Swarm intelligence

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Outline

- Swarm intelligence
- Ant foraging behavior
- From biology to optimization
- Ant System and Ant Colony Optimization
- Swarm-bots and other applications in engineering

Swarm Intelligence

Collective intelligence emerging in groups of (simple) agents.

Swarm Intelligence

Roots in models of social insects behavior:

- Foraging behavior
- Division of labor and task allocation
- Cemetery organization
- Nest building

Swarm Intelligence

Properties of collective intelligence systems:

- Distributed computation
- Direct and **indirect** interactions
- Agents equipped with simple computational capabilities
- Robustness
- Adaptiveness

Self-organization

Dynamical mechanisms whereby structures appear at the global level from interactions among lower-level components.

- Creation of spatio-temporal structures
- Possible coexistence of several stable states (multistability)
- Existence of bifurcations when some parameters are varied

Self-organization

Ingredients:

- Multiple interactions among agents
- Positive feedback
- Negative feedback

Self-organization

Ingredients:

- Multiple interactions among agents
  - Simple agents (e.g., rule based)
  - Sistems composed of many agents
- Positive feedback
- Negative feedback

Self-organization

Ingredients:

- Multiple interactions among agents
- Positive feedback
  - Reinforcement of most common behavior patterns
  - Amplification of random fluctuations and structure formation
- Negative feedback

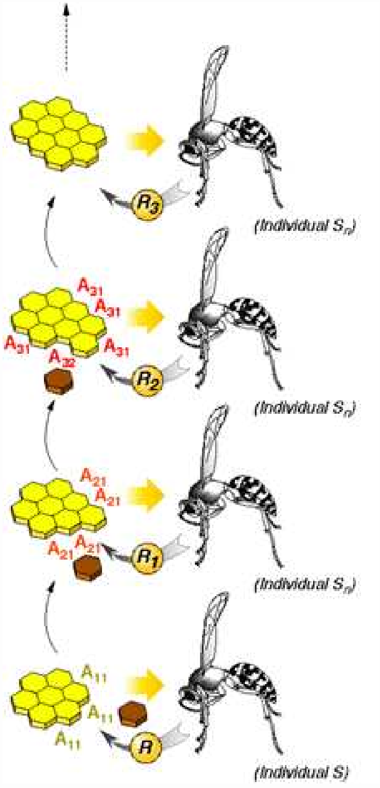
Self-organization

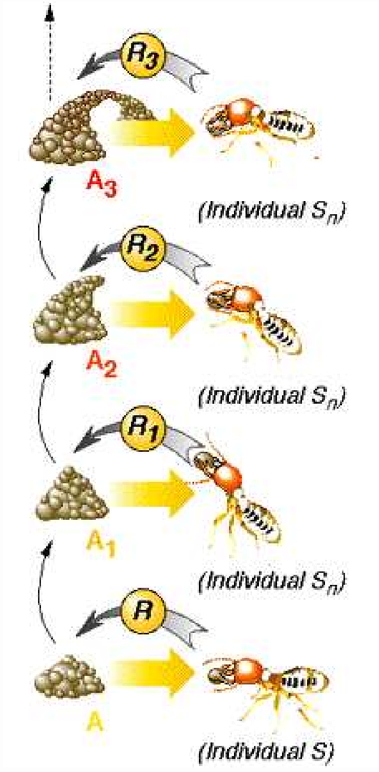
Ingredients:

- Multiple interactions among agents
- Positive feedback
- Negative feedback
  - Saturation
  - Competition
  - Resource exhaustion

Stigmergy

One agent modifies the environment and the other agent reacts to the changed environment.





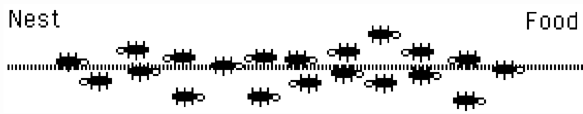
Ant Colony Optimization

- Population-based metaheuristic inspired by the foraging behavior of ants
- Ants can find the shortest path between the nest and a food source
- Heuristic strategy for optimization problems

The model

- While walking ants deposit a substance called *pheromone* on the ground
- They choose with higher probability paths that are marked by stronger pheromone concentrations
- Cooperative interaction which leads to the emergence of short(est) paths

Ant foraging behavior



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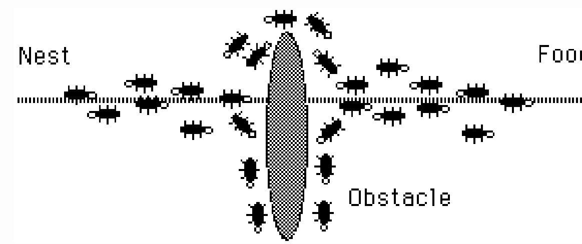

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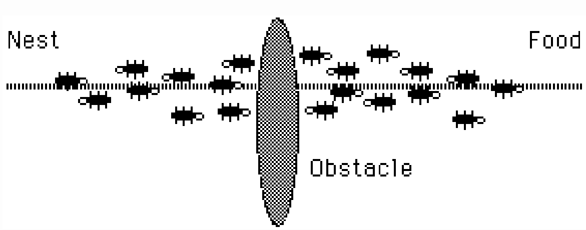

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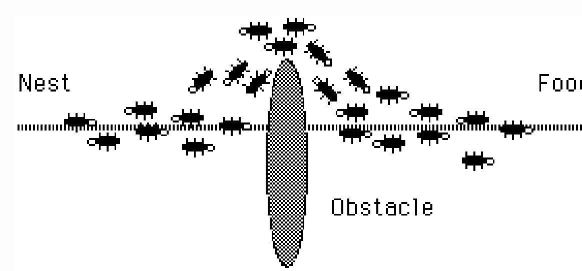
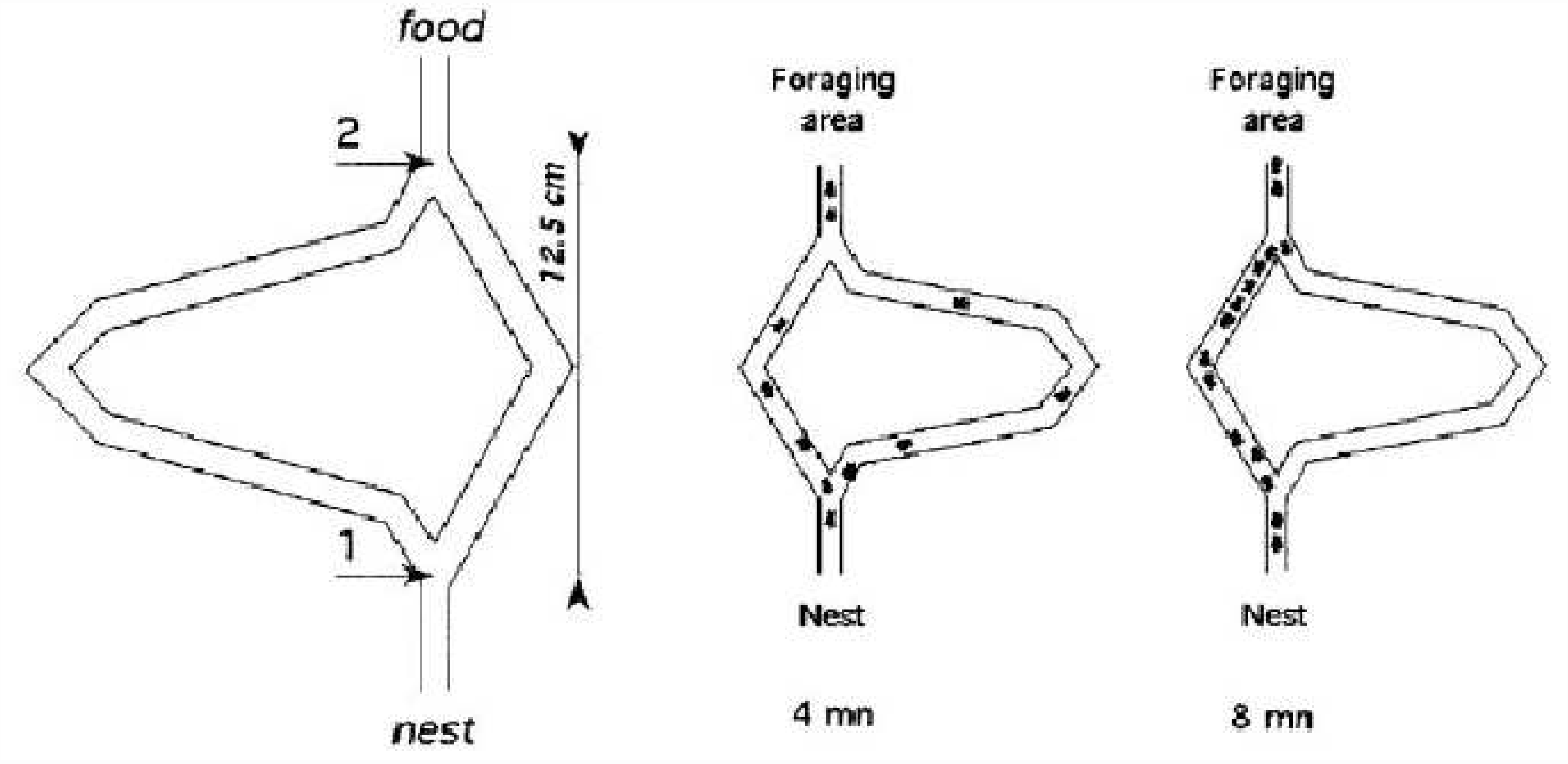


(4)

The double bridge



Ant Colony Optimization

Parametrized probabilistic model – the *pheromone model* – that is used to model the chemical pheromone trails.

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Ants incrementally construct solutions by adding components to a partial solution under consideration

Ants perform stochastic walks on the *construction graph*: a completely connected graph $\mathcal{G} = (\mathcal{C}, \mathcal{L})$.

ACO construction graph

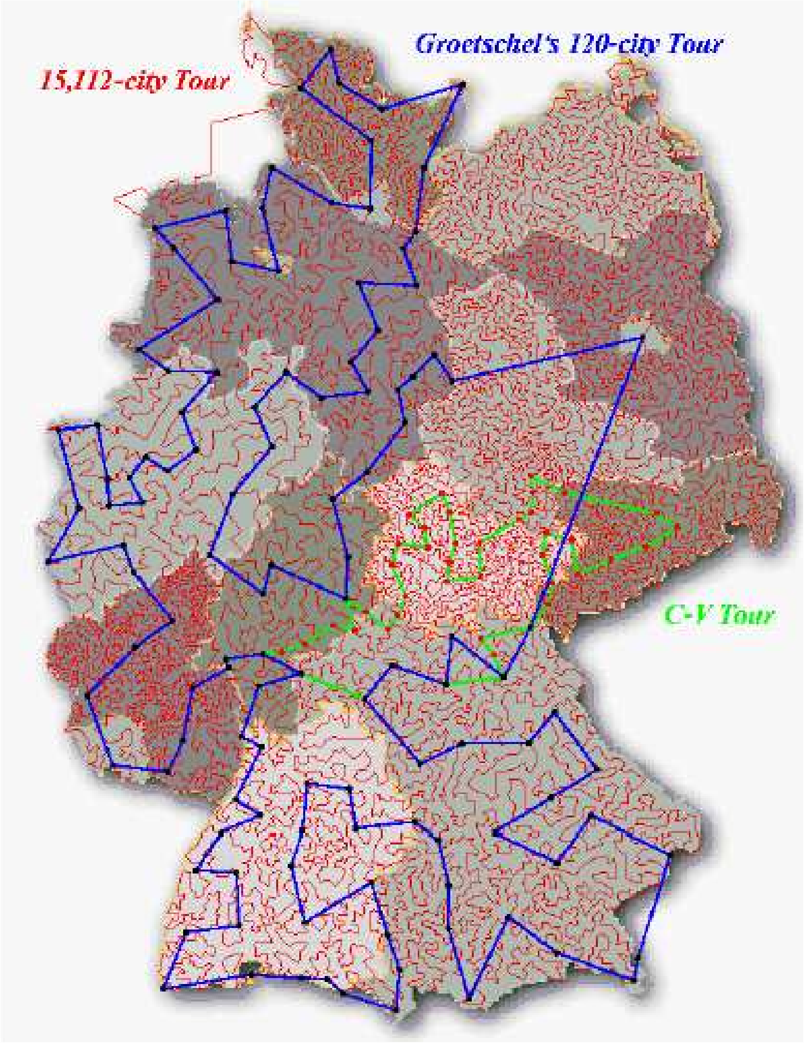
$\mathcal{G} = (\mathcal{C}, \mathcal{L})$

- vertices are the solution components $\mathcal{C}$
- $\mathcal{L}$ are the connections
- *states* are paths in $\mathcal{G}$

Solutions are *states*, i.e., encoded as paths on $\mathcal{G}$

Constraints are also provided in order to construct feasible solutions

Example: TSP



Example

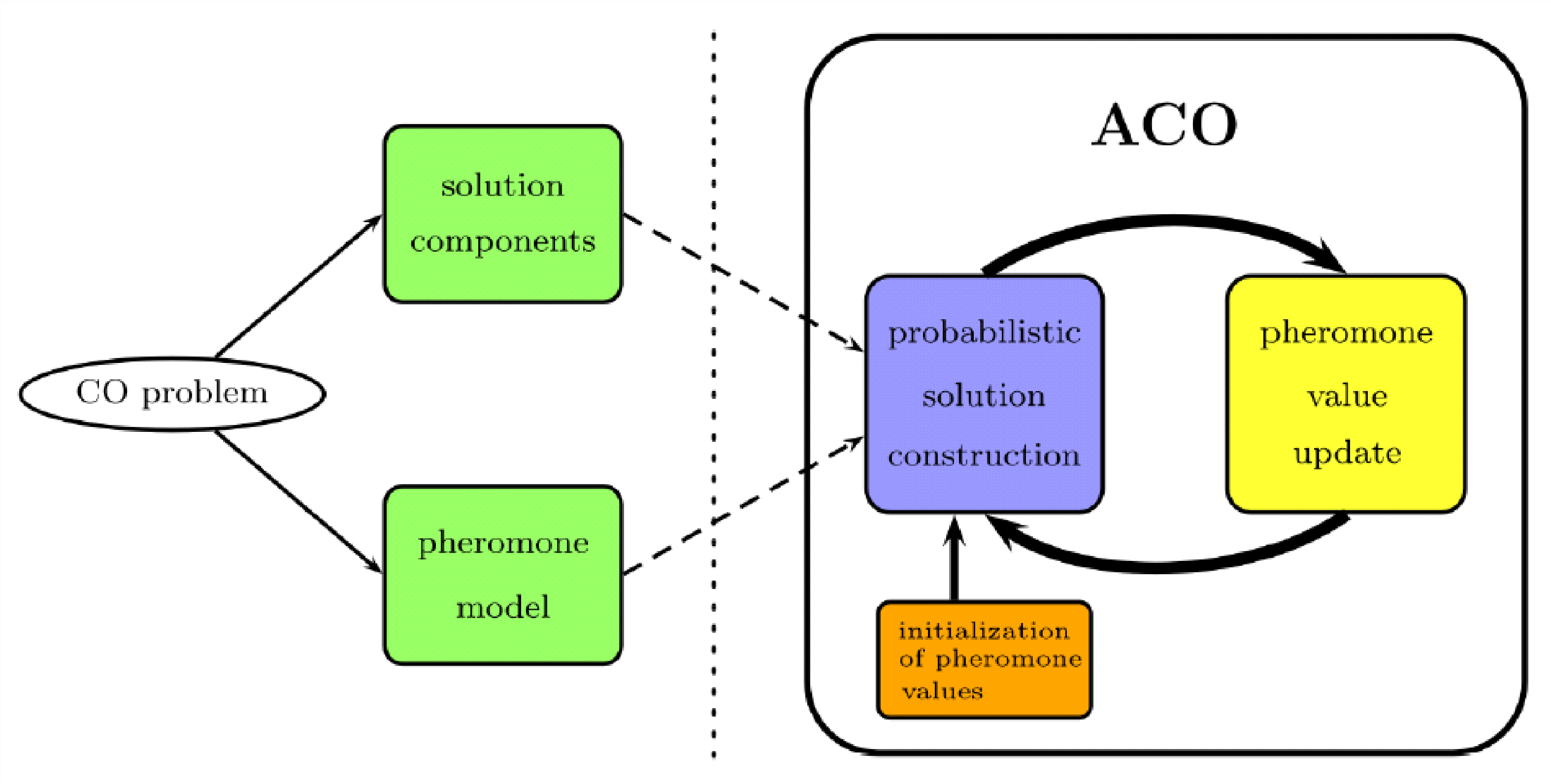
One possible TSP model for ACO:

- nodes of $\mathcal{G}$ (the components) are the cities to be visited;
- states are partial or complete paths in the graph;
- a solution is an Hamiltonian tour in the graph;
- constraints are used to avoid cycles (an ant can not visit a city more than once).

Sources of information

- Connections, components (or both) can have associated pheromone trail and heuristic value.
- Pheromone trail takes the place of natural pheromone and encodes a long-term memory about the whole ants' search process
- Heuristic represents a priori information about the problem or dynamic heuristic information

The basic principle



Ant system

- First ACO example
- Ants construct a solution by building a path along the construction graph
- The *transition rule* is used to choose the next node to add
- Both heuristic and pheromone are used
- The pheromone values are updated on the basis of the quality of solutions built by the ants

Ant system

InitializePheromoneValues()
while termination conditions not met **do**
  for all ants $a \in \mathcal{A}$ **do**
    $s_a \leftarrow$ ConstructSolution(τ,η)
  end for
  ApplyOnlineDelayedPheromoneUpdate()
end while

Ant system

The probability of moving from city i to city j for ant k is:

$$p_{ij}^{k} = \begin{cases} \frac{[\tau_{ij}]^{\alpha}[\eta_{ij}]^{\beta}}{\sum_{k \in \text{feasible}_k} [\tau_{ik}]^{\alpha}[\eta_{ik}]^{\beta}} & \text{if} \quad j \in \text{feasible}_k \\ 0 & \text{otherwise} \end{cases}$$

α e β weight the relative influence of pheromone and heuristic

Ant System

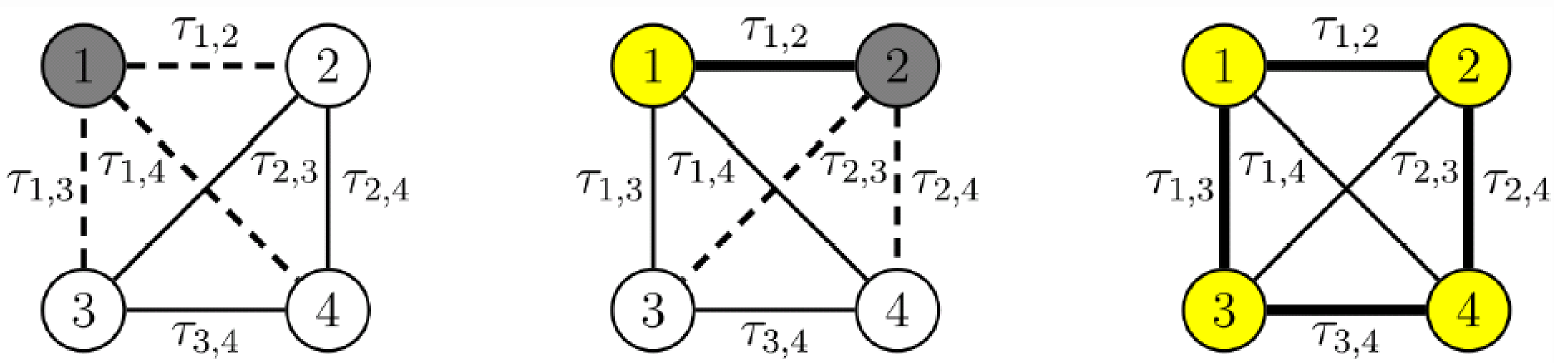
Pheromone update rule:

$$\tau_{ij} \leftarrow (1-\rho)\cdot\tau_{ij} + \sum_{k=1}^{m}\Delta\tau_{ij}^{k} \qquad (\rho : \text{evaporation coefficient})$$

$$\Delta\tau_{ij}^{k} = \begin{cases} \frac{1}{L_k} & \text{if ant } k \text{ used arc } (i,j) \\ 0 & \text{otherwise} \end{cases}$$

L_k: length of the tour built by ant k

A pictorial view



$$\mathbf{p}(e_{1,j}) = \frac{\tau_{1,j}}{\tau_{1,2} + \tau_{1,3} + \tau_{1,4}} \qquad \mathbf{p}(e_{2,j}) = \frac{\tau_{2,j}}{\tau_{2,3} + \tau_{2,4}}$$

High-level algorithm

while termination conditions not met **do**
ScheduleActivities
AntBasedSolutionConstruction()
PheromoneUpdate()
DaemonActions() {optional}
end ScheduleActivities
end while

Solution construction

- Ants move by applying a *stochastic local decision policy* that makes use of the pheromone values and the heuristic values on components of the construction graph.
- While moving, the ant keeps in memory the partial solution it has built in terms of the path it was walking on the construction graph.

Pheromone Update

- Ants can update the pheromone trail during solution construction (*online step-by-step pheromone update*).
- Ants can retrace the same path backward and update the pheromone trails of the used components according to the quality of the solution (*online delayed pheromone update*).
- *Pheromone evaporation* always applied $\rightarrow$ the pheromone trail intensity on the components decreases over time.

Daemon Actions

- Can be used to implement centralized actions which cannot be performed by single ants. E.g.,
  - local search procedure applied to the solutions built by the ants
  - collection of global information used to decide whether to deposit additional pheromone to bias the search process from an non-local perspective

ACO: State of the art

- $\mathcal{MAX}$-$\mathcal{MIN}$ Ant System
- Hyper-cube Framework
- Multi-level ACO
- Beam ACO

ACO applications

- Combinatorial optimization
- Mixed integer-continuous optimization
- Networks: AntNet

Other applications

- Clustering
- Division of labor and task allocation
- Coordinated motion
- Cooperative transport
- Self-assembling

The swarm-bots project

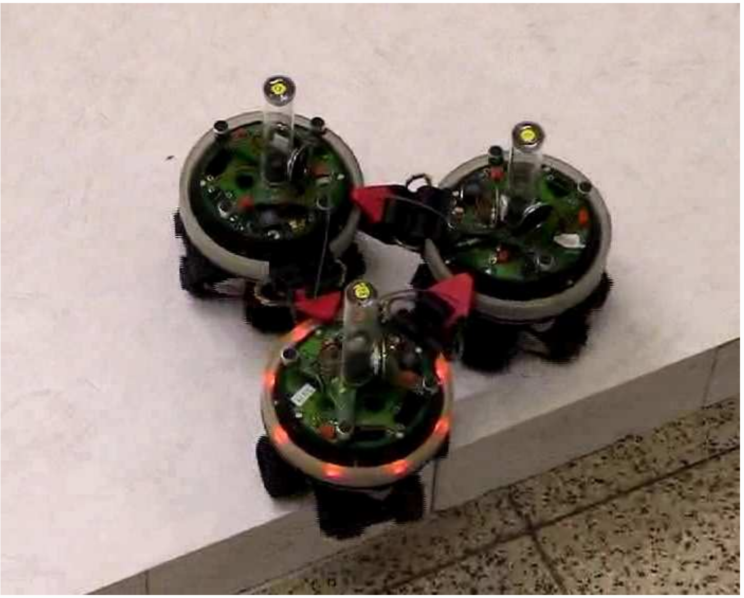
GOAL: Study a novel approach to the design and implementation of self-organising and self-assembling artefacts

Institutes involved:

- IRIDIA - Université Libre de Bruxelles (Belgium)
- EPFL - Lausanne (Switzerland)
- IDSIA - Lugano (Switzerland)
- CNR-IP - Rome (Italy)

Swarm-bots: results

- Hole/obstacle avoidance

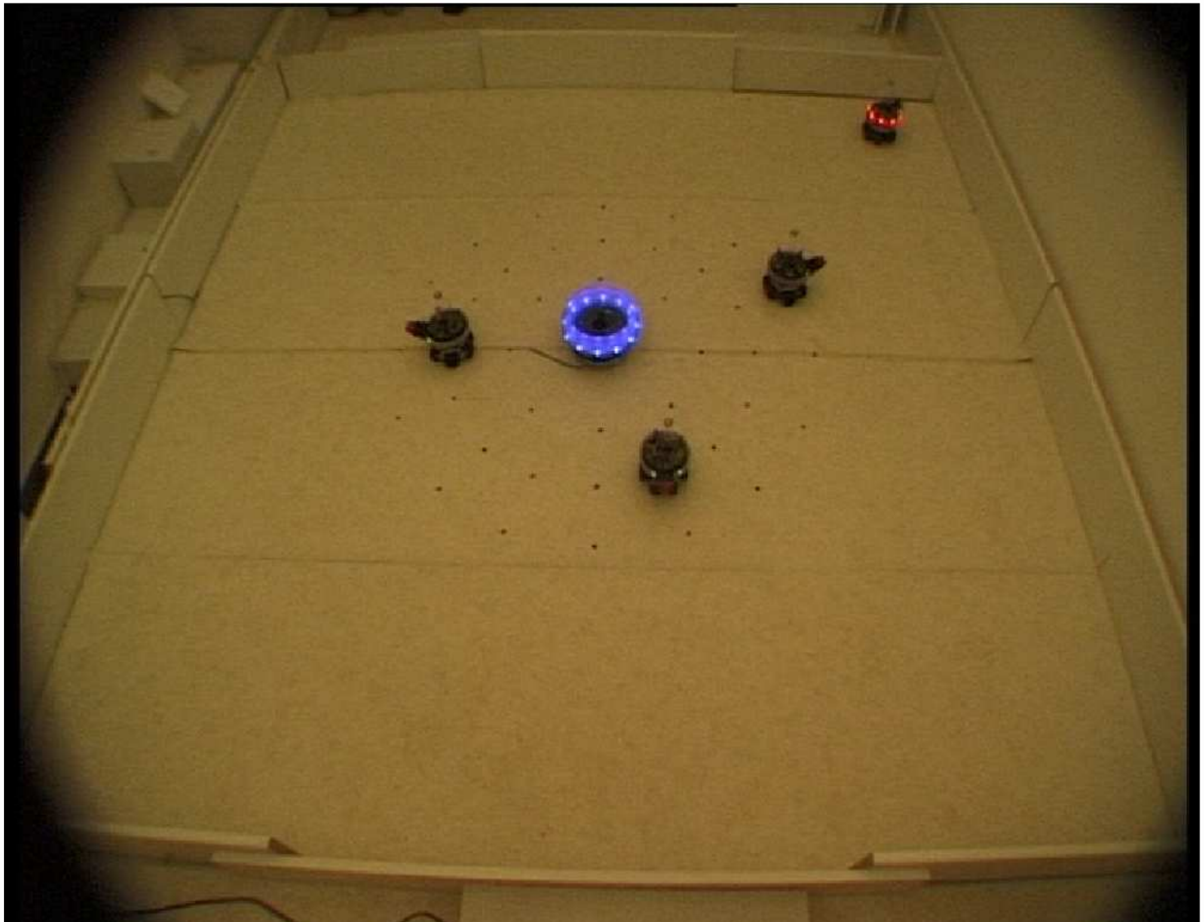


Swarm-bots: results

- Adaptive division of labour

Swarm-bots: results

- Finding object/goal



Swarm-bots: results

- Cooperative transport

References

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- E.Bonabeau, M.Dorigo, G.Theraulaz. *Swarm Intelligence. From natural to artificial systems*. Oxford University Press, 1999.
- C. Blum. Ant colony optimization: Introduction and recent trends. Physics of Life Reviews, 2(4):353-373, 2005.
- S.Camazine, J.-L.Deneubourg, N.R.Franks, J.Sneyd, G.Theraulaz, E.Bonabeau. *Self-Organization in Biological Systems*. Princeton University Press, 1999.

Internet resources

- http://iridia.ulb.ac.be/∼mdorigo/ACO/ACO.html
- www.swarm-bots.org