Course: Bio-Inspired Coordination of Multi-Agent Systems *

1 Course Description

Multi-agent systems exist on all scales in chemistry, molecular biology, entomology, and more recently, robotics. Here, dynamic interactions between large numbers of relatively simple individuals result in complex emergent global patterns. Take as an example the amazing coordination that occurs between thousands of bees in a hive, or millions of cells joining to form hierarchical organ systems with embedded parallel and distributed functions. The success of these systems is typically associated with robustness due to redundancy and the ability to adapt to perturbations and changing goal settings making this approach of great interest to robotics.

This class will survey state of the art approaches to the design of robust behavior of robot collectives. We will focus on coordination and control, agent design, and sources of inspiration in nature. Topics include: swarm intelligence, decentralized vs. centralized systems, distributed consensus, behavior-based robotics and physical intelligence, self-organizing and self-assembling systems, modular robotics, and special topics related to collective transport and construction. The class will be based on both paper discussions and a research project.

2 Assignments

This course will involve reading and reviewing research papers, leading, and participating in class discussions, and completing a major research project. Students will write several short paper reviews during the class; reviews are due before the relevant lecture by email. Prof. Petersen will give a general introduction to the topic in the beginning of each class, after which each student is expected to lead the class discussion in at least one lecture. There will be time set aside to come discuss your lecture plan with prof. Petersen if you wish. Finally, students will undertake a major research project of their choice. The final grade will be weighted 40% on class participation and 60% on the research project.

Students taking this class will gain experience reading and reviewing scientific papers, and practice strong presentation skills both oral and written. The class will cover work done by several of the robotics faculty at Cornell University. Finally, students will experience the process of designing and conducting a full research project related to robotics, modeling and simulation, or the study of insect collectives in nature.

Academic integrity: Students are expected to follow Cornell's Code of Academic Integrity. The purpose of this code is to provide for an honest and fair academic environment.

*TR 1:25-2:40pm Fall 2016. By assistant prof. Kirstin Petersen, Cornell University, ECE dept

3 Prerequisites

This class is intended for graduate students in the field of ECE, CS, MAE, and CAM. The class is capped at 15 students, the hope is to have students of diverse technical backgrounds joining. Students will fill out an online application form, and acceptance will be decided within the first week of classes.

Students are expected to have novice experience in programming (C/C++, Python, or Matlab) and fundamental statistics. Furthermore, students must be experienced in a subset of the following topics: rapid prototyping, CAD design software, microcontrollers, and/or design of fundamental circuits and motor drivers. Students experienced in analyzing biological or chemical systems are encouraged to join. Knowledge on control-, network-, and graph-theory would be beneficial, but is not required.

4 Tentative Schedule

Weeks 1-7 will have two lectures per week, TR 1:25-2:40pm. In these weeks we will discuss relevant topics in robot collectives from bio-inspiration, to practical design, simulation, and control. In week 4 you are expected to form project teams (2-3 people per team) dependent on expertise and scientific interest. In week 5 each team must hand in a 1-page project proposal and literature review. We will discuss the potential of each project in class; you may be asked to modify your intended project based on this discussion. You are expected to start actual work on your projects in week 6; if we need to purchase material/equipment now is the time to do so. Weeks 8-11 are dedicated solely to project work, meaning one short lecture per week and individual meetings with the professor to discuss project updates. In week 9 all teams will present their progress in class. By the end of week 12 all teams must hand in a paper describing their project; in week 13 all teams will present their project in class.

Week 1 - Intro to robot collectives and swarm intelligence

Section 1, Aug 23rd

No reading. The professor will go over class topics, requirements, expectations, and give a practical introduction to the field of robot collectives.

Section 2, Aug 25th

Please read ”How to read a paper” by Mitzenmacher [1], and review on swarm intelligence [2].

Optional reading: Beni et al. [3] from 1993 is interesting for historical interest. Parunak gives a great overview of the advantages and challenges regarding multi-agent systems [4]. Barca et al. gives another (more recent) decent review of swarm robotics [5].

Everyone will sign up for class presentations. We will also discuss some potential class projects.

Week 2 - Distributed versus centralized control

Section 1, Aug 30th

Please read ”How to review a manuscript” [6], ”Networked Robots” [7], and [8] on distributed intelligence. Write a review (max 1 page) about [8], due before the lecture.

Student presentation on the comparison of a centralized and decentralized controller by Dimarogonas [9].

Section 2, Sep 1st

Please read Theraulaz [10] regarding stigmergy, and Dorigo regarding ant colony optimization [11]. Write a review (max 1 page) about [11], due before the lecture.

Optional reading: If you have an interest in pheromones, there is a great historical paper by the famous E. O. Wilson [12].

Student presentation on the paper by Dorigo, Bonabeau, and Theraulaz [13].

Week 3 - Distributed consensus: synchronization and flocking

Section 1, Sep 6th

Please read about coupled oscillators and synchronization [14], and a robotic implementation [15]. Write a review (max 1 page) about [15], due before the class.

Optional reading: For a more detailed discussion on oscillators in animal gaits I highly recommend [16]. Also, Cornell Professor Thomas Seeley is world renowned for his studies on honeybee democracy [17].

Student presentation on biological oscillators [18].

Section 2, Sep 8th

Please read about flocking [19].

Optional reading: Great paper on networked systems [20]. Furthermore, Hauert shows an interesting hybrid approach to the problem of coordinating motion between many unmanned air vehicles [21].

Student presentation on Couzin and Leonard’s work regarding informed individuals [22] and [23].

Week 4 - Behavior based robotics and physical intelligence

Section 1, Sep 13th

Please read Rodney Brooks [24], ”Intelligence without Reason”.

Optional read: This paper describes the control architecture and implementation of one of the most famous robots by Rodney Brooks at MIT [25]. Another paper introduces the famous Braitenberg machines [26].

Student presentation on behavior based robotics [27]

Student presentation on chapters 3.1-3.3 in Introduction to AI [28].

Today you will have to pick a general topic of interest for your project. We will form teams in class; if you have a preference for team mates, please let the professor know up front. A week from now each team will have to hand in a 1 page project description and literature review.

Section 2, Sep 15th

Please read [29] regarding cockroach-inspired robot legs. Write a review (max 1 page) about [29], due before the lecture.

Optional reading: This is a fantastic paper on the ties between bio-inspired robots and biology by Barbara Webb [30].

Student presentation on lizard-inspired pitch control for jumping robots [31], gecko-inspired material for climbing robots [32], and work from Prof. Shepherd's lab on soft robots [33].

Student presentation on physical intelligence by Prof. Ruina's group (passive dynamic walkers) [34], Prof. Cohen's group ()reprogrammable origami) [35], and programmable materials in architecture [36].

Week 5 - Self-organization and self-assembly

Section 1, Sep 20th

Please read articles regarding self-organized adaptive shapes [37], the Kilobots 1024 robot system [38], and robots and cockroaches [39]. Write a review (max 1 page) about one of the three papers, due before the lecture.

Student presentation on spatial 1-2D organization [40] and [41].

Each team must hand in a 1-page project proposal and literature review, due before the lecture.

Section 2, Sep 22nd

Please read about self-assembling systems [42] and [43]. Write a review (max 1 page) about [43], due before the lecture.

Optional reading: Famous papers on self-assembly of DNA [44] and [45].

Student presentation on self-assembly of minimal particles [46].

We will discuss your project proposals and literature reviews in class. You may be asked to submit an updated version based on the feedback before the next class.

Week 6 - Modular robots

Section 1, Sep 27th

Please read [47] and [48] on modular self-reconfigurable robots. No review due.

Student presentation on CKbots from UPenn [49] and the paper from Professor Kress-Gazit [50].

Section 2, Sep 29th

Please read [51] on modular robot systems and [52] on the Swarmbots project from EPFL. No review due.

Optional reading: Other popular modular robotic systems include the ATRON modules from USD [53] [54], and Superbot from USC [55] [56] [57].

Student presentation on the RoboPebbles from MIT [58, 59].

Week 7 - Collective transport and construction

Section 1, Oct 4th

Please read [60] on ant collective transport, and [61] on robot collective transport. Write a review (max 1 page) about one of the papers, due before the lecture.

Student presentation on [62] microTugs; This student will also give a short presentation on [63] during the next lecture.

Section 2, Oct 6th

Please read [64], [65], and [66] on collective construction with multi-agent systems. Write a review (max 1 page) about one of the papers, due before the lecture.

The student who presented [62] last week, will present work by Professor Knepper [63] this week.

Fall break, Oct 8th-12th

Week 8 - Flexible topic and project work

Oct 13th

We will do individual team meetings (around 20-39 minutes per team) to discuss progress/issues during class hours. Mandatory attendance in these meetings.

Before really kicking off your project, I highly recommend reading Whitesides' paper on how to write a paper/conduct a project [67]. Although this was written for chemists, most of the points carry through to robotics.

Week 9 - Project work and midway presentations

Oct 18th - 20th

At this point your project should be well underway; every team will do a 15 minute progress presentation, with 15 minutes left for questions. Mandatory attendance.

Week 10 - Flexible topic and project work

Oct 25th - 27th

In the first half of the class, we will discuss methods and recent work related to the project chosen by one of the project teams.

Afterwards, We will do individual team meetings (around 20 minutes/team) to discuss progress/issues during class hours. Mandatory attendance in these meetings.

Week 11 - Flexible topic and project work

Nov 1st - 3rd

In the first half of the class, we will discuss methods and recent work related to the project chosen by one of the project teams.

Afterwards, We will do individual team meetings (around 20 minutes/team) to discuss progress/issues during class hours. Mandatory attendance in these meetings.

By now you should be past the implementation phase and focus on analyzing and presenting your data in a clear comprehensive way; a solid analysis is the key-stone to any good project.

Week 12 - Project work and paper writing

Nov 8th - 10th

In the first half of the class, we will discuss methods and recent work related to the project chosen by one of the project teams.

Afterwards, We will do individual team meetings (around 20 minutes/team) to discuss progress/issues during class hours. Mandatory attendance in these meetings.

By the end of this week, you you should be ready to wrap up the project and write a well-structured paper. Please don't underestimate the time it takes to write such a report; clear communication is the only means to distribute your work.

The paper should be formatted as if it were a submission to an IEEE robotics conference such as ICRA or IROS. 6-8 pages including references. You can find templates for latex here (recommended) or MS Word here

Week 13 - Project work and paper writing

Nov 15th - 17th

We will do individual team meetings (around 20-30 minutes) to discuss paper contents/progress during class hours. Mandatory attendance in these meetings.

Week 14 - Project work and paper writing

Nov 22nd

We will do individual team meetings (around 20-30 minutes) to discuss paper progress/setup during class hours. Mandatory attendance in these meetings.

The paper is due Monday of week 15 (Nov 28th) at midnight, but I strongly recommend getting it done before thanksgiving!

Thanksgiving break, Nov 23rd-28th

Week 15 - Project presentations

Nov 29th - Dec 1st

Each team will do a 20 minute presentation of their project in class, leaving 10 minutes for discussion.

5 Project Ideas

Here, I have highlighted a few possible project ideas; however, students are encouraged to design a project that suits their particular interest or general research agenda. Students should contact prof. Petersen as early as possible if they would like to work on the topics listed below so that the hardware can be ordered in good time.

Students are expected to work in teams of two or three people, but a single-person team is allowed if well reasoned. Several teams are welcome to work on the same topic.

- Self-assembly of geometrically programmed parts
- Wall of reconfigurable modules
- Collective transport with Elisa robots
- Ant studies
- Smart material and adaptive structures
- Mass production of soft robots

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