Multi-Robot Systems, Part II

October 31, 2002

Class Meeting 20

“A team effort is a lot of people doing what I say”. -- Michael Winner.

Objectives

- Multi-Robot Systems, Part II
  - Overview (con't.)
  - Multi-Robot Communication
  - Keeping Formation

Commonly Studied Tasks for Multi-Robot Teams

- Foraging: collection of randomly placed items
- Consuming: perform work on object in place (e.g., assembly, disassembly, etc.)
- Grazing: cover entire area adequately (e.g., for lawn mowing, etc.)
- Formations or flocking: team maintains a geometric pattern while moving
- Object transport: collectively moving object

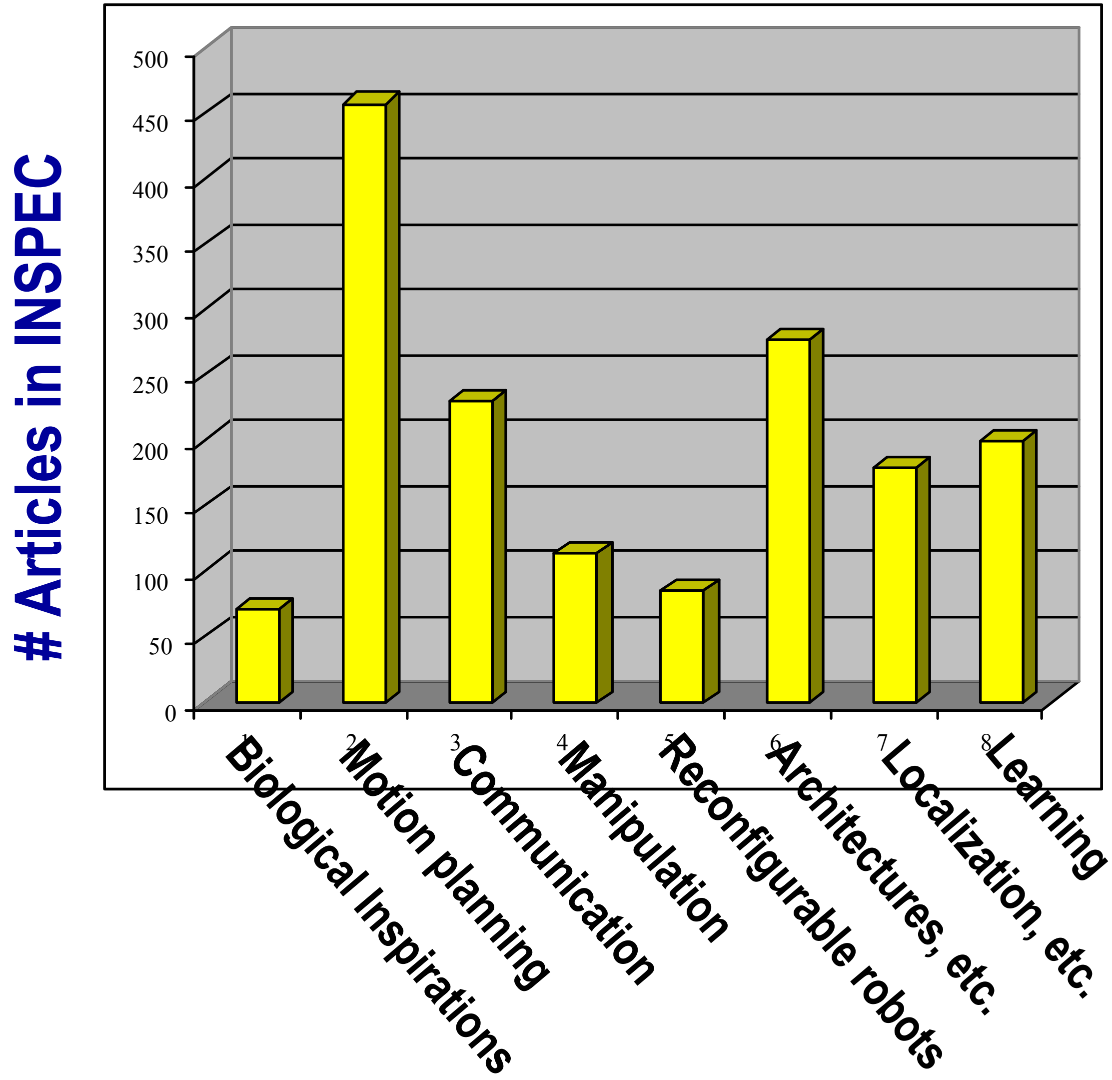
Eight Primary Areas of Prior Multi-Robot Research

1. Biological Inspirations
2. Motion Coordination
3. Communication
4. Object Transport and Manipulation
5. Reconfigurable Robotics
6. Architectures, Task Planning, and Control
7. Localization, Mapping, and Exploration
8. Learning

For each area:

- **Different extents of study**
- **Many excellent solutions**
- **Open research issues remain in all areas**

Relative Concentration in Each Area of Multi-Robot Systems



(Values based upon INSPEC search for years 1979 - 2001)

Not enough time this semester to cover these topics …

So…

Advertisement: Spring 2003 Course ☺

CS594, Section 30682:

“Distributed Intelligence in Autonomous Robotics”

Tuesday-Thursday, 11:10 – 12:25

Course will cover topics of distributed intelligence, including cooperative multi-robot systems, in detail.

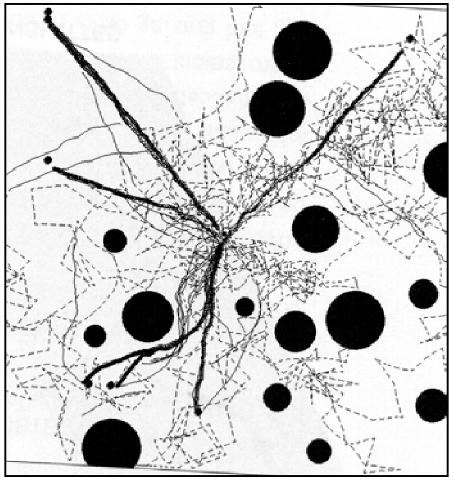
Topics We'll Cover Today in Multi-Robot Systems

- Communication (some aspects)

- Keeping Formation (some aspects)

Multi-Robot Communication

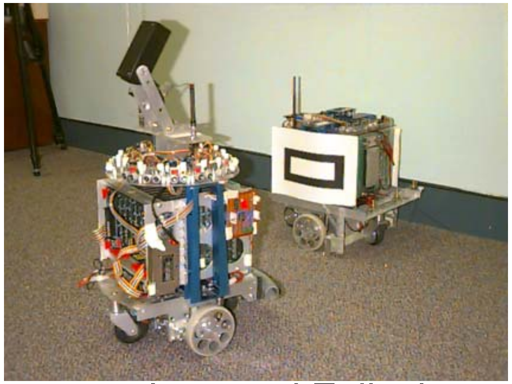
Objective of communication: Enable robots to exchange state and environmental information with a minimum bandwidth requirement



Balch and Arkin

Issues of particular importance:

- Information content
- Explicit vs. Implicit
- Local vs. Global
- Impact of bandwidth restrictions
- "Awareness"
- Medium: radio, IR, chemical scents, "breadcrumbs", etc.
- Symbol grounding



Jung and Zelinsky

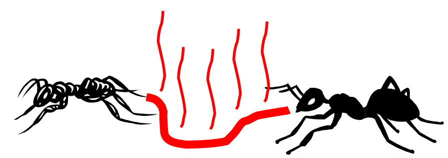
The Nature of Communication

One definition of communication:

“An interaction whereby a signal is generated by an *emitter* and ‘interpreted’ by a *receiver*”

- Emission and reception may be separated in space and/or time.
- Signaling and interpretation may innate or learned (usually combination of both)

- Cooperative communication examples:
  - Pheromones laid by ants foraging food
    - Time delayed, innate
  - Posturing by animals during conflicts/mating etc.
    - Separated in space, learnt with innate biases
  - Writing
    - Possibly separated in space & time, mostly learned with innate support and scaffolding



Multi-Robot Communication Taxonomy

Put forth by Dudek (1993) (this is part of larger multi-robot taxonomy):

- Communication range:
  - None
  - Near
  - Infinite
- Communication topology:
  - Broadcast
  - Addressed
  - Tree
  - Graph
- Communication bandwidth
  - High (i.e., communication is essentially “free”)
  - Motion-related (i.e., motion and communication costs are about the same)
  - Low (i.e., communication costs are very high
  - Zero (i.e., no communication is available)

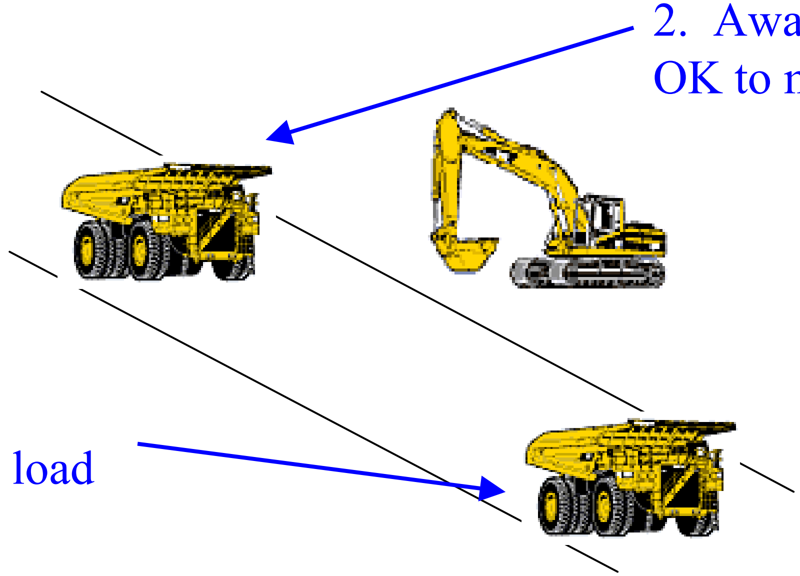
Explicit Communication

- Defined as those actions that have the express goal of transferring information from one robot to another
- Usually involves:
  - Intermittent requests
  - Status information
  - Updates of sensory or model information
- Need to determine:
  - What to communicate
  - When to communicate
  - How to communicate
  - To whom to communicate
- Communications medium has significant impact
  - Range
  - Bandwidth
  - Rate of failure

Implicit Communication

- Defined as communication “through the world”
- Two primary types:
  - Robot senses aspect of world that is a side-effect of another’s actions
  - Robot senses another’s actions

2. Awaiting truck knows it is OK to move into position



1. Truck leaves with full load

Three Key Considerations in Multi-Robot Communication

- Is communication needed at all?
- Over what range should communication be permitted?
- What should the information content be?

Is Communication Needed At All?

- Keep in mind:
  - Communication is not free, and can be unreliable
  - In hostile environments, electronic countermeasures may be in effect
- Major roles of communication:
  - Synchronization of action: ensuring coordination in task ordering
  - Information exchange: sharing different information gained from different perspectives
  - Negotiations: who does what?
- Many studies have shown:
  - Significantly higher group performance using communication
  - However, communication does not always need to be explicit

Over What Range Should Communication Be Permitted?

- Tacit assumption: wider range is better
- But, not necessarily the case
- Studies have shown: higher communication range can lead to decreased societal performance

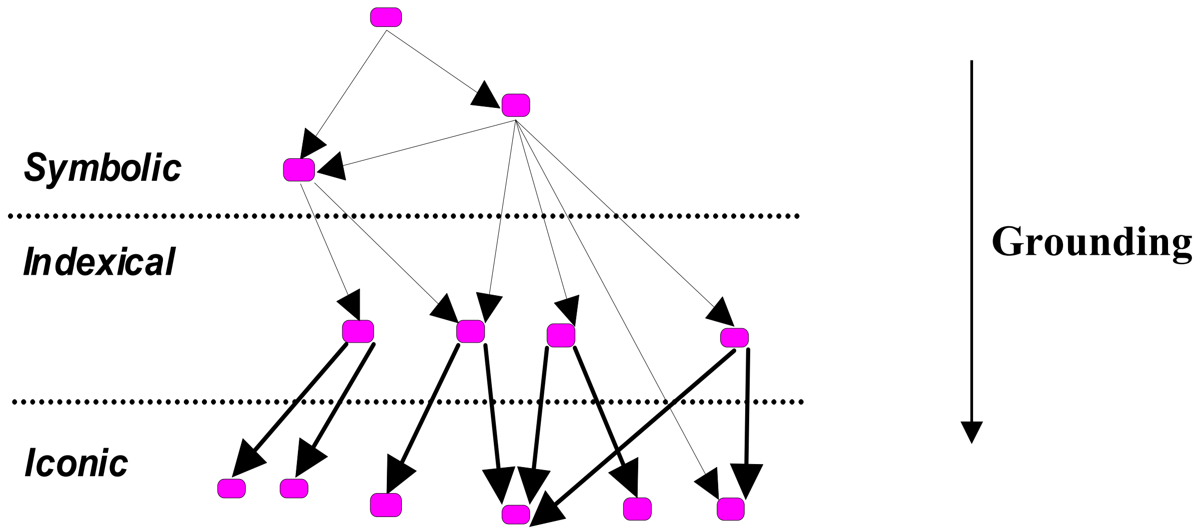
- One approach for balancing communication range and cost (Yoshida '95):
  - Probabilistic approach that minimizes communication delay time between robots
  - Balance out communication flow (input, processing capacity, and output) to obtain optimal range

What Should the Information Content Be?

- Research studies have shown:
  - Explicit communication improves performance significantly in tasks involving little implicit communication
  - Communication is not essential in tasks that include implicit communication
  - More complex communication strategies (e.g., goals) often offer little benefit over basic (state) information ➔ "display" behavior is a rich communication method

Case Study in Multi-Robot Communication: Symbol Grounding in Heterogeneous Robots, Jung, Australia, 1998

- The field of Linguistics is concerned with the structure of human communication -
  - Complex structure is observed in the *signals* humans use (speech, writing, etc.)



  - Provides *some* information about processes underlying generation and interpretation. However, ***does not*** imply that an analogous structure is used to represent the world (a wide-spread misconception within the AI and robotics communities)
- Sophistication of cooperative behavior and communication are typically correlated (supported by ethological evidence and robot studies)

Jung's Hypothesis: Symbolic communication required

- Assumptions:
  - Future robots will have a richer understanding of the world in which they operate.
  - Future multi-robot applications will require more sophisticated cooperation.
- Assertion:
  - More sophisticated cooperation will necessitate a corresponding increase in the sophistication of communication.
    - This will not be realized if communication is restricted to the sub-symbolic (iconic/indexical) level
- His conclusion:
  - Symbolic communication is a necessity.
- Implication:
  - Heterogeneous robots will be able to communicate at a high level about what they have 'seen' with disparate sensors
  - Can communicate procedural information (directions for action etc.)

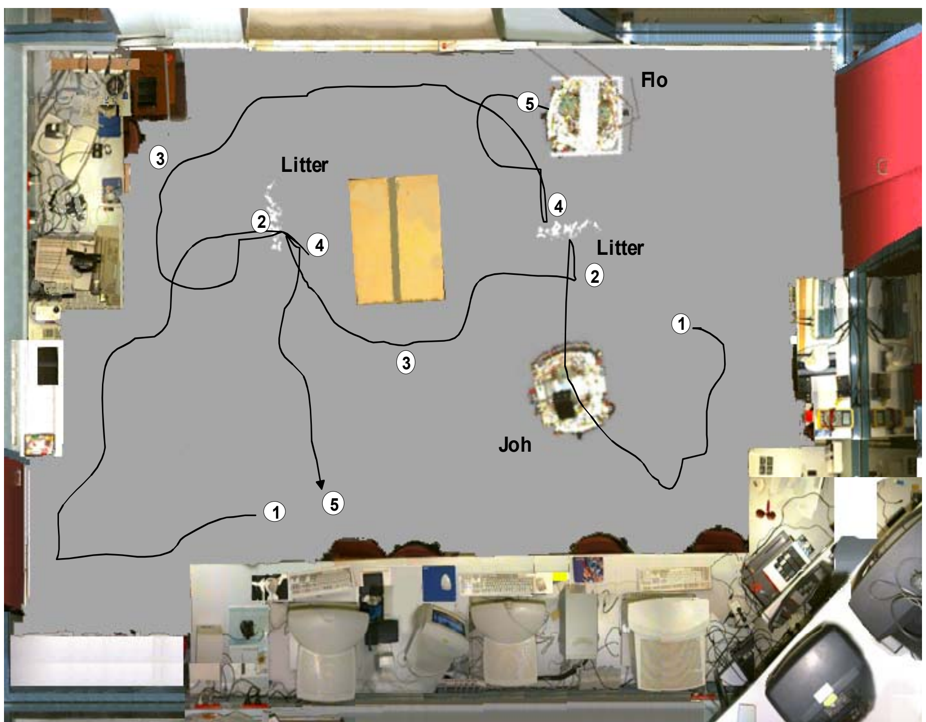
Symbolic communication in a multi-robot system

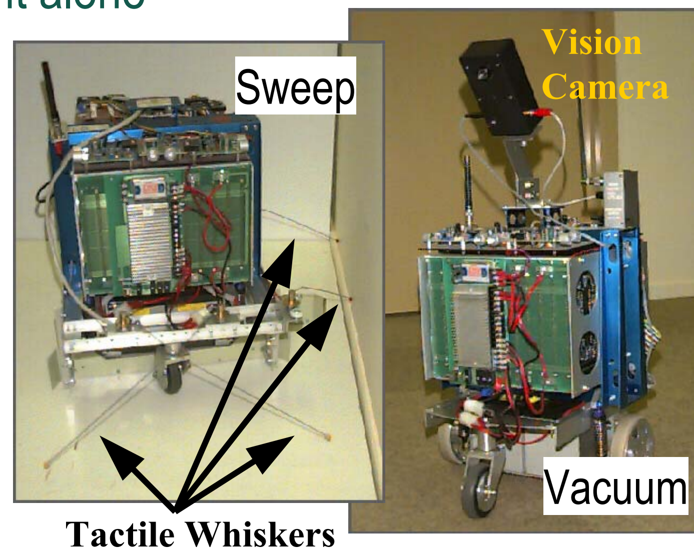
- What is necessary?
  - Some iconic representations in common
    - e.g. by possessing some physically identical sensory-motor apparatus
  - A common process that develops shared indexical groundings
    - e.g. a mechanism for learning correlations between icons
  - A common process that develops shared symbolic groundings

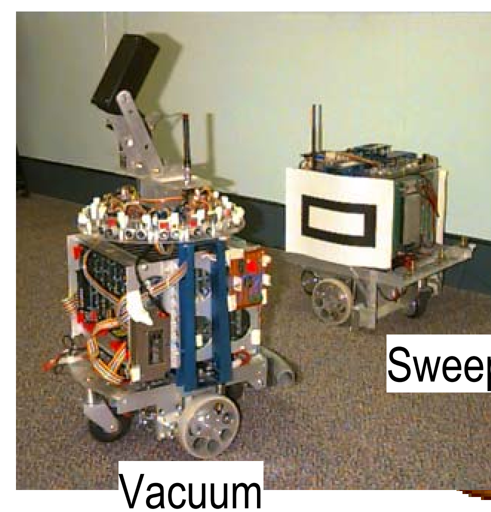
- Ideally...
  - A mechanism for learning new symbols through communicating known ones
    - e.g. interpretation and learning through metaphor

Jung Example: Symbolic communication of object location

- Task: inherently cooperative cleaning
  - Contrived task such that one robot can't accomplish it alone
  - Heterogeneous (two robots) (Flo and Jo)
  - Goal: Clean lab floor

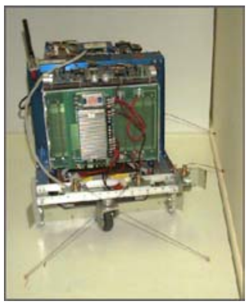




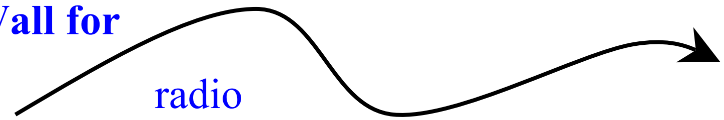


Question: How to Communicate Location?

- Sweep needs to communicate location at which it dumped a pile of litter to the vacuum



Location = FollowWall, TurnRight, FollowWall for ~5m



radio communication

Huh? What's a wall?

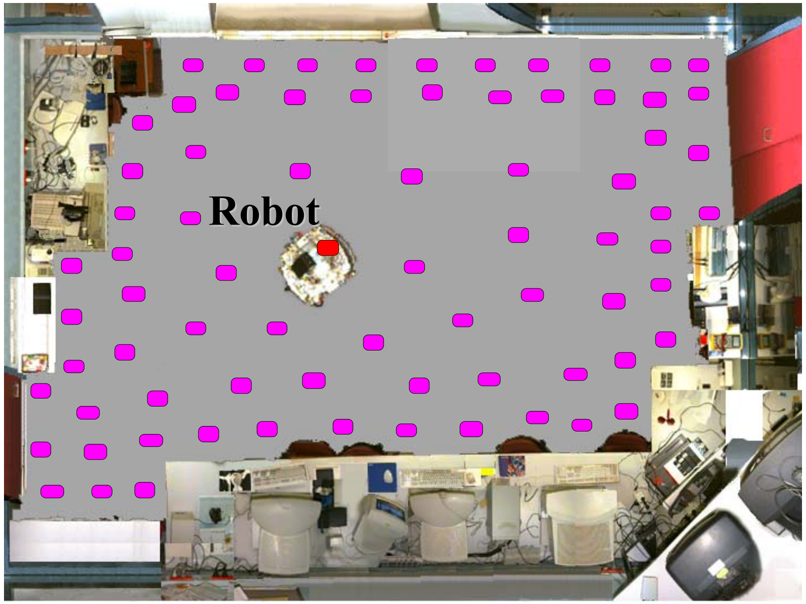
Primary navigation sensor - **whiskers**

Primary navigation sensor - **vision**

- One robot represents locations relative to landmarks that are recognized via touch, while the other uses vision (hence a different set of landmarks)

Some Detail… Navigation

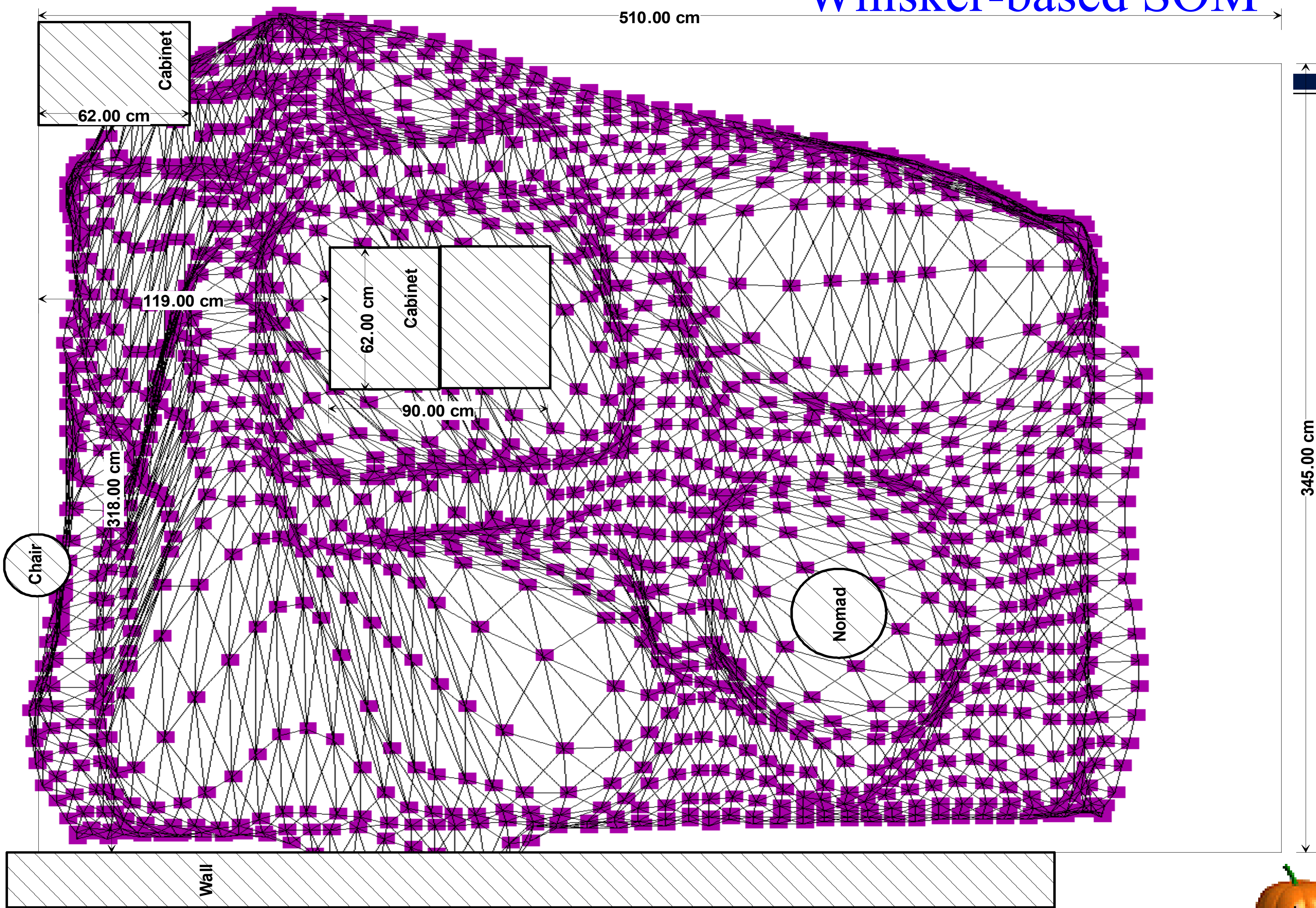
- Both robots use a Kohonen Self Organizing Map (SOM) to represent the spatial extent of an open area
  - Set of nodes that span area in accordance with visitation frequency distribution
  - Each node contains Odometry data
  - Odometry has cumulative error
  - Landmarks don't move
  - ⇨ Correct location by combining landmark and odometry data (Kalman filter)



- Hence, each robot can uniquely identify any location by its relationship to known landmark positions
  - But - landmarks are not shared (different sensory representations)

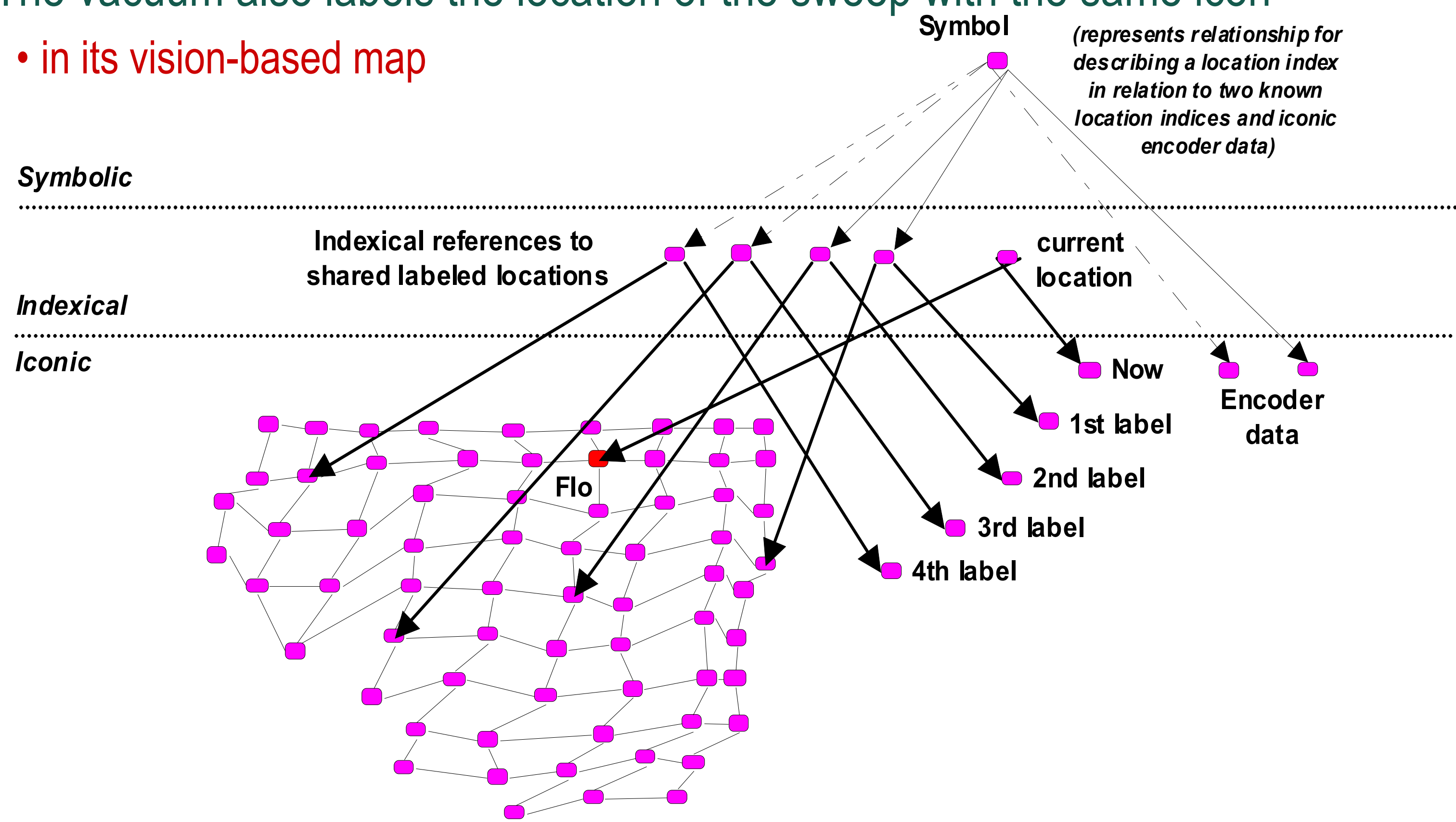
- Note: Self Organizing Map = "elastic net" of points that are fitted to the input signal space to approximate its density function in an ordered way.

Whisker-based SOM



Process for developing shared indexical groundings

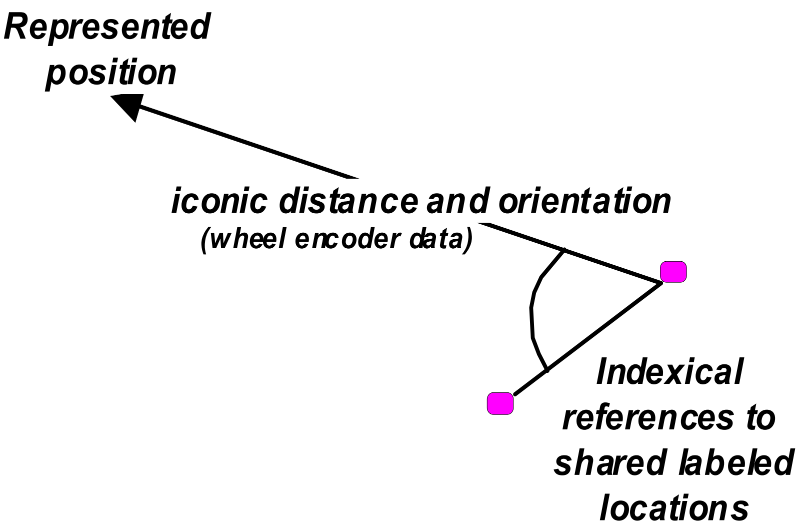
- Location labeling:
  - Initiated when the vacuum can see the sweep
  - Vacuum tells sweep to label its current location with an arbitrary icon
    - Sweep associates the icon with the icon for its current position
  - The vacuum also labels the location of the sweep with the same icon
    - in its vision-based map



Process that develops shared symbolic groundings

- System developer responsibility:
  - In this application, the symbol for representing positions relative to known labeled locations was common due to system developer programming it into both robots

- Obvious shortcomings:
  - Labor intensive to construct significant symbol system
  - Never learns new symbols
    - (just new locations)



Schematic of the <specific-geometric-relation-between> symbol used to communication locations

Jung: The way forward

- Learned symbolic communication
  - Recent work by Steels (VUB) demonstrated, "*the evolution of an open-ended set of meanings and words by a group of autonomous distributed agents in interaction with their physical environments through their sensory apparatus* ".
  - The system involves software agents playing a language game.
  - A stable lexicon is an emergent property of the system
- Jung believes these results can be transferred to cooperative multi-robot systems.
  - The language game may be replaced with (or subsumed into) a cooperative task.
  - Indexical references acquired provide the discriminations necessary for language formation
- Keep in mind … this is one opinion; other researchers have different opinions

Steels and Kaplan, "Bootstrapping Grounded Word Semantics", http://talking-heads.csl.sony.fr, 1999

Summary of Multi-Robot Communication

- Many types:
  - Implicit vs. explicit
  - Local vs. global
  - Iconic vs. symbolic
  - General "awareness"

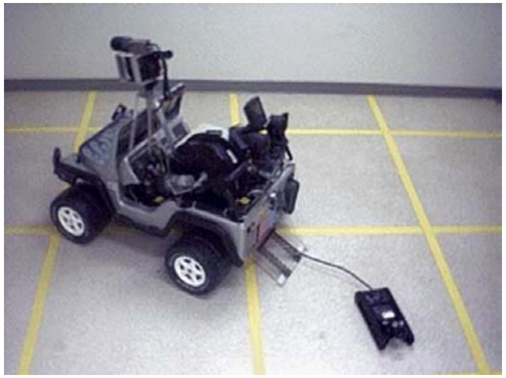
- Proper approach to communication dependent upon application:
  - Communication availability
  - Range of communication
  - Bandwidth limitations
  - Language of robots
  - Etc.

Motion Coordination

Objective: enable robots to navigate collaboratively to achieve spatial positioning goals

- Issues studied:
  - Multi-robot path planning
  - Traffic control
  - Formation generation
  - Formation keeping
  - Target tracking
  - Target search
  - Multi-robot docking

Parker

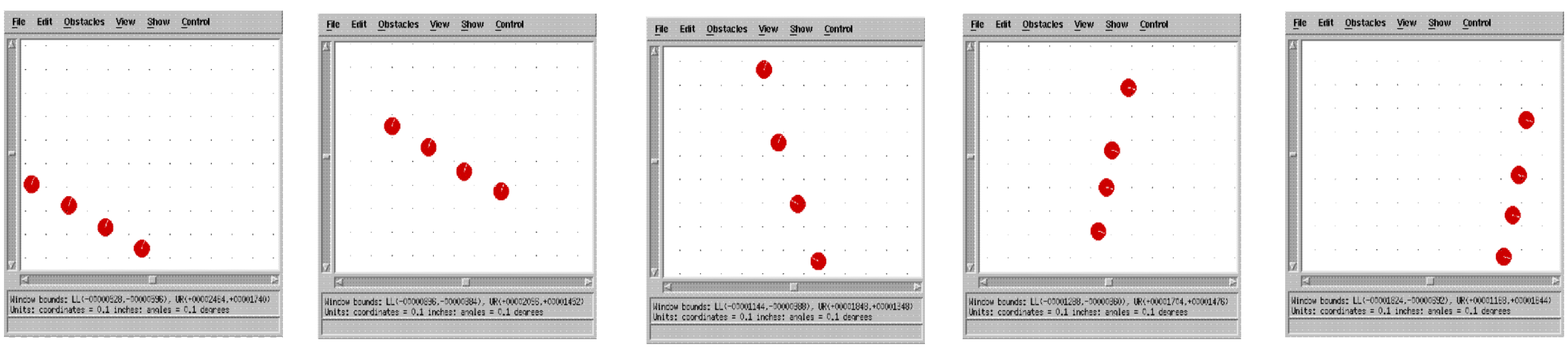


Murphy

Case Study: Formation-Keeping

- Objective:
  - Robots maintain specific formation while collectively moving along path
- Examples:
  - Column formation:

  - Line formation:



L. E. Parker, “Designing Control Laws for Cooperative-Agent Teams”, *Proc. of ICRA*, 1993.

Issue in Formation Keeping: Local vs. Global Control

- Local control laws:
  - No robot has all pertinent information
  - Appealing because of their simplicity and potential to generate globally emergent functionality
  - But, may be difficult to design to achieve desired group behavior

- Global control laws:
  - Centralized controller (or all robots) possess all pertinent information
  - Generally allow more coherent cooperation
  - But, usually increases inter-agent communication

Descriptions: Global Goals, Global Knowledge, Local Control

- Global Goals:
  - Specify overall mission the team must accomplish
  - Typically imposed by centralized controller
  - May be known at compile time, or only at run-time
- Global Knowledge:
  - Additional information needed to achieve global goals
  - E.g., information on capabilities of other robots, on environment, etc.
- Local Control:
  - Based upon proximate environment of robot
  - Derived from sensory feedback
  - Enables reactive response to dynamic environmental changes

Tradeoffs between Global and Local Control

- Questions to be addressed:
  - How static is global knowledge?
  - How difficult is it to obtain reliable global knowledge?
  - How badly will performance degrade without use of global knowledge?
  - How difficult is it to use global knowledge?
  - How costly is it to violate global goals?

- In general:
  - The more unknown the global information is, the more dependence on local control

Demonstration of Tradeoffs in Formation-Keeping

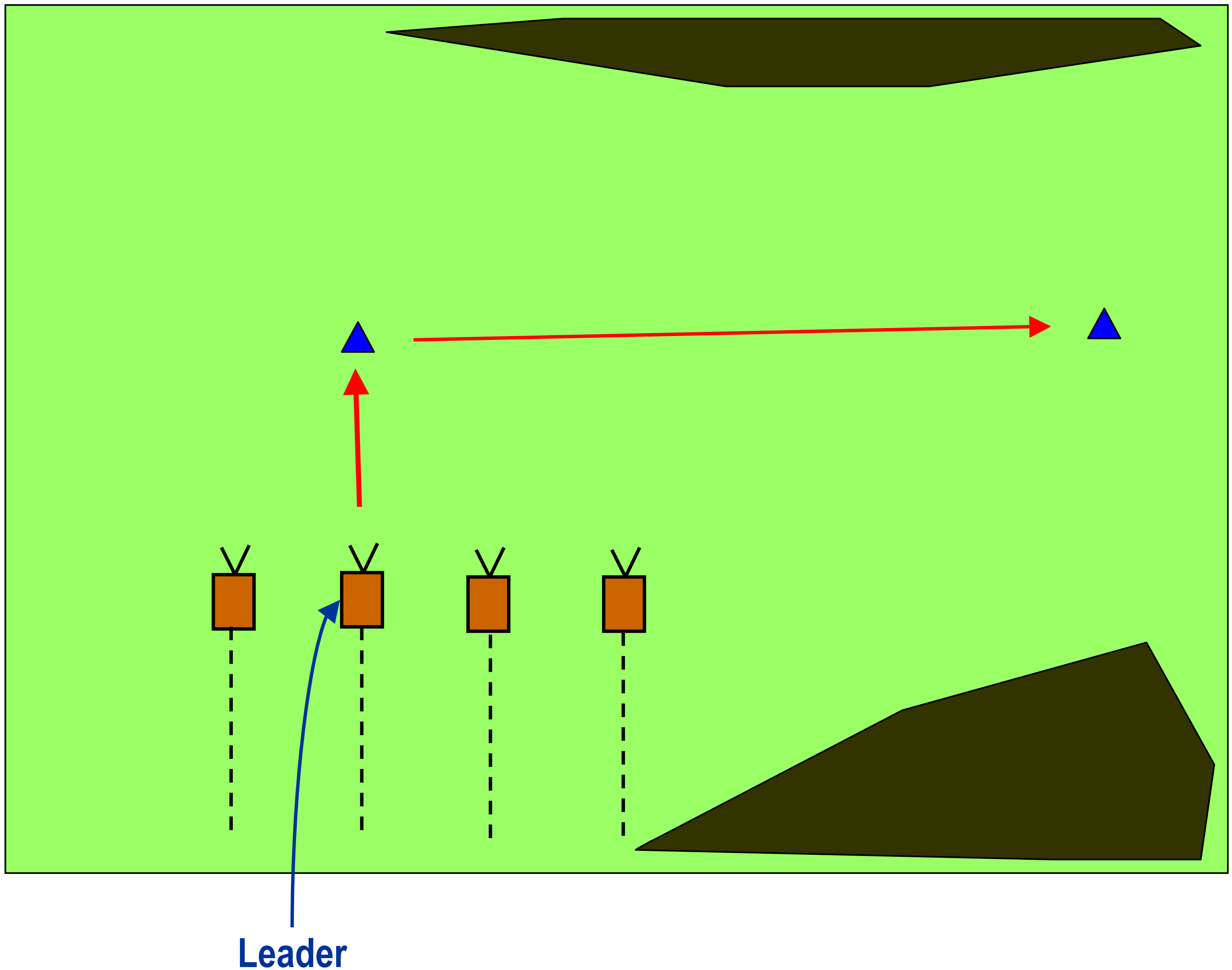
- Measure of performance: Cumulative formation error:

$$\sum_{t=0}^{t_{\max}} \sum_{i \neq leader} d_i(t)$$

Where $d_i(t)$ = distance robot i is from ideal formation position at time t

- Strategies to investigate:
  – Local control alone
  – Local control + global goal
  – Local control + global goal + partial global knowledge
  – Local control + global goal + more complete global knowledge

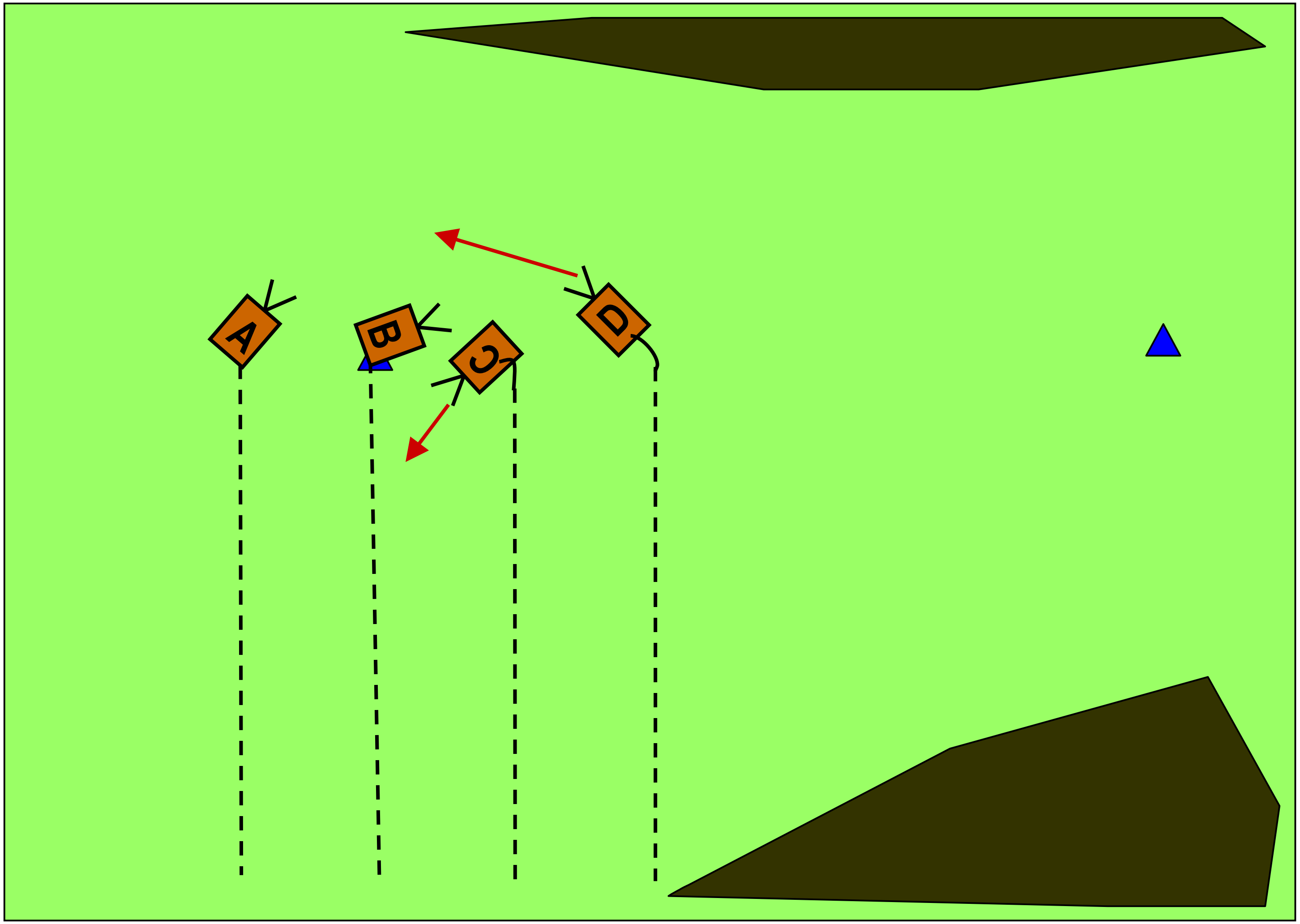
Formation Keeping Objective



Strategy I: Local Control

- Group leader knows path waypoints
- Each robot assigned local leader + position offset from local leader
- As group leader moves, individual robots maintain relative position to local leaders

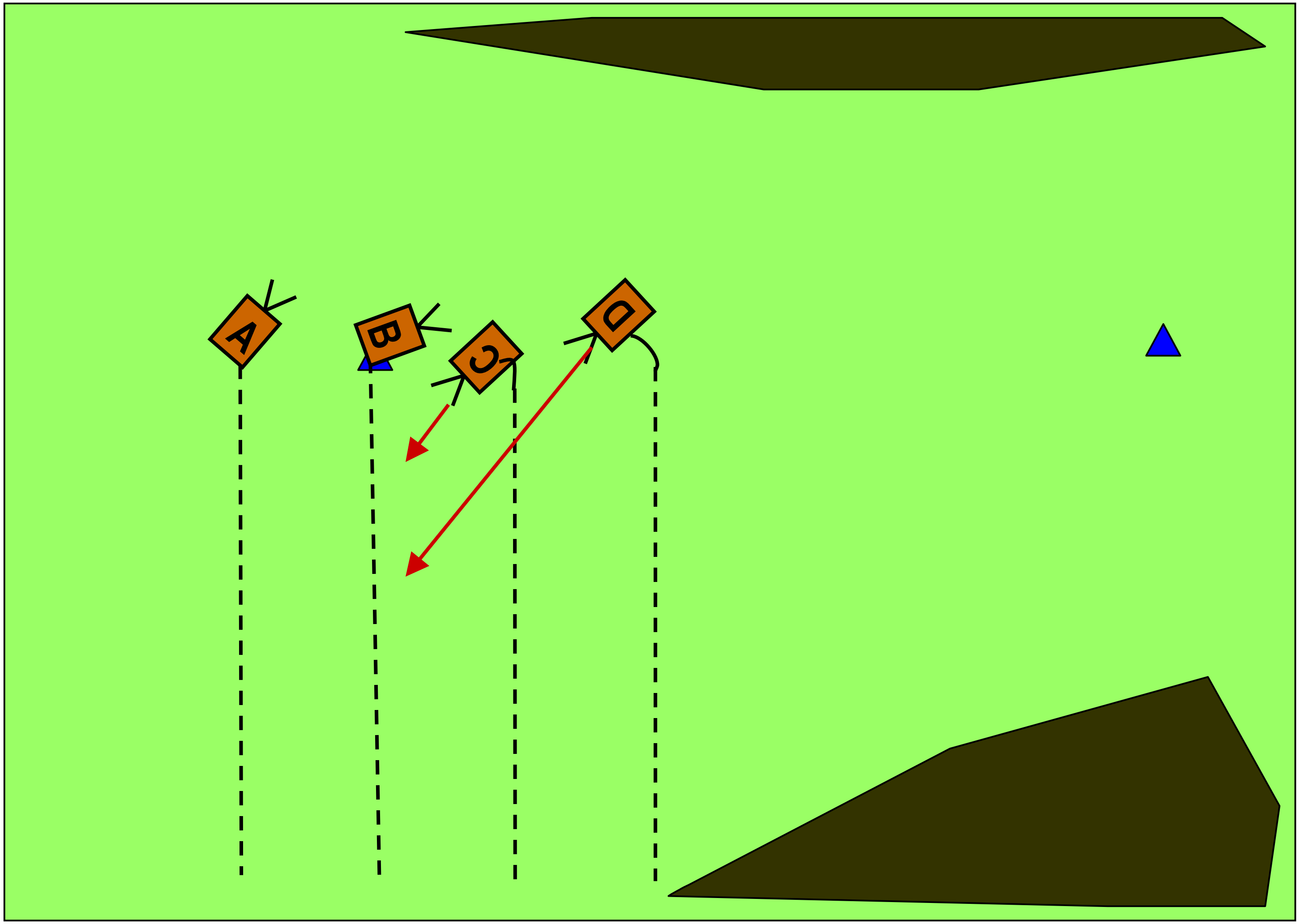
Results of Strategy I



Strategy II: Local Control + Global Goal

- Group leader knows path waypoints
- Each robot assigned global leader + position offset from global leader
- As group leader moves, individual robots maintain relative position to global leader

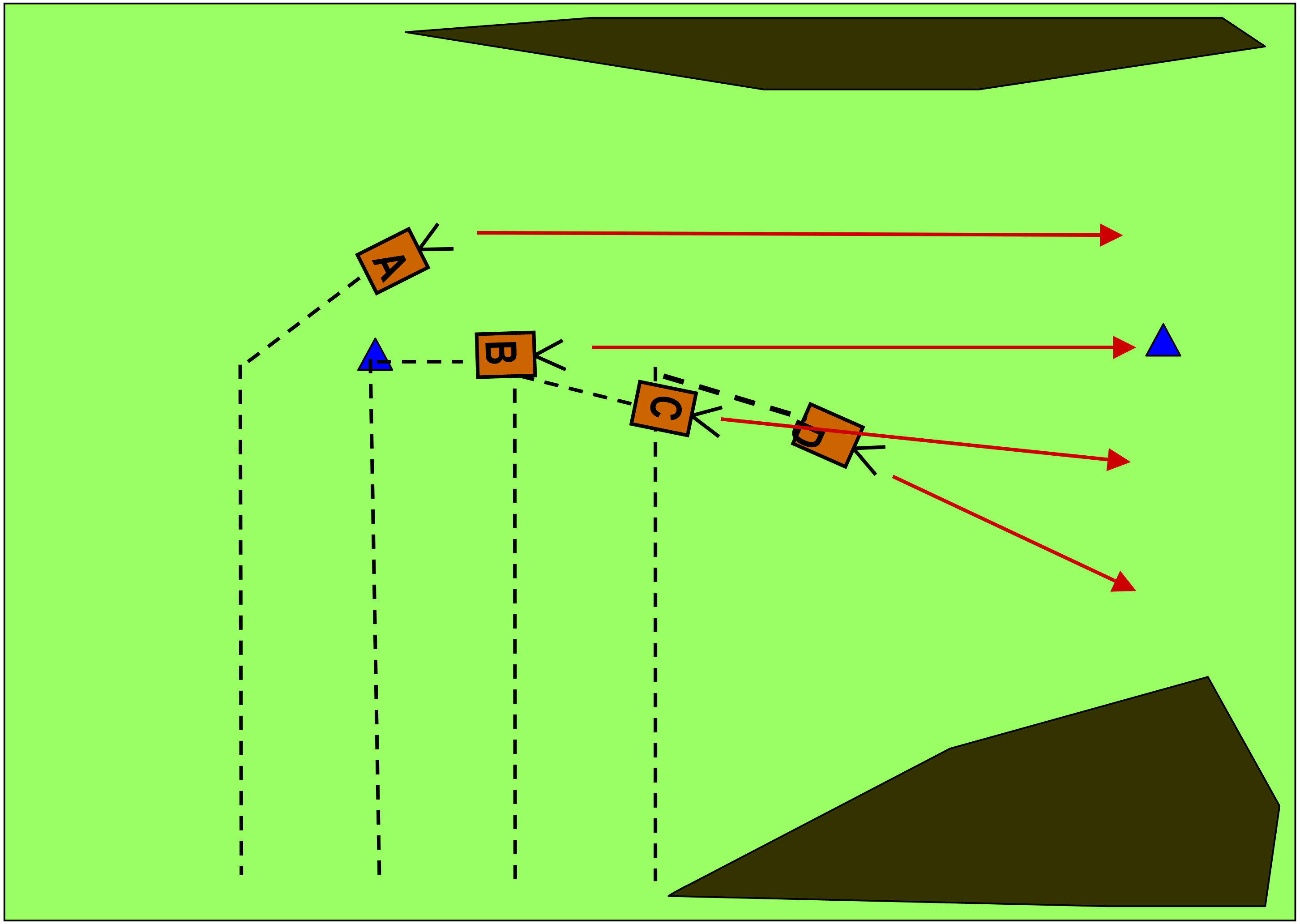
Results of Strategy II



Strategy III: Local Control + Global Goal + Partial Global Knowledge

- Group leader knows path waypoints
- Each robot assigned global leader + position offset from global leader
- Each robot knows next waypoint
- As group leader moves, individual robots maintain relative position to global leader

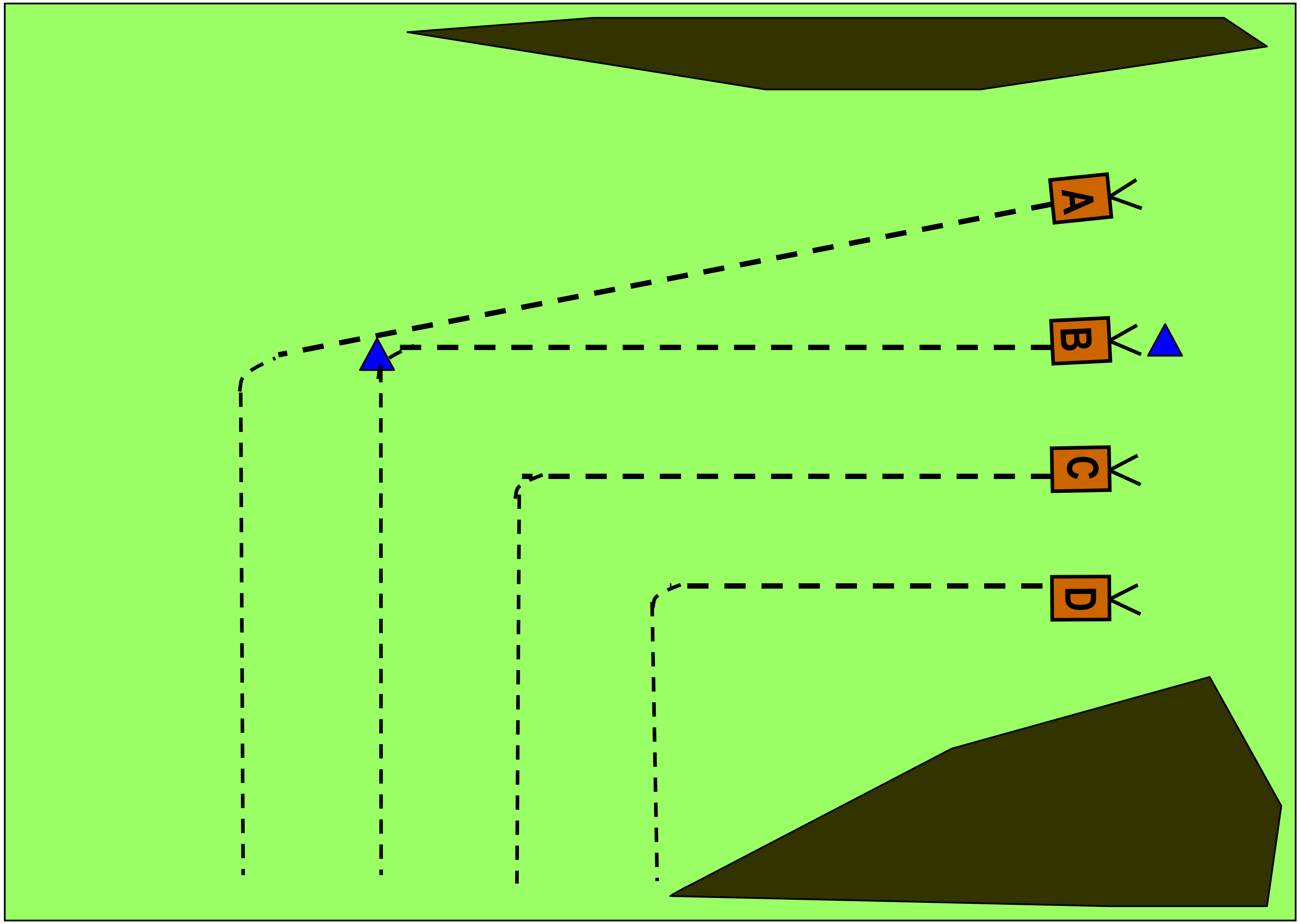
Results of Strategy III



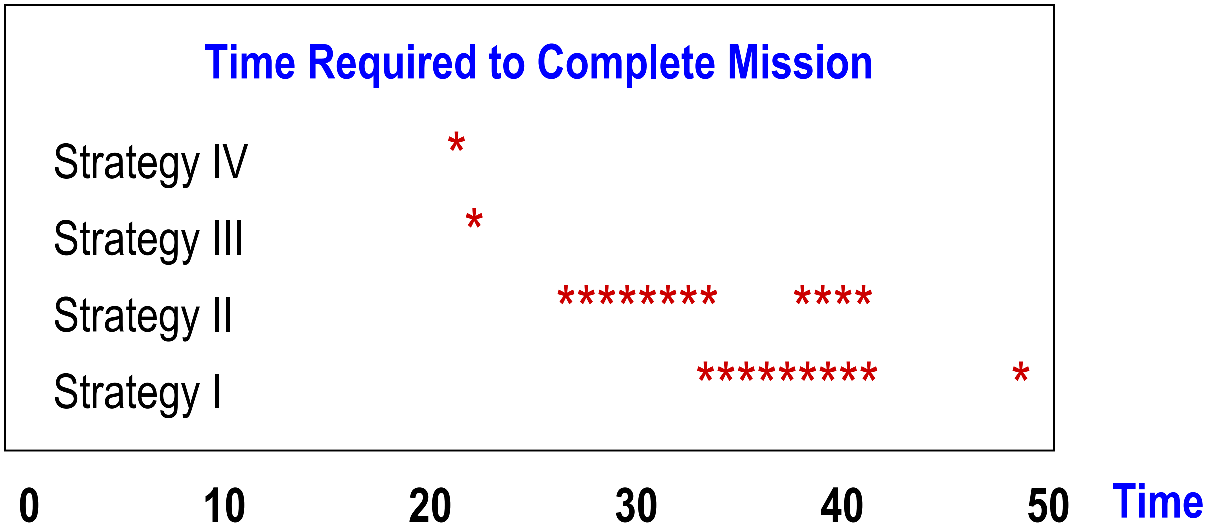
Strategy IV: Local Control + Global Goal + More Complete Global Knowledge

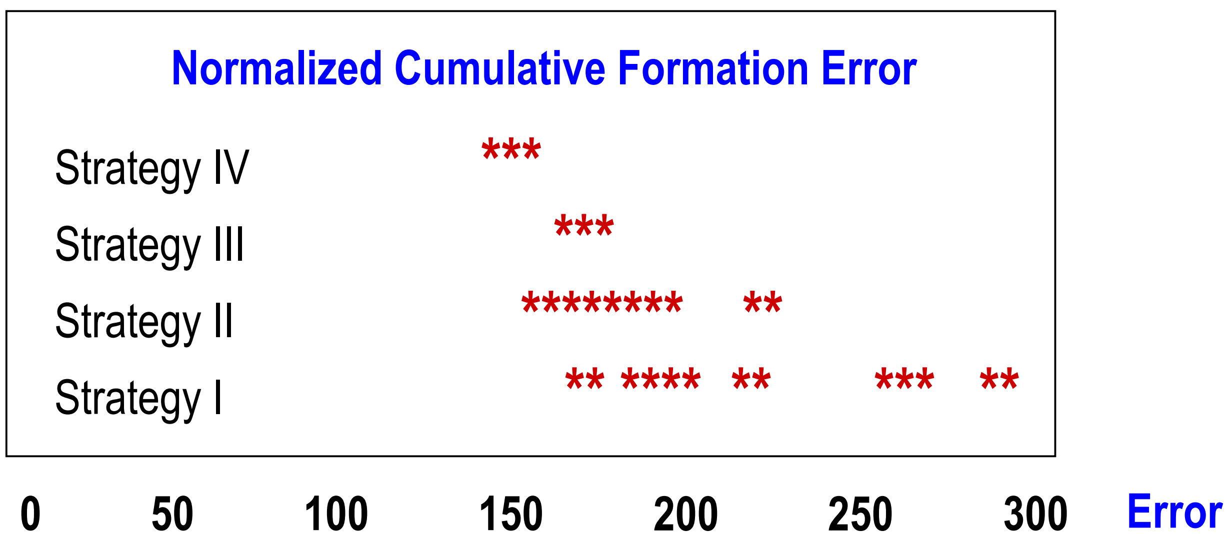
- Group leader knows path waypoints
- Each robot assigned global leader + position offset from global leader
- Each robot knows current and next waypoints
- As group leader moves, individual robots maintain relative position to global leader

Results of Strategy IV



Time and Cumulative Formation Error Results





Summary of This Formation-Keeping Control Case Study

- Important to achieve proper balance between local and global knowledge and goals
- Static global knowledge ==> easy to use as global control law
- Local knowledge ==> appropriate when can approximate global knowledge
- Local control information should be used to ground global knowledge in the current situation.

Another Case Study for Formation-Keeping: Balch & Arkin's Behavior-Based Control

- Applications:
  - Automated scouting (military)
  - Search and rescue
  - Agricultural coverge
  - Security patrols

- Approach:
  - Motor schemas
  - Fully integrated obstacle avoidance

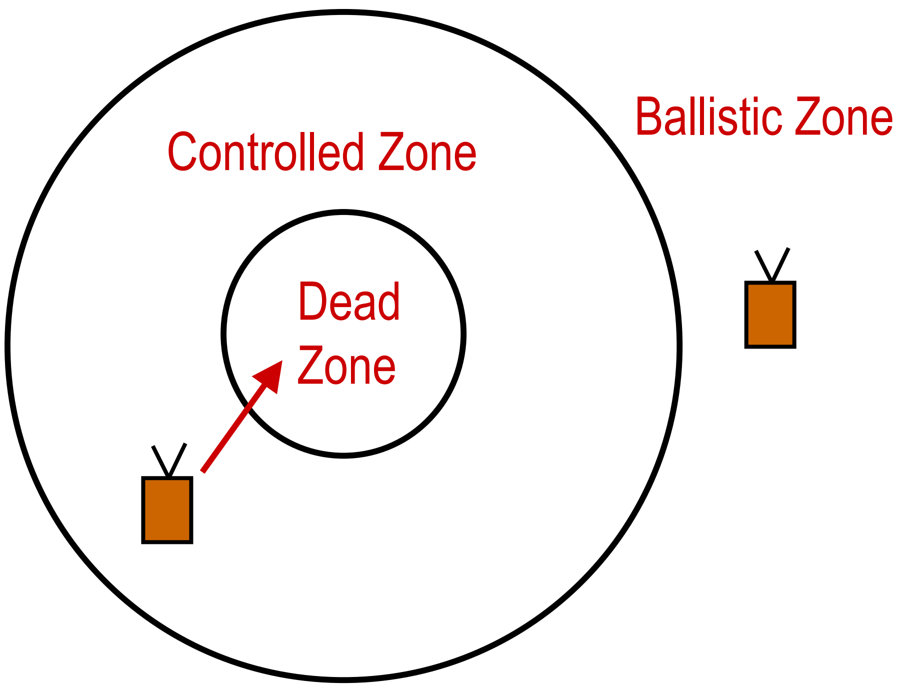
Motor Schemas Used for Formation-Keeping

- Move-to-goal
- Avoid-static-obstacle
- Avoid-robot
- Maintain-formation:
  - Perceptual schema: detect-formation-position
    - Accomplished by:
      - Determining robot’s desired location for the formation type in use
      - Determining robot’s relative position in the overall formation
      - Determining other robots’ locations
  - Motor schema output vector:
    - Computed toward position whose magnitude is based on how far out of position the robot is

Output Vector Magnitude Calculation

- Dead zone:
  - Robot is within acceptable positional tolerance.
  - Output vector magnitude is always 0.
- Controlled zone:
  - Robot is somewhat out of position.
  - Output vector magnitude decreases linearly from a maximum at zone's furthest edge to 0 at the inner edge.
  - Directional component: points toward dead zone's center.
- Ballistic zone:
  - Output vector magnitude is set to its maximum
  - Directional component points toward the center of the computed dead zone

Magnitudes:



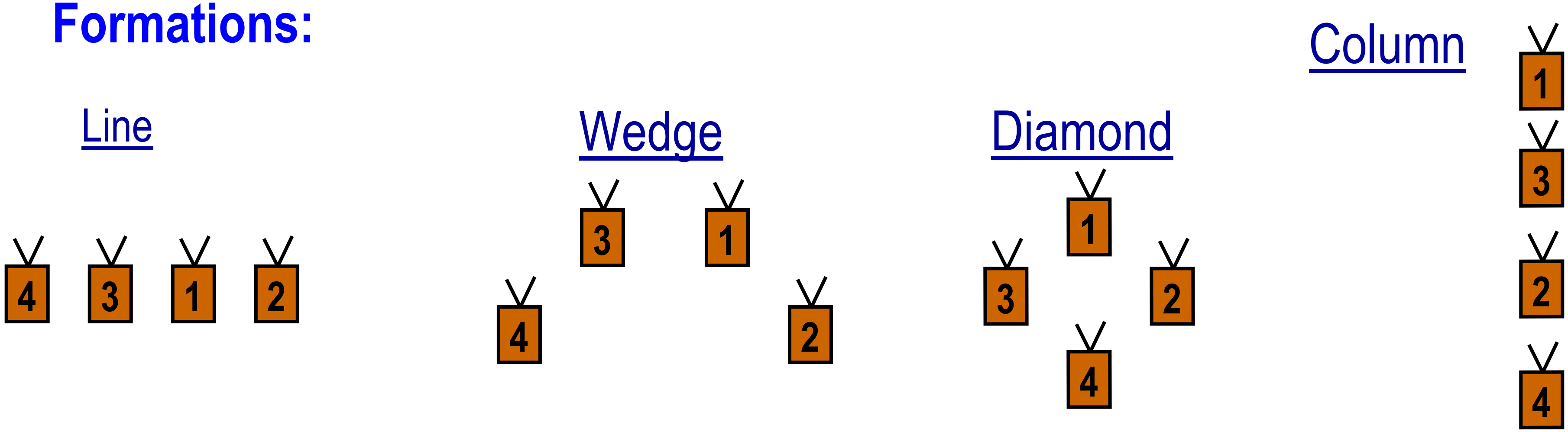
Formation and Obstacle Avoidance

- Barriers -- choices for handling include:
  - Move as a unit around barrier
  - Divide into subgroups

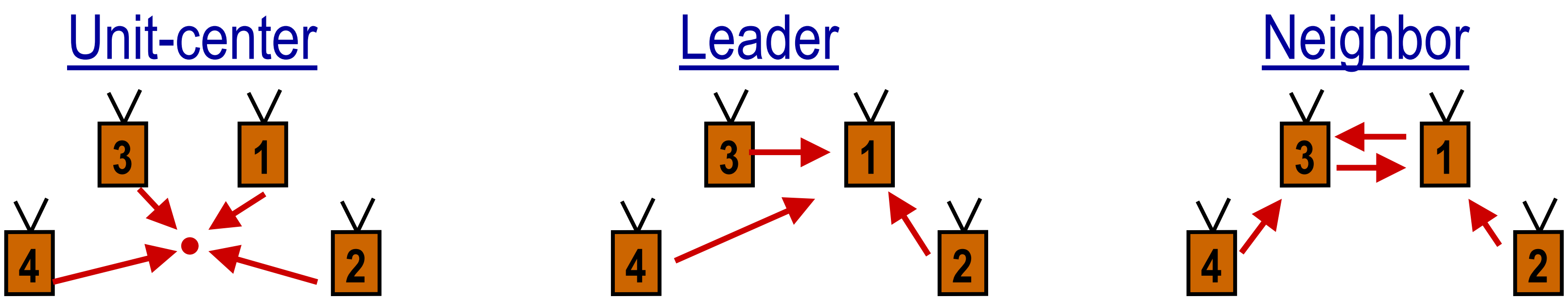
- Choice depends upon relative strengths of behaviors

Balch's Formation Types and Position Determination

Formations:



Position Determination:



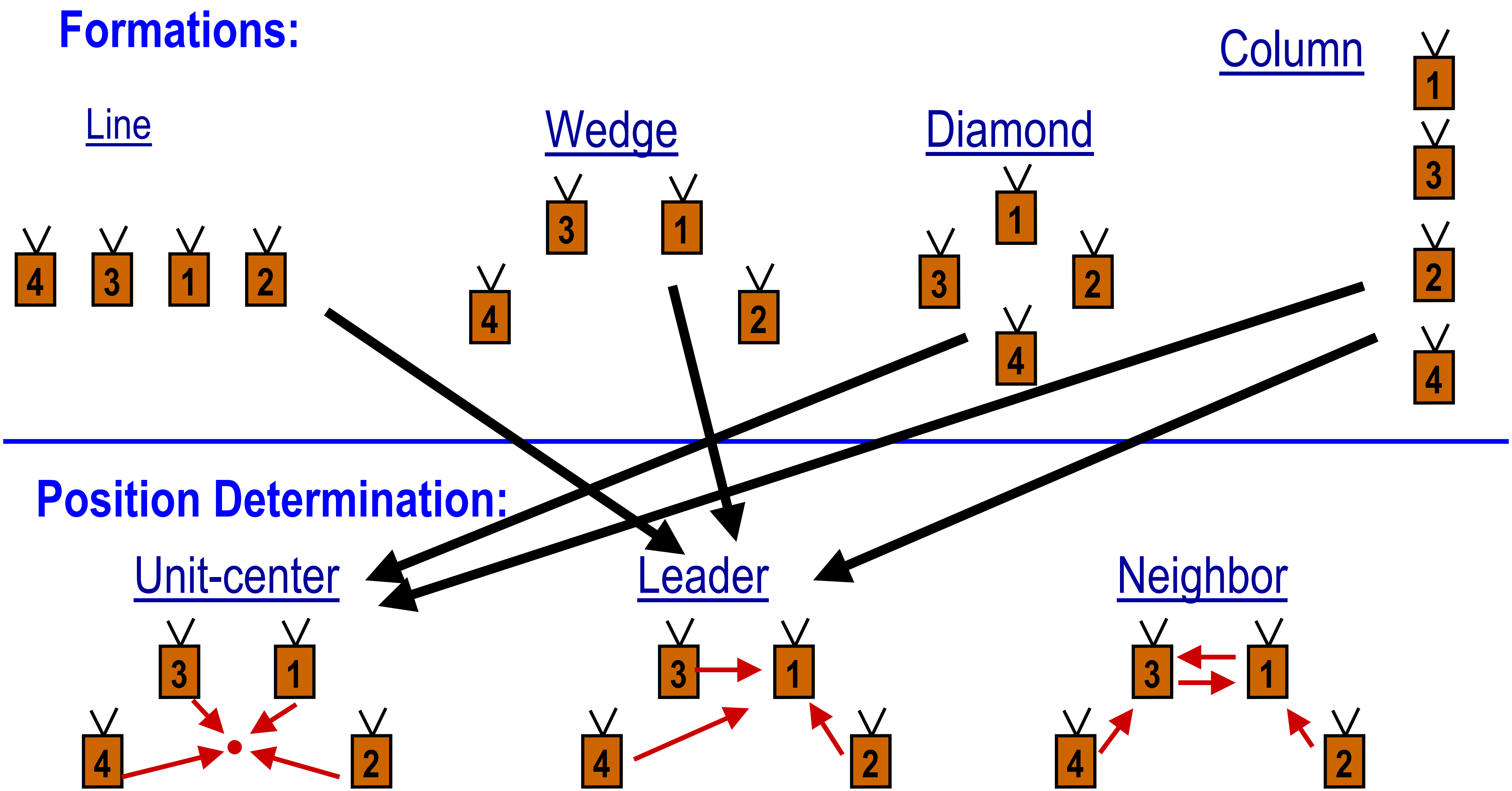
Requirements of Formation Techniques

- Unit-center approach:
  - Requires transmitter and receiver for all robots
  - Requires protocol for exchanging position information
  - Places heavy demand on passive sensor systems: each robot has to track 3 other robots that may be spread across a very large field of view
- Leader-referenced approach:
  - Requires only one transmitter for leader and one receiver for each follower robot
  - Thus, has reduced communications bandwidth
  - Require tracking only one robot
  - However, leader may be too far away to sense
  - Local interactions among robots may make little sense, if they aren't paying attention to each other
- Neighbor-referenced approach:
  - Requires tracking only one other robot
  - However, less information on global formation requirements ➔ could be more formation error

Balch's Formation Results

- For 90 degree turns:
  - Diamond formation best with unit-center-reference
  - Wedge, line formations best with leader-reference
- For obstacle-rich environments:
  - Column formation best with either unit-center or leader-reference
- Most cases:
  - Unit-center better than leader-center
  - Except:
    - If using human leader, not reasonable to expect to use unit-center
    - Unit-center requires transmitter and receiver for all robots, whereas leader-center only requires transmitter at leader plus receivers for all robots
    - Passive sensors are difficult to use for unit-center

Balch's Formation Types and Position Determination



Summary of Multi-Robot Systems

- Teams of robots can offer significant advantages over individual robots in terms of:
  - Performance
  - Sensing capabilities
  - Fault tolerance
- Problems with multi-robot systems include:
  - Inteference
  - Communications costs
  - Uncertainty in others' actions
- Typical generic tasks studied are:
  - Foraging
  - Flocking
  - Consuming
  - Moving material
  - Grazing

Summary of Multi-Robot Systems (con't)

- Communication plays central role in coordinating teams of robots
- Communication is not always necessary for cooperation, but can sometimes significantly improve results
- Formation keeping involves multiple types of formations and multiple strategies
- No single formation strategy is best for all cases
- Must consider tradeoffs in exchange of local and global information

Preview of Next Class (Tuesday, Nov. 5th)

- Navigation: Part I