Scalable Approaches to Deploying Swarms of Vehicles and Sensors

Vijay Kumar

GRASP Laboratory
University of Pennsylvania

www.swarms.org

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Scalable sWarms of Autonomous Robots and Mobile Sensors

An ARO MURI Project

www.swarms.org

Outline

- Why swarms?
  - Overview of approaches
- Field Experiments
  - Heterogeneous network of robots (UGVs, UAVs)
- Abstractions for control of large teams
  - Decentralized control with local information
  - Design of simple behaviors
  - Design of simple estimators

1. Motivation

Why Swarms?

- Robot networks - applications with large numbers of networked robots, embedded computers, high data rate sensors (cameras)
  - ¥20 Trillion industry* by 2013, Network robot forum
- n ↑ (1-10 to 10's to 100's)?

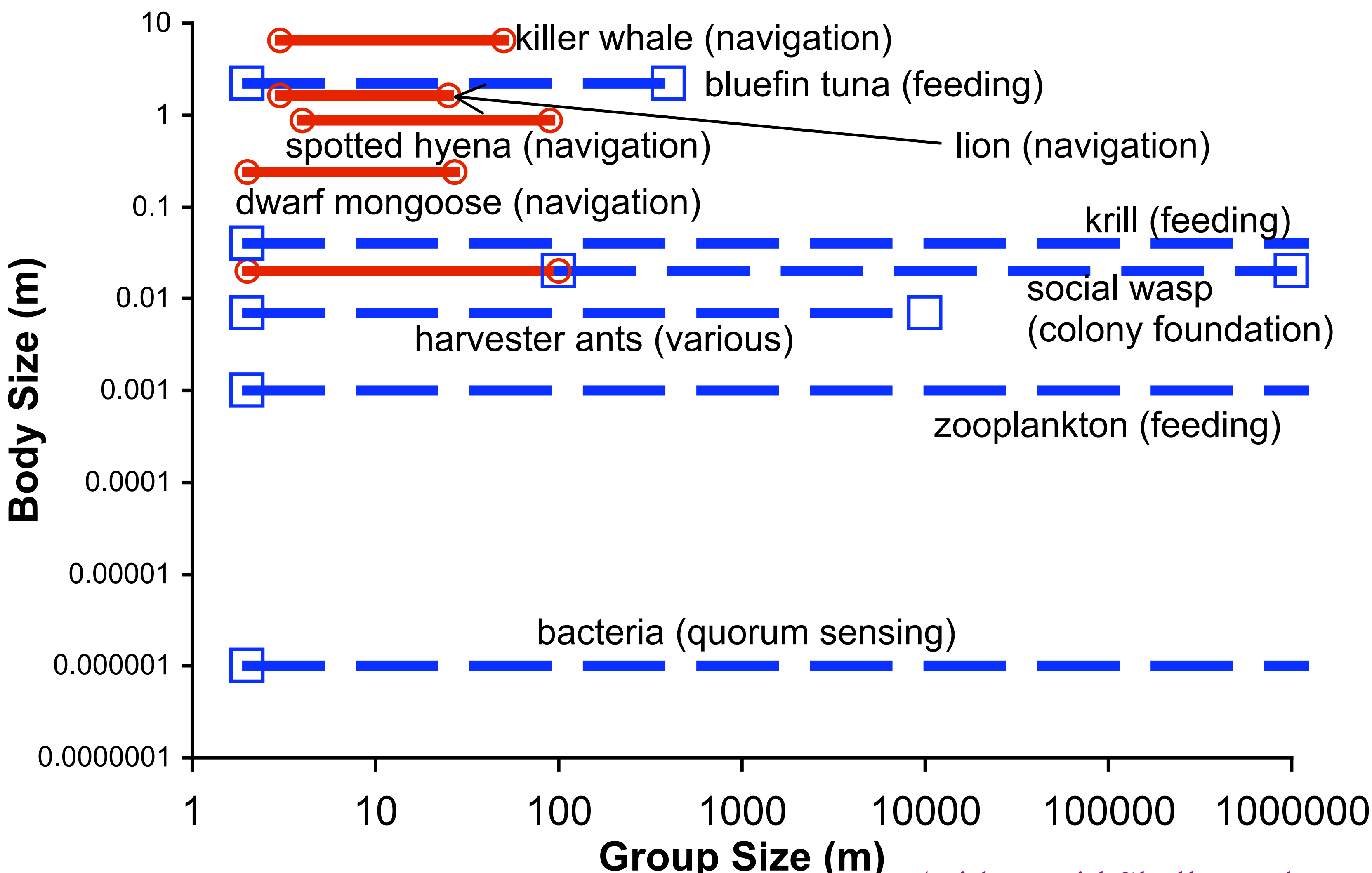
Research problems: Communication, control and perception

- Self aware, localize, organize
- Navigation/mobility with local sensing/communication
- Integrate information

*Japanese Ministry of Internal Affairs and Communications, "Toward the Realization of Network Robots", 2003.

Swarming in Nature

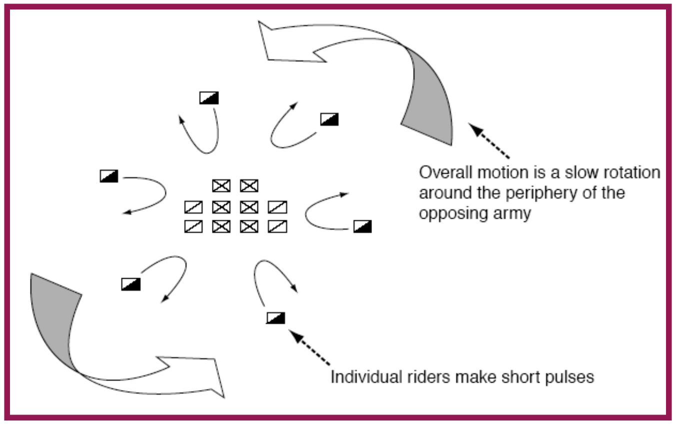
http://www.swarms.org/



(with David Skelly, Yale Univ.)

Swarming in the Military

Scythians vs. Macedonians, Central Asian Campaign, 329-327 B.C.

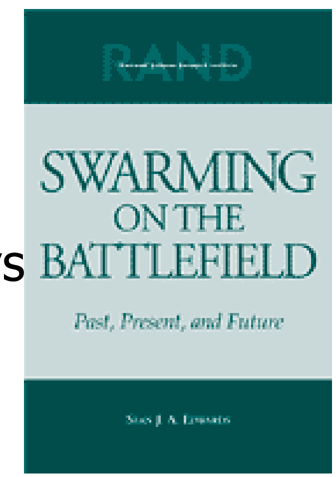


Mongols, “the ultimate swarmers” vs. Eastern Europeans, Battle of Liegnitz, 1241

- Decentralizated command and control
- Communication for situational awareness
- Emphasis on mobility

German U-boats use “wolfpack tactics” versus British convoys of the Atlantic, 1939-1945

- Use of “radio tactics” for “self-organization”



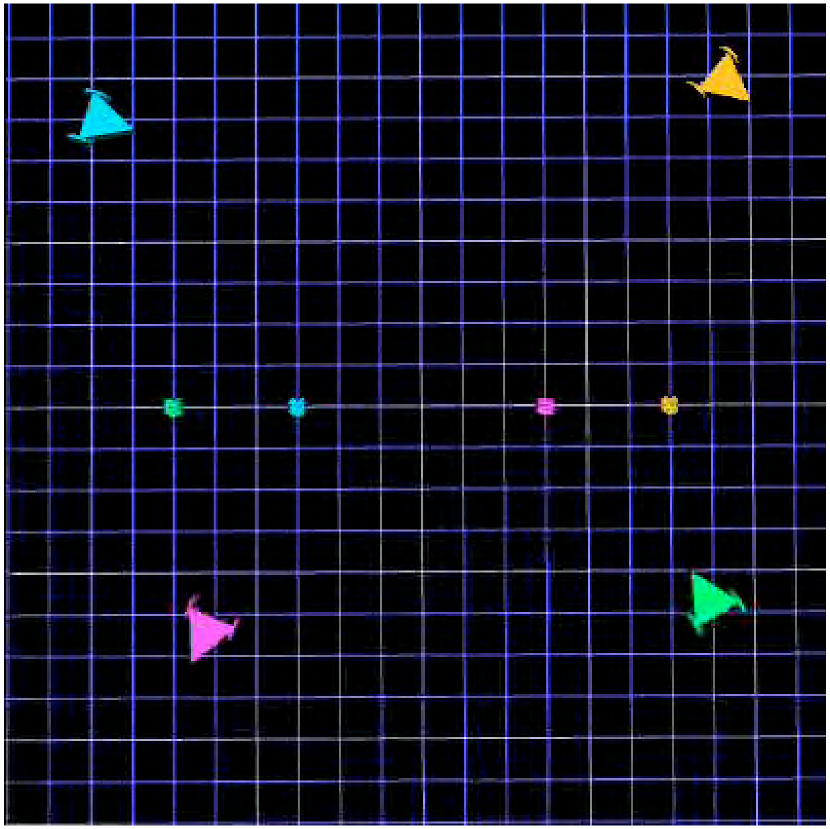
Approaches to Control/Planning: Taxonomy

	Centralized	Decentralized
Vehicles identified		
Identical vehicles (anonymous)		

Approach 1

Centralized planning

	Centralized	Decentralized
Vehicles identified		
Identical vehicles		

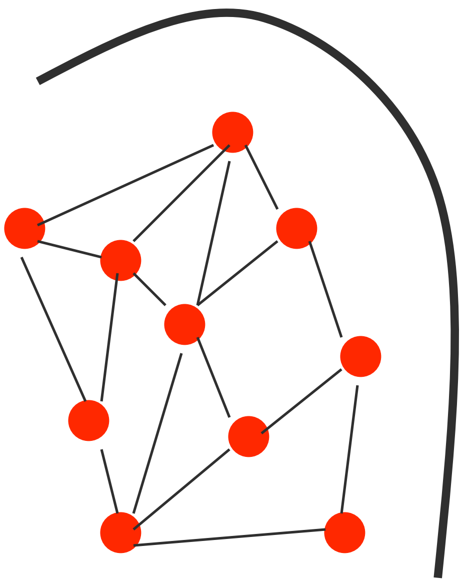


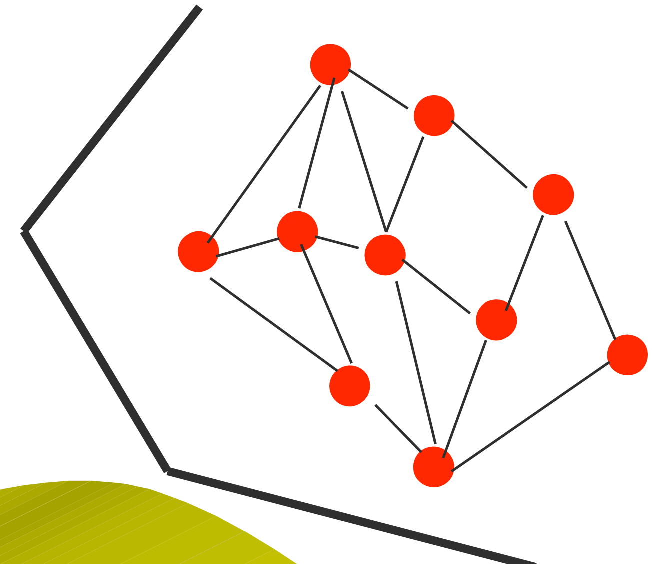
Exponential growth in complexity!

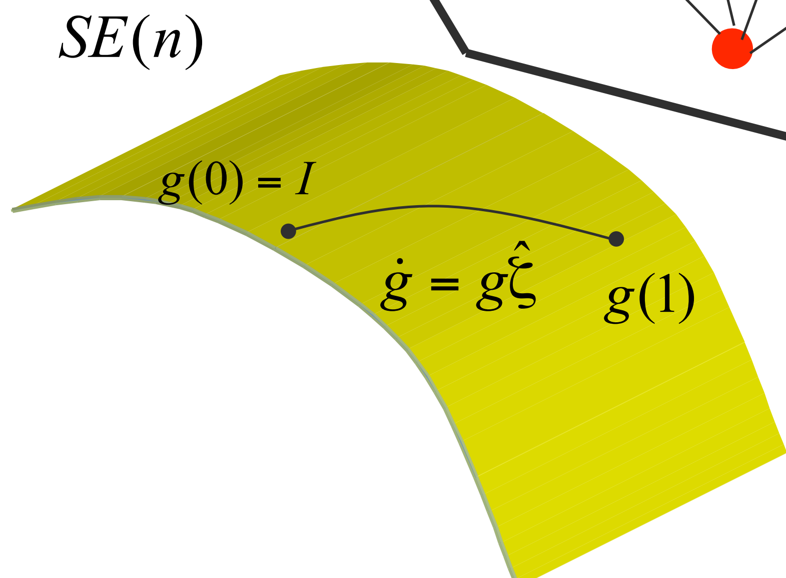
Zhang, H., Kumar, V., and Ostrowski, J., "Motion Planning under Uncertainty," IEEE International Conference on Robotics and Automation, Leuven, Belgium, May 16-21, 1998

Approach 2

- Centralized planning in "smaller" space
- Decentralized control

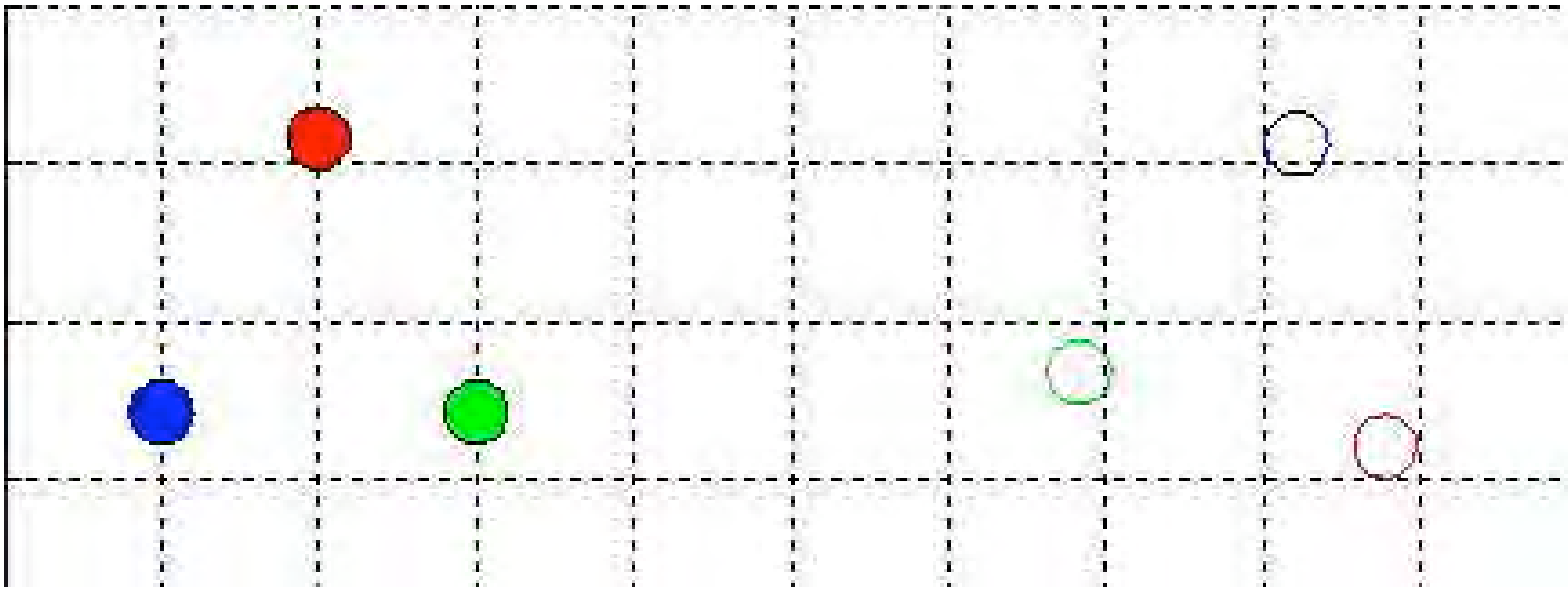






Zefran, Kumar and Croke, ITRA, 1996

Approach 2



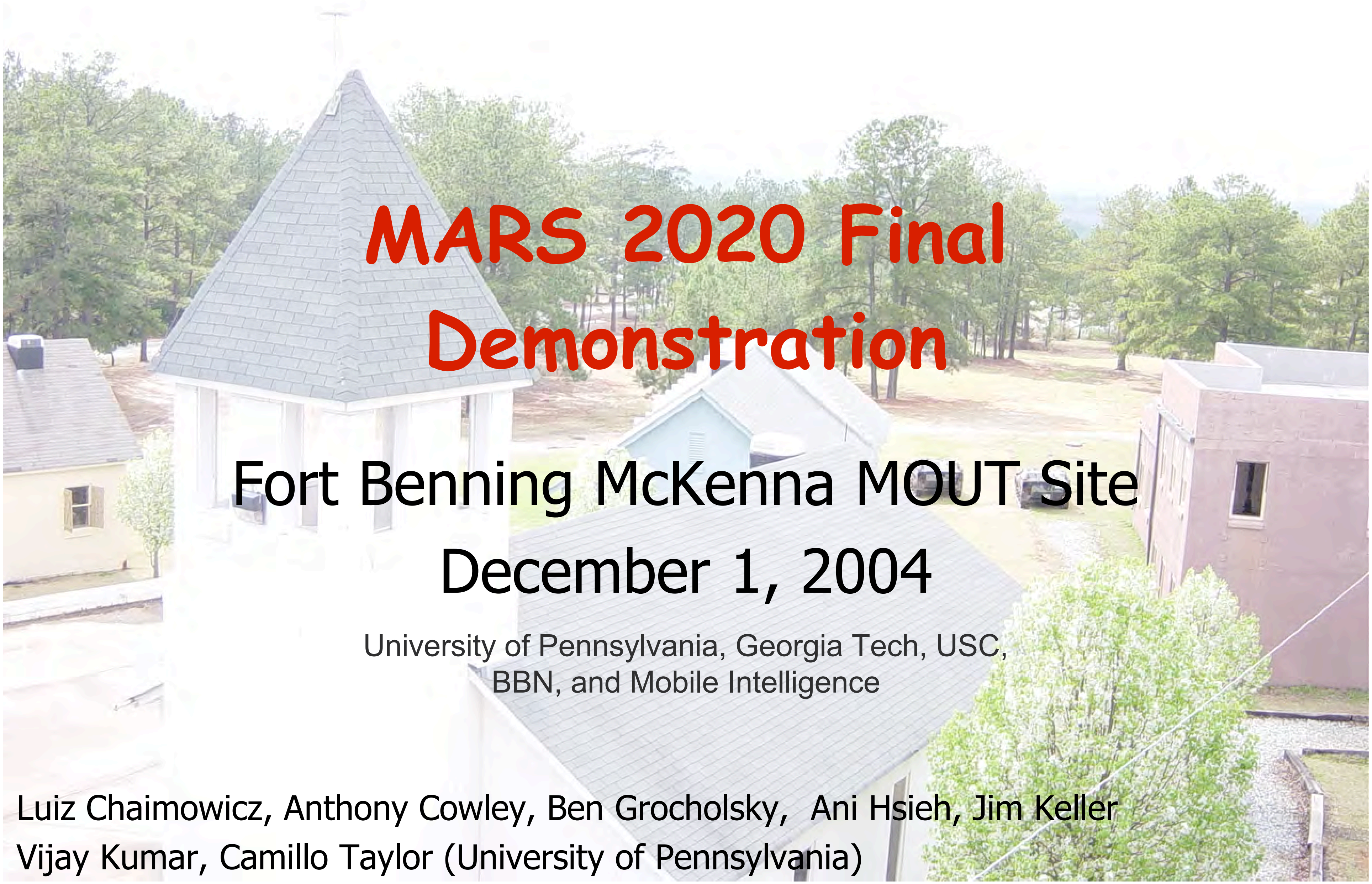
	Centralized	Decentralized
Vehicles identified	PLANNING	CONTROL
Identical vehicles		

Belta and Kumar, ASME, 2001

- Each robot has a single sensor (omnicam)
- Task imposes constraints on relative positions (and orientations)
- Formation to maintain constraints

	Centralized	Decentralized
Vehicles identified		
Identical vehicles		

[Pereira, Kumar and Campos, IJRR 2004]



MARS 2020 Final Demonstration

Fort Benning McKenna MOUT Site
December 1, 2004

University of Pennsylvania, Georgia Tech, USC,
BBN, and Mobile Intelligence

Luiz Chaimowicz, Anthony Cowley, Ben Grocholsky, Ani Hsieh, Jim Keller
Vijay Kumar, Camillo Taylor (University of Pennsylvania)

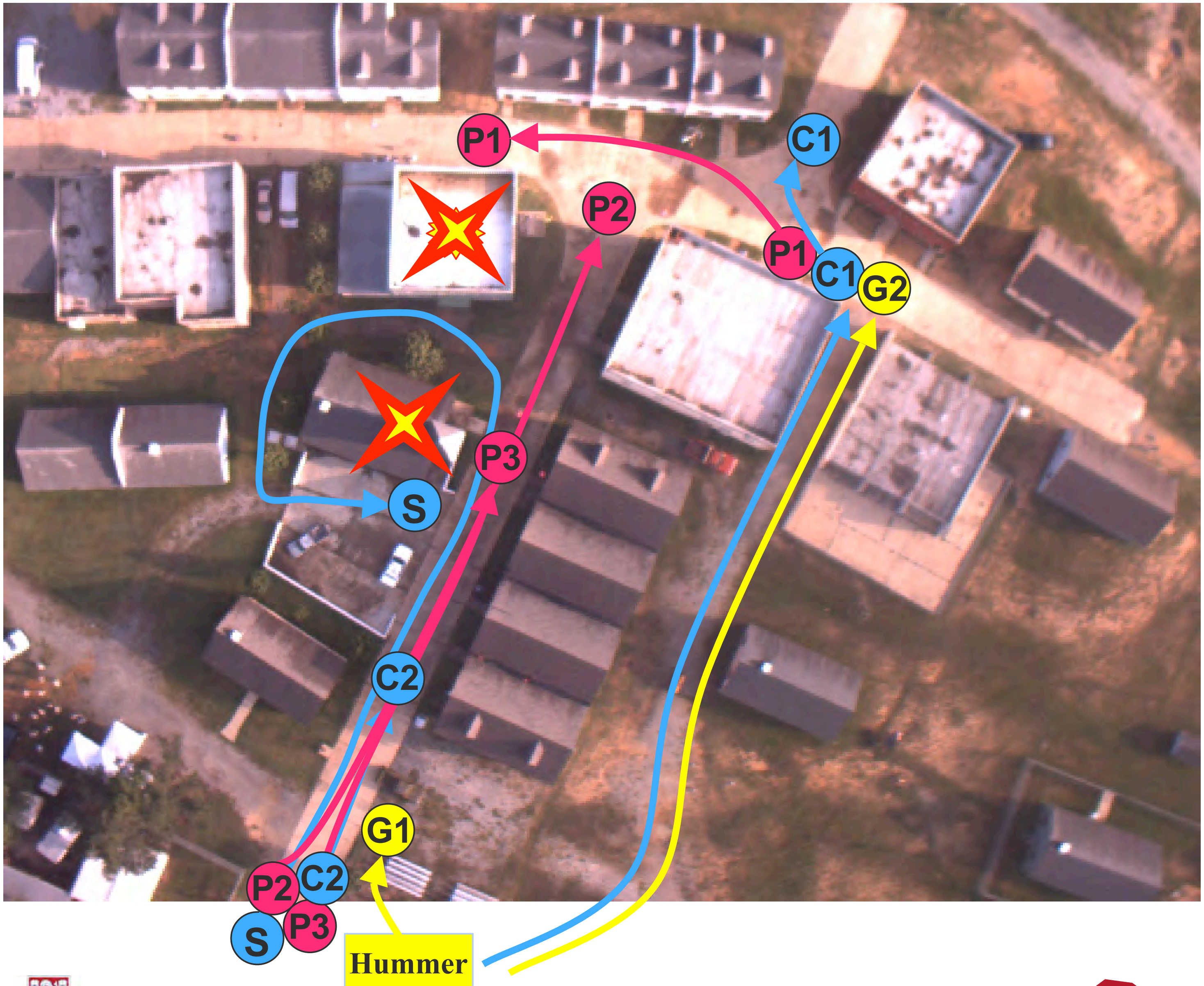
MARS 2020

Network-centric team of heterogeneous platforms

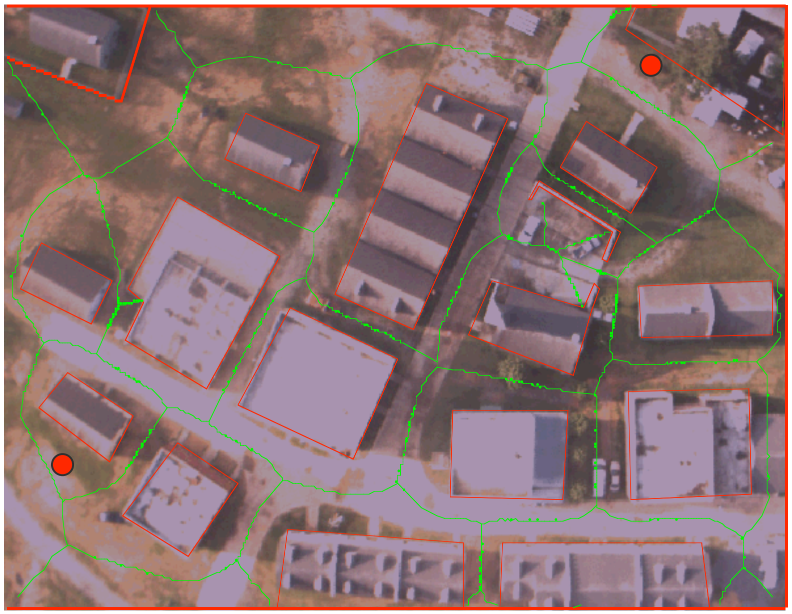
- Adapt to variations in communication performance and strive to maximize suitably defined network-centric measures for perception, control and communication
- Provide situational awareness for remotely-located humans in a wide range of conditions
- Integrate heterogeneous air-ground assets in support of continuous operations in urban environments

Network of UAVs and UGVs

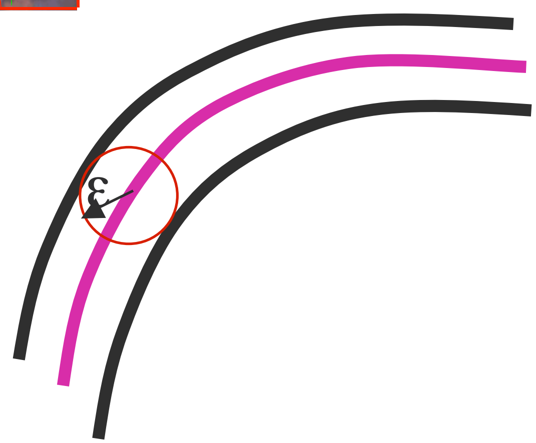
"Google" for Robot Networks



UGV Navigation with Uncertainty



1. Bearing control
   - Control θ
2. Velocity control
   - Control (v, ω)
3. Position control
   - Go to (x, y)
4. Path control
   - Stay within ε of path



Field Experiments

ICRA 2004, 2005, 2006

Scaling up

Single operator tasking a heterogeneous team of robots for persistent surveillance

Network-centric approach to situational awareness

- Independent of who is where, and who sees what
- Fault tolerant

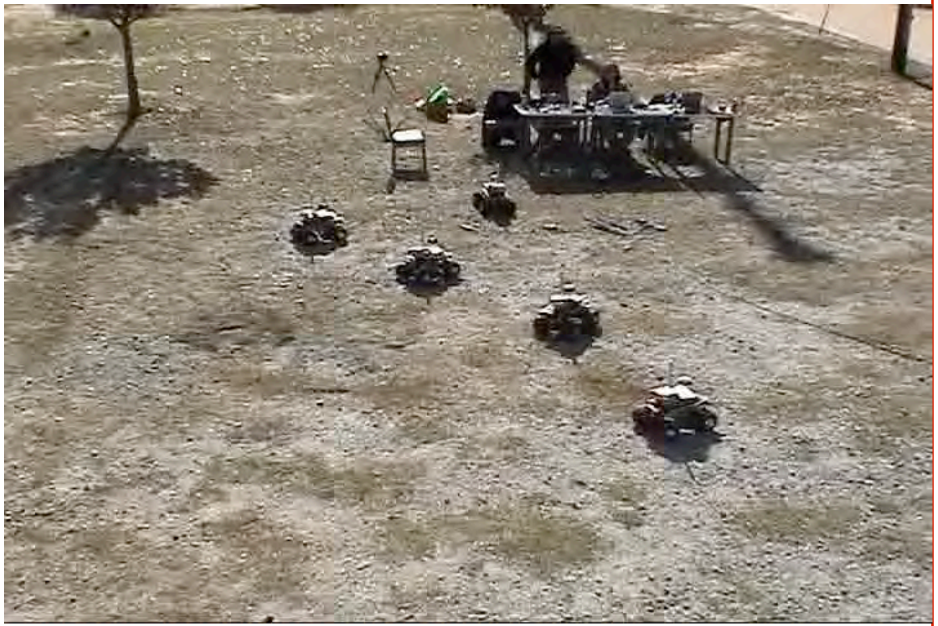
Decentralized control

But…

Robots are identified

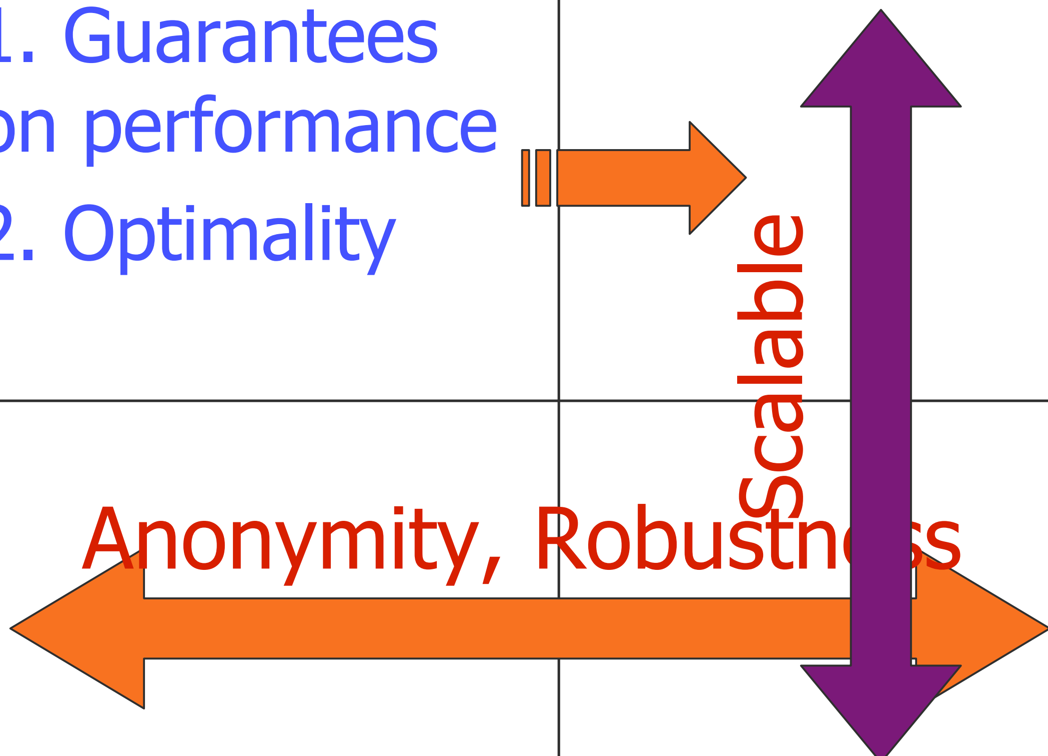
- Control involves maintaining "proximity graph"

Robots are connected through a communication network

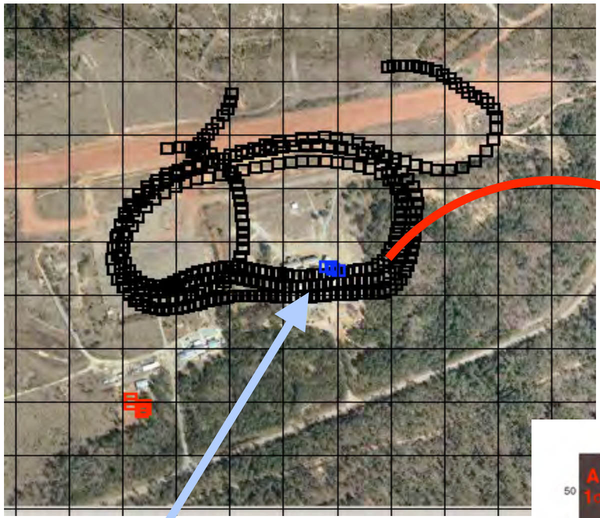


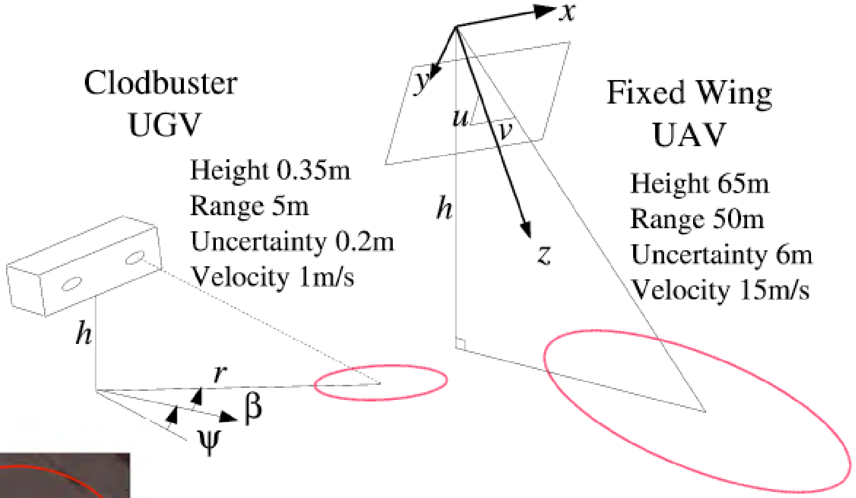
Taxonomy of Approaches

	Centralized	Decentralized
Vehicles identified	1. Guarantees on performance 2. Optimality	
Identical vehicles		



Cooperative search, identification, and localization





With anonymous robots

Information Model: Shared

$$\begin{bmatrix} x^R_{k+1} \\ x^T_{k+1} \end{bmatrix} = \begin{bmatrix} x^R_k \\ x^T_k \end{bmatrix} + \begin{bmatrix} u_{k+1} \\ 0 \end{bmatrix}$$

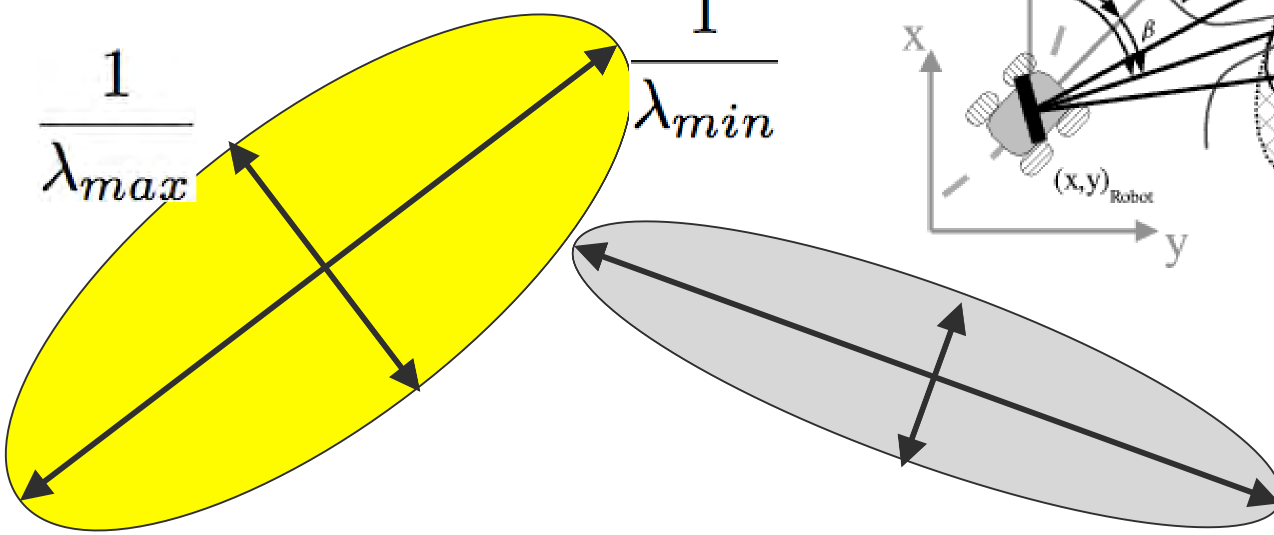
$$\begin{bmatrix} z^R_k \\ z^T_k \end{bmatrix} = \begin{bmatrix} x^R_k \\ h(x^T_k) \end{bmatrix} + \begin{bmatrix} 0 \\ v_k \end{bmatrix}$$

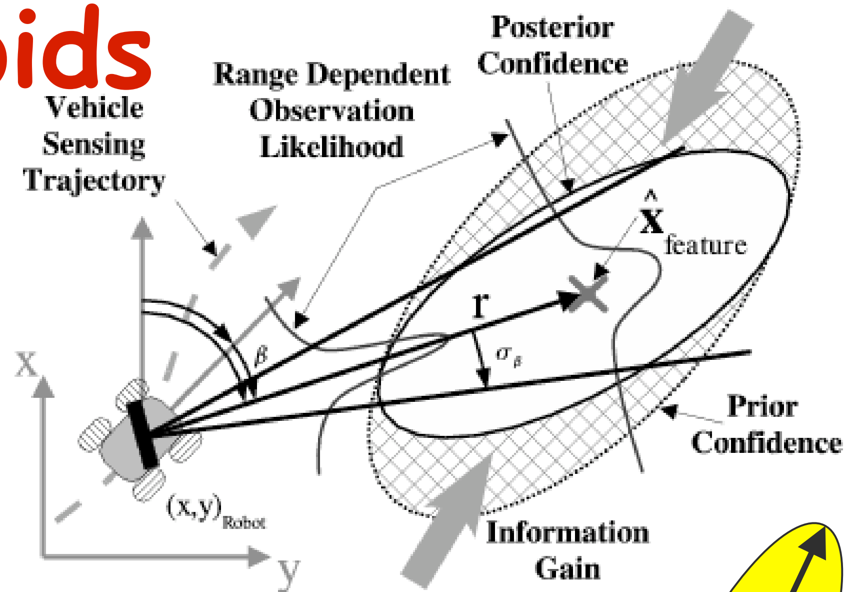
$$v_k \sim N(0, R_k)$$

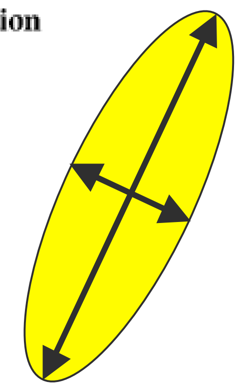
$$P_k = E(x_k x'_k) \qquad Y_k = P_k^{-1}$$

$$Y_{k+1} = Y_k + I_k \qquad I_k = H_k^T R_k^{-1} H_k$$

Confidence Ellipsoids



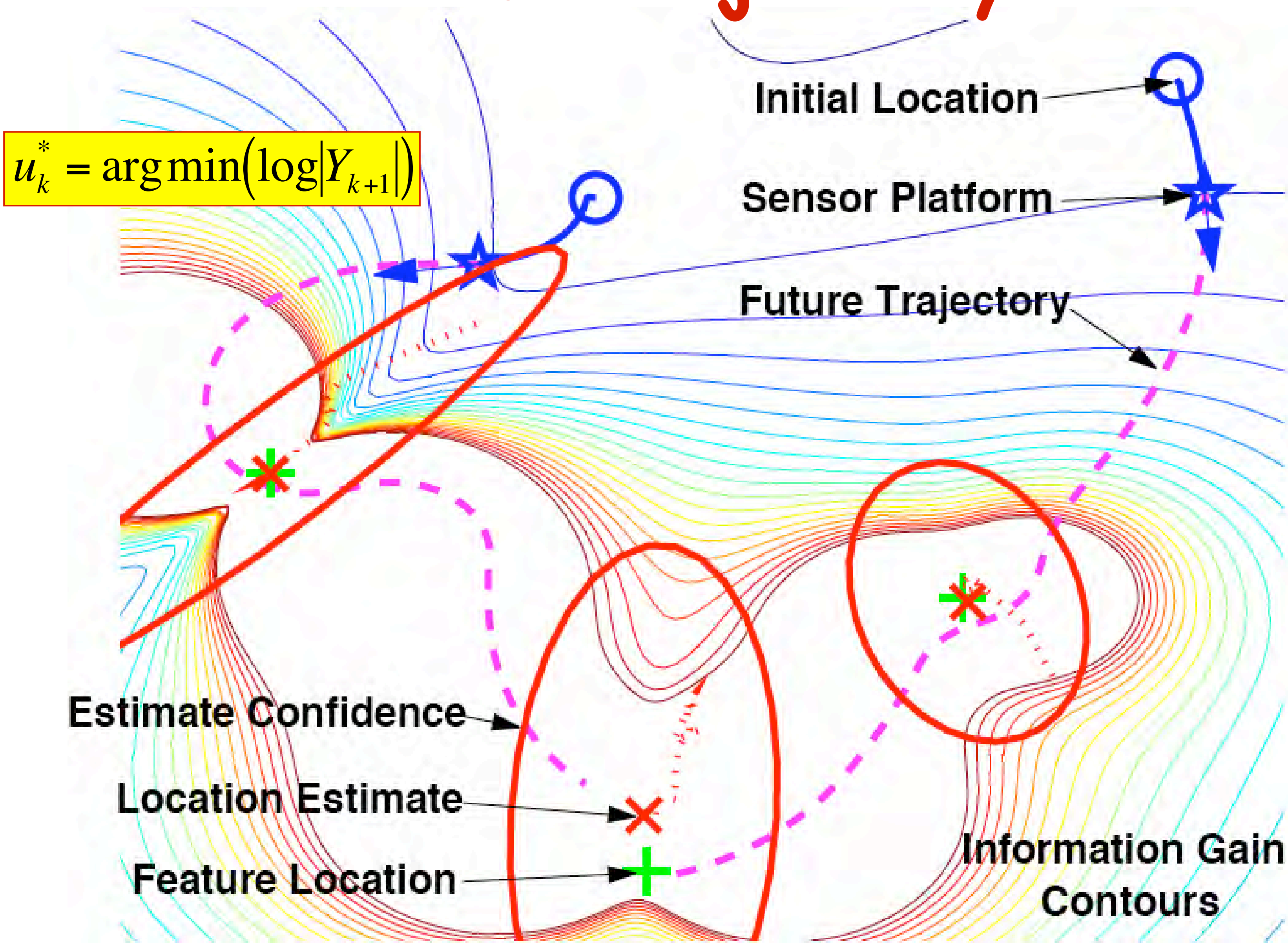




$$Y_k \quad + \quad I_{k+1} \quad = \quad Y_{k+1}$$

$$\lambda_{min}(Y_k) + \lambda_{min}(I_k + 1) \leq \lambda(Y_{k+1}) \leq \lambda_{max}(Y_k) + \lambda_{max}(I_{k+1})$$

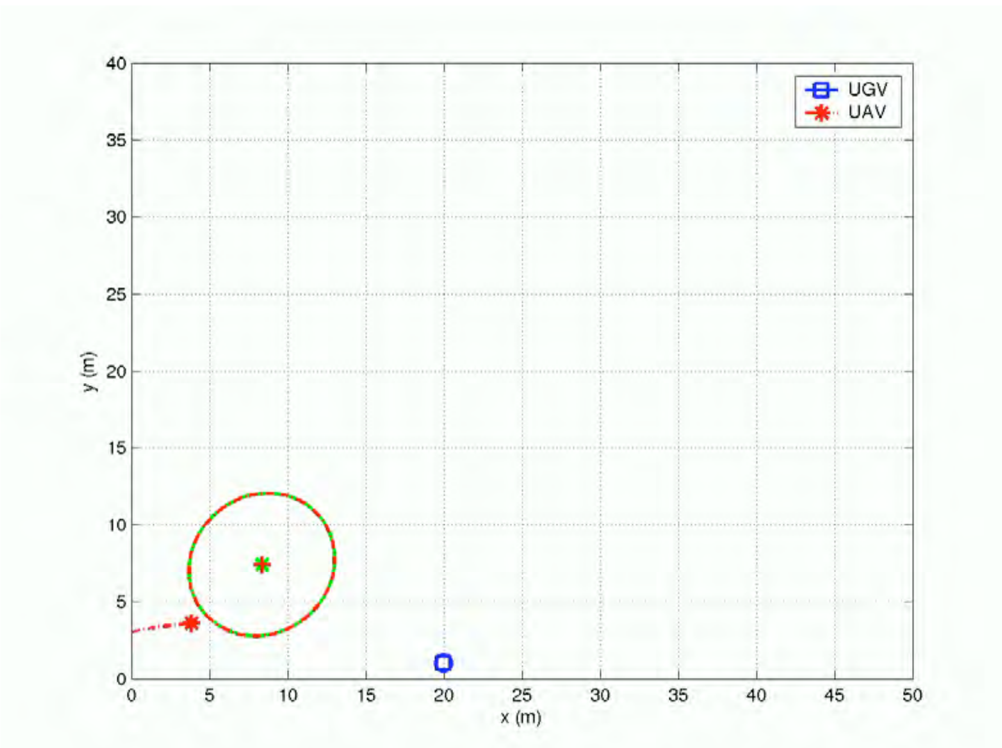
UGV Trajectory





UAV search pattern

UGV identification and localization of potential targets



Grocholsky *et al*, ISER 2004, Singapore

In theory, theory and practice are the same.
In practice, they are not.

Yogi Berra
Yankees catcher

Things do go wrong …

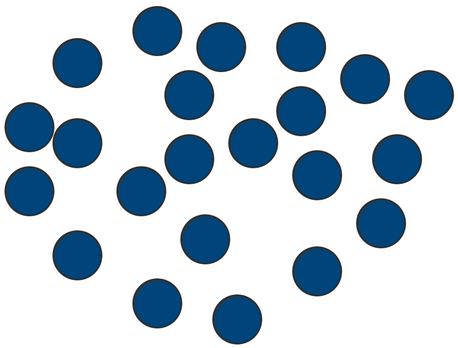
Taxonomy of Approaches

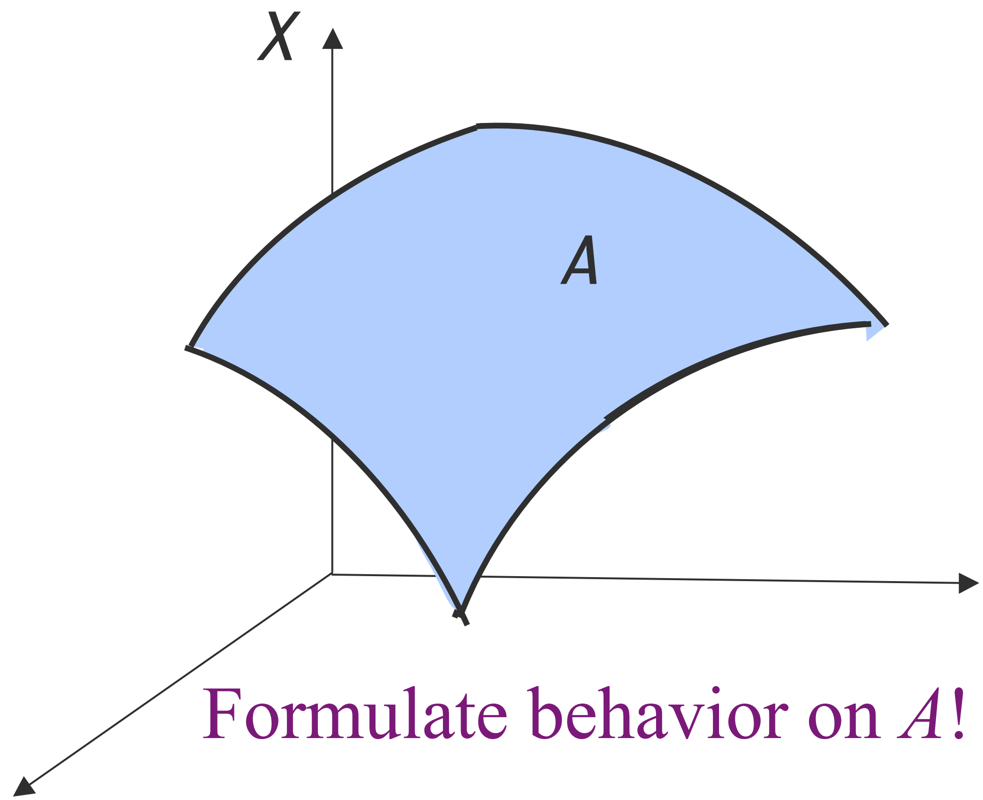
	Centralized	Decentralized
Vehicles identified		
Identical vehicles		Shared information • global knowledge of cost • guarantees

Scalable Approaches to Swarming

Abstractions of groups

Abstraction





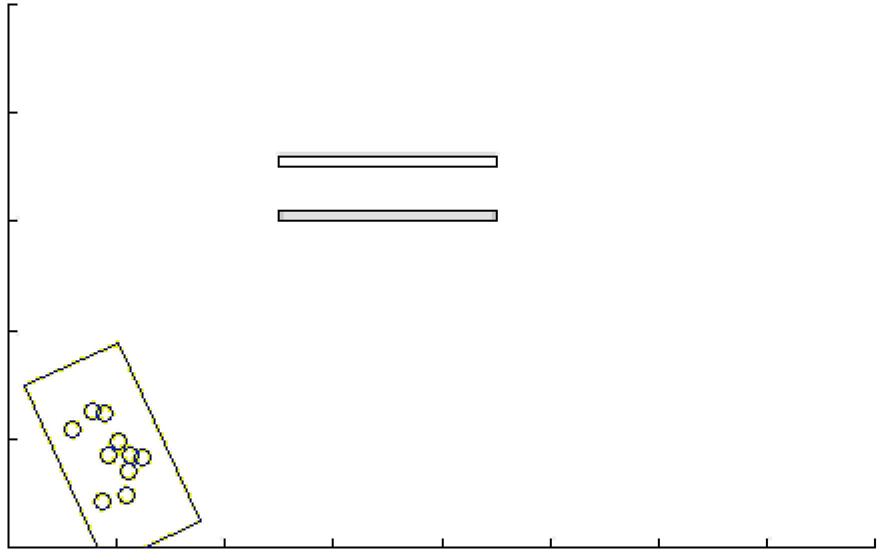
Formulate behavior on A!

1. $\dim(A) \ll \dim(X)$
2. $\dim(A)$ is independent of N

Control of Shapes and Motion

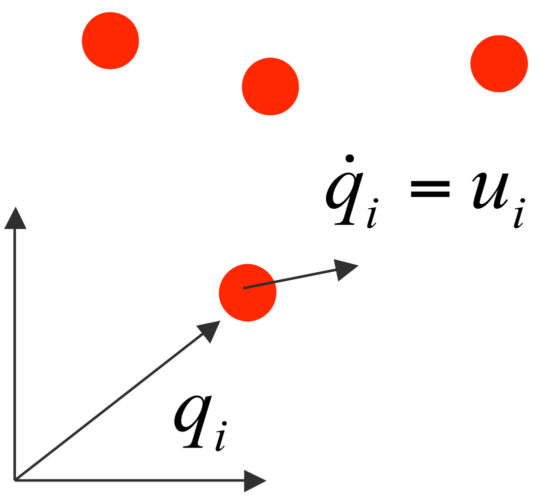
Example

1. Abstraction is the bounding rectangle

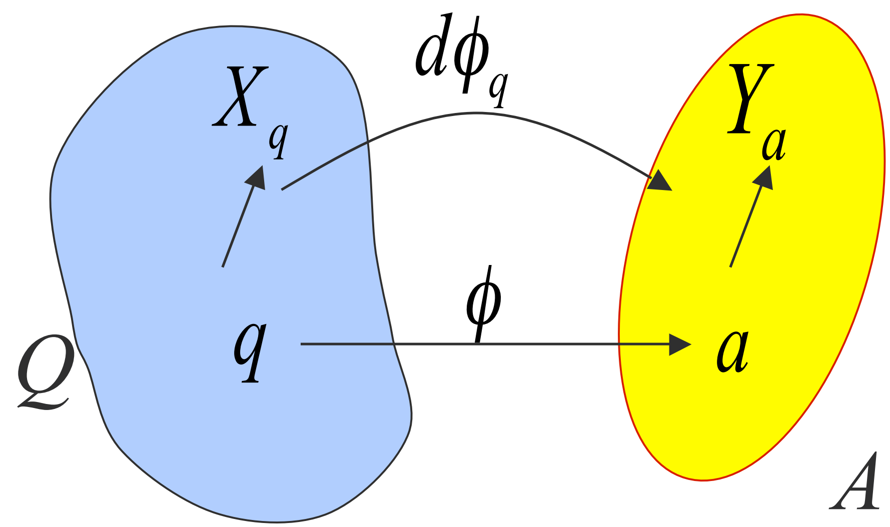


2. Robot behaviors consistent with the abstraction
   - Controllers regulate the shape/orientation of the rectangle
   - Estimates estimate the shape/orientation of the rectangle

Abstractions for Swarms



$$Q = \{q \mid q = [q_1, \ldots q_N]\} = \Re^{2N}$$



Behavior $X_Q \in TQ$

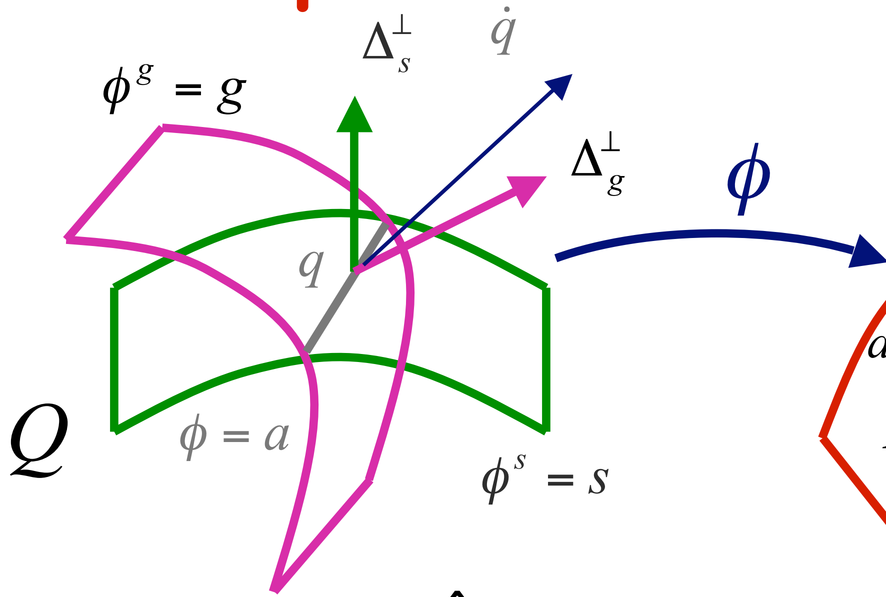
Abstraction: $\phi : Q \to A$

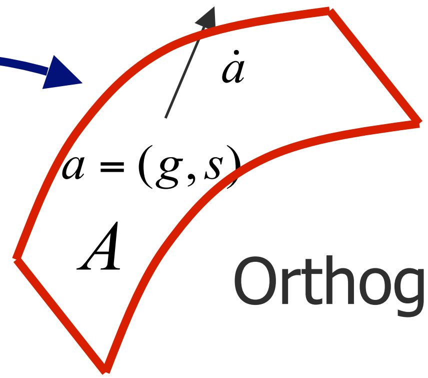
Abstract behavior $Y_A \in TA$

1. ϕ is a submersion
2. dim(A) << dim(Q) & independent of N

Inverse Problem: Given desired Y_A find X_Q

Properties: Abstraction & Controller



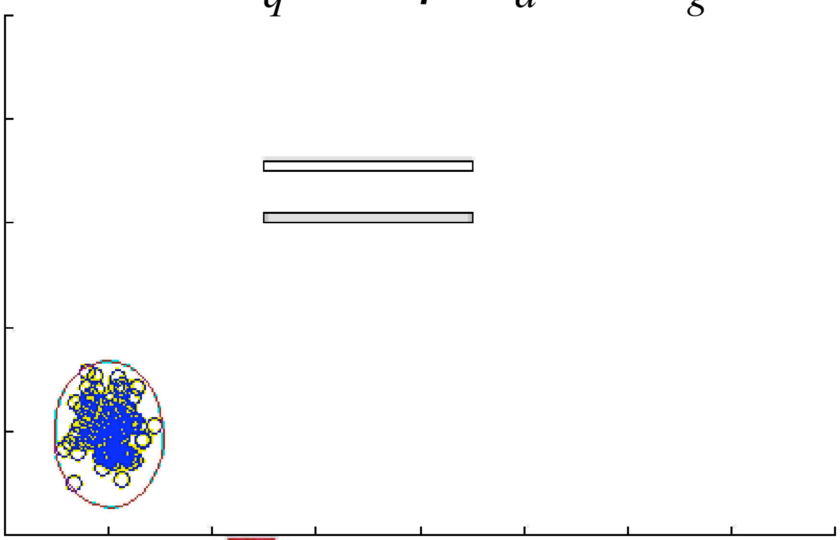


Product structure, A=G x S

Left invariance

Orthogonality

$$X_q^* = d\hat{\phi}^+ Y_a \in \Delta_g^{\perp} \oplus \Delta_s^{\perp}$$



Probabilistic guarantees
- e.g., 99% of the team will stay within ellipsoid

Geometric properties (e.g., colinearity, parallelism) are preserved

Belta, C., and Kumar, V. "Abstractions and Control Policies for a Swarm of Robots," IEEE Transactions on Robotics, vol.20, no.5, 2004: 865-875.

Abstract behavior

1. Plan trajectory ($g^{des}(t)$, $s^{des}(t)$) to attain a desired formation and pose (g^{des}, s^{des})

2. Control on the abstraction manifold

$$u_s = \dot{s}^{des}(t) + K_s(s^{des}(t) - s(t))$$

$$u_g = \xi^{des}(t) + K_g(e_g(t)),$$

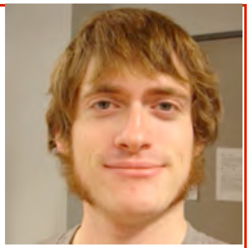
$$\hat{\xi}_g^{des}(t) = (g^{des}(t))^{-1}\dot{g}^{des}(t); \quad \hat{e}_g(t) = log(g^{-1}(t)g^{des}(t))$$

3. Robot behaviors

$$\dot{q} = \gamma(s)\omega X_q^{\omega} + \dot{\mu} X_q^{\mu} + \eta(s)\dot{s} X_q^{s}$$

The closed loop system globally asymptotically converges to the submanifold $g = g^{des}$, $s = s^{des}$.

Extensions



Primitives and Composition of Groups

Split: Groups can dynamically split when faced with obstacles or other unforeseen situations.

Merge: Groups that are moving to the same goal will merge when both groups can are “close”

Global guarantees from local information

Extensions to higher dimensions

Nathan Michael, ICRA 2006, RSS (submitted), 2006.

More complex shapes

$s(x, y) = 0$

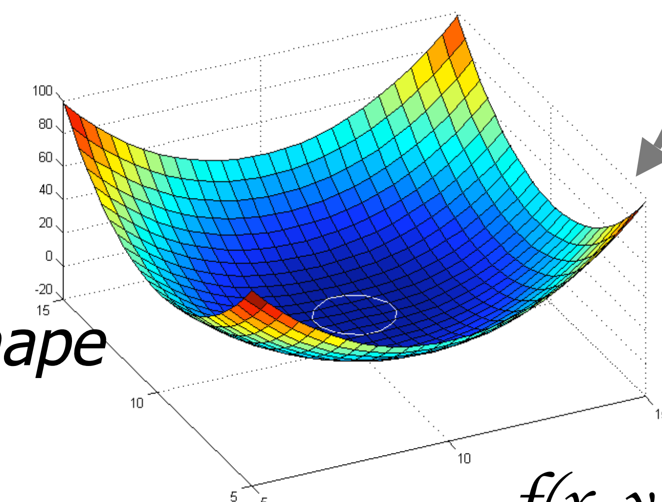
Shape Function

Given a desired shape, S, and its implicit function representation,

$$s(x, y) = 0,$$

the *shape function* is a map

$$f : \mathcal{R}^2 \rightarrow \mathcal{R} \quad f(x, y) = [s(x, y)]^2$$



$f(x, y)$

Shape Discrepancy Function

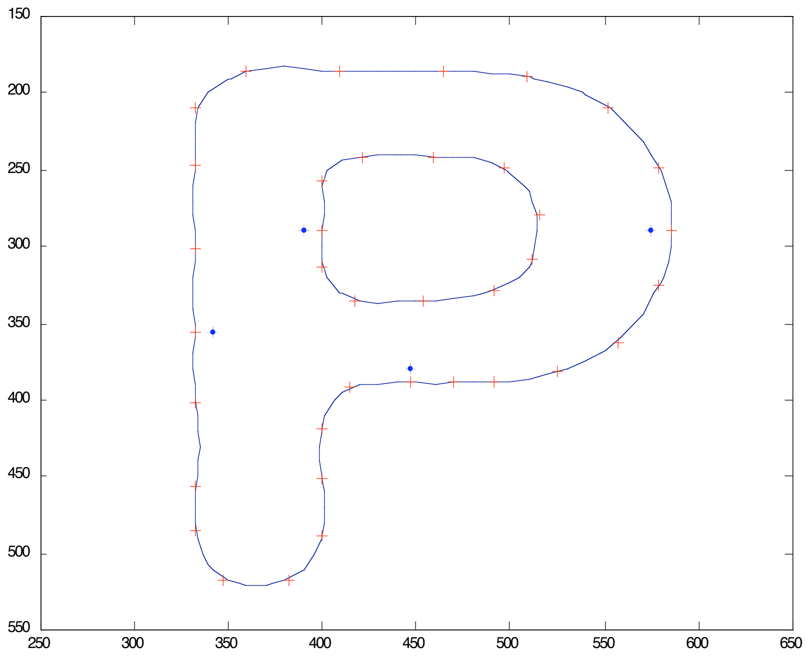
Given a formation of robots, the *shape discrepancy function* is the map

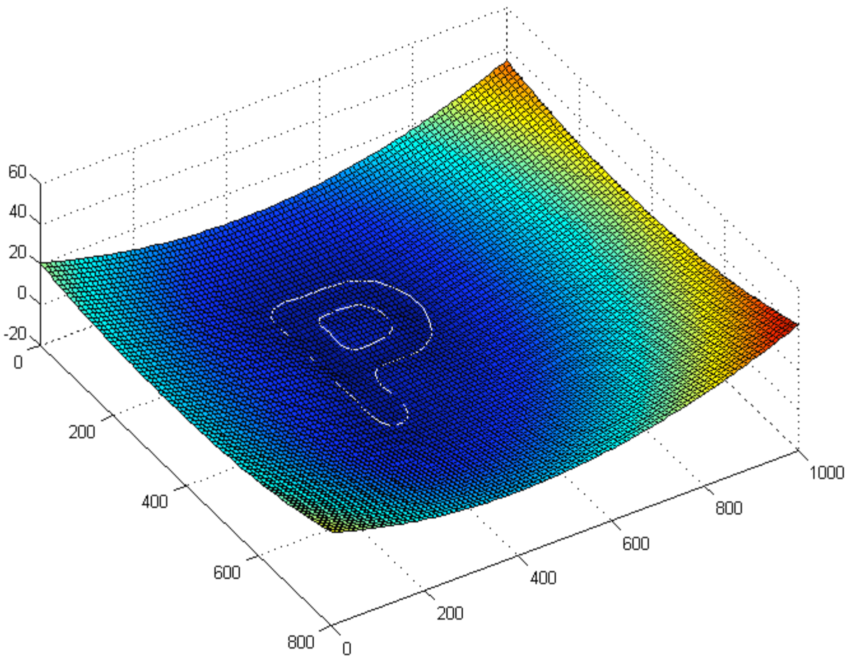
$$\phi_S : Q \rightarrow \mathcal{R}, \ \phi_S(\mathbf{q}) = \sum_i f(x_i, y_i)$$

Hsieh and Kumar, ICRA 2006

Synthesizing Implicit Functions

Example: letter 'P' with 41 constraints:





Chaimowicz, L., and Kumar, V. "Pattern Generation with a Swarm of Robots," IEEE Int. Conf Robotics Automation, Barcelona, 2005.

Decentralized Control

Dynamics

Given N robots with the dynamics

$$\dot{q}_i = v_i, \ \dot{v}_i = u_i$$

A desired shape

$$s(x, y) = 0,$$

And the decentralized controller

$$u_i = \boxed{-\nabla_i f(q_i)} - \boxed{Cv_i} - \boxed{\sum_j \nabla_i g_{ij}(q_i, q_j)}$$

Convergence to pattern damping Interactions with neighbors

Pattern Generation

Result 1

For a system of N robots each with dynamics

$$\dot{q}_i = v_i, \; \dot{v}_i = u_i$$

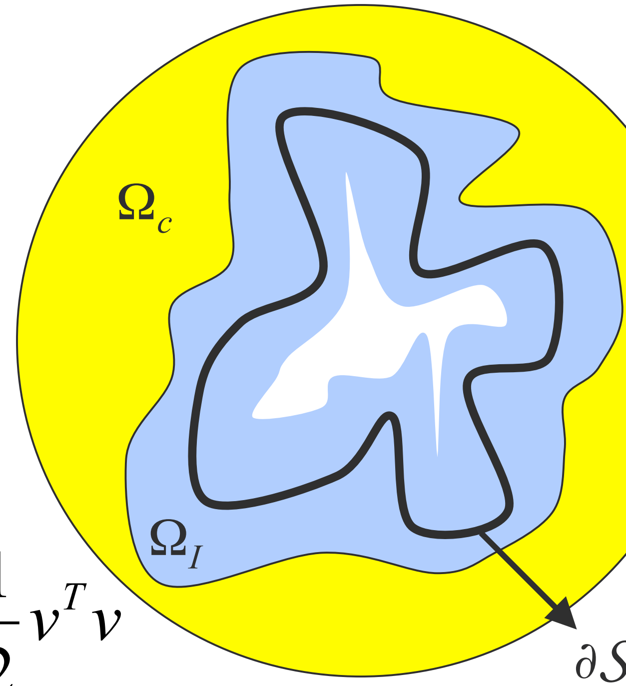
shape function, f, and control

Symmetric!

$$u_i = -\nabla_i f(q_i) - C v_i - \boxed{\sum_j \nabla_i g_{ij}(q_i, q_j)}$$

the equilibrium points minimize the shape discrepancy function.

Pattern Generation



Result 2

For the initial conditions given by

$$x_0 \in \Omega_c,$$

$$\Omega_c = \{x \in X \mid V(q, v) \le c\},$$

where

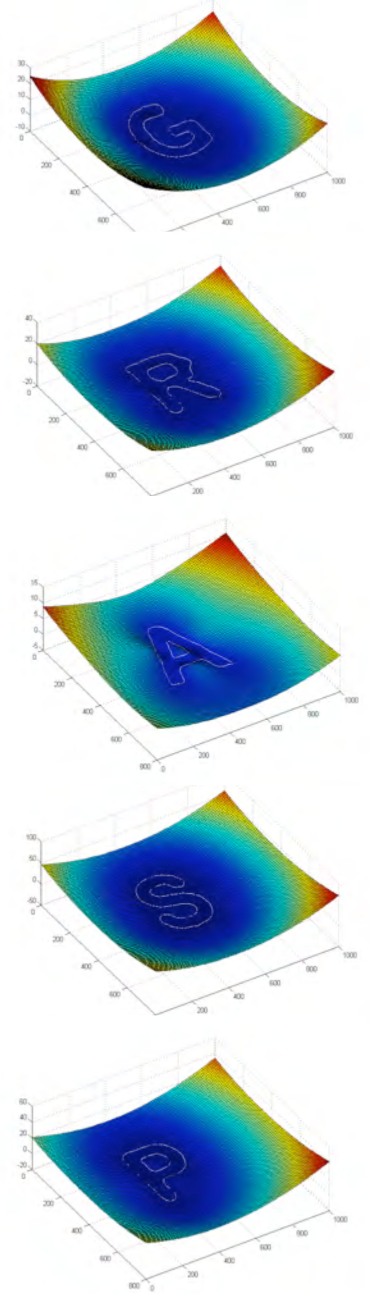
$$V(q,v) = \phi_S + \sum_i \sum_{j \in N_i} g_{ij} + \frac{1}{2} v^T v$$

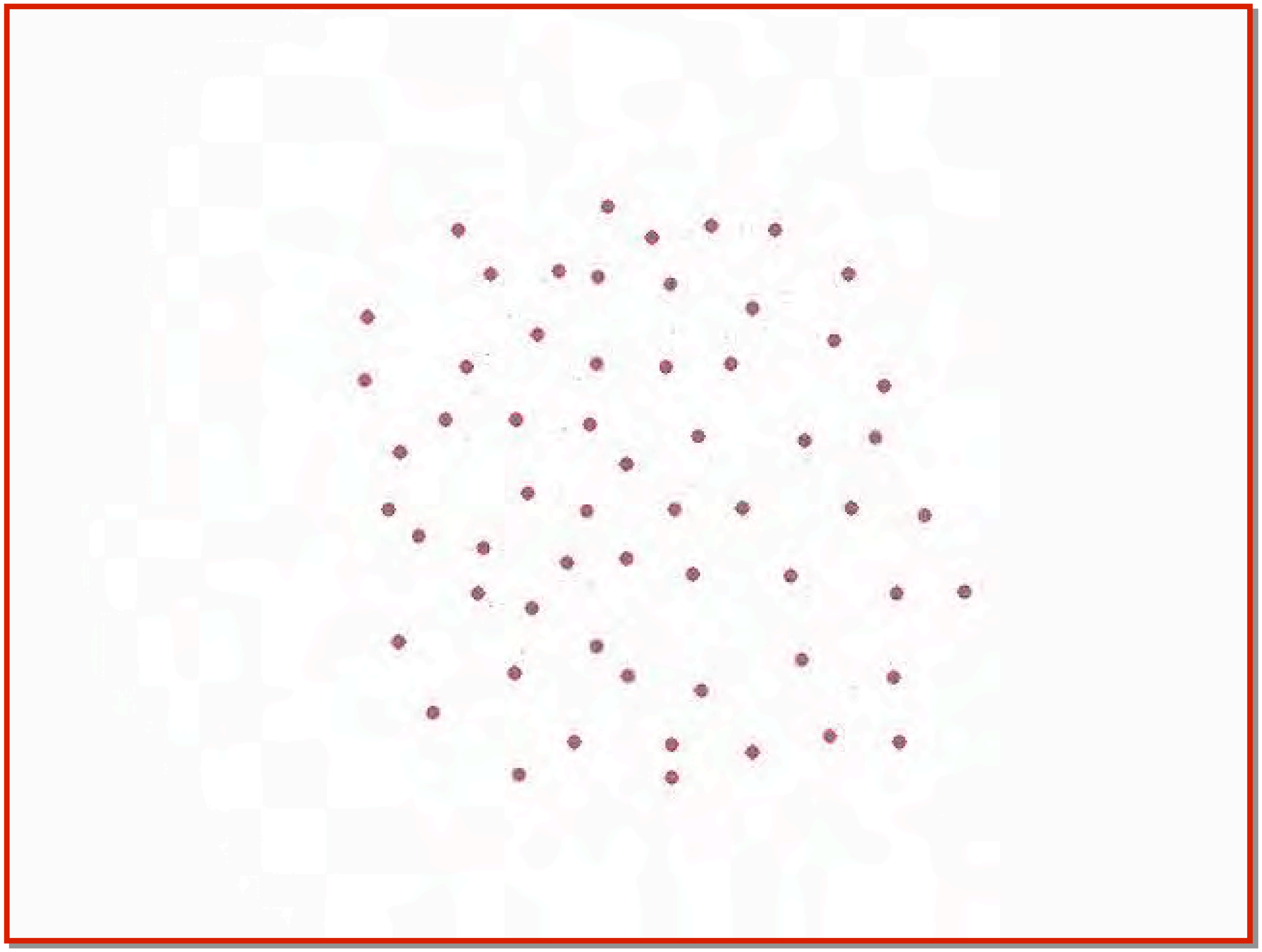
the system converges to some invariant set, $\Omega_I \subset \Omega_c$, such that the points in Ω_I minimizes the shape discrepancy function. Also the set

$$\Omega_S \subset \Omega_I \subset \Omega_c$$

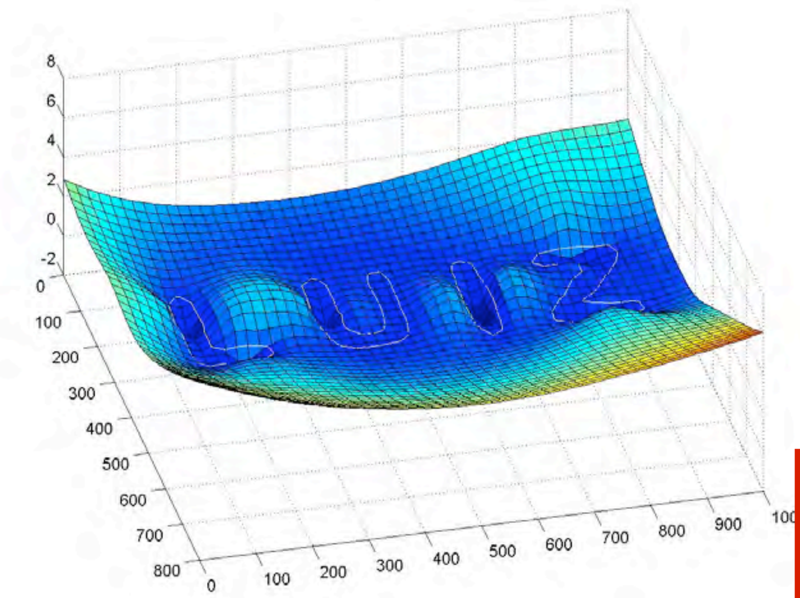
is a stable sub manifold.

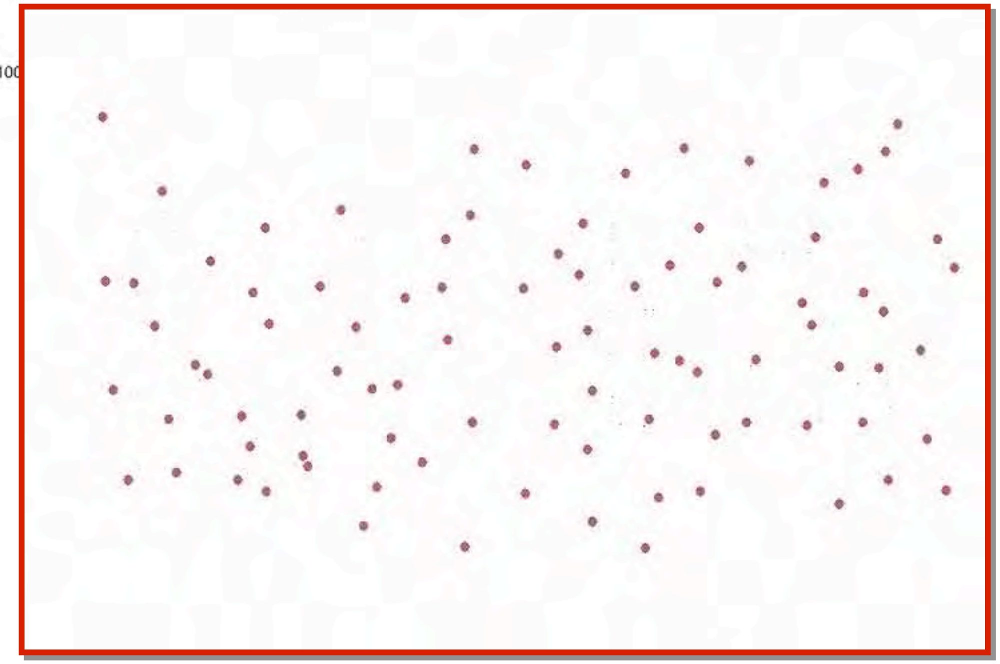
Simulations



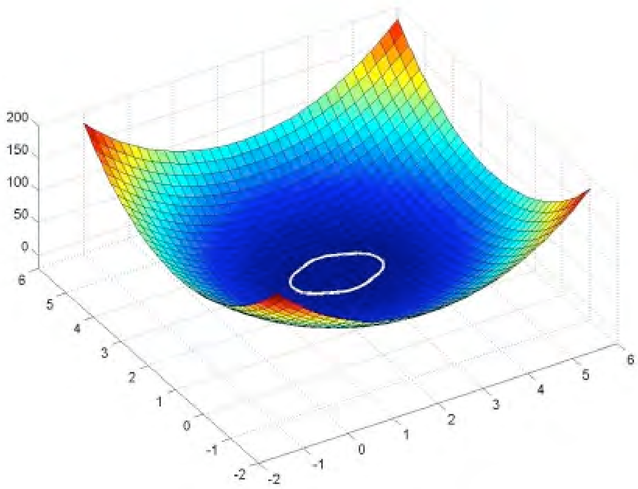


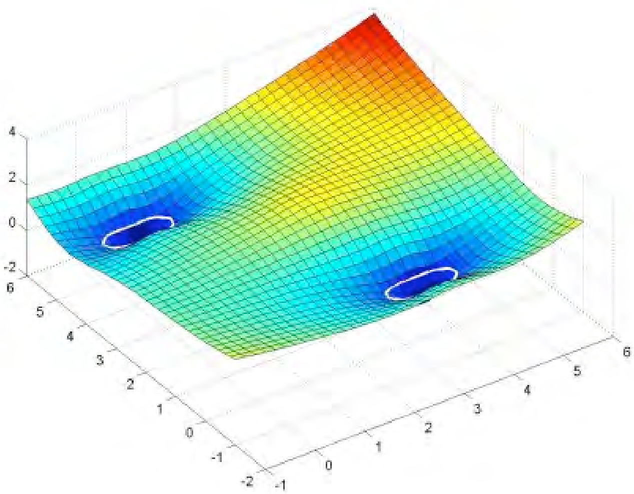
Simulations

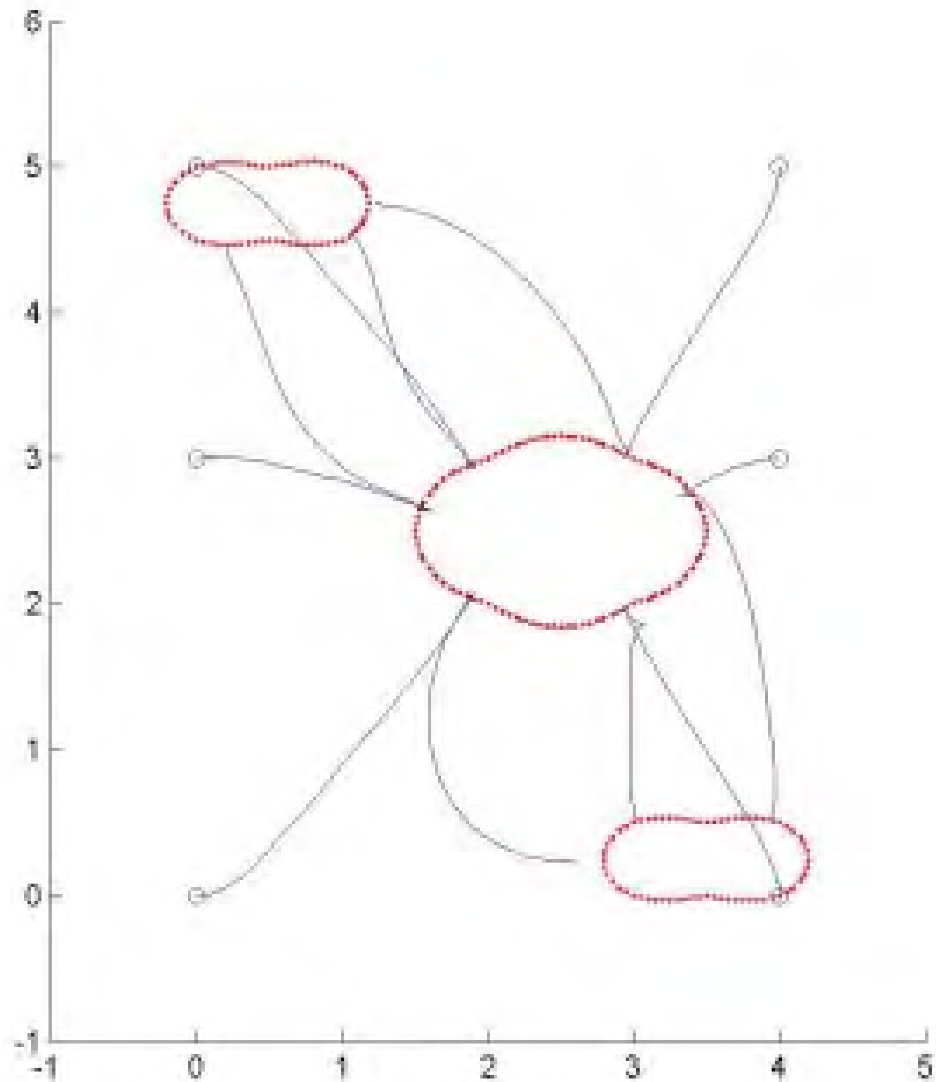




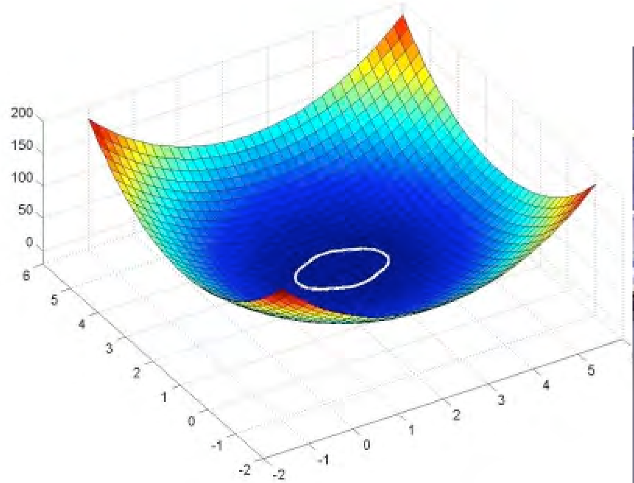
Experiments

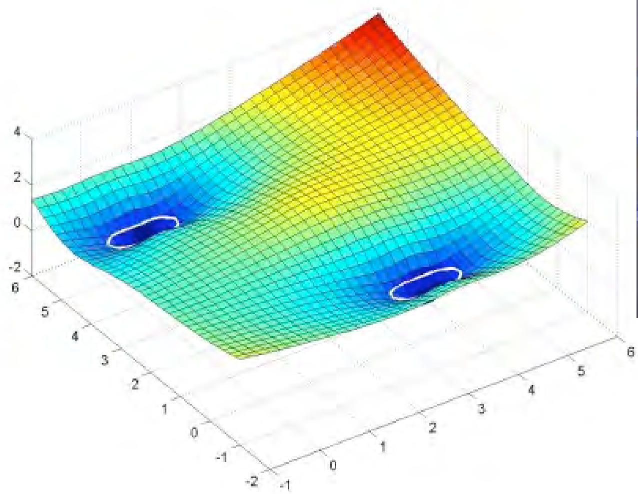






Experiments

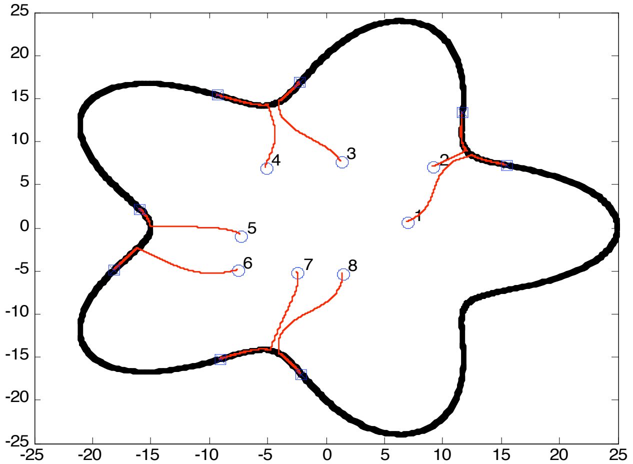




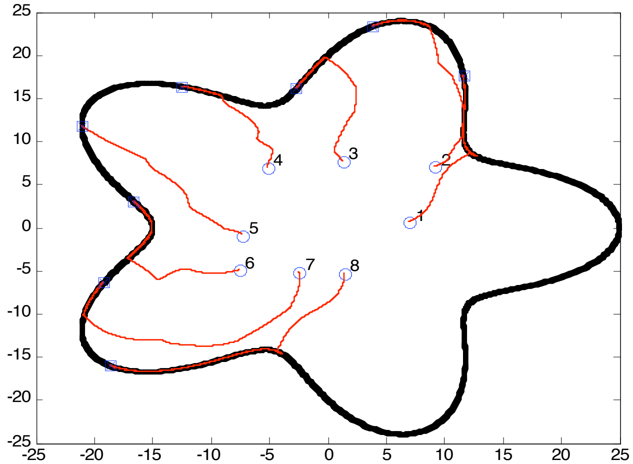
Pattern Generation

Result 3

For any smooth star convex shape, S, the system of N robots converges asymptotically to Ω_S.

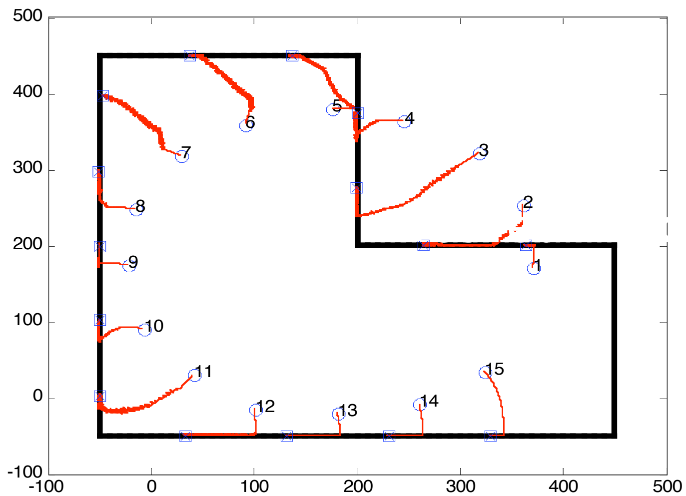


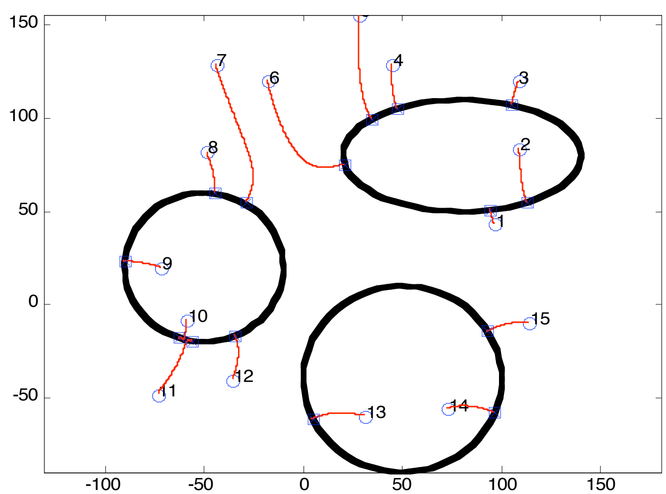
Without constraints on neighbors



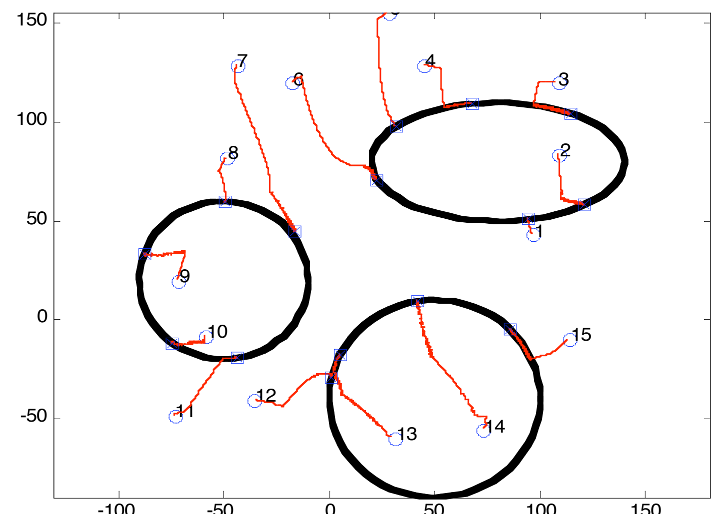
With a specified proximity graph

Union of star shapes





Without constraints on neighbors



With a specified proximity graph

Beyond Pattern Formation and Navigation …

Biological Models for Construction

Termites construct mounds as tall as 5 m to store food and house brood following 2 simple rules [Kugler 1990]

Heppner, F., & Grenander, U. A Stochastic Nonlinear Model for Coordinated Bird Flocks. In *The Ubiquity of Chaos.* AAAS, Washington DC, 1990.

Animal Groups in Three Dimensions: How Species Aggregate (1997) Ed. Julia K. Parish and William M. Hamner.

Biological Models (2)

Pack of wolves surrounds larger and more powerful moose.

Predator-prey model [Korf 1992]

Moose: Moves to maximize its distance from nearest wolf

Wolves: Each wolf moves toward the moose and away from nearest wolf

Biological Models for Decision Making

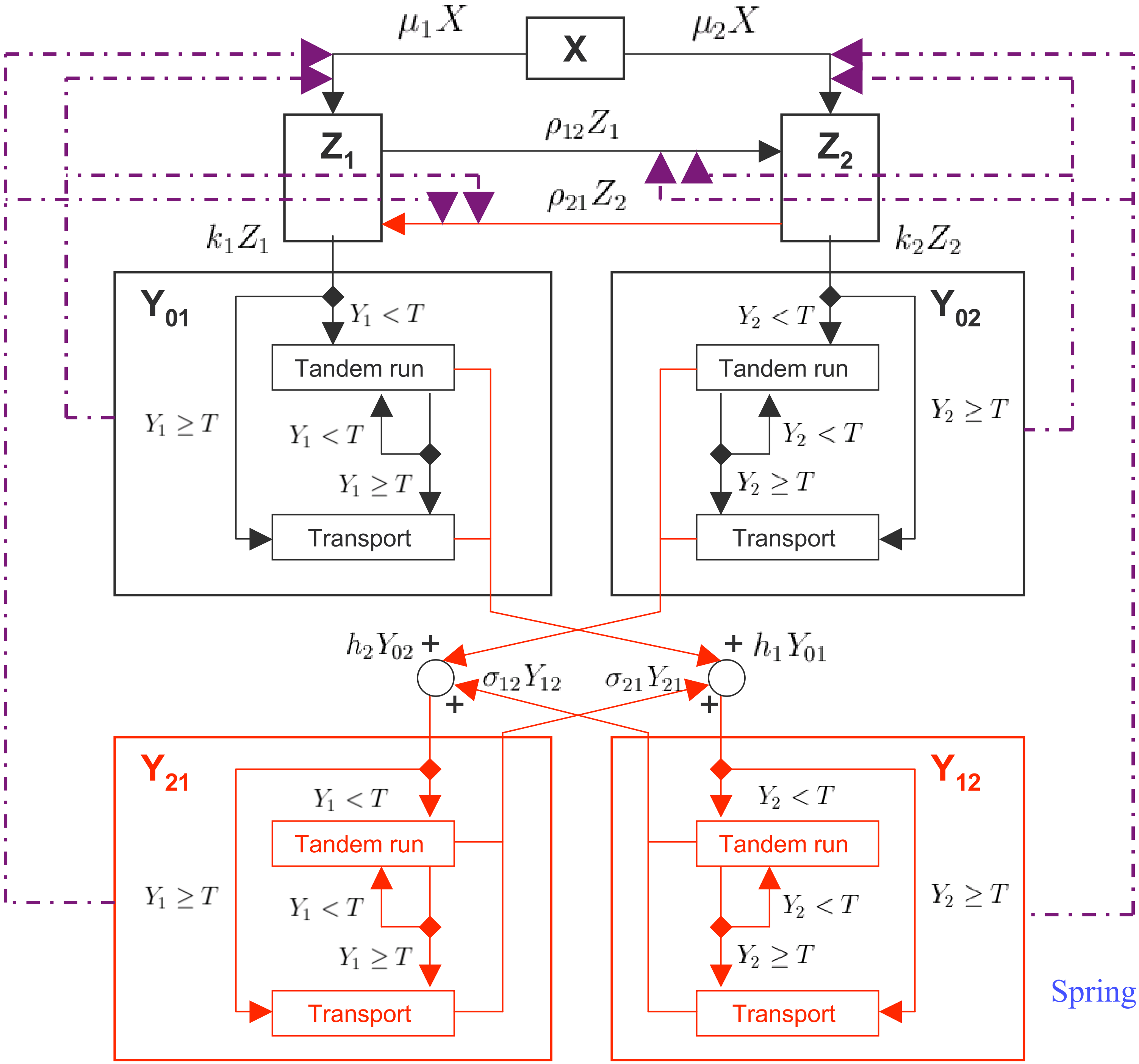
Honey bees and ants scouting for nests

Three simple rules
- Explore
- Rate nests
- Recruit
  - Tandem run; or
  - Transport

Information gathering
Evaluation
Deliberation
Consensus building

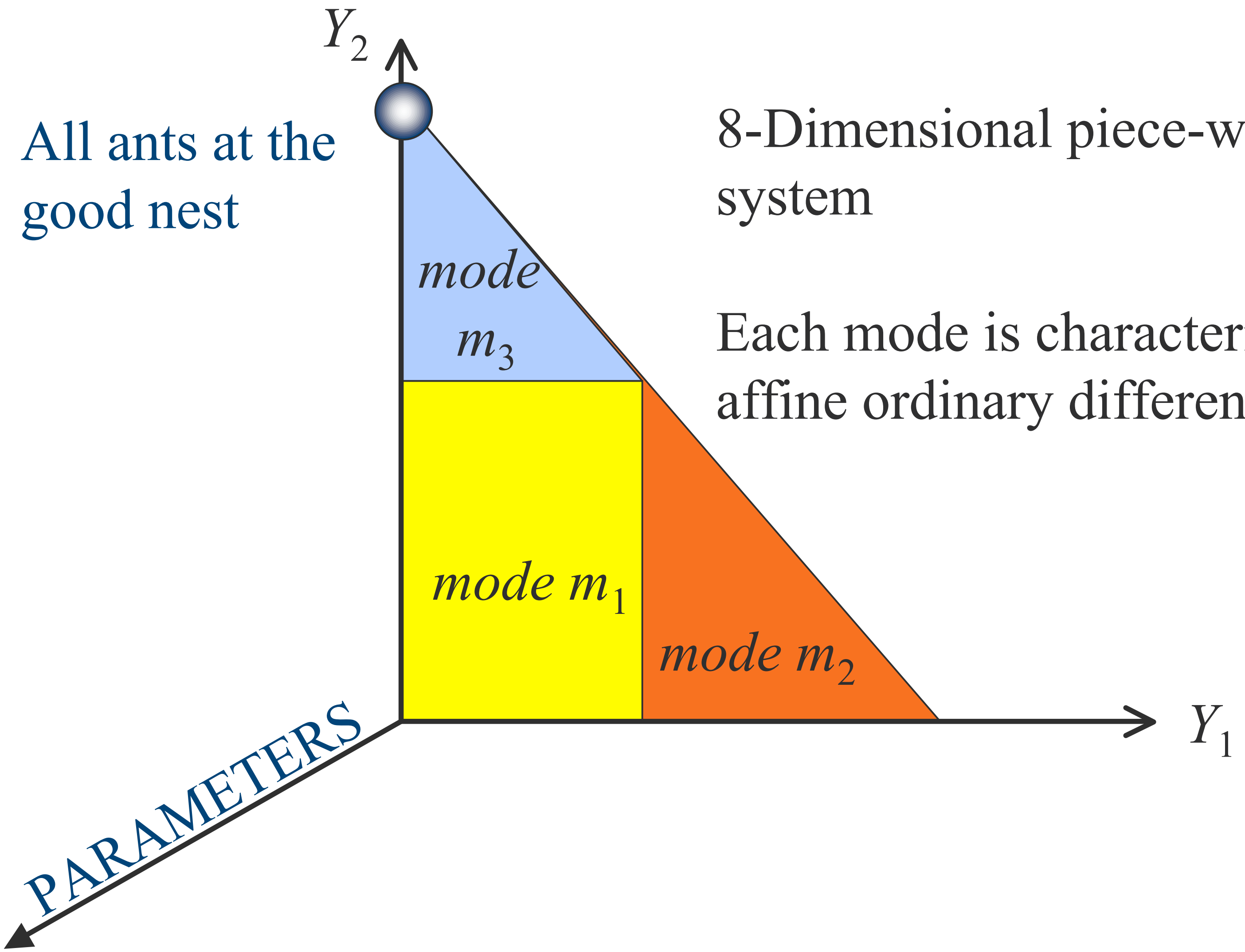
Franks *et al*, *Trans. Royal Society*, 2002

[Stephen Pratt, Princeton/ASU]



Spring Berman

No ants left behind!



8-Dimensional piece-wise smooth system

Each mode is characterized by multi-affine ordinary differential equations

Spring Berman

Summary

Keys to scaling

- Decentralized behaviors
- Anonymity
- Derived from local information
- Simplicity

Our experimental systems

- Decentralized, simple; but robots were identified

Control on abstraction manifold

- Patterns or shapes
- Group motion

Challenges

- Bottom-up design of behaviors
- Providing guarantees with anonymity
- Bio-inspired and not bio-mimicry