Communication in Multi-Robot Teams

February 11, 2003

Class Meeting 9
Announcements

• Next class (Thursday): Exam #1
• Closed book, closed notes
• **BRING A CALCULATOR**

• Topics:
  – All lectures and readings through Thursday, Feb. 6
  – Introduction/Overview
  – Biological Inspirations
  – Swarming/flocking/schooling
  – Metrics and evaluation
  – Search/coverage
  – Sensor networks
Announcements

• Note: Reading #11 is now optional (i.e., Chapter 3 of *Robot Teams* text)
Objectives

• Understand key issues in multi-robot communication

• Understand impact of communication in Balch’s case study with Foraging, Consuming, and Grazing
Multi-Robot Communication

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

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
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”
- Very similar to concept of “Stigmergy”
- Two primary types:
  - Robot senses aspect of world that is a side-effect of another’s actions
  - Robot senses another's actions

1. Truck leaves with full load
2. Awaiting truck knows it is OK to move into position
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
Study of Communication


• Objective of this research: determine importance of communication

• Method:
  – Simulated and physical robot experiments
  – Three types of tasks
    • Forage
    • Consume
    • Graze
  – Three types of communication
    • None
    • State
    • Goal
The Three Tasks: (1) Forage

- Robot wanders looking for attractors
- After encountering attractors, robot attaches itself and returns it to home base
- Different attractor masses $\rightarrow$ different robot carrying speeds

Simulation of Forage:
- Dashed lines: Wandering
- Solid lines: Acquire, attach, and returning attractor to home base
Three Tasks: (2) Consume

• Similar to consume, except robots perform work on object in place after attachment to it

• Different attractor masses $\rightarrow$ different speeds of consuming
Three Tasks: (3) Graze

- Objective: completely cover (or “visit”) the environment
Parameters for Communications Study

• Number of attractors
  – Affects how long it takes to accomplish task

• Mass of attractors
  – “Transportability” factor for Forage
  – “Workability” factor for Consume

• Graze coverage:
  – % required to be covered
Design of Robot Team Behaviors

• Based on motor schemas (Arkin)

• Let’s again review basics of motor schemas (see also class notes from January 23rd)…
Key Aspects of Motor Schemas

- Triggers / releasers determine when a behavior should be activated
- Perceptual schema processes sensory input to provide needed information to motor control
- Motor schema is the behavioral response when behavior is triggered
- Multiple motor schemas operate concurrently
- Provides a language for connecting action and perception
- Behavioral responses are all represented as vectors generated using a potential fields approach
- Coordination is achieved by vector addition
- No predefined hierarchy exists for coordination; instead, behaviors are configured at run-time
- Pure arbitration is not used; each behavior can contribute in varying degrees to robot’s overall response
Behaviors and Schema Theory

- Schema:
  - Consists of:
    - Information on how to act and/or perceive (knowledge, data structures, models)
    - Computational process by which it achieves the activity (algorithm)
  - Is a generic template for how to do some activity
Example of Toad’s Feeding Behavior Using Schema

Releaser:
Appearance of small, moving object

Sensory Input:
Toad’s vision

FEEDING BEHAVIOR

Perceptual Schema:
get coordinates of small, moving object

Motor Schema:
turn to coordinates of small, moving object

Pattern of Motor Actions:
Toad’s legs
Output of Motor Schemas Defined as Vectors

- **Output Vector:** consists of both orientation and magnitude components

- $V_{\text{magnitude}}$ denotes magnitude of resultant response vector
- $V_{\text{direction}}$ denotes orientation
Motors Schemas Achieve Behavioral Fusion via Vector Summation

\[ R = \sum (G_i \cdot R_i) \]

Behavioral fusion

Behavior 1 \rightarrow \text{Behavioral fusion}

Behavior 2 \rightarrow \text{Behavioral fusion}

Behavior 3 \rightarrow \text{Behavioral fusion}

Behavior 4 \rightarrow \text{Behavioral fusion}
An Explanation of Finite State Acceptor (FSA) Diagrams

- FSAs consist of several states that define the task
- **State**: corresponds to separate assemblage of motor schemas that are active in that state
- **Transitions**: correspond to perceptual triggers that provide necessary information to activate motor schemas
• Finite State Acceptor for Foraging:

```
Wander ————> Encounter ————> Acquire
        /       |       \
       /   Deposit———> Attach
        
Deliver
```
FSAs in Balch’s Communications Study

- Finite State Acceptor for Consuming:

  ![Diagram showing states and transitions: Wander, Acquire, Consume. Transitions include Encounter, Complete, Attach.]
FSAs in Balch’s Communications Study

- Finite State Acceptor for Grazing:
Defined Motor Schemas for Communications Study

- Noise
- Avoid-static-obstacle for objects
- Avoid-static-obstacle for robots
- Detect-attractor
  - Move-to-goal
  - Detect-attachment
  - Detect-deposit
  - Consume attractor
  - Detect-ungrazed-area
  - Detect-grazed-area
  - Probe
  - Graze

- Output of each motor schema is a directional vector.
- Different states use different combinations of motor schemas
Motor Schemas In Forage Task

- Noise
- Avoid-static-obstacle for objects
- Avoid-static-obstacle for robots
- Detect-attractor
- Move-to-goal
- Detect-attachment
- Detect-deposit
- Consume attractor
- Detect-ungrazed-area
- Detect-grazed-area
- Probe
- Graze
Motor Schemas in Forage Task

- Noise
- Avoid-static-obstacle for objects
- Avoid-static-obstacle for robots
- Detect-attractor
- Move-to-goal
- Detect-attachment
- Detect-deposit
  - Consume attractor
  - Detect-ungrazed-area
  - Detect-grazed-area
  - Probe
  - Graze

Deliver
Motor Schemas in **Consume** Task

- Noise
- Avoid-static-obstacle for objects
- Avoid-static-obstacle for robots
- Detect-attractor
  - Move-to-goal
  - Detect-attachment
  - Detect-deposit
  - Consume attractor
  - Detect-ungrazed-area
  - Detect-grazed-area
  - Probe
  - Graze

Same as for Forage
Motor Schemas In **Consume** Task

- Noise
- Avoid-static-obstacle for objects
- Avoid-static-obstacle for robots
- Detect-attractor
- Move-to-goal
- Detect-attachment
- Detect-deposit
- Consume attractor
- Detect-ungrazed-area
- Detect-grazed-area
- Probe
- Graze

**Same as for Forage**
Motor Schemas in **Consume** Task

- Noise
- Avoid-static-obstacle for objects
- Avoid-static-obstacle for robots
- Detect-attractor
- Move-to-goal
- Detect-attachment
- Detect-deposit
- **Consume attractor**
  - Detect-ungrazed-area
  - Detect-grazed-area
  - Probe
  - Graze

**Consume**
Motor Schemas in **Graze** Task

- Noise
- Avoid-static-obstacle for objects
- Avoid-static-obstacle for robots
- Detect-attractor
- Move-to-goal
- Detect-attachment
- Detect-deposit
- Consume attractor
- Detect-ungrazed-area
- Detect-grazed-area
- Probe
- Graze

*Different from Forage/Consume*
Motor Schemas In Graze Task

- Noise
- Avoid-static-obstacle for objects
- Avoid-static-obstacle for robots
- Detect-attractor
- Move-to-goal
- Detect-attachment
- Detect-deposit
- Consume attractor
- Detect-ungrazed-area
- Detect-grazed-area
- Probe
- Graze

Same as for Forage
Motor Schemas in **Graze** Task

- Noise
- Avoid-static-obstacle for objects
- Avoid-static-obstacle for robots
- Detect-attractor
- Move-to-goal
- Detect-attachment
- Detect-deposit
- Consume attractor
- Detect-ungrazed-area
- Detect-grazed-area
- Probe
- Graze
Forms of Inter-Robot Communication

- **No communication; Robots able to detect:**
  - Other robots
  - Attractors
  - Obstacles

- **State communication**
  - Robots can detect internal state of other robots (e.g., wander, acquire, deliver, etc.)
  - For these studies, detect only “wander” and “everything else”
  - Behaviors modified here, so that:
    - Robots transition to acquire if it discovers another robot in acquire, deliver, consume, or graze

- **Goal communication**
  - Robots communicate location of detected attractors
Simulation Studies: Experimental Parameters

• Metric: Time of task completion
• Duration: 8000 steps
• Task factors:
  – # attractors: 1-7
  – Mass of attractors: 1-8
  – Graze coverage: 13-95%
• Environmental factors:
  – Static, flat
  – Obstacle coverage: 10-25%
  – Obstacle radius: 1-4
• Sensor/motor constraints:
  – Fixed: velocity, graze swath, consume rate
  – Fixed: Attractor sensor range = obstacle sensor range = 1/5 communication range
• Control parameters:
  – (see paper)

• For each set of parameters, average over 30 runs
Baseline Simulation Results: Time to Complete with No Communication

Forage

Consume

Graze
Baseline Simulation Results: Speedup with No Communication

- Speedup: performance improvement of multiple robots over one robot alone

Forage  Consume  Graze

Average speedup:

0.93  0.82  1.07
Key Points from Baseline Simulation Results

• For a given number of attractors, more robots complete a task faster than fewer robots

• For a given number of robots, it takes longer to complete a task with more attractors

• Speedup is greater in scenarios where larger numbers of attractors are present
## Results with Communication

<table>
<thead>
<tr>
<th>Task</th>
<th>Average improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Forage:</strong></td>
<td></td>
</tr>
<tr>
<td>State vs. None</td>
<td>16%</td>
</tr>
<tr>
<td>Goal vs. None</td>
<td>19%</td>
</tr>
<tr>
<td>Goal vs. State</td>
<td>3%</td>
</tr>
<tr>
<td><strong>Consume:</strong></td>
<td></td>
</tr>
<tr>
<td>State vs. None</td>
<td>10%</td>
</tr>
<tr>
<td>Goal vs. None</td>
<td>6%</td>
</tr>
<tr>
<td>Goal vs. State</td>
<td>-4%</td>
</tr>
<tr>
<td>Goal vs. State (low mass)</td>
<td>-1%</td>
</tr>
<tr>
<td><strong>Graze:</strong></td>
<td></td>
</tr>
<tr>
<td>State vs. None</td>
<td>1%</td>
</tr>
<tr>
<td>Goal vs. None</td>
<td>1%</td>
</tr>
<tr>
<td>Goal vs. State</td>
<td>0%</td>
</tr>
</tbody>
</table>
Typical Runs for Forage with Different Communication Types

No Communication  State Communication  Goal Communication
Typical Runs for Consume with Different Communication Types

No Communication  State Communication  Goal Communication
Implementation Also on Physical Robots: Forage Task
“Take Home” Message from Balch Communications Study

• Communication improves performance significantly in tasks with little environmental communication (i.e., with little communication “through the world”, or no stigmergy)

• Communication is not essential in tasks which include implicit communication (i.e., communication “through the world”, or stigmergy)

• More complex communication strategies offer little or no benefit over low-level communication
Remember!!

• Exam #1 next class (Thursday)