CPE 482 - Lecture 5
Multi-Robot Systems

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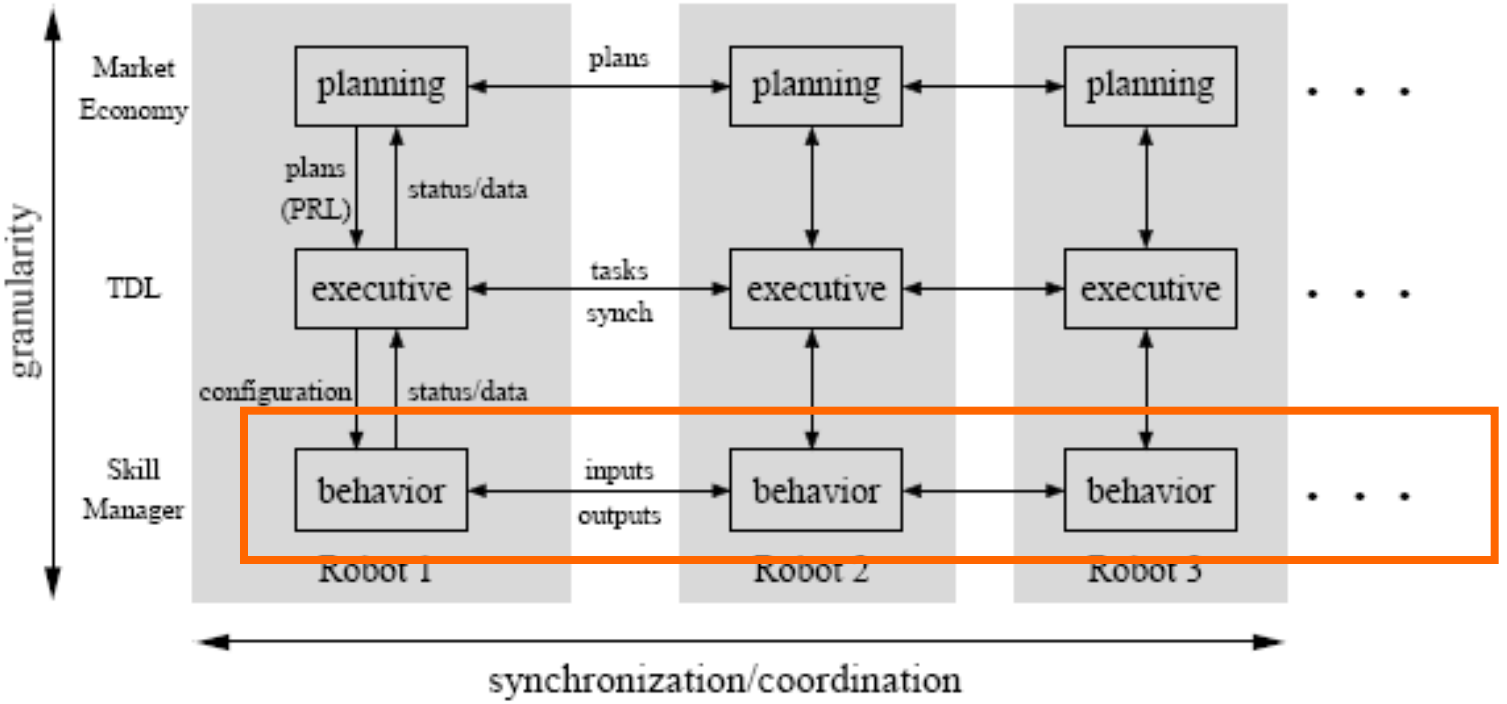
Term: Spring 2008

Figures courtesy of Siegwart & Nourbakhsh

Multi-Robot System Architectures

- Reid Simmon's Layered architecture



Robot Formations

1. Inspirations from Nature
2. Applications
3. Formation Types
4. Referencing
5. Example Approaches

Inspirations from Nature

- Geese Flocking
  - Why the V formation?
  - Used for energy efficiency
    - Reduced drag since middle geese benefit from vortex off wing tips.
    - Formation changes to let first and last geese rest
  - Used for tracking
    - Allows good way to monitor geese just ahead for following and collision avoidance.

Aerospaceweb.org

Inspirations from Nature

- Zebra Herding
  - Use stripes to confuse predators when herding
  - More sensors to detect predators when together
  - Form semi-circle when predator spotted
  - Move semi-circle formation as predator gets closer
  - Other formation to surround young foals
  - In fleeing situations, stallion stays back to defend herd
  - All formations utilize repulsion between animals for safety

http://www.bio.davidson.edu/people/vecase/Behavior/Spring2004/delk/delk.html

Robot Formations

1. Inspirations from Nature
2. Applications
3. Formation Types
4. Referencing
5. Example Approaches

(Potential) Applications

- Biological Sampling with AUVs
- Military Convoys
- Border security systems
- Search & Rescue
- Aerial Fire Fighting
- Farming
- …

Robot Formations

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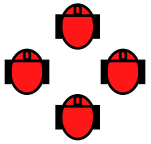
5. Example Approaches

Formation Types

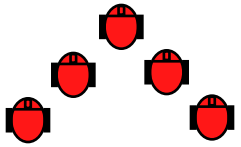
- Several common formations exist:
  - Line

  - Column

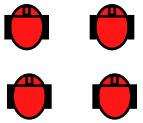
  - Diamond



Wedge or V



Square



Robot Formations

1. Inspirations from Nature
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5. Example Approaches

Referencing Systems

- Relative Positioning Systems
  1. Unit center referencing
  2. Leader referenced
  3. Neighbor referenced

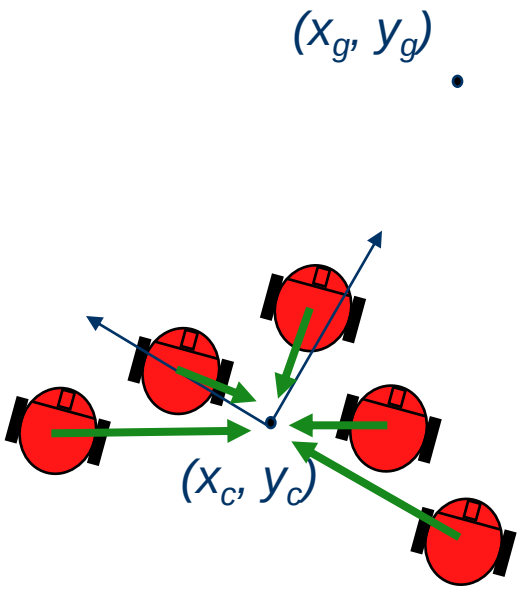
- Relative Trajectory Systems
  4. Predetermined formation trajectory

Referencing Systems

1. Unit center referencing
   - At each time step, determine center as average location for *i*..*n* robots

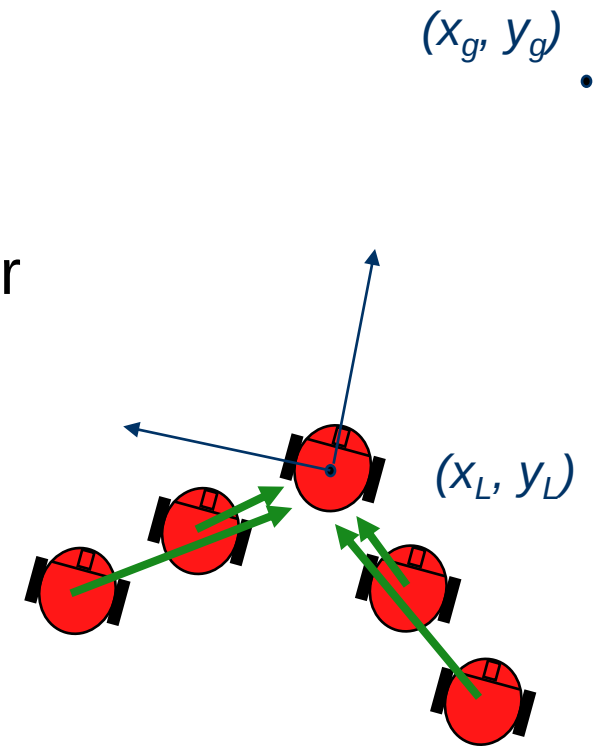
     $x_c = \frac{\Sigma x_i}{n}$ $\quad$ $y_c = \frac{\Sigma x_i}{n}$

   - Anchor coordinate frame to (x_c,y_c), but orient it towards goal (x_g,y_g)
   - Robots determine their position in formation relative to (x_c,y_c).
   - Control based on relative position



Referencing Systems

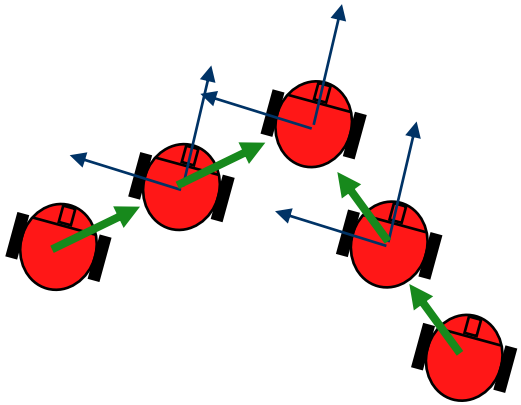
2. Leader referencing
   - A single robot is selected as the leader *L*.
   - All other robots determine their position in formation with respect to (x_L, y_L)
   - By controlling the leader, the whole group is controlled.



Referencing Systems

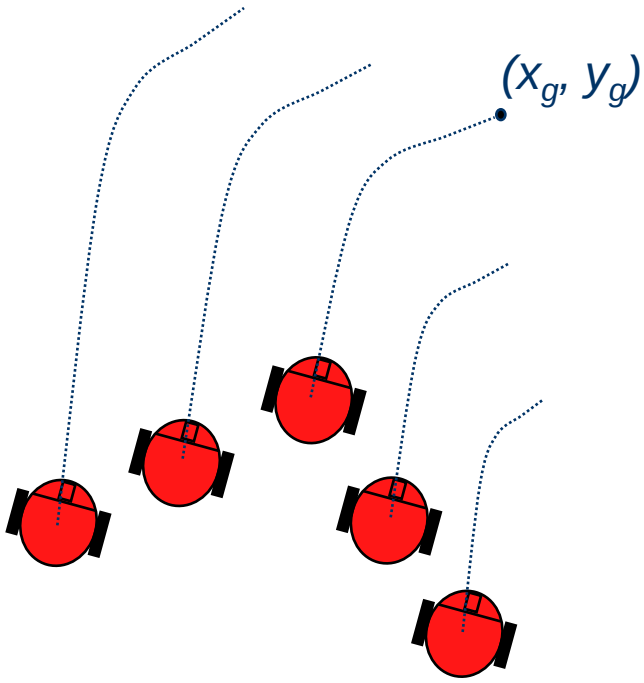
3. Neighbor referencing
   - Each robot determines their position in formation with respect to a neighbor
   - By controlling the leader, the whole group is controlled.

(x_g, y_g)



Referencing Systems

4. Predetermined Formation Trajectory referencing
   - First, Determine trajectory for leader robot *L*
   - Based on Leader referencing, determine trajectory for all other robots
   - Robots track individual trajectories
   - Leader robot could be fictitious



Robot Formations

1. Inspirations from Nature
2. Applications
3. Formation Types
4. Referencing
5. Example Approaches
    1. Behavior Based Formation Control
    2. Kinematics based control law
    3. Platooning

Behavior Based Formation Control

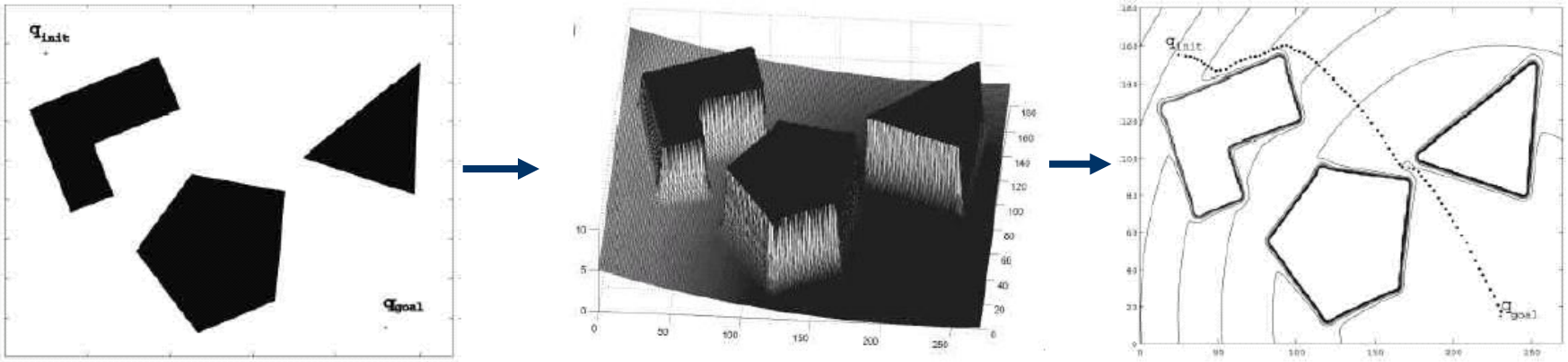
- Behavior Based Formation Control for Multi-Robot Teams: T. Balch and R. Archin (1999)
  - Main Steps to formation Keeping
  - Core Behaviors:
    - Artificial Potential Fields
    - Motor schemas
  - Coordinating Behaviors
  - Simulations & Experiments

Behavior Based Formation Control

- Main Steps
  - Formation Estimation
    - Several methods exist to determine relative positions of robots:
      - Direct sensing via vision, sonar,.. of other robot positions.
      - Communicating GPS type state estimates
    - Estimation delays cause errors.
  - Formation Control
    - Use Behaviors based on Motor Schemas to direct robots into formation positions.

Behavior Based Formation Control

- Artificial Potential Fields
  - Obstacles and other robots create repulsive forces
  - The goal creates an attractive force
  - Control robot to follow the vector representing the sum of all forces

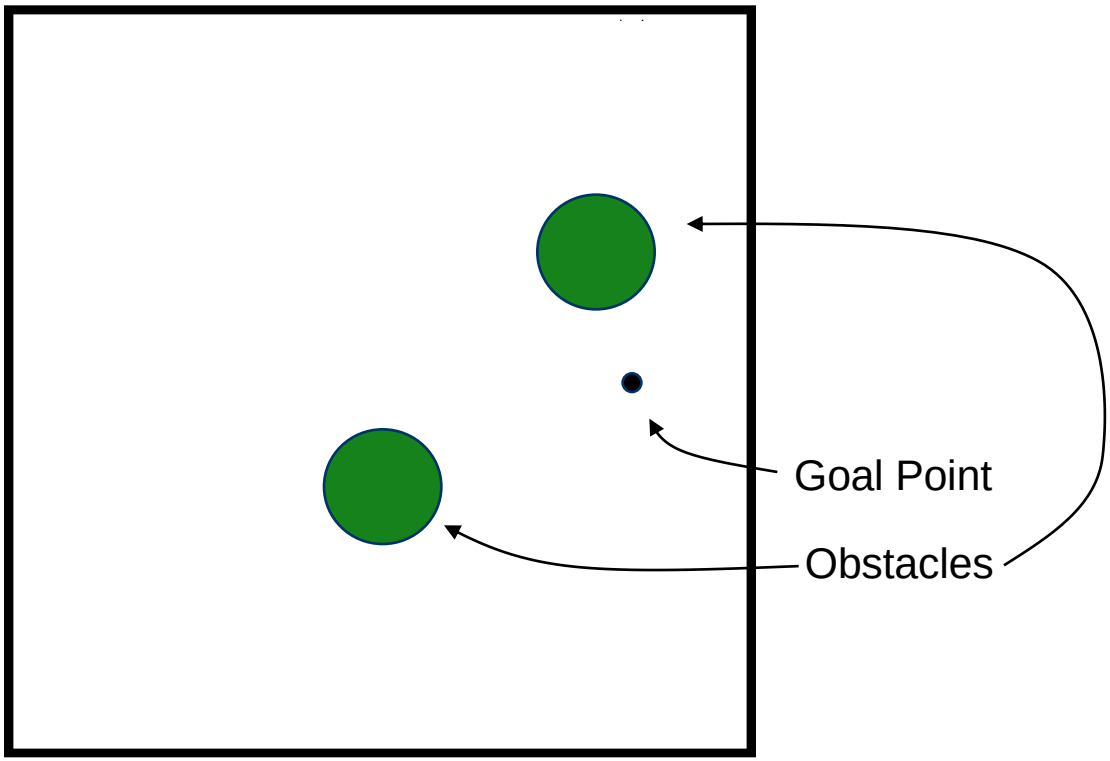


Behavior Based Formation Control

- Motor Schemas
  - Different Schemas each generate a vector defined by magnitude and direction.
  - These vectors are combined by weighted summation
  - The robot will try to follow the resulting vector.
  - Easy to implement
  - Fast

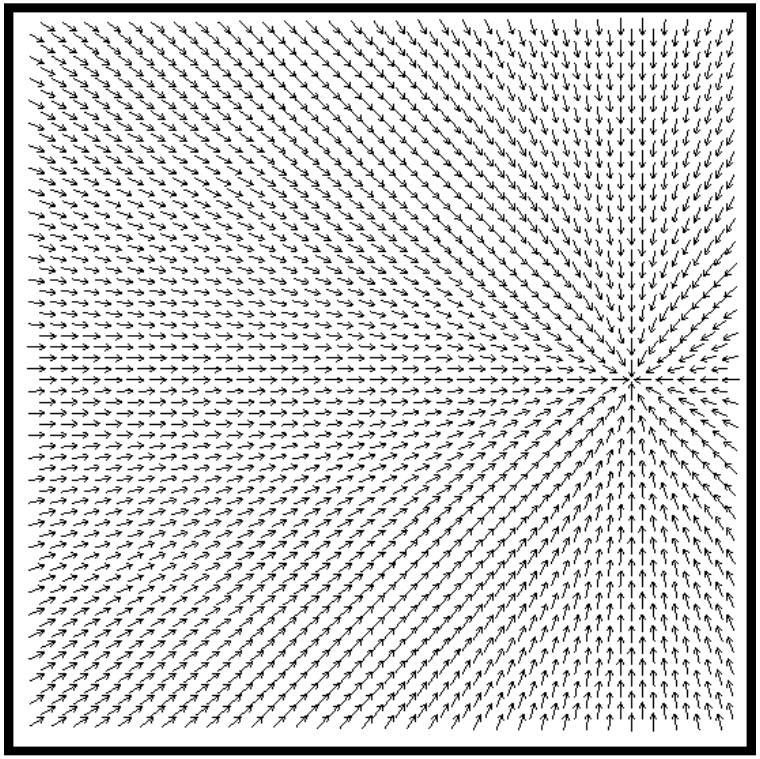
Behavior Based Formation Control

- Example WorkSpace



Behavior Based Formation Control

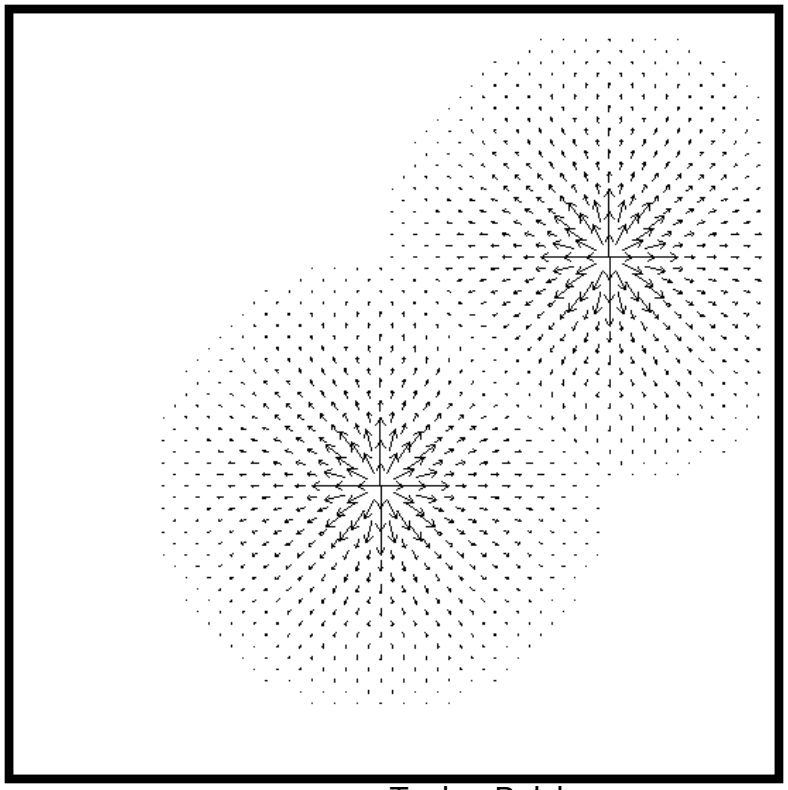
- Move to Goal Motor Schema



Tucker Balch

Motor Schemas: Avoid Obstacle

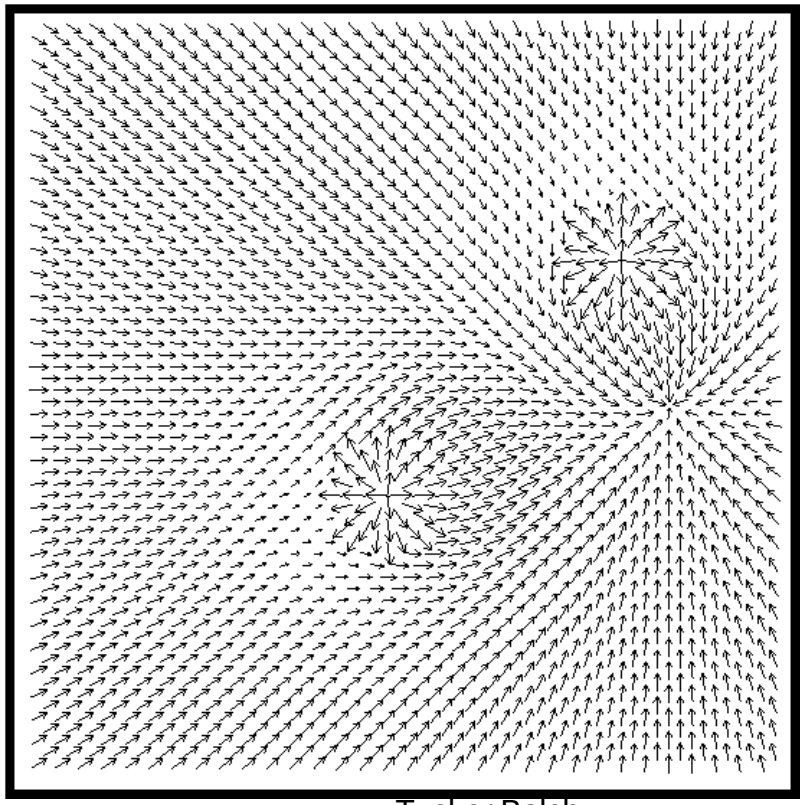
- Avoid Obstacle Motor Schema



Tucker Balch

Motor Schemas: Avoid Obstacle + Move to Goal

- Avoid Obstacle + Move to Goal Motor Schemas



Behavior Based Formation Control

- Formation Control Motor Schemas:
  - Move to goal
  - Avoid static obstacle
  - Avoid robot
  - Maintain formation
  - Noise to reduce chance of local min/max

Behavior Based Formation Control

- Formation Control Motor Schema Gains (Balch & Arkin 99):

Parameter	Value	Units
avoid-static-obstacle		
gain	1.5	
sphere of influence	50	meters
minimum range	5	meters
avoid-robot		
gain	2.0	
sphere of influence	20	meters
minimum range	5	meters
move-to-goal		
gain	0.8	
noise		
gain	0.1	
persistence	6	time steps
maintain-formation		
gain	1.0	
desired spacing	50	meters
controlled zone radius	25	meters
dead zone radius	0	meters

Behavior Based Formation Control

- Simulations & Experiments:
  - Balch & Archin compared the performance of leader centered vs. unit centered based on:
    - Path Length Ratio: average path length of robot divided by the straight line distance to goal.
    - Position Error: Average displacement from correct position.
    - Time out of formation: Average time robot was within 5m of formation position.

Balch & Archin, 1999

Behavior Based Formation Control

- Simulations & Experiments:
  - Leader Referencing on a 90 degree turn

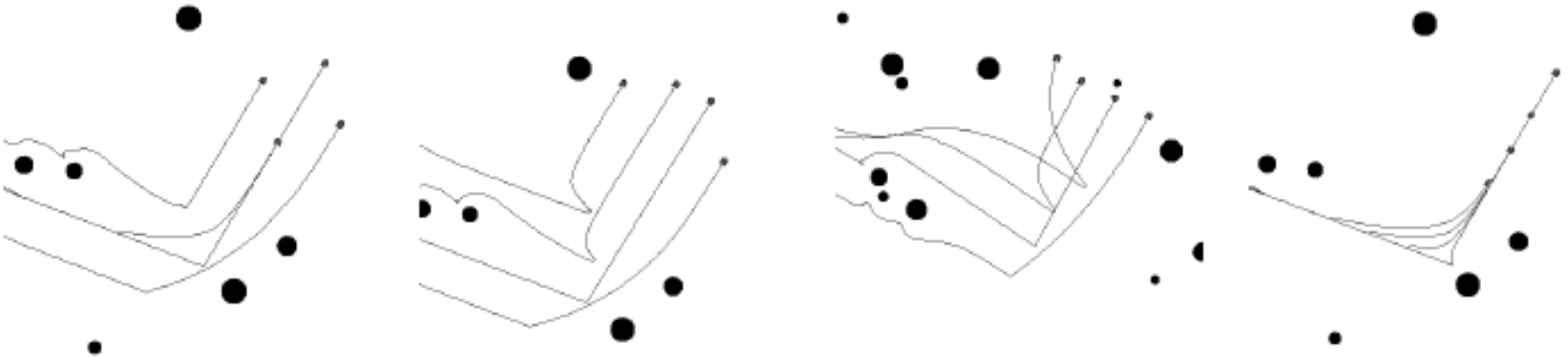


Fig. 6. Four robots in leader-referenced *diamond*, *wedge*, *line* and *column* formations.

Balch & Archin, 1999

Behavior Based Formation Control

- Simulations & Experiments:
  - Leader vs. Center Referencing on a 90 degree turn

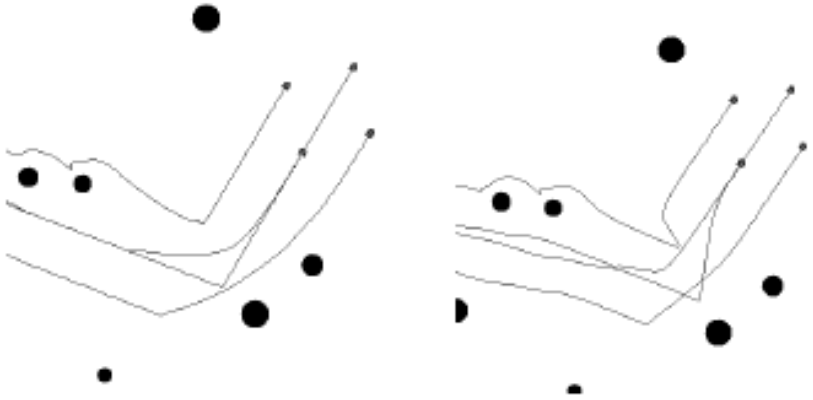


Fig. 7. Comparison of leader-referenced (left) and unit-center-referenced (right) *diamond* formations.

Balch & Archin, 1999

Behavior Based Formation Control

- Simulations & Experiments:
  - Balch & Archin compared the performance of leader centered vs. unit centered based on:
    - Path Length Ratio: average path length of robot divided by the straight line distance to goal.
    - Position Error: Average displacement from correct position.
    - Time out of formation: Average time robot was within 5m of formation position.

Behavior Based Formation Control

- Simulations & Experiments:
  - Comparing different referencing over different formations.

Formation Type	Path Ratio		Position Error		Time out of Formation	
	Unit	Leader	Unit	Leader	Unit	Leader
diamond	1.03 (0.08)	1.06 (0.08)	6.8 (0.2) m	11.4 (5.9) m	20.8 (0.3) %	21.6 (10.8) %
wedge	1.04 (0.09)	1.06 (0.09)	9.4 (4.5) m	9.1 (6.2) m	25.6 (6.0) %	17.3 (9.6) %
column	1.04 (0.06)	1.16 (0.02)	8.4 (5.6) m	21.1 (17.3) m	22.4 (8.1) %	32.4 (22.8) %
line	1.04 (0.10)	1.05 (0.06)	8.5 (5.5) m	8.2 (5.1) m	25.7 (7.4) %	18.9 (10.8) %

TABLE II

PERFORMANCE FOR A 90 DEGREE TURN FOR BOTH UNIT-CENTER AND LEADER-REFERENCED FORMATIONS, SMALLER NUMBERS ARE BETTER. THE STANDARD DEVIATION IS INDICATED WITHIN PARENTHESES.

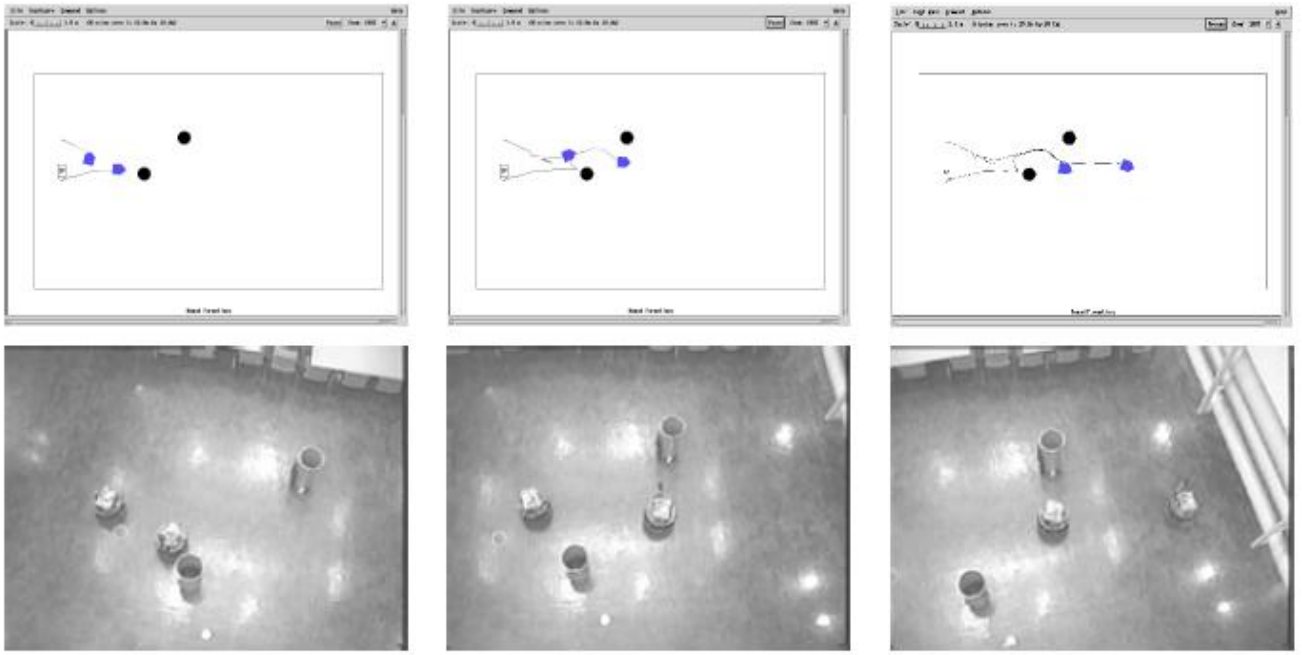
Balch & Archin, 1999

Behavior Based Formation Control

- Simulations & Experiments:
  - Summary of Turn results:
    - Unit center referencing better suited to Diamond and Column based on positioning error.
    - Leader referencing better suited to Line and Wedge based on time out of formation.

Behavior Based Formation Control

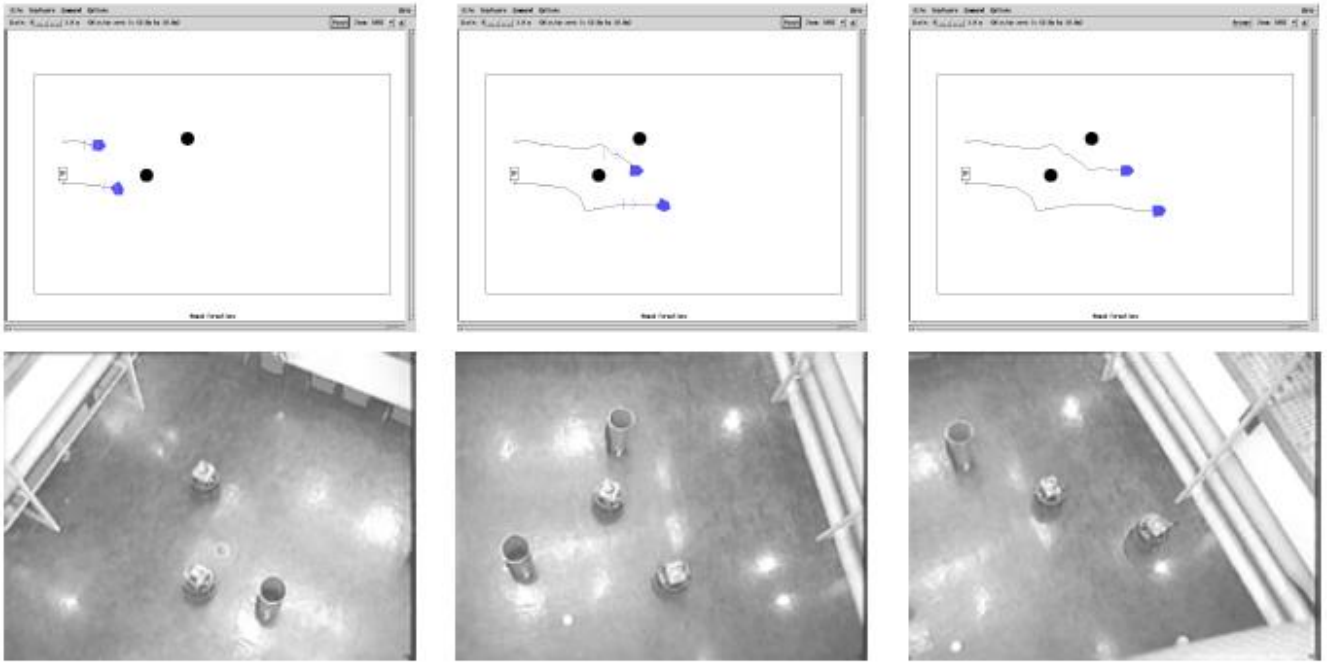
- Simulations & Experiments:
  - Obstacle Avoidance in Line Formation



Balch & Archin, 1999

Behavior Based Formation Control

- Simulations & Experiments:
  - Obstacle Avoidance in Wedge Formation



Balch & Archin, 1999

Behavior Based Formation Control

- Simulations & Experiments: UGVs