On Distributed Coordination in Robotic Networks

Gossip Coverage and Frontier-based Pursuit

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Distributed Coordination Algorithms

Team of robotic agents tasked with performing a joint mission in an environment

Each individual

- *senses* its immediate surroundings
- *communicates* with nearby agents
- *processes* information gathered
- *performs* local action in response

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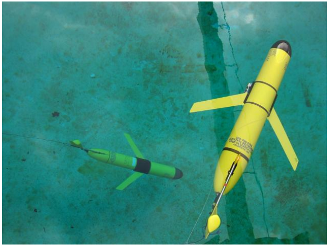
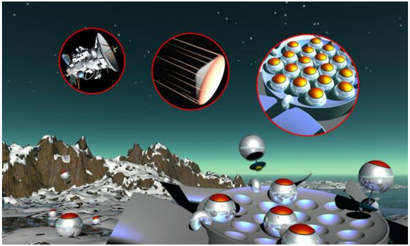
Algorithm design goal

Design individual control and communication laws such that the group reaches a desired goal

Applications





Ocean monitoring gliders from `noc.soton.ac.uk`, warehouse robots from KIVA Systems,

hopping planetary explores from NASA

Papers in this Talk

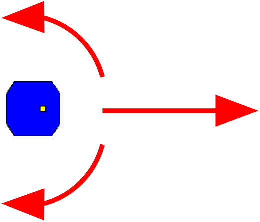
- J. W. Durham, A. Franchi, and F. Bullo. Distributed pursuit-evasion with limited-visibility sensors via frontier-based exploration. In *IEEE Int. Conf. on Robotics and Automation*, Anchorage, Alaska, May 2010. To appear
- J. W. Durham, R. Carli, P. Frasca, and F. Bullo. Discrete partitioning and coverage control with gossip communication. In *ASME Dynamic Systems and Control Conference*, Hollywood, CA, October 2009
- J. W. Durham and F. Bullo. Smooth nearness-diagram navigation. In *IEEE/RSJ Int. Conf. on Intelligent Robots & Systems*, pages 690–695, Nice, France, September 2008

Collaborators: Ruggero Carli, Antonio Franchi, Paolo Frasca, and my advisor Francesco Bullo.

Outline

Hardware

Robot Model



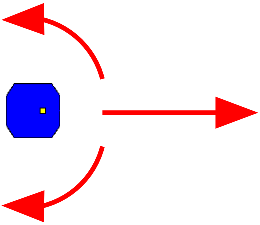
Differential drive

- Translational velocity v
- Rotational velocity $\dot{\theta}$

Physical state

$\mathcal{X} = (x, y, \theta)$

Robot Model



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Physical state

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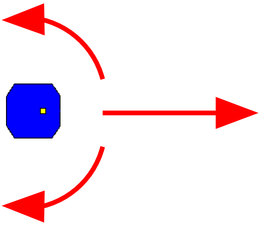
In theory state is an integral of velocities

Robot Model



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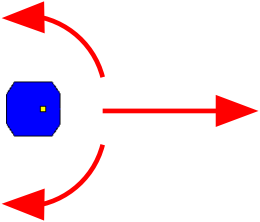
In practice measurement of actual velocities is imperfect, integrals diverge

Robot Model



Differential drive

- Translational velocity v
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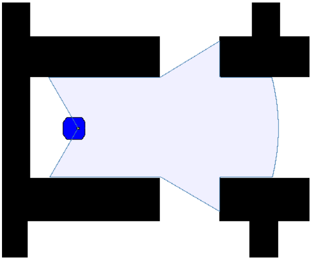
In practice measurement of actual velocities is imperfect, integrals diverge

Either must accept position errors or use sensors for localization

Sensor Model



Sensor footprint

$\mathcal{S}(x, y, \theta)$ is the intersection of visibility polygon from (x, y) and the area perceivable by the sensor oriented by θ

Sensor footprint can be used for:

- Obstacle detection
- Localization
- Intruder detection

Control and Communication Models

Processor State

$\mathcal{W}$: the state of the robot's processor – stored data, current behavior

Communication Alphabet

$\mathcal{L}$: set of messages a robot can send to other robots

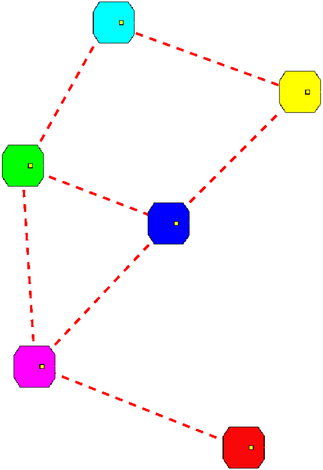
Network Connectivity Models

Communication Graph

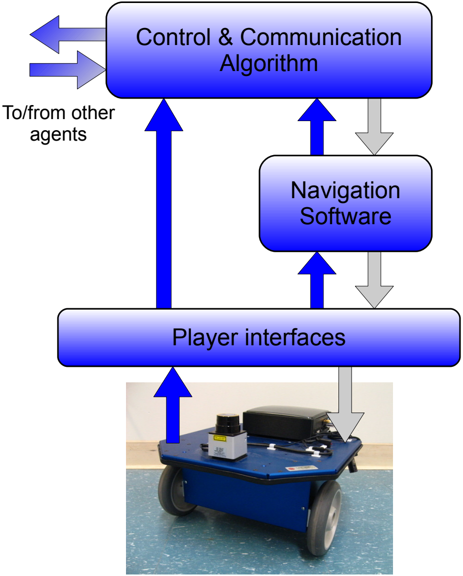
Many possible models for which agents can communicate

Combinations of:

- Network geometry
- Physical proximity
- Current robot roles
- Randomness



Robotic Software Overview



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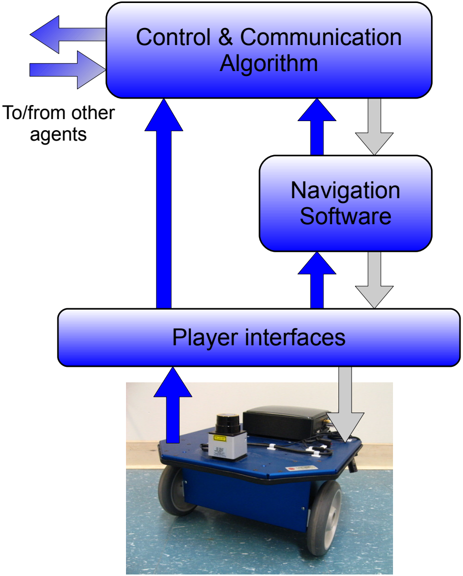
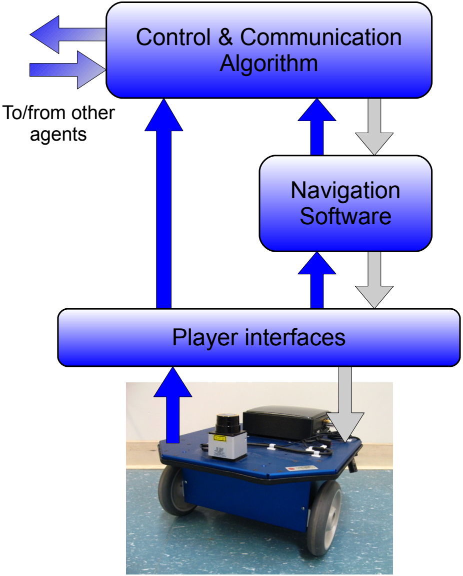


Player/Stage is an open-source robotics software library

Features

- Player provides interfaces for hardware
- Each robot is a server on a TCP/IP network
- Stage simulates hardware, interfaces to algorithms are the same

Robotic Software Overview



SND Navigation handles local path planning and execution

Algorithm design can focus on:

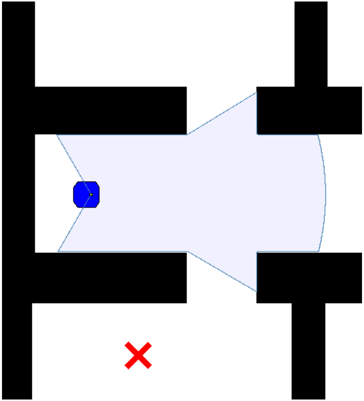
- Desired positioning of robot
- Communication for coordination

Smooth Nearness Diagram Navigation

Evolution of ND+ Nav by J. Mingues, J. Osuna, L. Montano

Input: $\mathcal{S}$, desired pose (x, y, θ)

Output: v and $\dot{\theta}$



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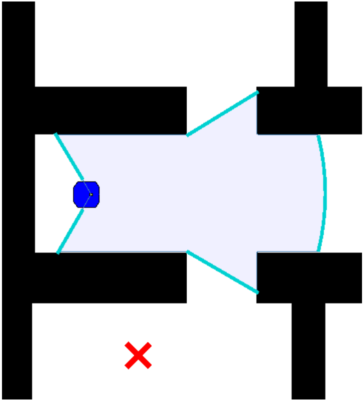
- Find gaps in sensor footprint



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Input: $\mathcal{S}$, desired pose (x, y, θ)

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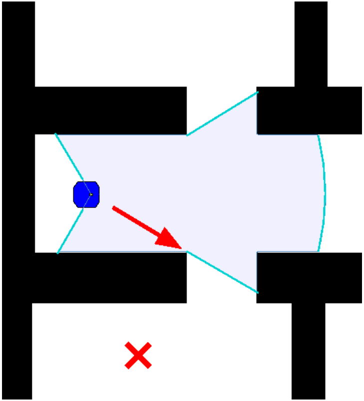
- Find gaps in sensor footprint
- Pick best gap to drive towards



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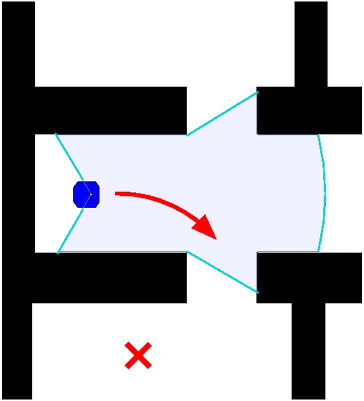
- Pick best gap to drive towards
- Adjust commands based on nearby obstacles



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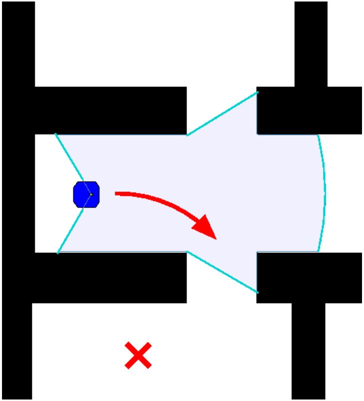
Available as the `snd` driver in Player/Stage



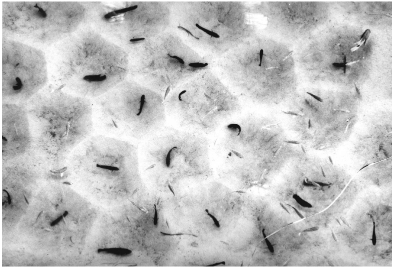
Summary of Robotic Network Model

Algorithm Design Requirements

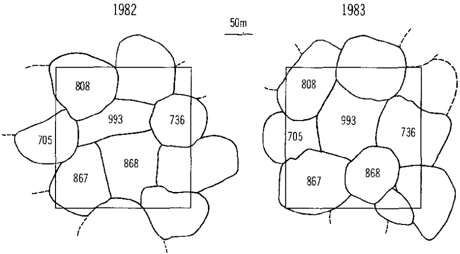
1. **Data structures**
   - Correct or account for errors in (x, y, θ)
   - Processor state $\mathcal{W}$ and communication alphabet $\mathcal{L}$
2. **Update functions**
   - Message-generation function
   - Processor state transition function
   - Motion control function to pick desired pose
3. **Communication graph model**

Motivation

Biological examples of coverage control



Tilapia mossambica, Barlow et al '74



Sage sparrows, Petersen et al '87

Related Prior Work I

Lloyd's Algorithm

- take convex environment Q with density function $\phi : Q \to \mathbb{R}_{\geq 0}$
- place N robots at $p = \{p_1, \dots, p_N\}$
- partition environment into $v = \{v_1, \dots, v_N\}$
- define expected quadratic deviation

$$H(v,p) = \int_{v_1} f(\|q - p_1\|)\phi(q)dq + \ldots + \int_{v_N} f(\|q - p_N\|)\phi(q)dq$$

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Theorem (Lloyd '57 "least-square quantization")

1. *at fixed partition, optimal positions are centroids*
2. *at fixed positions, optimal partition is Voronoi*
3. *Lloyd algorithm: alternate p-v optimization*

$\longrightarrow$ *convergence to the set of centroidal Voronoi partitions*

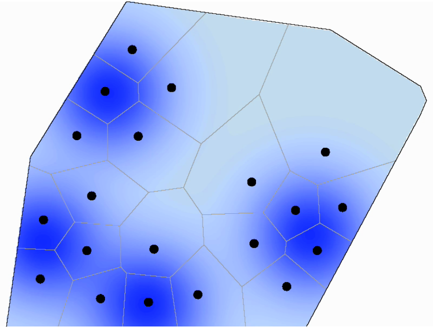
Related Prior Work II

Distributed Coverage Control

At each comm round:

1: acquire neighbors' positions
2: compute Voronoi region
3: move towards centroid of own Voronoi region

Result: convergence to the set of centroidal Voronoi partitions

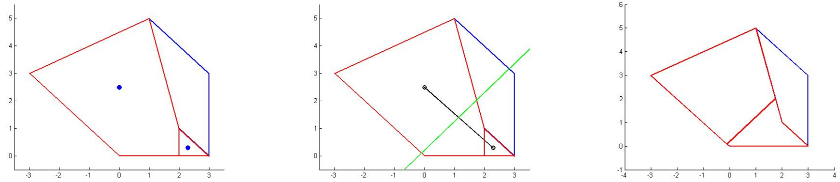


J. Cortés, S. Martínez, T. Karatas, and F. Bullo. Coverage control for mobile sensing networks. *IEEE Transactions on Robotics and Automation*, 20(2):243–255, 2004

Related Prior Work III

Gossip coverage in continuous space

- Pairwise territory exchange between neighbors
- Regions may be non-convex during evolution
- Result: convergence to the set of centroidal Voronoi partitions



P. Frasca, R. Carli, and F. Bullo. Multiagent coverage algorithms with gossip communication: control systems on the space of partitions, March 2009. Available at http://arXiv.org/abs/0903.3642

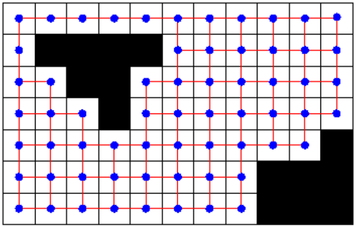
Discretized Environments

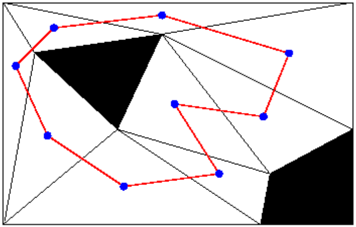
Domain is a weighted graph $G = (Q, E, w)$

Required properties

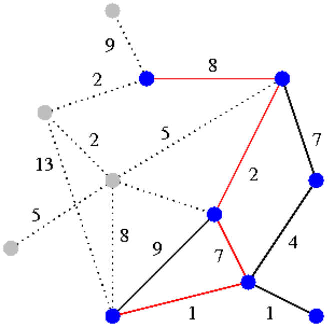
- G must be connected
- All edge-weights w must be positive

G can easily represent a non-convex environment with holes

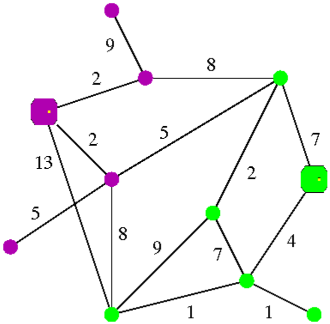




Voronoi Iteration on Graphs



Distances are shortest path lengths in connected sub-graphs of G



Vertices join partition of centroid they are closest to

Cost Function

Centroid p_i of sub-graph v_i is vertex which minimizes

$$H_i(h, v_i) = \sum_{k \in v_i} \text{dist}_{v_i}(h, k)$$

Total cost

$$\mathcal{H}_{\text{multi-center}}(p, v) = \sum_{i=1}^{N} H_i(p_i, v_i)$$

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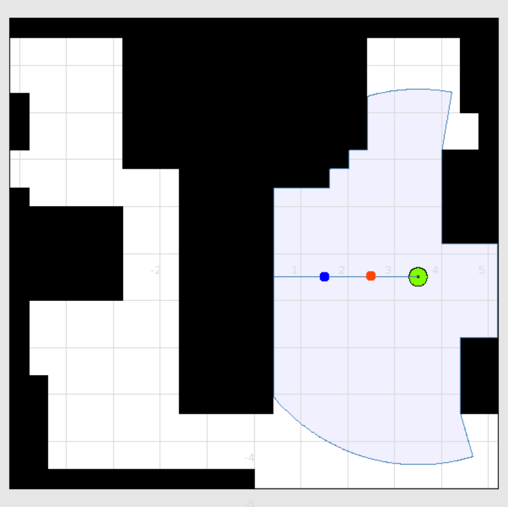
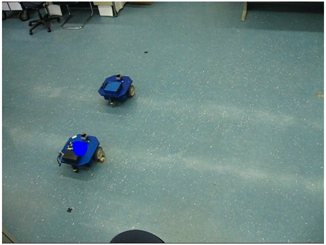
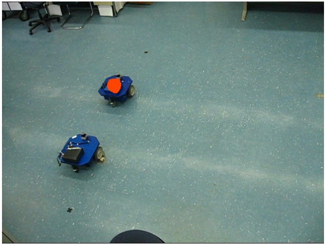
Minimize expected distance between random vertex and closest robot

Hardware Experiment







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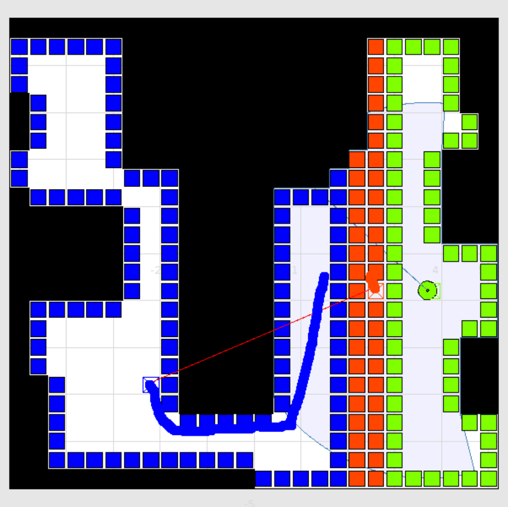

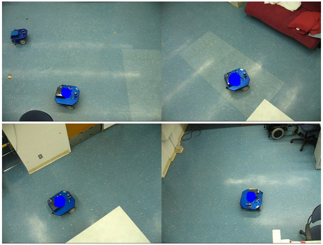

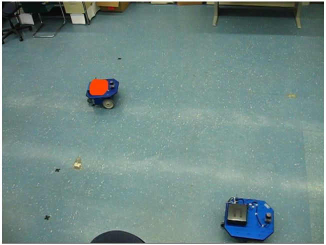

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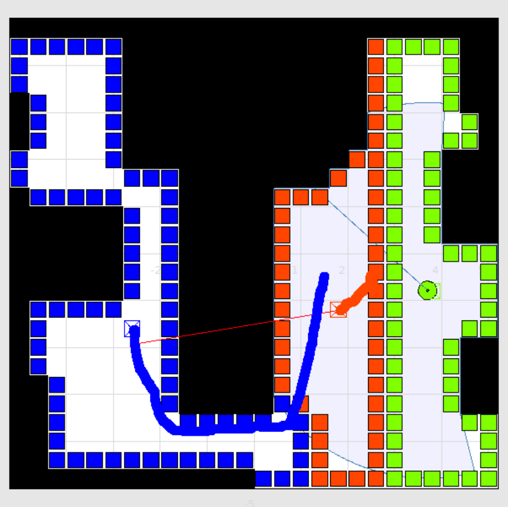

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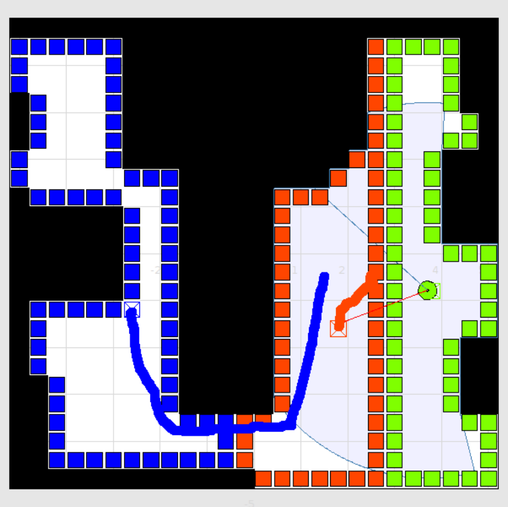

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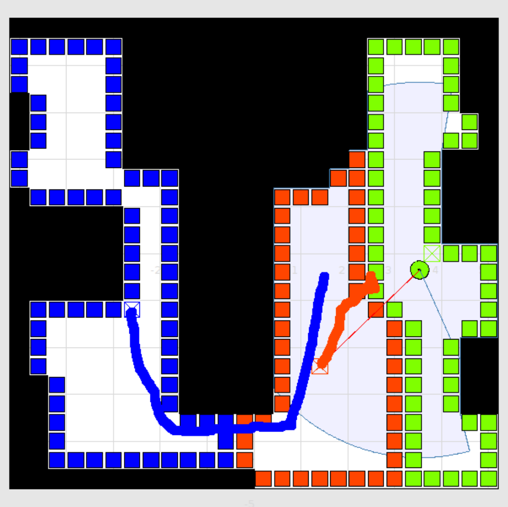

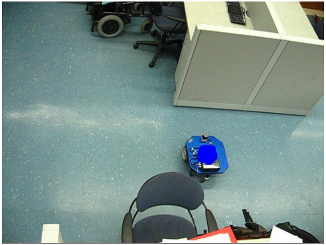

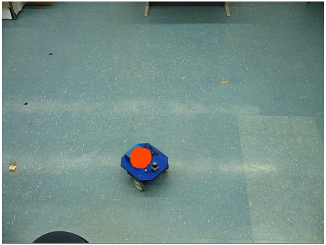

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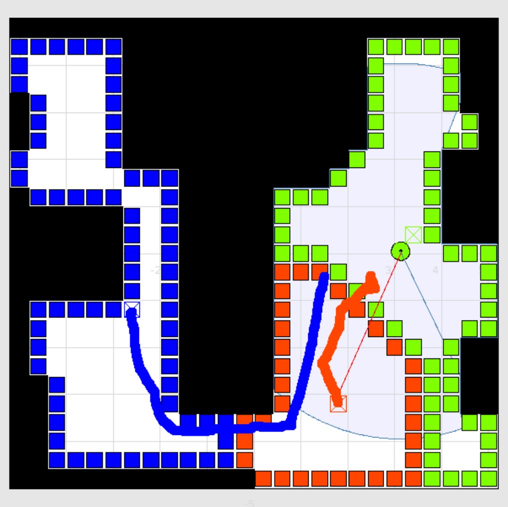

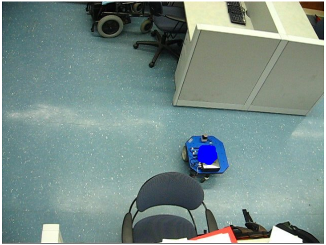

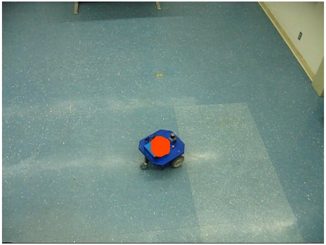

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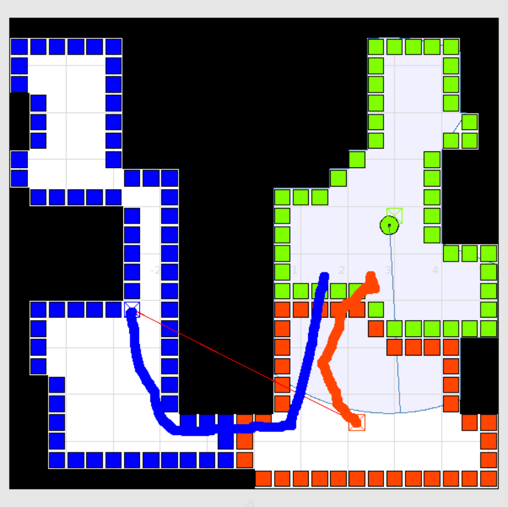

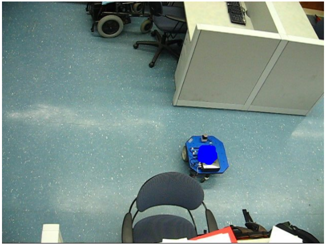

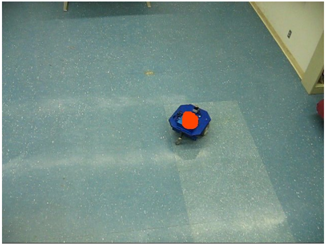

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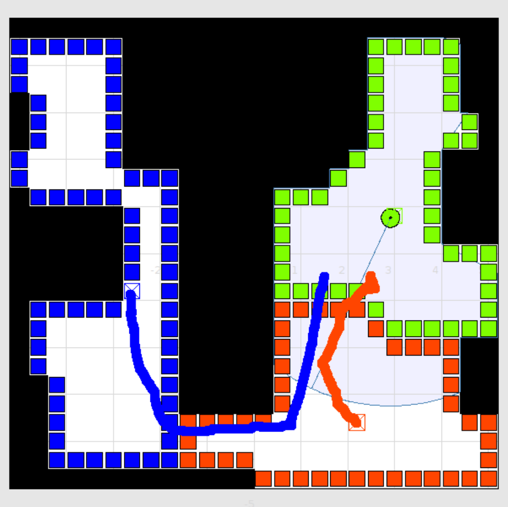
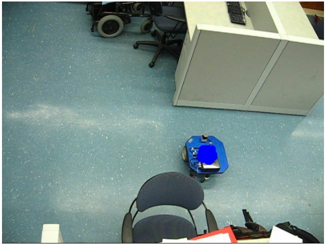
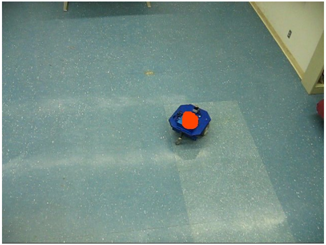
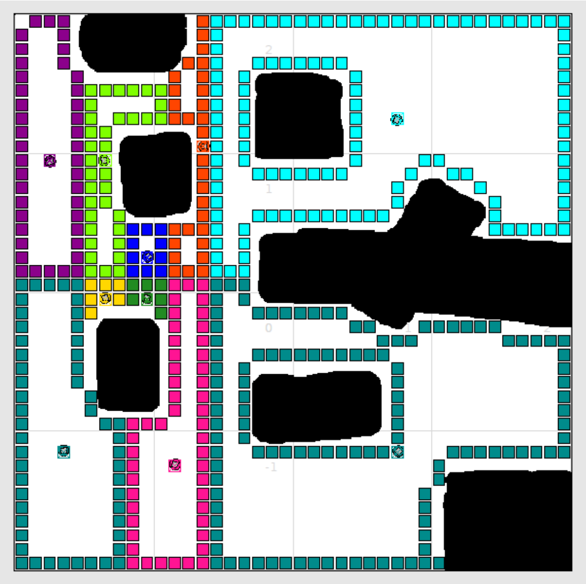






Simulation Movie



Gossip Coverage Assumptions

Map assumptions:

- Team is provided an initial connected N-partition of environment
  - Initial agent partitions are connected
  - Cover space without overlap

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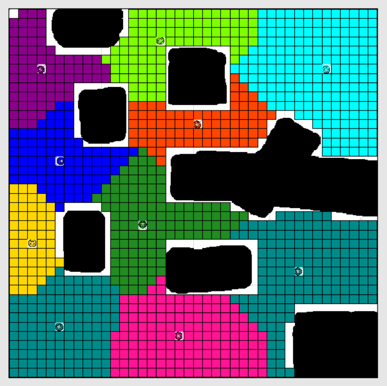
Communication assumptions:

- Given infinite time, each agent will talk to each of its neighbors an infinite number of times
- Two options:
  - There exists a finite upper bound on the time between conversations for each pair
  - There is a non-zero probability for each pairwise communication occurring at all times

Algorithm Claims

1. Maintain connected *N*-partition during evolution
   - Each region is connected
   - No overlap
2. Total cost decreases whenever agents exchange territory
3. Provable convergence to a single centroidal Voronoi partition in finite time



Convergence Theorem

- X finite set of connected N-partitions of graph G
- Algorithm defines set-valued map $T : X \rightarrow X$

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Version of the LaSalle Invariance Principle

Requirements for convergence

1. X is compact, positively invariant under T
2. $\mathcal{H}_{\text{multi-center}}$ non-increasing under T, decreasing under $T \setminus \{id\}$
3. $\mathcal{H}_{\text{multi-center}}$ and T are continuous on X
4. One of two communication assumptions
   - There exists a finite upper bound on the time between conversations for each pair (i, j)
   - There is a non-zero probability for each pair (i, j) to communicate at all times

Computational Complexity

$$H_i(h, v_i) = \sum_{k \in v_i} \text{dist}_{v_i}(h, k)$$

Key computation

Distances from h to all $k \in v_i$

- If edge-weights are uniform, can use BFS in linear time
- Otherwise, must use Dijkstra in log-linear time

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Computing centroid

Most computationally complex piece, three options:

- Exhaustive search in $\mathcal{O}(|v_i|^2)$
- Gradient descent in $\mathcal{O}(|v_i| \log |v_i|)$
- Center of mass approximation in $\mathcal{O}(|v_i|)$

Summary

Chief contributions

- Converge to a single centroidal Voronoi partition in finite time
- Coverage control which works in non-convex environments with holes
- Computation can scale well to large areas with many robots

Ongoing Work in Coverage Control

Current directions

- Motion protocol
  - Agents will patrol boundary of territory to meet neighbors
  - Can model need to meet neighbors as tasks on boundary
- Local broadcast communication
  - More realistic model of wireless communication
  - Requires overlapping territories during evolution

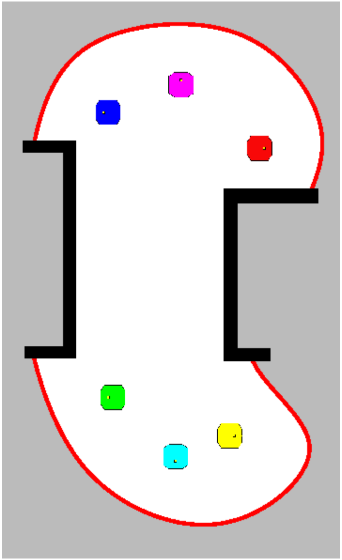
Our Clearing Problem

T34 security bot from tmsuk and Alacom in Japan

The Team: Robots with limited-range sensors

The Mission: Guarantee detection of any evaders in an unknown environment

Exploration Inspiration

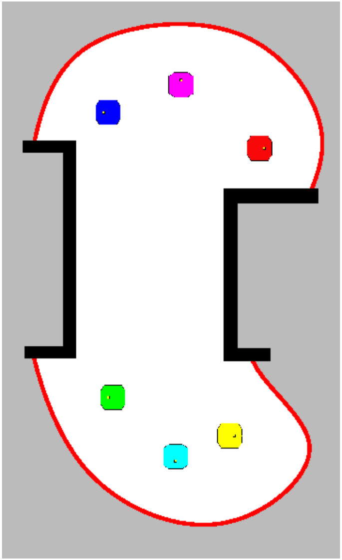


Observation

Clearing an environment is a constrained form of exploration

- For stationary evaders, cleared = explored
- Otherwise, cleared can be recontaminated

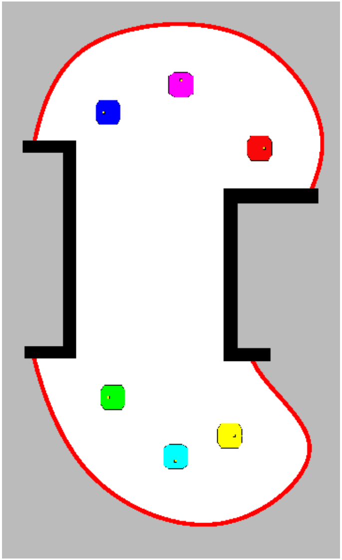
Exploration Inspiration



For exploration

Frontier: Boundary between explored and unexplored areas

Exploration Inspiration



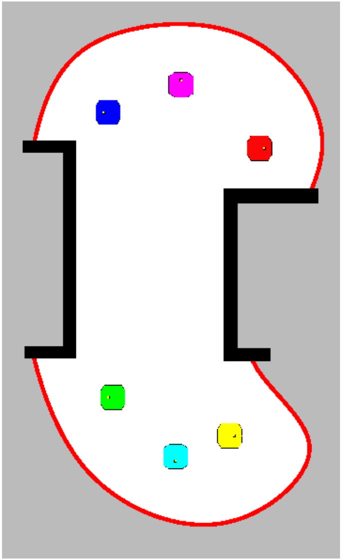
For exploration

Frontier: Boundary between explored and unexplored areas

For pursuit-evasion

Frontier: Boundary between cleared and contaminated areas

Exploration Inspiration



For exploration

Frontier: Boundary between explored and unexplored areas

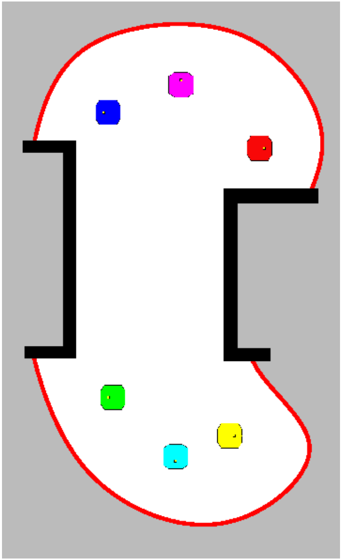
For pursuit-evasion

Frontier: Boundary between cleared and contaminated areas

Our Approach

- Completely cover frontier at all times
- Continuously push back frontier

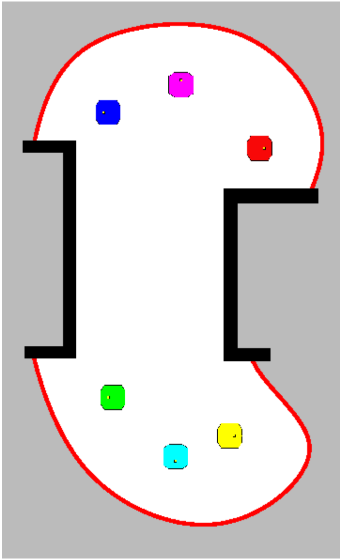
Key Issues



Existing methods for computing global frontier require:

- Global map
- Global localization (to build global map)

Key Issues



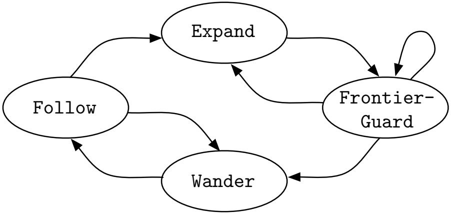
Existing methods for computing global frontier require:

- Global map
- Global localization (to build global map)

Our new method requires:

- Complete coverage of frontier at all times
- Mutual localization between neighboring robots

Distributed Algorithm Roles



Leaders

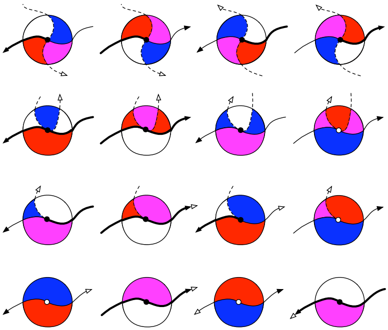
Frontier-Guard: Key role for algorithm. Cover local frontier and dispatch agents to expand it.
Expand: Agent moving to a viewpoint it was assigned.

Non-Leaders

Follow: Waiting for orders from a guard.
Wander: Cleared local area, now searching for a guard to follow.

Distributed Global Frontier

Each frontier-guard stores its local oriented frontier arcs

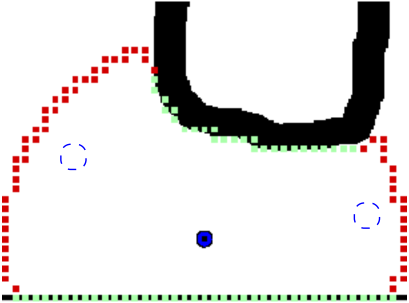


Frontier Updating

When a new guard reaches its viewpoint, it must:

1. Ask for frontier arcs from neighboring guards
2. Inform neighbors of frontier segments inside footprint
3. Classify local frontier based on intersections

Viewpoint Planner



Assumption: Sensor footprints are circular

Goal: Pick new viewpoints V

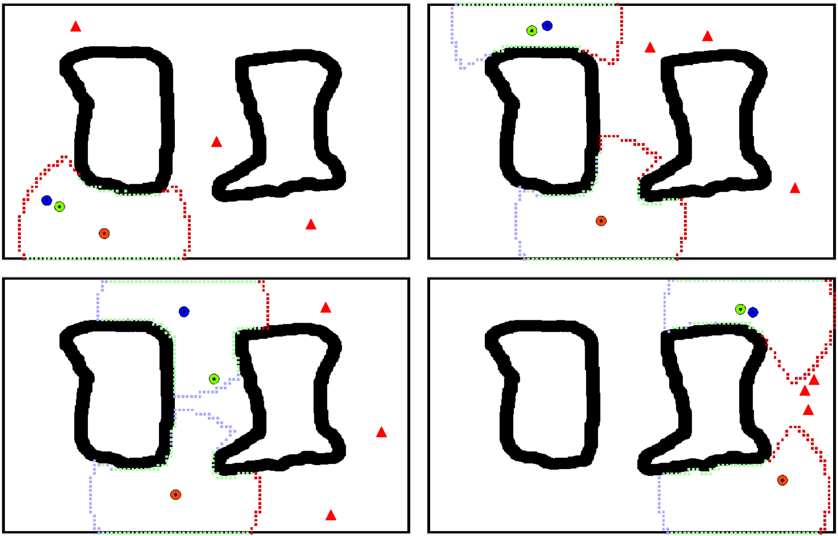
- Minimize $|V|$
- Maximize area exposed

Viewpoints required for angular width Ω of arc:

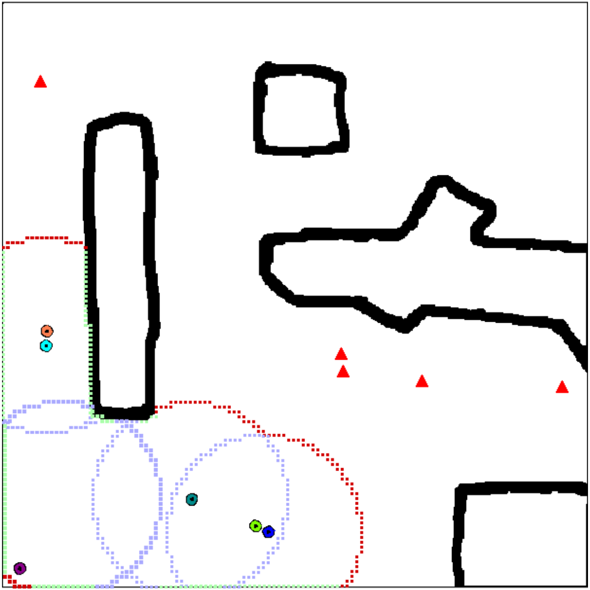
- $\Omega \leq \frac{2\pi}{3}$: $|V| = 1$
- $\Omega = 2\pi$: $|V| = 3$

For intermediate, choice of what to optimize

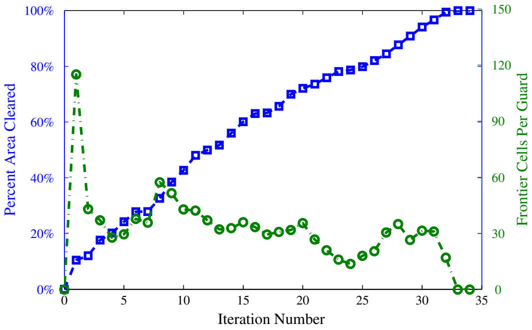
Example Simulation



Movie

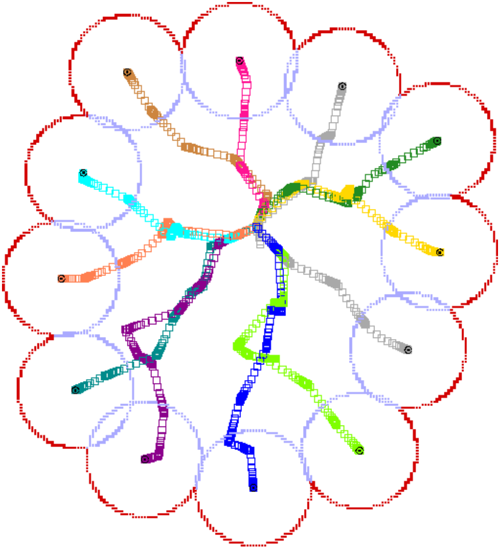


Frontier Coverage



- Frontier cell count per guard does not grow with area cleared
- Distributed storage requires only constant memory per agent

Empty Space



Summary

Chief contributions

- Online clearing algorithm which works in non-convex environments with holes
- Distributed storage and updating of global frontier
- Requires only mutual localization

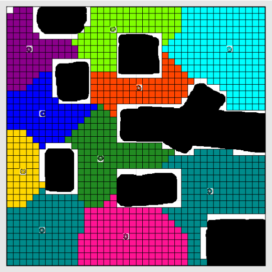
Ongoing Work in Pursuit-Evasion

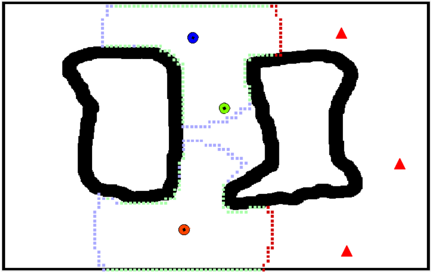
Current directions

- Distributed hardware implementation and experiments
- Viewpoint planner for circular sector sensor footprints
- Bounds on number of agents necessary to clear a map

Conclusion

- Distributed coordination algorithm framework for hardware
- Two parallel algorithm implementations:
  1. Coverage of discretized environments
  2. Frontier-based pursuit-evasion





The End

Questions?