California Institute of Technology

EE150

Swarm Intelligence

Winter 2000

Table of Contents:

Overview:

Swarm Intelligence is a new computational and behavioral metaphor for solving distributed problems; it is based on the principles underlying the behavior of natural systems consisting of many agents, such as ant colonies and bird flocks . The approach emphasizes distributedness, direct or indirect interactions among relatively simple agents, flexibility, and robustness. Applications include optimization algorithms, communications networks, and robotics. In this course we study natural sy stems exhibiting swarm intelligence, and apply the principles to the control of real and simulated distributed robotic systems in the new collective robotics lab in Moore. The lab features 4 Khepera robots, controlled by 68xxx microcontroller family and 14 Moorebot robots, equipped with Linux PC processing power and wireless LAN communications; distributed robot simulators are also available. Lab work and projects are a major component of the course.

The use of multiple mobile robots offers significant advantages over the use of single mobile robots: key features are the possibility of distributed sensing, distributed action, distributed learning, task dependent reconfigurability, a nd the enabling of robustness and system reliability through redundancy. Swarm Intelligence provides a new way to control multiple robot systems - the emergent strategy, where local interactions between simple robots and the environment combine and self-o rganize in such a way as to achieve the required task. The technique is inspired by the biological examples provided by social insects - bees, wasps, ants, and termites - and by swarming, flocking, herding, and shoaling phenomena in vertebrates. The abili ties of such systems appear to transcend the abilities of the constituent individual agents; in all the biological cases studied so far, the emergence of high level control has been found to be mediated by nothing more than a small set of simple low level interactions between individuals, and between individuals and the environment.

The Course will cover the following topics:

1. Introduction to swarm intelligence, collective computation, and collective action.
2. Natural examples of swarm intelligence: social insects - ants, bees, wasps, termites; emergent control of collective movement - bird flocks, grazing herds, fish schools.
3. Ant based algorithms for combinatorial optimization problems, and telecommunications routing.
4. Division of labor, task allocation, task switching, and task sequencing.
5. Clustering, brood sorting, data analysis, and graph partitioning.
6. Nest building, and self-assembling.
7. Cooperative transport by insects and robots.
8. Introduction to the Collective Robotics Lab, robots, and control methods.
9. Projects on MooreBots and simulators applying swarm intelligence principles.

Lecturers:

Dr. Alcherio Martinoli

Owen Holland

Prof. Rodney Goodman

Grad. Lecturer: Sanza Kazadi

Homework Organization:

There will be approximately seven homework assignments. The homeworks will be handed out at the Tuesday lecture and are due at 5pm the following Tuesday in the EE 150 box outside of Room 036 Moore or on file in the dedicated directories in your accounts. No late work will be accepted, unless previous arrangements have been made with the instructor. The homeworks count for 30% of your final grade.

Labs Organization:

Each week there will be a four hour lab conducted in 04 Moore or 310A Moore. The lab will consist of either a demo (in which case there will be no write-up) or a student run lab. Write-ups for the lab will be due with the homework the following week.

No late work will be accepted, unless previous arrangements have been made with the instructor. The labs count for 40% of your final grade.

Collaboration Policy:

Unless otherwise noted, you may collaborate with your fellow EE 150 students on the homework assignments. Collaboration means that you may discuss the problems and make notes during the discussion, but you may not look at that scratch work or other student's work when writing up your homework. You may not divide up the task of doing problem sets in the interpretation of collaboration. You may discuss lecture material with anyone.

Final Project:

There will be no mid-term exam for this course. The final exam will be replaced by an end-of-term project. Each project will be based on the readings and/or labs of the course. Each project must be proposed by the students and run on the equipment or simulations made available during the course. Projects will be carried out in groups of two or three. The final project is worth 30%.

- Final project proposals
- Projects:
  - Differentiation in CA by Charless Fowlkes and Augusto Callejas
  - VLSI Power Optimization using a Swarm Engineering Approach by Philip C. Tsao
  - Collective Exploration: Plume Tracking with GA by Justin David Smith
  - Dancing Kheperas by Joseph Chen
  - (Non)Cooperative Predation with GA Evolution by Matt Wilhelm
  - Cooperative Predators by Naru Sundar, Amit Kenjale, and Jason Meltzer
  - Lattice Error Correction by Stephanie Chow

Topics:

Most of the topics addressed in this lecture are covered in the book "Swarm Intelligence: From Natural to Artificial Systems", E. Bonabeau, M. Dorigo, and G. Theraulaz, Santa Fe Studies in the Sciences of Complexity, Oxford University Press, 1999.

- Week 1:
  - Tuesday
    - Organization meeting, timetable.
    - Behavior based vs AI, insects vs mammals, single vs multi-agent (758 kB pdf).
    - Introduction of key concepts such as autonomy, swarm intelligence, and adaptation (24 kB pdf)
    - Overview of tools to be used in the course (51 kB pdf).
  - Thursday
    - Social insects, stigmergy, ant foraging behavior, and self-organization (6.2 MB pdf)
- Week 2:
  - Tuesday
    - Trail laying, positive feedback (9.2 MB pdf).
  - Thursday
    - Telecommunication routing (1.9 MB pdf).
- Week 3:
  - Tuesday
    - Introduction to simulation tools: StarLogo, Khepera 2D simulator, and Webots (230 kB pdf).
  - Thursday
    - Flocking and collective movement. (2.6 MB pdf).
- Week 4:
  - Tuesday
    - Introduction to autonomous collective robotics, puck pushing and sorting, brood sorting

(13.8 MB pdf).

- Thursday
  - Division of labor and fixed-threshold task allocation (1 MB pdf).
  - Adaptive-threshold task allocation (2.8 MB pdf).
  - Introduction to Khepera and specific tools for collective autonomous robotics (234 kB pdf).

- Week 5:
  - Tuesday
    - From models to real robots: understanding collective experiments at different levels (1.5 MB pdf).
  - Thursday
    - Self-assembling in social insects (3.9 MB pdf).
    - Self-assembling in robots (2.8 MB pdf).
- Week 6:
  - Tuesday
    - Swarm engineering and ant-based combinatorial algorithms (8.0 MB pdf).
  - Thursday
    - Modelling of 3D nest structures (1.8 MB pdf).
    - Introduction to Genetic Algorithms: evolution of 2D and 3D structures (35 kB pdf).
- Week 7:
  - Tuesday
    - Evolution of robot controllers: single-robot experiments (145 kB pdf).
  - Thursday
    - Evolution of robot controllers: multiple-robot experiments (252 kB pdf).
    - Discussion of possible proposal for final projects (12 kB pdf).
- Week 8:
  - Tuesday
    - Collaborative transportation with robots (619 kB pdf).
    - Project proposals presented in class by students.
  - Thursday
    - Task allocation and contact rate regulation in ants (invited lecture of Prof. D. M. Gordon, Stanford University, CA).
- Week 9:
  - Tuesday
    - Student progress presentations.
  - Thursday
    - Student progress presentations.
- Week 10:
  - Tuesday
    - No lecture.
  - Thursday
    - Final student project presentations and demos.

Reading / Homeworks / Labs:

Chapter and section numbers refer to the book "Swarm Intelligence: From Natural to Artificial Systems", E. Bonabeau, M. Dorigo, and G. Theraulaz, Santa Fe Studies in the Sciences of

Complexity, Oxford University Press, 1999.

- Week 1:
  - Reading: chapter 1.
  - Lab: Introduction lab with real robots demonstrations in Moore 04.
- Week 2:
  - Reading:
    - sections 2.1-2.2, 2.7-2.8.
    - Schoonderwoerd R., Holland O., Bruten J., and Rothkrantz L. Ant-Based Load Balancing in Telecommunications Networks. Adaptive Behavior, 1996, Vol. 5, pp. 169-207.(85 kB ps.gz)
    - Lab: Trail following and minimum path choice (6 kB pdf).
  - Hwk 1: Extended minimum path choice (3 kB pdf).
- Week 3:
  - Reading:
    - Webots reference manual (288 kB pdf).
    - Webots user guide (1.1 MB pdf).
    - Brogan D. C. and Hodgins J. K.Group Behaviors for Systems with Significant Dynamics. *Autonomous Robots*, 1997, Vol. 4, No. 1, pp. 137-153 (223 kB ps.gz).
  - Lab: Webots tutorial (90 kB pdf).
  - Hwk 2: Flocking in Webots (21 kB pdf).
- Week 4:
  - Reading:
    - Chapter 3 and 4 (not 4.4, 4.5).
    - Khepera user manual (670 kB pdf).
    - Holland O. and Melhuish C. Stigmergy, Self-Organization, and Sorting in Collective Robotics. *Artificial Life*, 1999, Vol. 5, pp. 173-202 (8.29 MB pdf).
    - Krieger M. B. and Billeter J.-B. The Call of Duty: Self-Organised Task Allocation in a Population of Up to Twelve Mobile Robots. *Robotics and Autonomous Systems*, 2000, Vol. 30, No. 1-2, pp. 65-84 (1 MB pdf).
    - Lab: Clustering demonstration with the MooreBots.
  - Hwk 3: Distributed aggregation and segregation algorithms in Webots (30 kB pdf).
- Week 5:
  - Reading:
    - Sections 6.1, 6.4.1-6.4.3.
    - A. Martinoli. Swarm Intelligence in Autonomous Collective Robotics: From Tools to the Analysis and Synthesis of Distributed Collective Strategies. Ph.D. Thesis Nr. 2069, October, 1999, DI-EPFL, Lausanne, Switzerland, chapter 4.
    - Khepera gripper manual (127 kB pdf).
  - Lab: Khepera tutorial (68 kB pdf).
  - Hwk 4: Arena cleaning with Khepera: serial controlled mode (7kB pdf).
- Week 6:
  - Reading:
    - sections 2.3-2.6, 6.2, 6.3, 6.4.4, 6.5.
    - Dorigo M. and Gambardella L. M. Ant Colony System: A Cooperative Learning Approach to the Traveling Salesman Problem. *IEEE Trans. on Evolutionary Computation*, 1997, Vol. 1,No. 1,pp. 53-66 (186 kB pdf).
    - Khepera BIOS Manual (670 kB pdf).

  - Lab: Swarm engineering (37 kB pdf).
  - Hwk 5: Swarm engineering: puck-collection (43 kB pdf).
- Week 7:
  - Reading:
    - chapter 7
    - Floreano D. and Mondada F. Evolution of Homing Navigation in a Real Mobile Robot. *IEEE Trans. on System, Man, and Cybernetics: Part B*, 1996, Vol. 26, No. 3, pp. 396-407 (656 kB ps.gz).
    - Moorebot manual (35 kB pdf).
  - Lab: Moorebot tutorial (43 kB pdf).
  - Hwk 6: Clustering with Khepera: download mode (9 kB pdf).
- Week 8:
  - Reading: Gordon D. M. The Organization of Work in Social Insect Colonies. *Nature*, 1996, Vol. 380, pp. 121-124.
  - Hwk: final project.
- Week 9:
  - Hwk: final project.
- Week 10:
  - Hwk: final project.

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Feedback

Send comments and questions:

- on content and general information to Dr. Alcherio Martinoli, alcherio@micro.caltech.edu
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