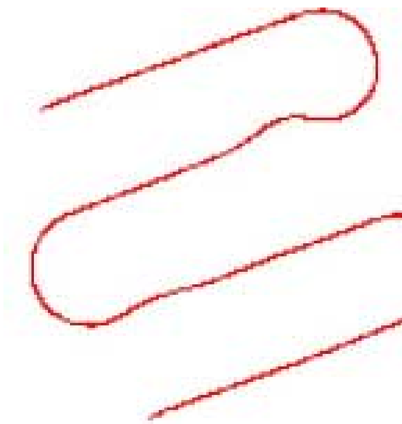
Pittsburgh, PA

Homogeneous Robot Navigation Planner

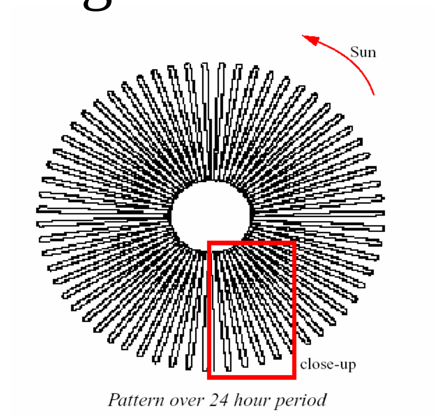
- Straight Rows (Back and Forth Pattern)
- Spiral Pattern
  - Start in Middle following circular pattern
  - Increase the circles radius every half circle
- Sun-following Pattern
  - Following nearly a straight row
  - Slight curve to maintain proper orientation

Simulated Examples of Coverage Patterns

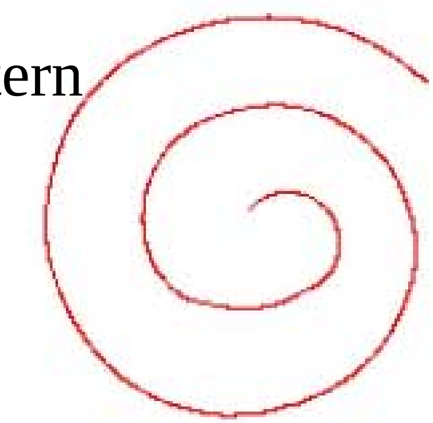
Straight Row Pattern



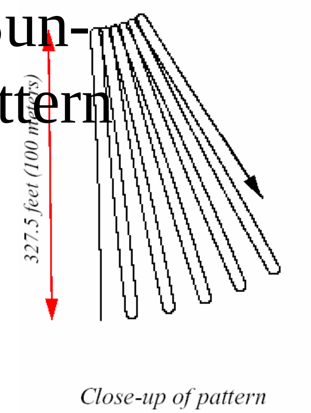
Sun-Following Pattern



Spiral Pattern

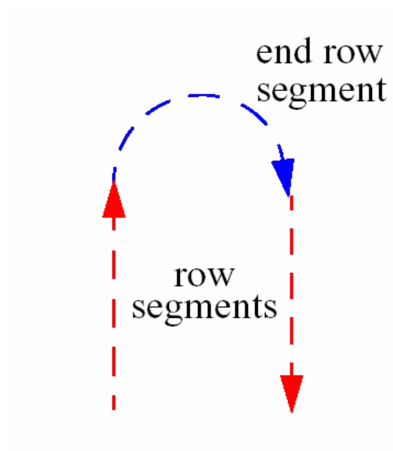


Close-up of Sun-Following Pattern

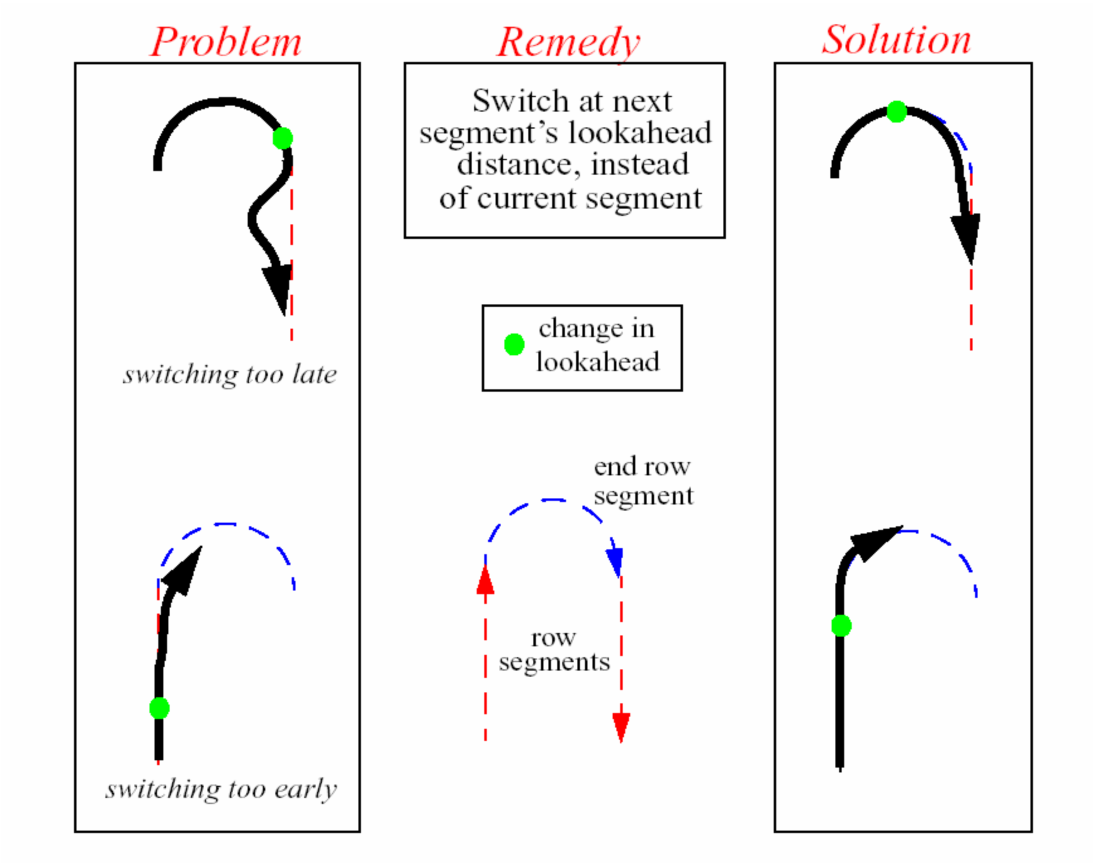


Navigation Solutions

- Lookahead Distance:
  - Large
    - Gradual and smooth regaining of path
    - Very time consuming
  - Short
    - Regaining path quicker
    - May result in oscillations
- Segments
  - Straight row pattern
    - Each row
    - Each half-circle turn at the ends
  - Spiral Pattern
    - Each half circle



Navigation Solutions



Navigation Information Gained

- Possible Searching Patterns
  - Straight Row
  - Spiral
  - Sun-Following (Not Efficient)

- Look Ahead Distance

Thank You for Your Time

Any Questions?