Self-organized Flocking with a Mobile Robot Swarm

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Swarm robotics

- Inspiration from social insects and animals. Ex. ants, bees, termites, birds, fish, etc.


- Development of
  - robust
  - scalable
  - flexible

  coordination algorithms for a swarm of robots

- Extra constraints on coordination mechanisms
  - Local communication
  - No robot IDs
  - No P2P communication
  - No leaders
  - Minimal complexity

Flocking in Nature

Flocking: A group of animals, such as birds and fishes, moving and maneuvering as if they are a 'super-organism'.

Characteristics

- Rapid, directed movement
- No dedicated leader
- No collisions
- Robust and scalable

Advantages

- Protection against predators
- Energy efficiency
- Accuracy in long-range migration

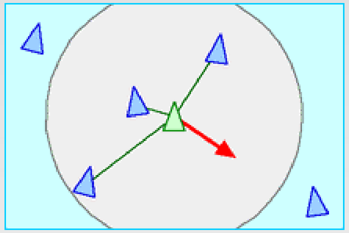
Reynolds' Flocking Algorithm

Reynolds, C.: **Flocks, herds and schools: A distributed behavioral model.** In: Proceedings of the 14th annual conference on computer graphics and interactive techniques (SIGGRAPH'87), pp. 25–34. ACM Press, New York (1987)

Synthesis of flocking for the first time

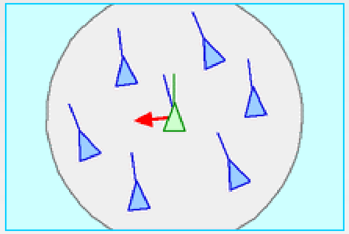
"Flock refers generically to a group of objects that exhibit general class of polarized, non-colliding, aggregate motion."

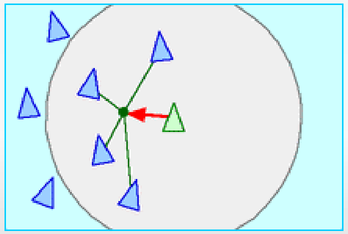
Assumption: Individuals can sense bearing, range and orientation of their neighbors.
Such sensors are not available on most robot platforms.



Separation: Individuals avoid collisions with their neighbors

Alignment: Individuals match their velocity to the average of their neighbors





Cohesion: Individuals move towards the geometric center of their neighbors

Robotics

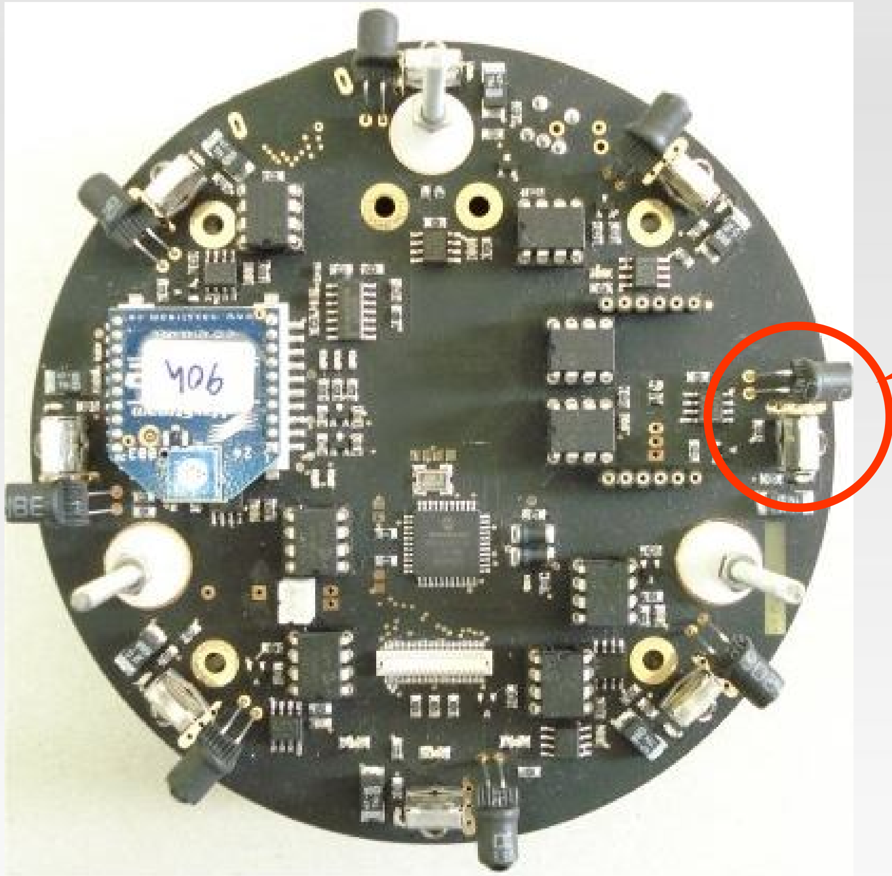
- **Mataric (1994)**. Sense obstacles using IR. Localize itself wrt stationary beacons using sonar → broadcast its position in local proximity. Homing direction known a priori → pseudo-flocking. 20 robots.
- **Kelly et al. (1996)**. Sense obstacles with sonar. Sense bearing and distance of neighboring robots with a custom active IR system. Flocking in constrained environment. Leader election with RF. 10 robots.
- **Hayes et al. (2002)**. Sense range and bearing of neighboring robots with emulated sensors. Collision avoidance + velocity matching (flock centering). 10 robots.
- **Spears et al. (2004)**. Sense range and bearing of neighboring robots by rotating two IR sensors. Attraction/repulsion + viscous force → lattice formation. Moving lattice → pseudo-flocking. 7 robots
- **Nembrini (2005).** Sense obstacles using IR. Sense robots using an omni-directional IR. Local wireless communication among robots. Coherent movement towards a beacon in an environment with obstacles. Limited success with real robots. 7 robots.

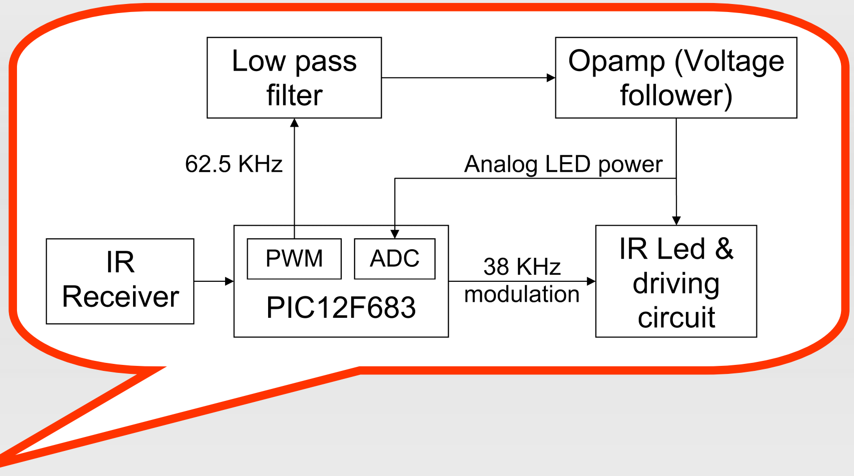
Self-organized flocking as seen in nature has not been achieved yet

Kobot

- Designed specifically for swarm robotics research focusing on flocking
- Novel IR sensing system (IRss) for range measurement and kin detection
- Communication and magnetic compass modules utilized for heading measurement
- Wireless parallel programming through communication module
- 2 high quality DC gear head motors for actuation
- CD-sized, 350gr, 10hr battery life (2000mAh)

Infrared Sensing System



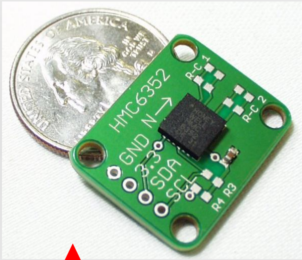


- Modulated IR
- 8 independent sensors@45°
- Kin-detection
- Range measurement
- 8 discrete levels
- 21 cm detection range
- Robust to ambient lighting
- Robust to crosstalk and interference

Virtual Heading Sensor (VHS)

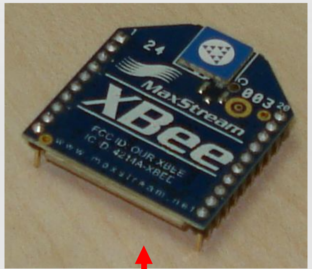
Compass

Measures heading of robot wrt the North-pole



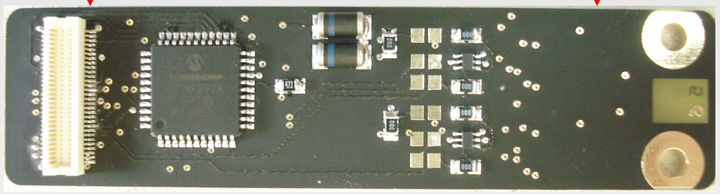
XBee module

Broadcasts heading of the robot



I^2C

RS-232



Main Controller

Kobots can detect their **relative headings** with respect to each other.

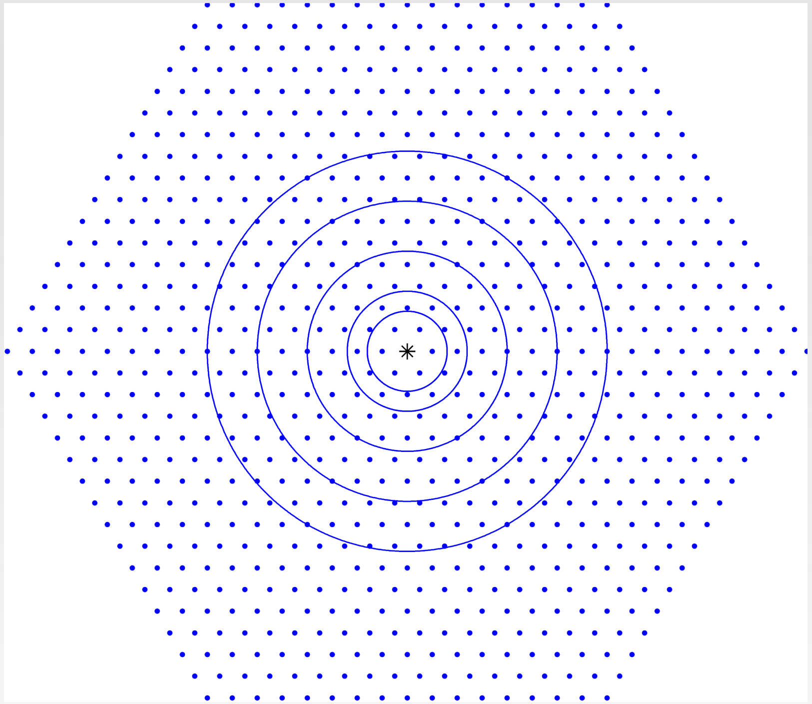
Assumption: The sensed North remains approximately the same within the wireless communication range of the robots

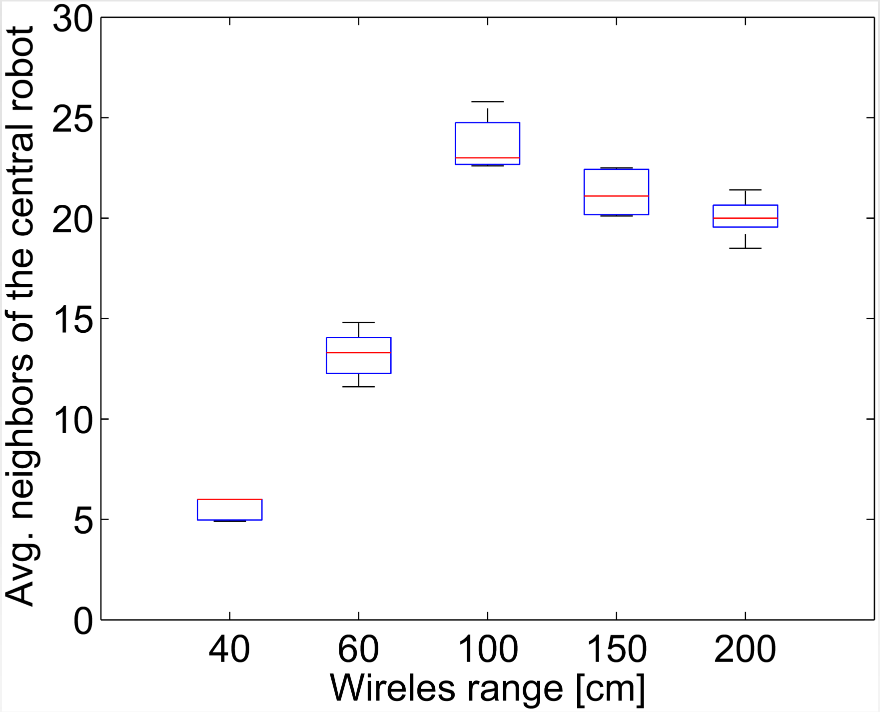
Modeling VHS

- Two main characteristics:
  - **Number of VHS neighbors**: Depends on the range of communication, the number of robots within the range, the frequency and duration of communication
  - **Nature and amount of noise:** Depends on noise characteristics of the digital compass → modeled using the vectorial noise model

VHS Characteristics

Communication Range Experiment

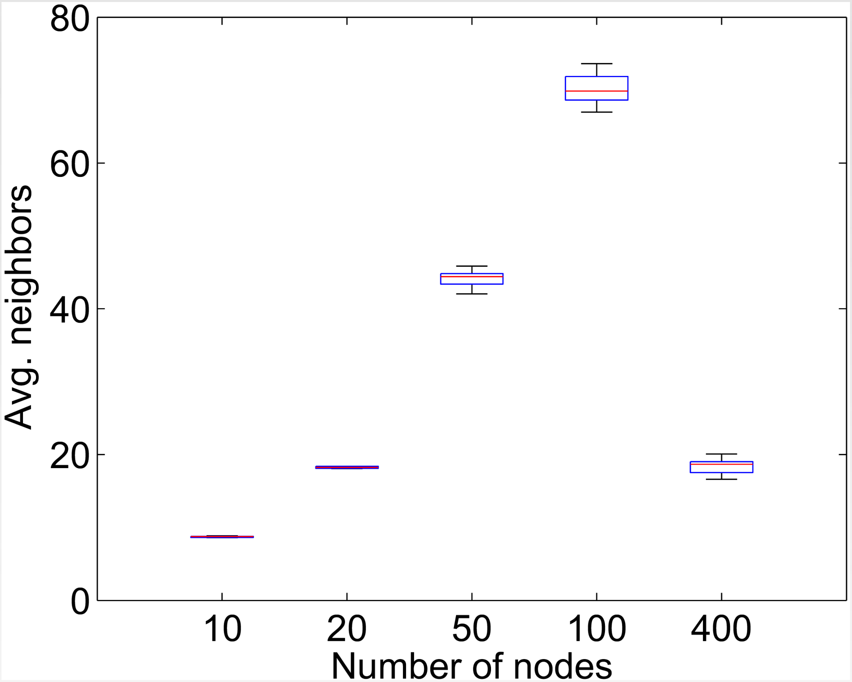




(1)Prowler, a wireless network simulator, utilized in the experiments due to utilization of more nodes than available physically
(2)Perceived neighbors depends on communication range
(3)Saturation at 20 perceived robots

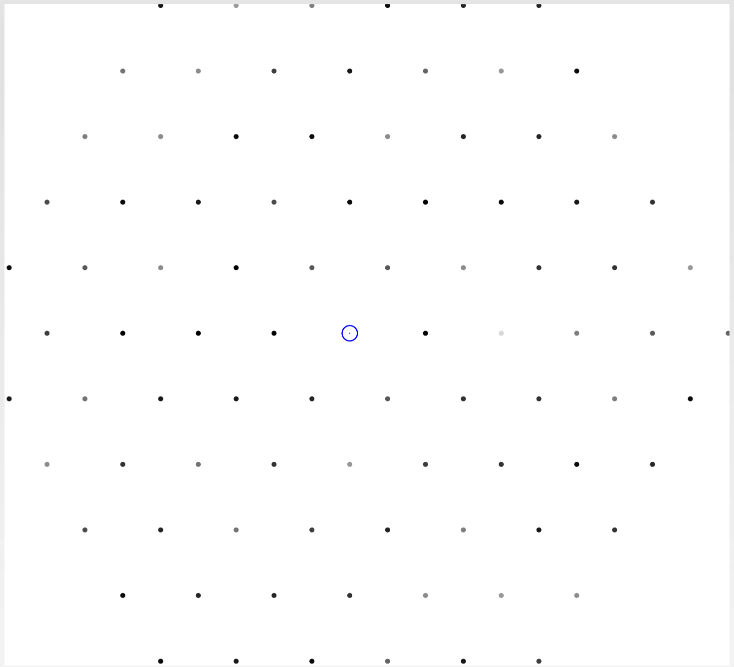
VHS Characteristics

Group Size Experiment



(1)Communication range set to its maximum
(2)Saturation at 20

Isotropy of communication



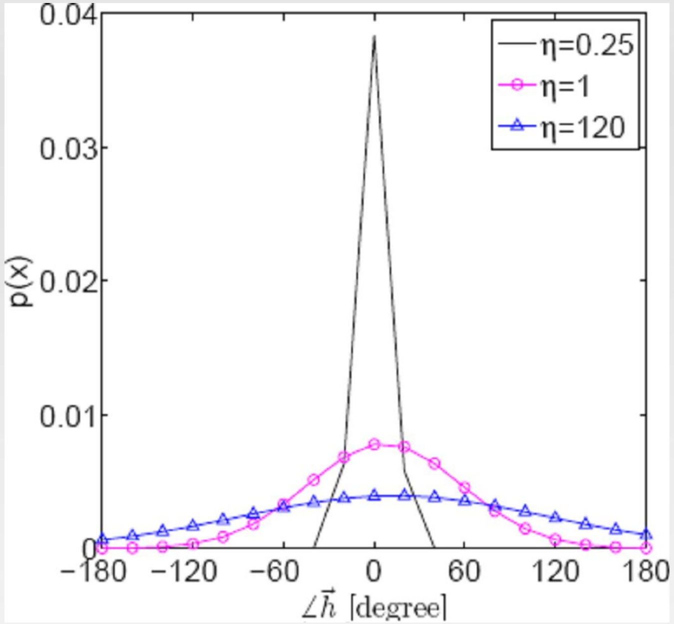
(1)No directional preference in neighbor selection
(2)Totally random neighbors

Modeling Noise in VHS

$$\theta_j = \angle(e^{i\theta_a} + \eta e^{i\xi})$$

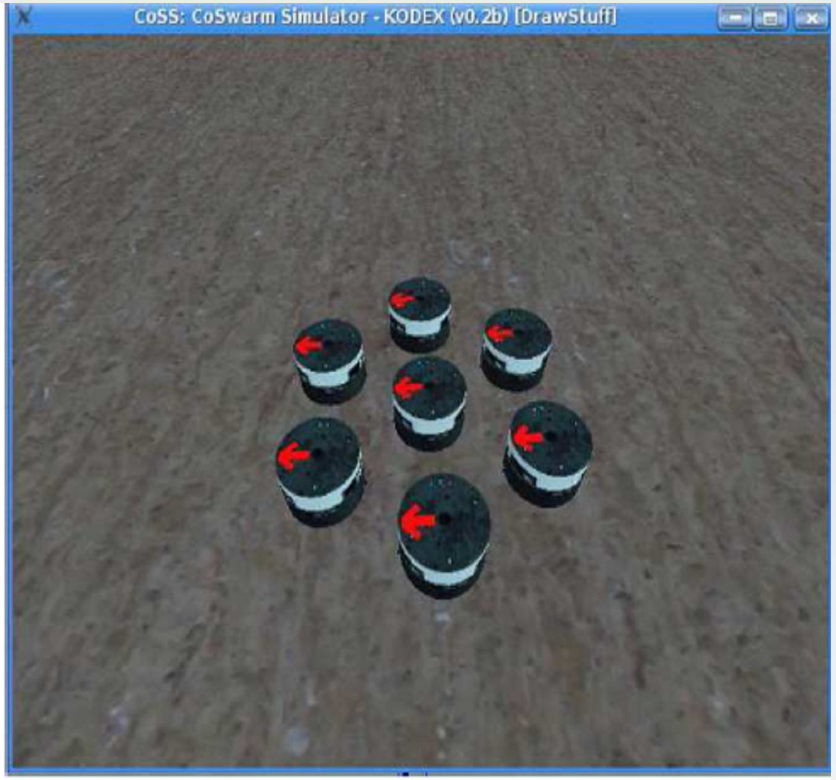
θ_a → **actual heading**

θ_j → **noisy heading**



(1)Heading measurements are subjected to vectorial noise
(2)Each noise vector has a direction of ξ and a magnitude of η
(3)ξ is a delta-correlated random variable with a uniform distribution in [-π, π]

CoSS Simulator



(1)Co-swarm simulator built on top of Open Dynamics Engine (ODE)
(2)IRss and VHS modeled using sensing characteristics
(3)Kobot modeled using basic cylindrical geometries and actuation characteristics
(4)Used to conduct experiments with large groups

Flocking Behavior

$$a = \alpha h + \beta p$$

$$\boldsymbol{h} = \frac{\sum_{j \in \mathcal{N}} e^{i\theta_j}}{\| \sum_{j \in \mathcal{N}} e^{i\theta_j} \|}$$

$$\mathbf{p} = \frac{1}{8} \sum_{k=0}^{7} f_k e^{i\phi_k}$$

Heading Alignment (h)

Matching heading to the average of VHS neighbors

Proximal control (p)

Maintenance of optimal distance with nearby robots → attraction/repulsion force based on distance

Obstacle avoidance → repulsion force based on distance

Motion Control

Forward velocity (*u*)

$$u = \begin{cases} \left(\frac{\mathbf{a}}{\|\mathbf{a}\|}.\hat{a}_c\right)^{\gamma} u_{max} & \text{if } \frac{\mathbf{a}}{\|\mathbf{a}\|}.\hat{a}_c \geq 0 \\ 0 & \text{otherwise} \end{cases}$$

Angular velocity (ω)

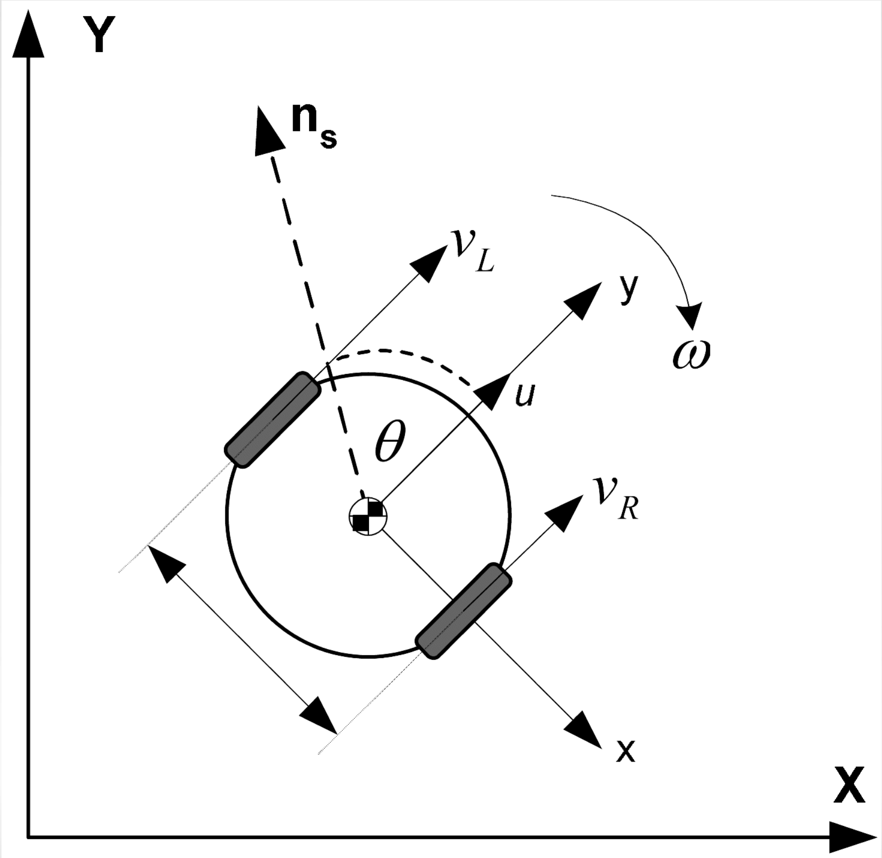
$$\omega = (\angle \mathbf{a} - \angle \hat{a}_c) K_p$$

Rotational speed of the right motor (N_R)

$$N_R = \left(u - \frac{\omega}{2} l\right) \frac{60}{2\pi r}$$

Rotational speed of the left motor (N_L)

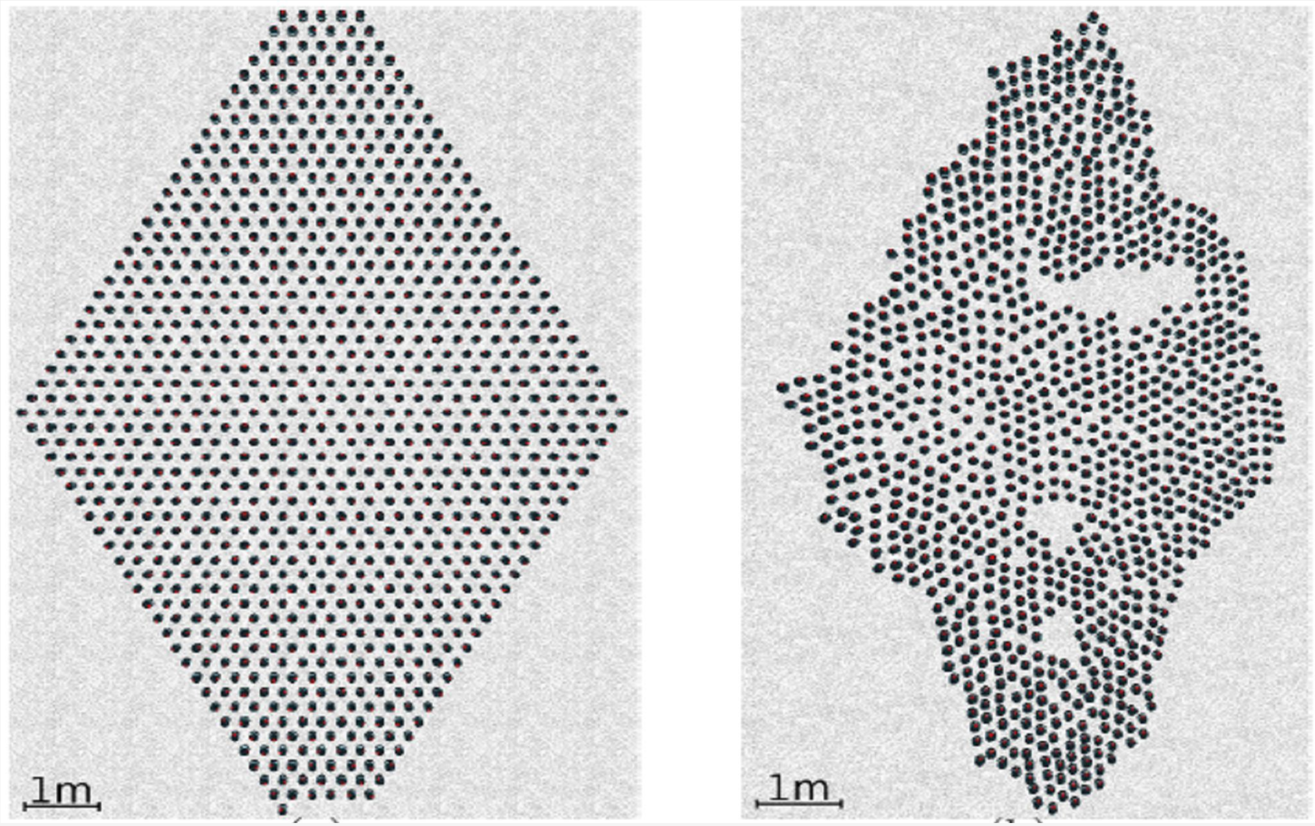
$$N_L = \left(u + \frac{\omega}{2} l\right) \frac{60}{2\pi r}$$



Full-Fledged Flocking

- Turgut A.E., Celikkanat H., Gokce, F. and Sahin, E. (2008) . **Self-Organized Flocking in Mobile Robot Swarms**. Swarm Intelligence, vol 2, no:2-3.
- Turgut, A.E., Çelikkanat, H., Gökçe, F., Şahin, E.: **Self-organized flocking with a mobile robot swarm.** In: Proceedings of the 7th International Conference on Autonomous Agents and Multi-agent Systems (AAMAS 2008), pp. 39–46. (2008)

Flocking with a Swarm of 1000 Kobots



(1)Controller parameters: $R = 20\text{m}$, $\eta = 3$ and $N = 10$

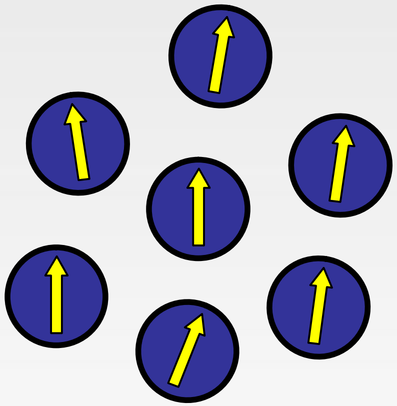
(2)VHS characteristics: $\alpha = 0.125$, $\beta = 2$, $u_{max} = 0.07\text{m/s}$ and $K_p = 0.5$

(3)Total displacement of the group is 110 m after 2000 s

Metrics of Flocking Behavior

- **Order:** Measures the average alignment of the group

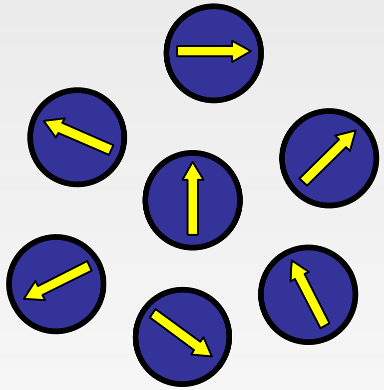
Aligned group



$\psi \approx 1$

$$\psi(t) = \frac{1}{M} \left| \sum_{k=1}^{M} e^{i\theta_k} \right|$$

Unaligned group



$\psi \approx 0$

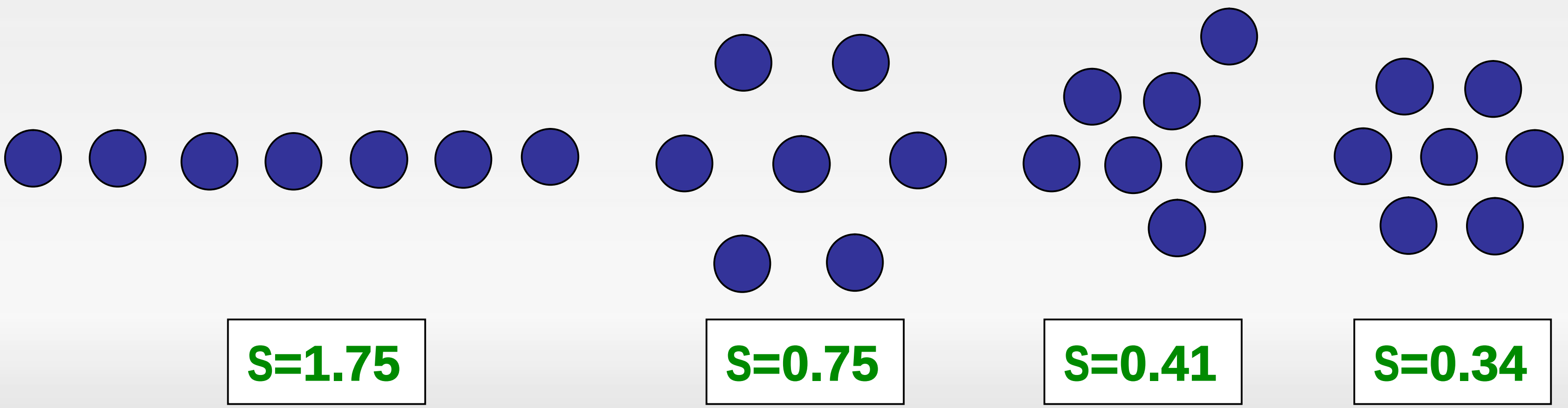
Metrics of Flocking Behavior

- **Entropy:** Measures the positional order of the group

$$\mathrm{H}(h) = \sum_{k=1}^{K} p_k \log_2(p_k)$$

$$\|\vec{r}_i - \vec{r}_j\| \leq h$$

$$\mathrm{S} = \int_0^{\infty} \mathrm{H}(h)\, dh$$



Metrics of Flocking Behavior

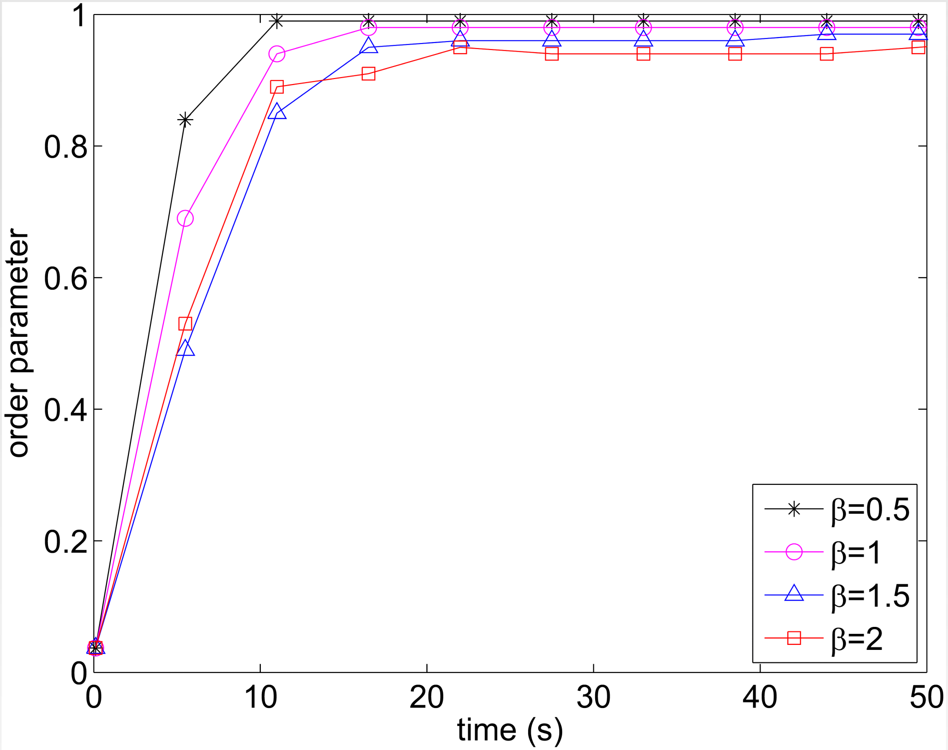
- **Average angular velocity:** Measures the rms value of the angular velocity of the group $$\omega_{rms} = \frac{1}{M}\sum_{i=1}^{M}\sqrt{\langle \omega_i^2 \rangle_t}$$
- **Average forward velocity:** Measures the displacement of the group at a unit time
- **Success rate:** Measures the ratio of successful runs out of total runs of a particular experiment

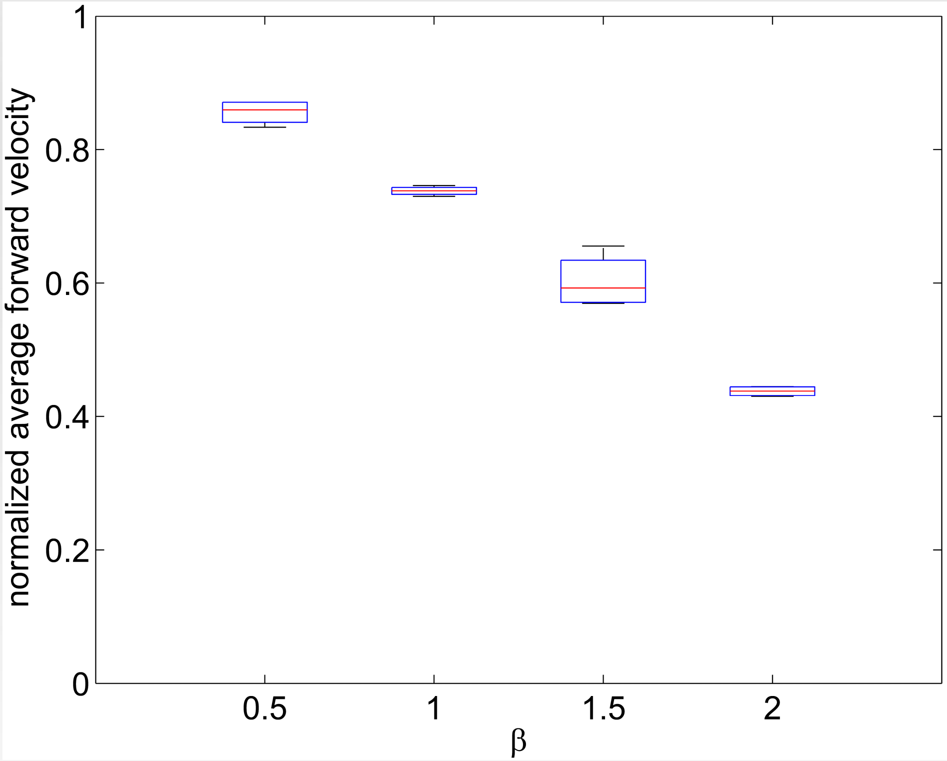
Analysis of Flocking Behavior

- Controller parameters
  - Weight of proximal control behavior
  - Maximum forward speed
  - Proportional gain
- Virtual heading sensor characteristics
  - Heading noise
  - Number of perceived neighbors
  - Range

Weight of Proximal Control

$$a = \alpha h + \beta p$$

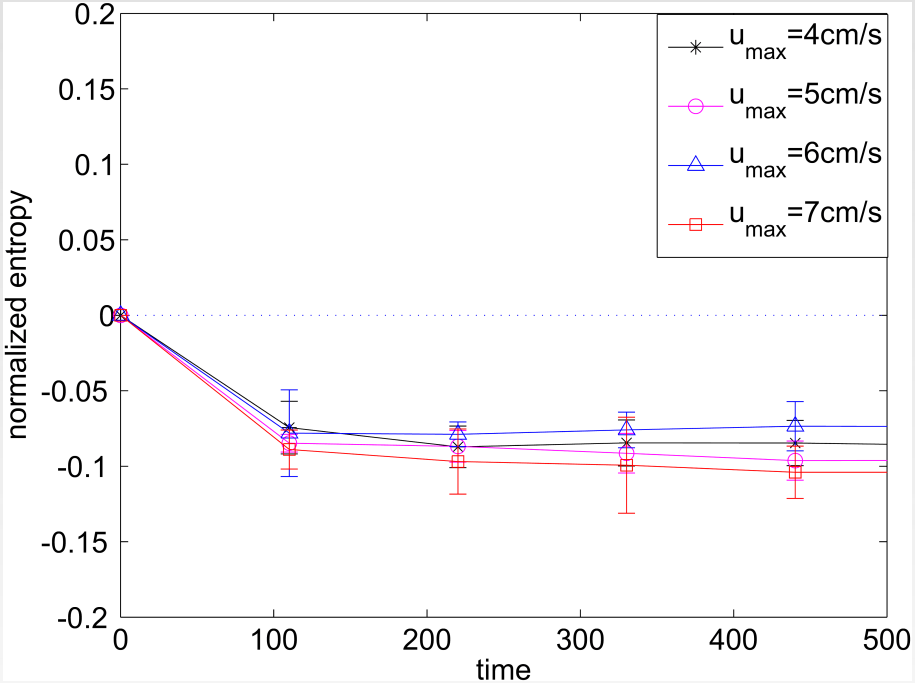


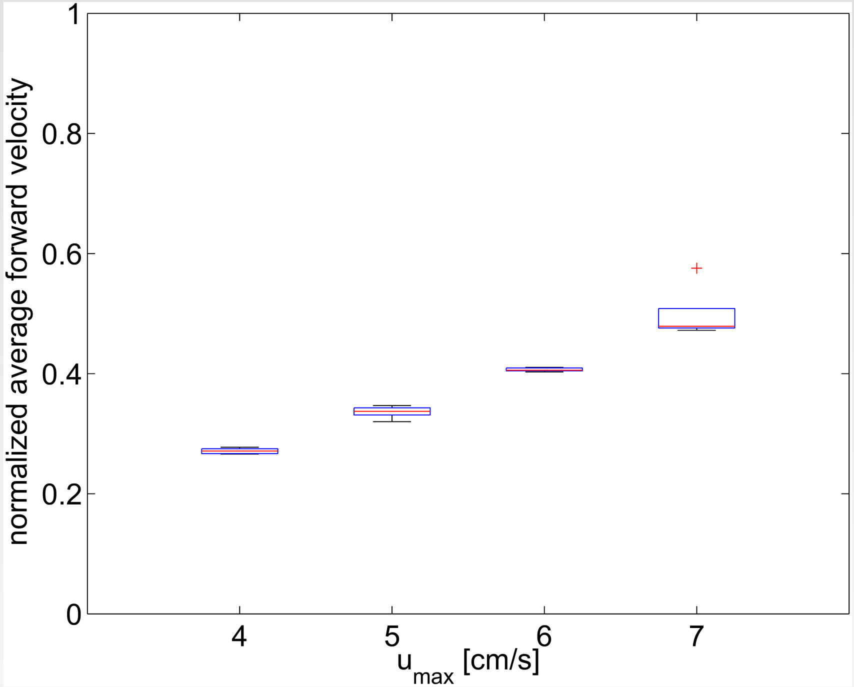


(1)β enables cohesion, small β cannot preserve connectivity
(2)β decreases average forward velocity

Maximum Forward Speed

$$u = \begin{cases} \left(\frac{\mathbf{a}}{\|\mathbf{a}\|}.\hat{a}_c\right)^\gamma u_{max} & \text{if } \frac{\mathbf{a}}{\|\mathbf{a}\|}.\hat{a}_c \geq 0 \\ 0 & \text{otherwise} \end{cases}$$

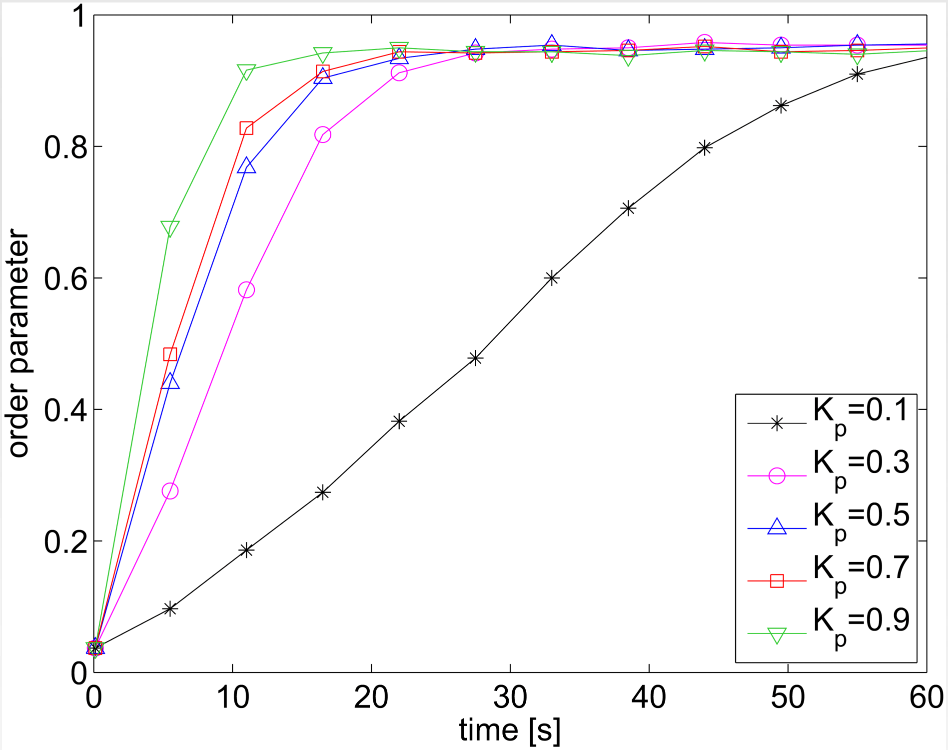


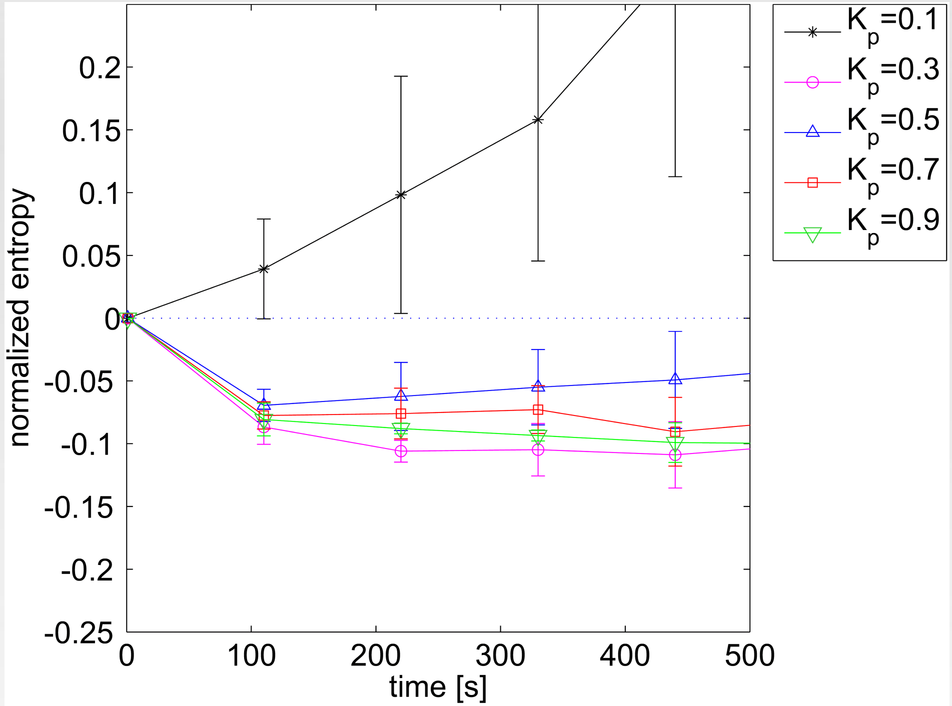


(1)Increasing u_{max} increases the average forward velocity
(2)Order and entropy not effected

Proportional Gain

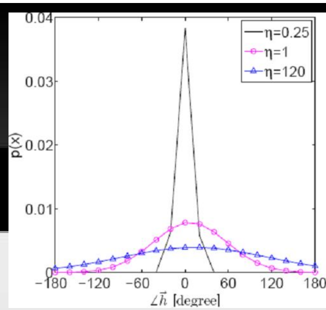
$$\omega = (\angle \mathbf{a} - \angle \hat{a}_c) K_p$$

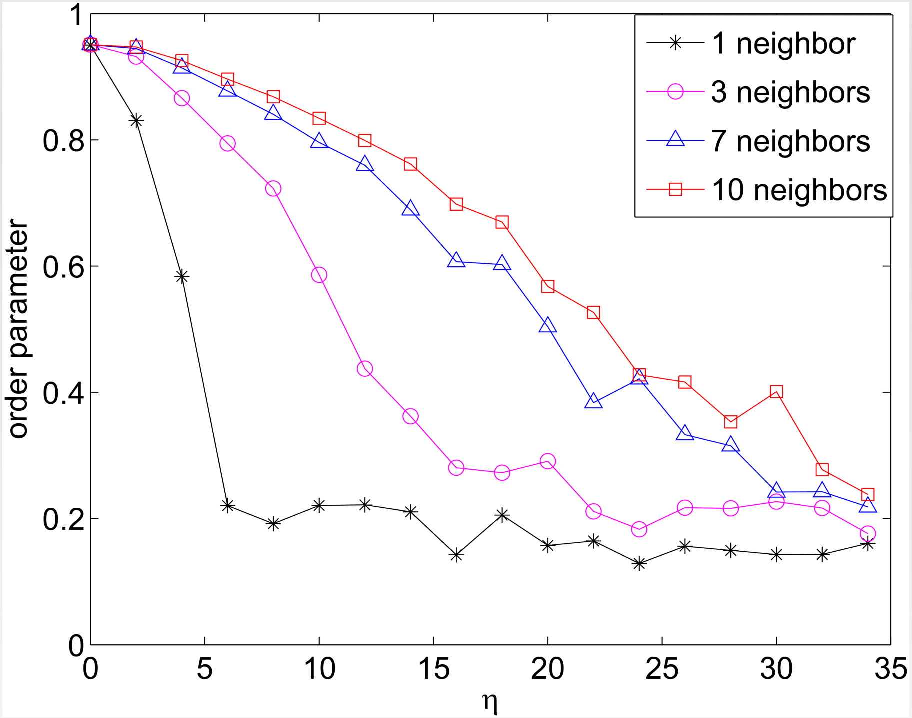


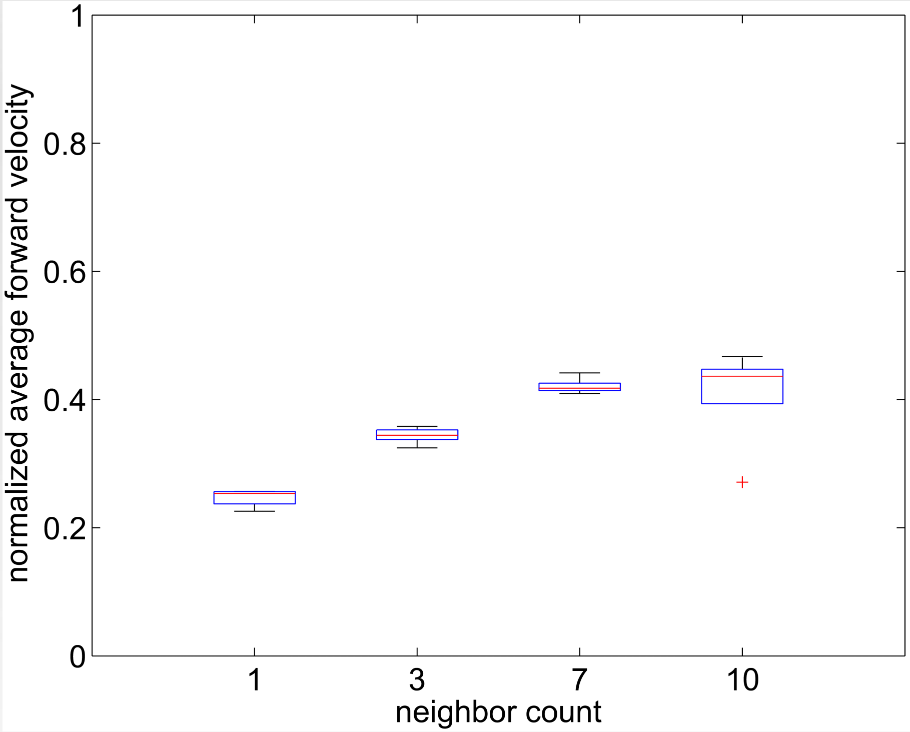


(1)Kp effects connectivity of the group
(2)Smaller Kp fails to maintain connectivity
(3)Large Kp decreases the average forward velocity

Heading Noise/Number of Perceived Neighbors







(1)Behavior robust to sensing noise
(2)Number of perceived neighbors increases robustness to noise

Range

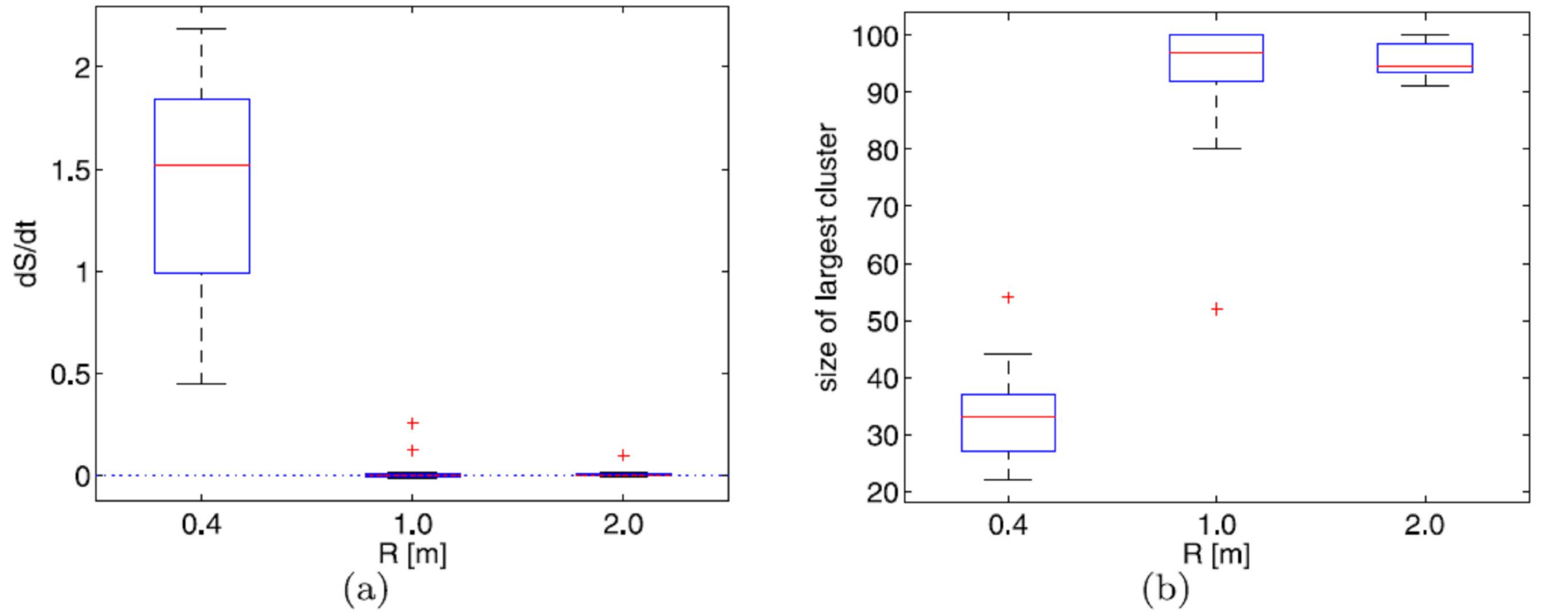


Fig. 18 The range of wireless communication (R) experiments. (**a**) Box-plot of the rate of change of entropy. (**b**) Box-plot of the size of the largest cluster

(1)Size of the flock depends on the range of communication
(2)Flock separates into smaller clusters when R<150cm
(3)Clusters have aligned and cohesive motion

Discussions

Range experiments

(1)Aligned motion is not observed when the range of communication is local
(2)Results are in accordance with the Mermin-Wagner (Mermin et al.; 1966) which states that long-range order cannot be achieved with short-range interactions
(2)Due to quasi-static movement of robots long-range interactions only be possible when the communication range covers the whole group

Simulations of VNM

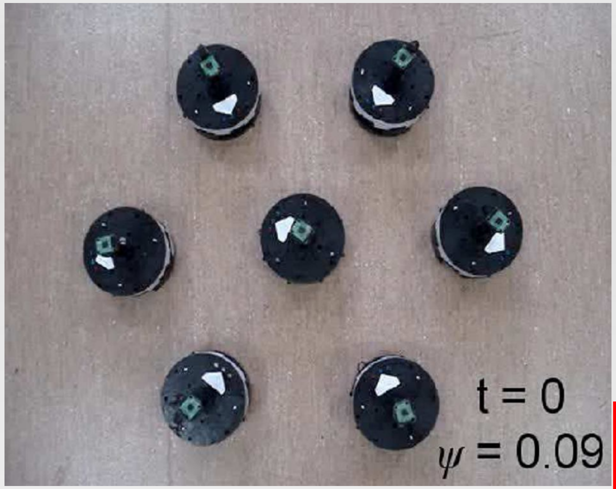
(1)Aligned motion of particles are observed only when a distant particle exists in the neighbors of particles
(2)This is due to the fact that information cannot spread in the group with stationary particles having only local neighbors

Simulations of SDP

(1) In SDP, particles are diffusing with respect to each other unlike quasi-static nature of Kobots, hence information is spread among the flock even with local neighbors

Modeling and Analysis

headings unaligned



disordered system

Phase Transition

Density of the robots
Sensing noise
Number of VHS neigh.
Actuation noise

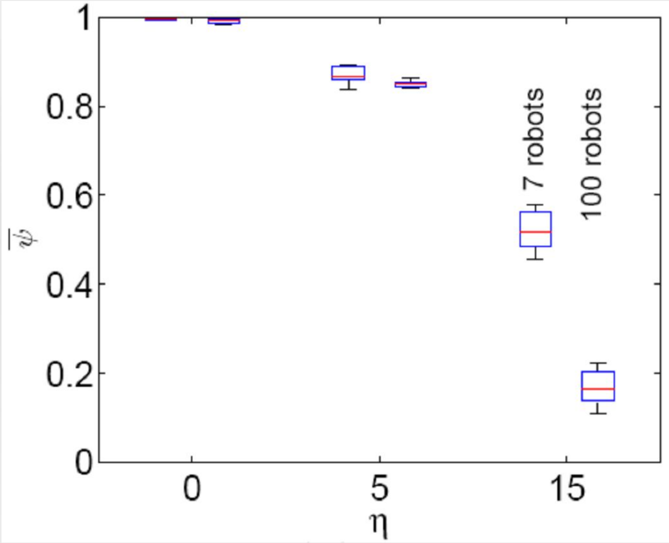
headings aligned

ordered system

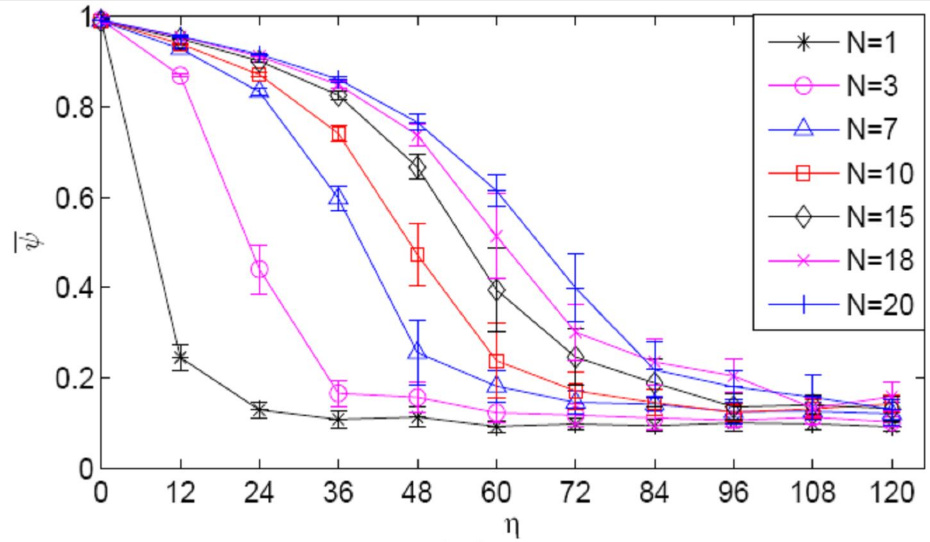
1. **Model the phase transition in flocking using a simple model**
2. **Analytical treatment of the model to predict the critical noise value**
3. **Numerical treatment of the model to predict the phase transition diagram**

• Turgut A.E., Huepe, C, Celikkanat H., Gokce, F. and Sahin, E. (2008) . Modeling Phase Transition in Self-Organized Mobile Robot Flocks. 6th International Conference on Ant Colony Optimization and Swarm Intelligence (ANTS'08).

Phase Transition in Flocking



- (1) One VHS neighbor
- (2) 7 and 100 robots



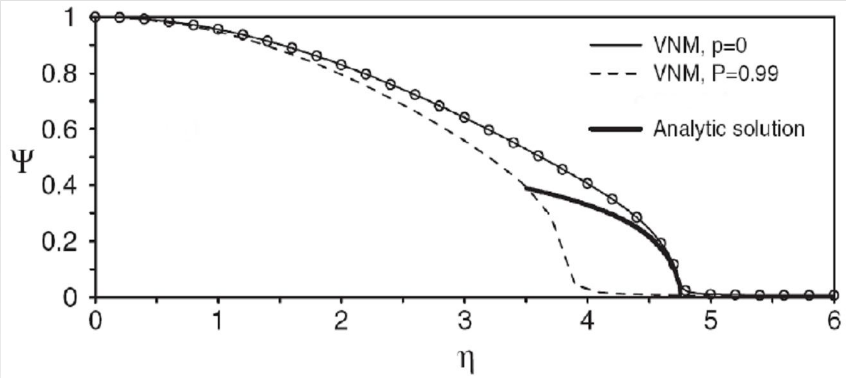
- (1) Several VHS neighbor values tested
- (2) 100 robots

- (1) An increase in noise decreases the order for a constant number of VHS neighbors.
- (2) An increase in the number of neighbors increases the robustness to noise.
- (3) Finite size effects observed in the 7-robot case.
- (4) Disorder-to-order phase transition is continuous.

Phase transition in mass-less particles (from statistical physics)

- **Vectorial network model**:

  Transition from unaligned to aligned motion below a critical noise value. (Aldana et al.; 2003)
  - Stationary particles
  - Actuation noise
  - Local/global neighbors
  - Heading alignment



1. **No restriction in the turning rate of particles.**
2. **No inertia like term.**
3. **Inconvenient to model phase transition in flocking.**

Stiff-Vectorial Network Model

$\mathcal{H}(t) = \{\vec{h}_1(t), \vec{h}_2(t), \cdots, \vec{h}_M(t)\}$ where $\vec{h}_j(t) = e^{i\theta_j(t)}$ is the heading vector of the j^{th} particle

$$\vec{h}_j(t+1) = \kappa e^{i\theta_j(t)} + \lambda \sum_{k=1}^{N} e^{i\theta_k(t)} + \eta \sum_{k=1}^{N} e^{i\xi_k(t)}$$

Persistence term

Models the inertia of the robots

Interaction term

Models the heading alignment with randomly chosen VHS neighbors

Noise term

Models the sensing noise in VHS

Analytical Solution of S-VNM

- Computation of the critical noise value(η_c) in terms of κ, λ and *N*.
- Compute the probability density function (PDF) of each term.
- At the steady-state PDF of $\theta_j(t+1) = \theta_j(t)$ → closed expression for the PDF of θ_j.
- Find the value of η at which a constant distribution of θ_j becomes unstable → η_c. Below which the distribution assumes a preferred direction.

Analytical Solution of S-VNM

- $\Gamma = 1$ determines η_c in terms of model parameters and for the specific parameter set to capture the dynamics of flocking (κ=1.5, λ=22)

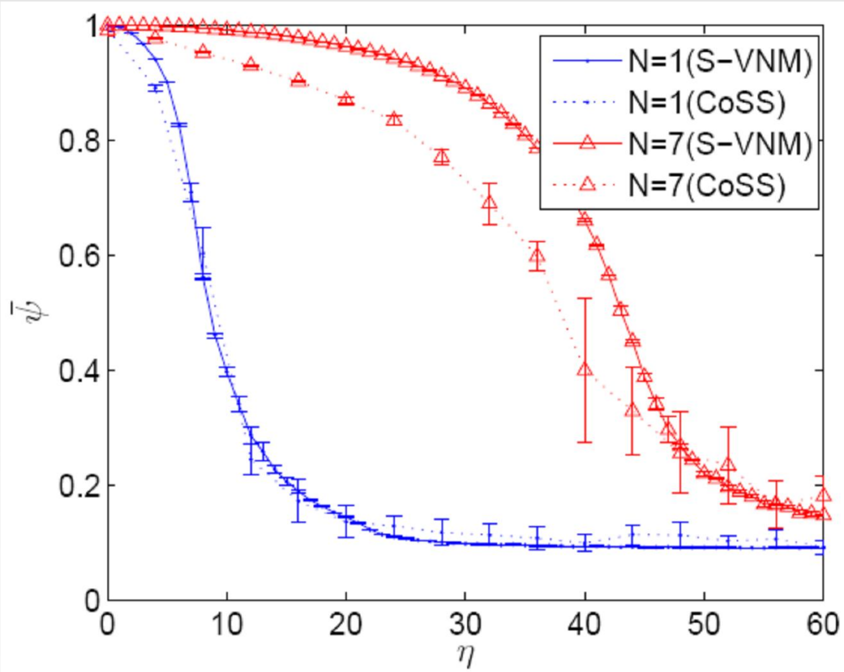
$$\Gamma = \frac{\sqrt{\pi}\; e^{\frac{-\kappa^2}{2N(1+\eta^2)}}}{2\sqrt{N(1+\eta^2)}} \left[(N+\kappa)\, I_0\left(\frac{\kappa^2}{2N(1+\eta^2)}\right) + \kappa\, I_1\left(\frac{\kappa^2}{2N(1+\eta^2)}\right)\right]$$

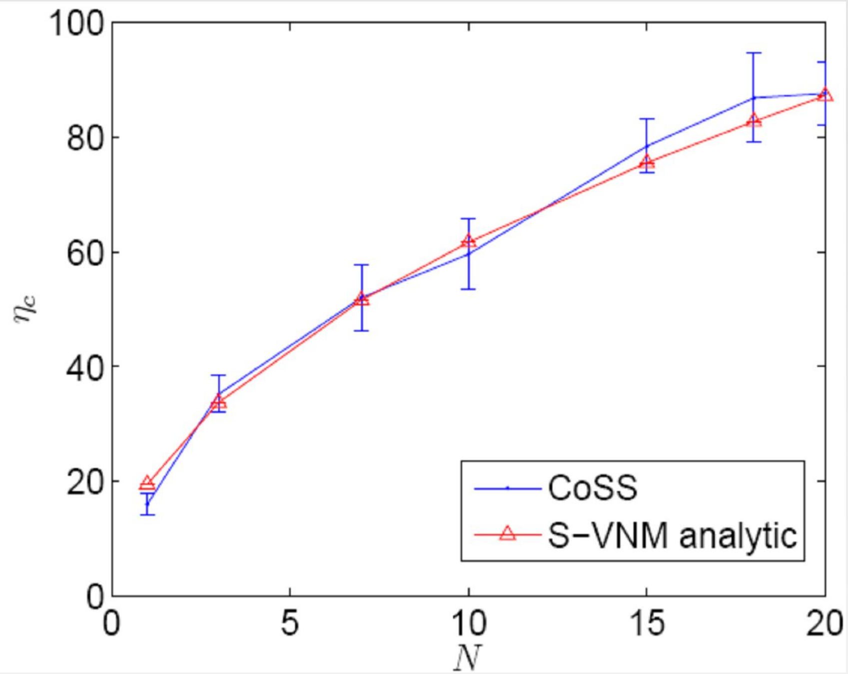
1 0

- And neglecting κ since it is small, the result becomes

$$\eta_c = \lambda\sqrt{\frac{N\pi}{4}}$$

Results of S-VNM





(1) Numerical solution
(2) N=1 and N=7

(1) Analytic results
(2) Valid for N>5

Controlling flocking

- Adding "direction preference":

$$a = \alpha h + \beta p + \gamma d$$

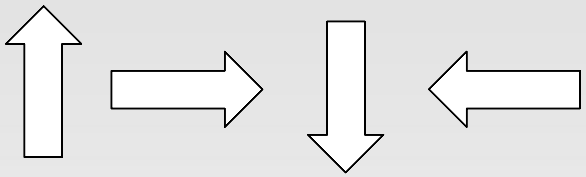
- Some robots are "informed" of a direction of preference

- They try to align with the preferred direction:
  - no universal leaders
  - no explicit communication of information
  - some robots have a tendency to move in a specific direction

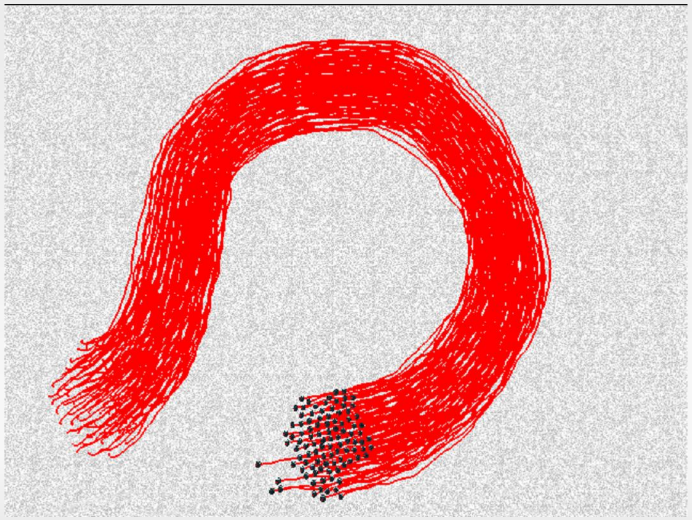
• Celikkanat H., Turgut A.E., and Sahin, E. (2008) . Control of a Mobile Robot via Informed Robots. 9th International Symposium on Distributed Autonomous Robotic Systems (DARS'08).

Controlling Swarm of 100 Robots

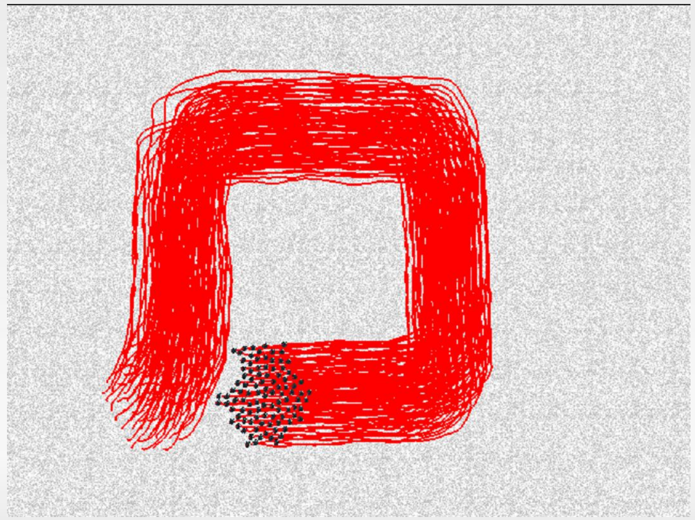
- 100 robots in flock
- "Information" changes every 120 seconds:



10 informed

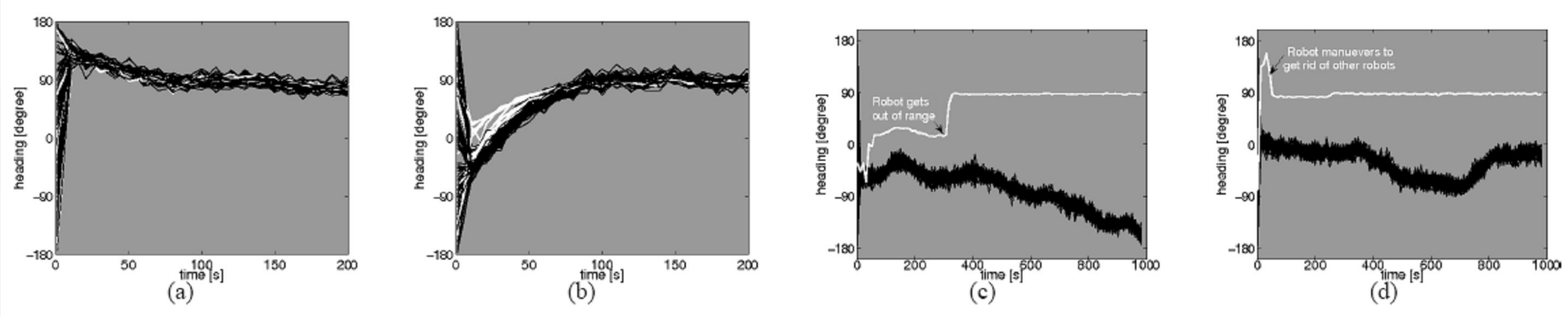


50 informed

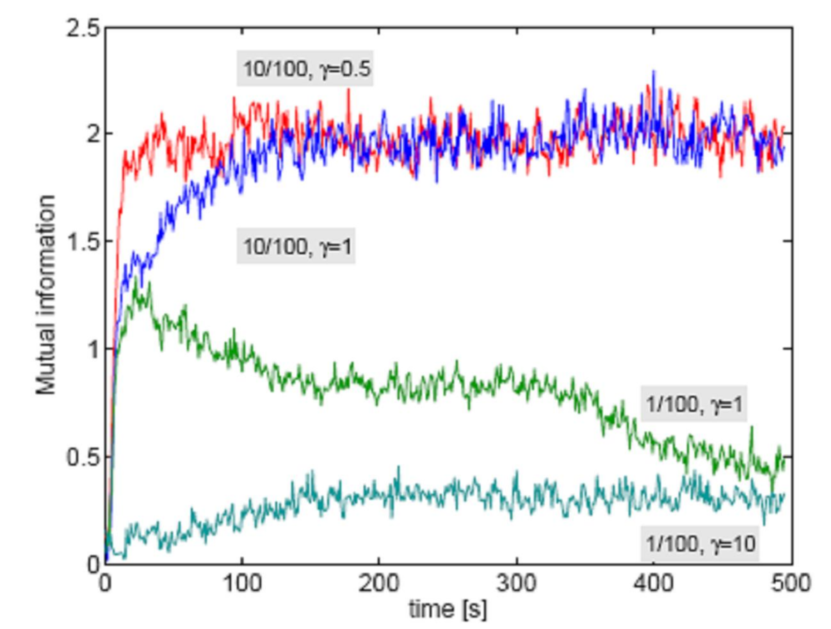


Mutual Information

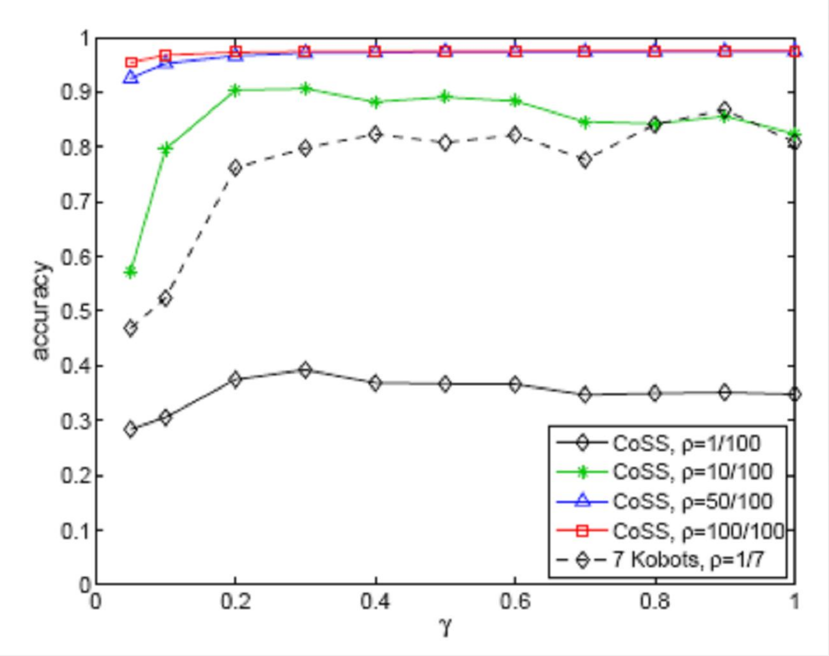
$$a = \alpha h + \beta p + \gamma d$$

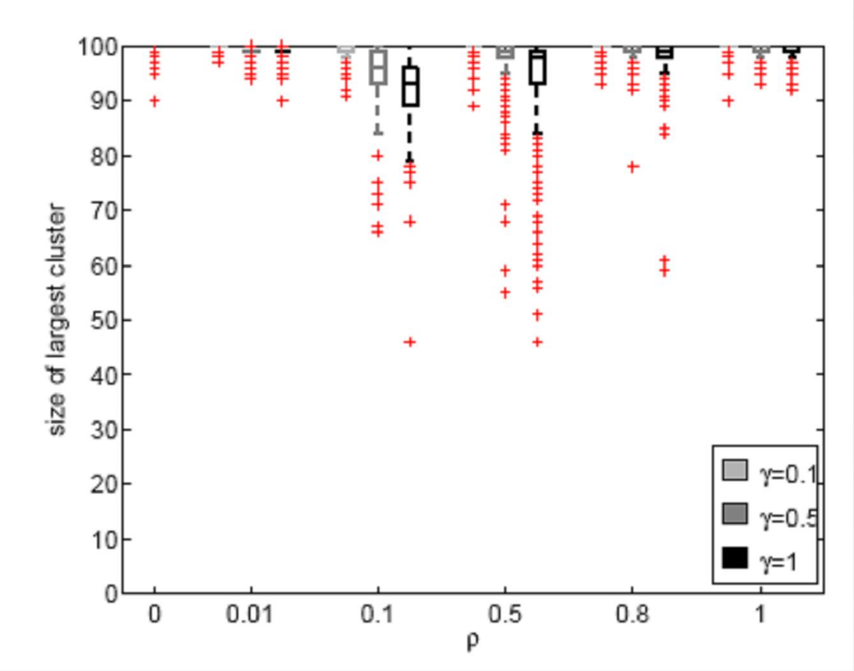


- Rate of transfer between informed and naïve robots measured as Mutual Information.



Controllability





Questions?

Thanks for your attention!

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