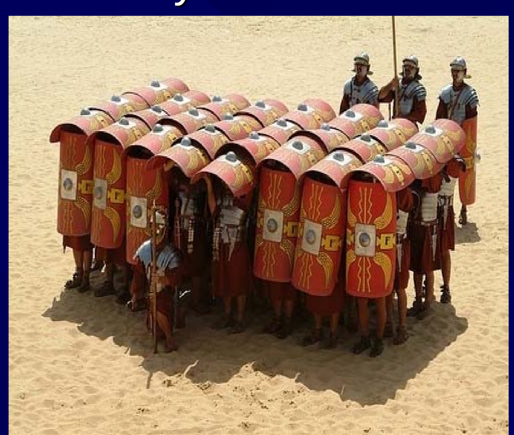
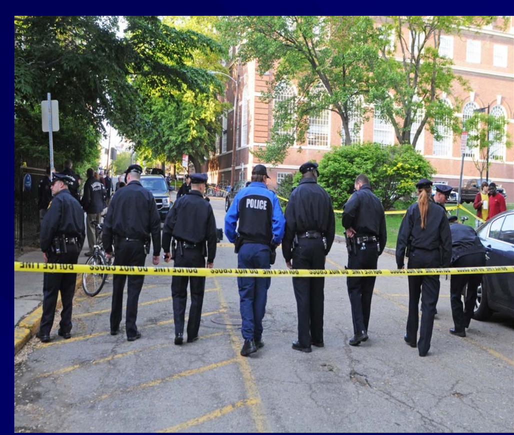
Distributed Formation Control of Heterogeneous Robots with Limited Information

Michael de Denus, John Anderson, and Jacky Baltes

Autonomous Agents Laboratory, Department of Computer Science
University of Manitoba
Winnipeg, Manitoba, Canada R3T2N2

Motivation

- Formations allow orderly movement of a group while positioning individuals in a useful manner
- Useful for defensive or offensive positioning, aerodynamic effects, natural division of individual sensory focus

- Heterogeneity is also advantageous – economics of dangerous domains, diversity of skills, parsimony. Perception, locomotion, knowledge may differ

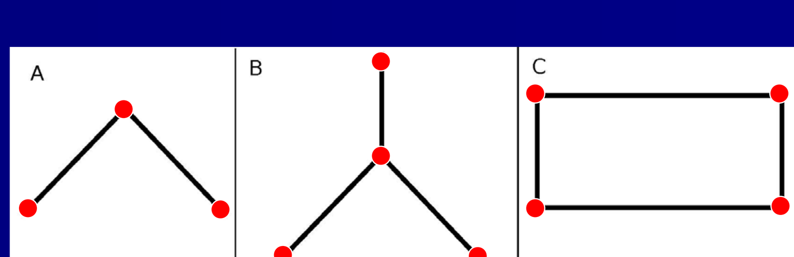
Limitations in Prior Work

- Much prior work in formation control, but lack of focus on heterogeneity – assumed similarity of moving abilities, sensing
- Also knowledge of others: team size, identity, common frame of reference [Leonard and Fiorelli]
- Many approaches are at least partly centralized (restricting some computation to a single robot [Hattenberger et al.], restricting roles - leader/follower/hierarchy [Kwan et al., Consolini], or a separate server for computation [Rampinelli et al.])
- Many approaches expect extensive communication across all robots (e.g. [Hadaegh et al.)
- Our approach is inspired by dangerous environments such as USAR:
  - Robots may be lost at any time, and new unknown robots may arrive – should require as little assumption of others as possible, and maximum decentralization
  - Robots do follow a target but have no predefined relationships; no single robot is essential
  - Communication is necessary only with immediate neighbours, unreliable over greater distances
  - One exception to shared knowledge: desired formation & its representation, external goal

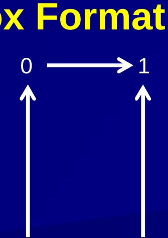
Formations

- Formations are built by referencing a neighbour [Balch & Arkin]: Each robot has **one** target it maintains position relative to (only restriction).
- Any formation consists of a collection of **segments**, each of which is a managed chain of robots
- Each segment has associated angle and distance at which robots should keep their targets – may be specified as functions (e.g. curves rather than lines)
- Each segment has a desired relative length in the overall formation, expressed as a proportion of **B**, base length in the formation
- Start and end of any segment are **entry points**, and robots at those positions (entry point robots) handle joining and merging operations, and estimating segment length. Entry point robots may belong to >1 segment (neighbour set – leading/trailing by direction of target)

= Entry point



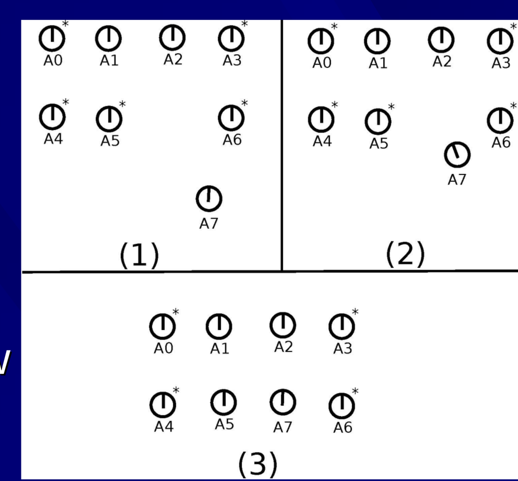
Box Formation



Segment ID	Leading Neighbour Set	Trailing Neighbour Set	Relative Length	Distance Function	Angle Function
0	1	0	1	d=1	a=0
1	0	2	2	d=1	$a=\frac{\pi}{2}$
2	3	2	1	d=1	a=0
3	1	3	2	d=1	$a=\frac{\pi}{2}$

Joining a Formation

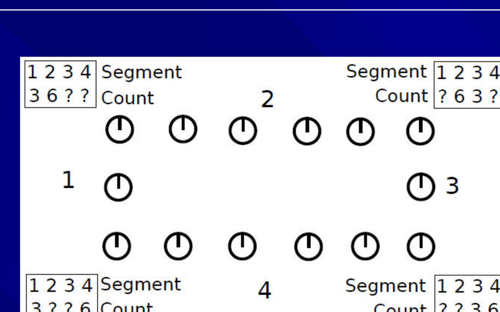
- An agent attempts to join a formation when it encounters another agent. If neither is in a formation, they form the entry points for the longest segment; encountering a non-entry point agent results in a denial response with the ID of an entry point or a target robot that can be queried
- Eventually an entry point is reached (marked *); estimates exist of size of neighbouring segments, and agent (A7) is directed to least-satisfied segment. A5 recognizes it has a new target and drops entry point status



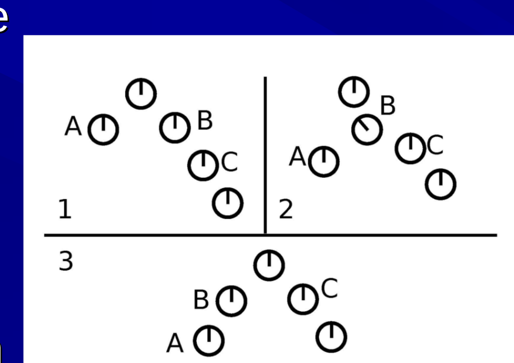
- Established formations can merge when entry point agent encounters another formation, requests a join; each encountering agent estimates whole formation size, smaller transitions to line (message up the chain) and each joins larger formation in turn
- Heuristic and decentralized – if communication is lost partway, partial formation join, but the rest is close and likely to be picked up soon
- Must also be able to note lost agents (failure, unsuccessful obstacle navigation)

Balancing Formations

- Entry point robots maintains heuristic estimates of their segment sizes. Sends out counting message to neighbours, which is passed and incremented Becomes stale on communication loss. Avoids non-immediate neighbor communication

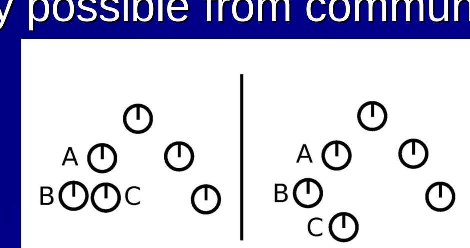


- Uses known segments and formation description to estimate size of unknown segments, assuming whole formation is in proportion to known parts
- Balancing is done by entry point robots shuffling others between segments: neighbor in most overpopulated segment is told to move to most underpopulated neighbour, who gets pushed down that segment: distributed processing shuffles across multiple segments over time
- e.g., B moved from R to L by telling A to adjust target and having B tell C – may break if comm. lapses, but will immediately encounter same entry point and rejoin



- Inconsistency possible from communication loss:

B and C try to occupy same position (target A)



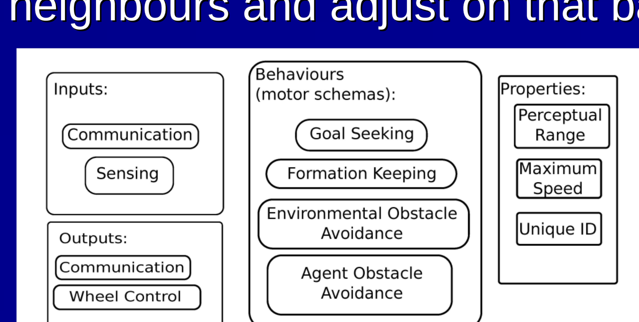
Agent C joined wrong Segment

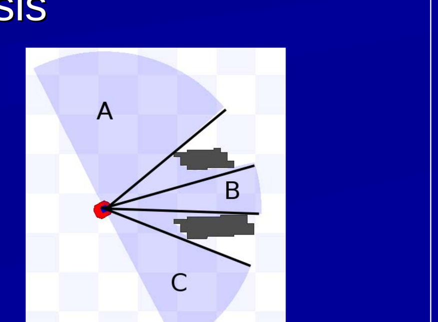
Solution: heartbeat message will eventually uncover extra robot(s), random selection told to drop and rejoin @ entry point

Solution: Entry point robot checks self and target's segment membership for consistency at intervals; mismatch leads self or neighbours to drop/rejoin

Implementation

- Pioneer II in Player/Stage with laser & fiducial scanner, using 4 behaviours: target following, goal seeking, static and robot obstacle avoidance
- Heterogeneity: 3 different sensor ranges, 3 speeds
- Sensor loss must be handled by querying immediate neighbours for relative position of unseen target
- Speed differences: query speed of current neighbours and adjust on that basis



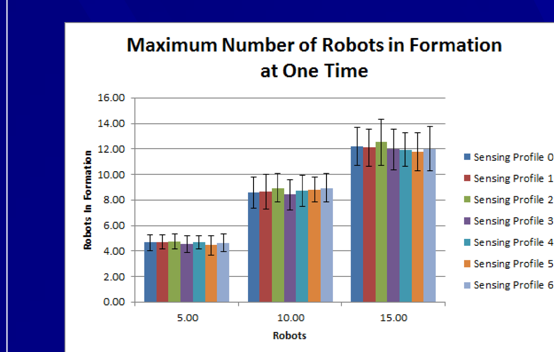


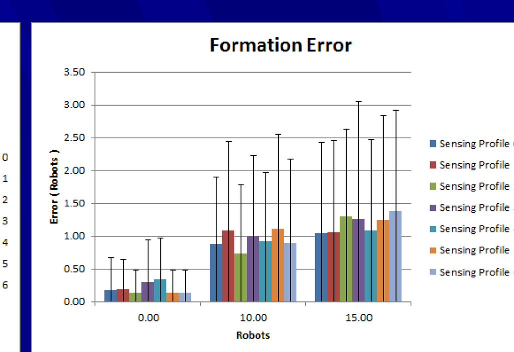
Evaluation

- Ran a series of trials in environments (40m x 1000m) with and a V formation (45 angle, 2m separation. Distributed robots randomly in a 6m x 6m area, with goal at opposite length of field (experiments not in this paper added obstacles)
- ***Formation Error:*** total # agents in formation determines optimal lengths of each segment; segment error is sum of absolute value of difference between optimal and observed in each segment; formation error is sum of all segments
- ***Sensory Abilities:*** *Good*: 10m sensing range; *Moderate:* 8m, *Poor:* 6m
- Defined profiles for population breakdowns with given ability (rounding filled with moderate robots)

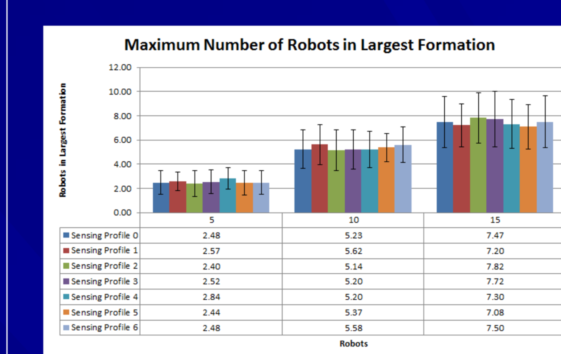
Profile Number	Poor	Moderate	Good
0	0%	100%	0%
1	25%	75%	0%
2	50%	50%	0%
3	0%	75%	25%
4	0%	50%	50%
5	25%	50%	25%
6	50%	0%	50%

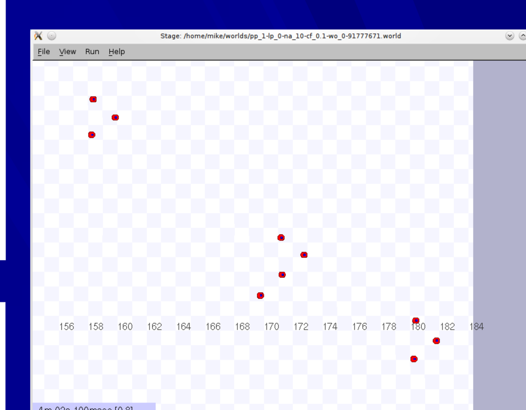
- Experimented with 5, 10, 15 robot teams
- 50 trials in each category. Trials complete after 5 minutes or no segment changes after 10 seconds
- ***Scaling with Sensory Heterogeneity:***

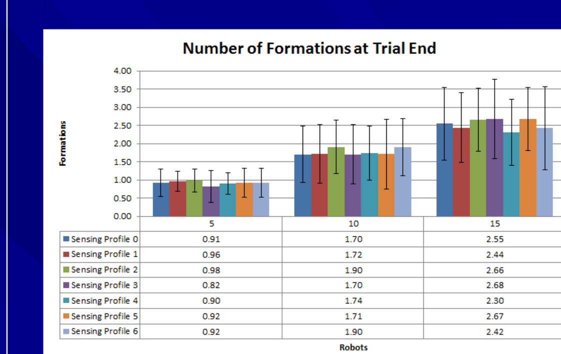




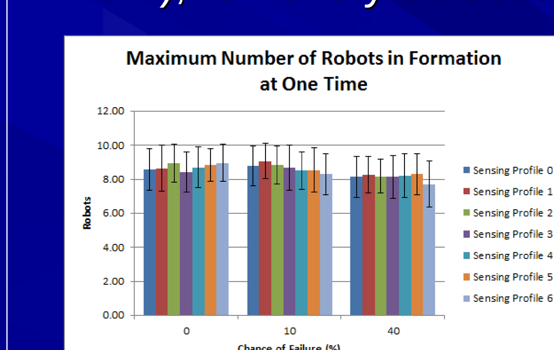
- High standard deviation in formation error because trial end can interrupt a merge/balance

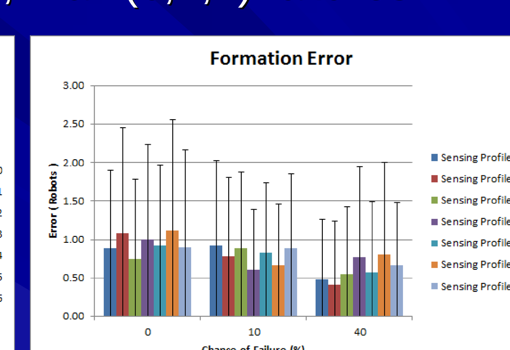






- Approach adapts to heterogeneous sensing
- Difficult for last few formations to merge: no specific behaviour to promote encounters
- Similar results from heterogeneous locomotion (good, moderate, poor: 3, 2, 1 m/s in profiles)
- ***Robustness (Coping with Failure):***
- 10 robot team, Robot failures at 3 rates (0, 0.1, 0.4), run every 30 secs, max (0,1,2) failures





- Similar results to no failures

Discussion

- Robust ,scalable, decentralized, under challenging conditions : no foreknowledge of others on a heterogeneous team or team size
- Still issues with forming one single formation - experiment with non goal-directed motion
- Currently working with larger teams, dealing with size heterogeneity, varying terrain, obstacles
- Currently moving to Citizen Eco-Be (V2) Robots in mixed reality to experiment with obstacles that can disable physical robots without damage