1 Exam format

The oral exam will take place in English. No time for preparing the questions is foreseen: the student will enter the examination room when called in and will start the exam. We recommend the students will be available outside the room 5-10 minutes before the assigned slot.
The exam will in total last between 15 and 18 minutes and involve three topics (5 to 6 minutes each) with related set of questions and answers (Q&A sessions). The first topic (**Topic 1**) will be inspired by the presentation of the course project. The second topic (**Topic 2**) will be concerned with a randomly chosen handout out of a list of selected primary reading manuscripts (see the numbered handouts below; about half of the primary readings mentioned in the syllabus have been selected for this purpose). The chosen handout will serve as topic selector. In case the randomly drawn handout will be concerned with a topic too close to that of Topic 1, a new handout will be drawn again randomly. The expected level of quantitative/algorithmic understanding of the handout will be aligned with that used in the related slides; while the questioning will focus on the aspects covered in the lecture, some additional questions on the content of the handout not explicitly mentioned in the lecture slides might be possible. The third topic (**Topic 3**) will focus on any of the content covered in the course. The main instructor will be responsible for leading the Q&A session. As in any other oral exam, a neutral observer will be there to ensure the exam fairness.
The students will be asked to argue technically and document their answers with the help of pen and paper (we are expecting as precise as possible answers with plots, algorithmic formulations, flowcharts, equations, and so on). <u>In particular, on the first two topics, for bringing the external observer up to speed and initiate the Q&A session, it is useful to be able to summarize in one minute the central question tackled in the project or covered in the paper. This should be done also by sketching the problem graphically (e.g., robotic scenario, modeling or algorithmic schema) while verbally commenting.</u> The written paper will be kept as exam record. The whole exam will take place around a table. For sanitary measures, we will ask students to sanitize their hands before approaching the examination table; we will provide all material for the exam (pens, paper, printed handouts) and keep aerating the room from time to time. No material brought by the students is allowed.

2 Literature to be considered for the examination

- **Lecture notes**: all.
- **Reading material**:
  All papers and book chapters distributed will help the students to better understand the lecture slides. In particular, primary reading documents will be very useful in view of the exam preparation; the numbered handouts mentioned below should be read carefully and deeply understood. Secondary reading documents is at disposal of the students for better understanding of the concepts explained in the lecture but they do not represent independent examination material. Sometimes, even in primary reading, not all aspects of a paper are covered explicitly in the lecture. Students

should check out lecture slides for guidance and unless is a primary reading listed in the numbered handout below, such aspects will not be examined. In any case, we are expecting that the formalism covered in the slides is properly understood and students can reconstruct it. The exercises will be treated in the same way of the reading material: they should have helped students to better digest the lecture content but we will certainly not ask specific questions related to a lab assignment or solution if not covered explicitly in the lecture as well.

3 Preparation hints and sample questions for Topic 1

The goal Q&A session related to Topic 1 is to further discuss the content of the course project carried out in teams of three (default) or two students. The questions the students will be asked will be concerned with the theoretical aspects of what was actually implemented rather than with specific code details or technical aspects, such as how to allocate memory for a structure or how to use the transmitter in Webots. Furthermore, the questions will be inspired by the presentation submitted by the student team. Any team member is expected to be able to answer questions on any part mentioned in the presentation.

To give you a better idea, below are a few sample questions that should clarify the format of what can be asked:

- Can you explain the bidding mechanism you have chosen for allocating the tasks to the robots in your project? How did you select the algorithmic parameters?
- Can you explain this counter-intuitive result coming from your performance evaluation metric?
- Which solution-sharing strategy did you used while learning the flocking behavior with PSO? Why did you choose this approach?

4 Sample questions and selected handouts for Topic 2 and 3

Here below is a series of potential questions the student could be asked to answer, organized per main topic covered in the lecture. <u>Students should keep in mind this is not an exhaustive list!</u> However, it should give you a quite precise idea about what to expect during the exam.

4.1 Metaheuristic Optimization

Keywords: ACO, PSO; application to networking (e.g., routing), robotics (e.g., control design and optimization), operational research (e.g., TSP)

4.1.1 Selected handouts

1. Bonabeau E., Dorigo M., and Theraulaz G., "Swarm Intelligence: From Natural to Artificial Systems", SantaFe Studies in the Sciences of Complexity, Oxford University Press, 1999, Ch. 2 (pp. 39-56).
2. Bonabeau E., Dorigo M., and Theraulaz G., "Swarm Intelligence: From Natural to Artificial Systems", Santa Fe Studies in the Sciences of Complexity, Oxford University Press, 1999, Ch. 2 (pp. 93-107).

3. Di Mario E. and Martinoli A., "Distributed Particle Swarm Optimization for Limited Time Adaptation with Real Robots". Chirikjian G. and Hsieh A., editors, Special issue on Distributed Robotics, *Robotica*, 32(2): 193-208**,** 2014
4. Di Mario E., Navarro I., and Martinoli A., "A Distributed Noise-Resistant Particle Swarm Optimization Algorithm for High-Dimensional Multi-Robot Learning", *Proc. of the 2015 IEEE International Conference on Robotics and Automation*, May 2015, pp. 5970–5976.

4.1.2 Sample questions

- What are the differences between AS and ACS? How do they work? Can you write the pseudocode of the algorithm? You could be asked to elaborate your explanations on a simple example graph.
- What are the differences between AntNet and ACS? And those between the way real and virtual ants operate? You could be asked to elaborate your explanations on a simple example graph.
- What is the TSP problem? Why is it difficult? How does an ant choose its next path? How does the elitism mechanism work? How can be local search combined with the metaheuristic principles? What are the advantages of each of the two components?
- How does PSO work? Can you write the pseudocode of the algorithm? How do you choose the meta parameters of the algorithm (e.g., particle numbers, neighborhood type, etc.) as a function of the fitness landscape? You could be asked to elaborate your explanations using vectors in a 2-dimensional space, point out specific differences, etc.
- What do you need to do for dealing with noisy fitness/performance function? How many techniques you know for handling a noisy performance evaluation? What are advantages and drawbacks of each of these variants? Can you illustrate with a flowchart or pseudocode one of these variants? How does OCBA work?
- What type of adaptation (optimization) strategies do you know for a collective (e.g., multi-robot) system? What are the key 3 criteria/axes to classify these strategies? Can you illustrate with one specific example how they can be applied?
- What is the credit assignment problem in collective systems? Can you give examples (possibly based on lecture case studies) on which this problem will arise? Do you know possible methods for solving the credit assignment problem in a collective system?

4.2 Coordination and Division of Labor

Keywords: stigmergy; self-organization; trail-laying/following mechanisms; ant networks and bridge experiments; Reynolds rules; graph-based distributed control; flocking and formations; threshold-based algorithms; market-based algorithms

4.2.1 Selected handouts

5. Bonabeau E., Dorigo M., and Theraulaz G., "Swarm Intelligence: From Natural to Artificial Systems", SantaFe Studies in the Sciences of Complexity, Oxford University Press, 1999, Ch. 2 (pp. 25-36).
6. Bonabeau E., Dorigo M., and Theraulaz G., "Swarm Intelligence: From Natural to Artificial Systems", SantaFe Studies in the Sciences of Complexity, Oxford University Press, 1999, pp. 109-139 (Chapter 3).

7. Kalra N. and Martinoli A., "A Comparative Study between Threshold-Based and Market-Based Task Allocation". *Proc. of the Eight Int. Symp. on Distributed Autonomous Robotic Systems*, July 2006, Minneapolis/St. Paul, MN, U.S.A. Distributed Autonomous Robotic Systems 7 (2006), pp. 91–102.
8. Reynolds C. W. "Flocks, Herds, and Schools: A Distributed Behavioral Model, in Computer Graphics", *Proc. of SIGGRAPH '87*, 21(4), pp. 25-34, 1987.
9. Gowal S., "A Framework for Graph-Based Distributed Rendezvous of Nonholonomic Multi-Robot Systems", EPFL Thesis no. 5845, Ch. 6 and 7 (pp. 49-60), 2013.

4.2.2 Sample questions

- What are the key ingredients of self-organization? Identify the key ingredients of self-organization in a given experiment we saw in the course and give supporting rationale.
- What are the differences between qualitative and quantitative stigmergy? Can you illustrate them with some examples?
- What are the bridge experiments discussed in the course? Why do they work? What happen in case a source of food or a branch is added later? Why certain ant species do get stuck when a shorter branch is added at later time? What happen if we have more than two paths on the bridge or more than two sources of food to choose from?
- What are the differences between formation and flocking? Do you know a simple algorithm able to maintain the formation of a group of robots? (formulate with pseudo-code). Do you know a simple algorithm able to maintain a flock of robots? (formulate your answer with pseudo-code). What sensing/communication/computation capabilities do you need for running them? Which one will be more expensive in terms of sensing/communication/computation?
- How many and what are the Reynolds rules? How do they work? What happens if you leave one of them out?
- Can you explain how a continuous consensus control law is working? Can you do an example in 1D or 2D? What is the Laplacian of a network? You could be asked to calculate the Laplacian for a small graph. What localization information you need to run a Laplacian control law? Can you give two different localization strategies needed to implement a Laplacian control law on a multi-robot system? How can you achieve different formation topologies in the context of a Laplacian control law?
- How do threshold-based algorithms work? How do market-based algorithms work? Can you explain with an example? How are tasks defined typically in one of the other class of algorithms?
- For a given problem, can you define the stimulus, threshold or the local/global objective functions? Can you write the macroscopic equation for a single-task two-caste system? Can you formulate different demand evolutions?
- How many variants of threshold-based and market-based algorithms do you know? Can you explain with an example these variants?

4.3 Multi-Level Modeling

Keywords: submicroscopic models (e.g., Webots), microscopic models (e.g., multi-agent); macroscopic models (e.g., mean field); modeling assumptions; differences between modeling levels; linear and nonlinear models; parameter calibration; steady state analysis

4.3.1 Selected handouts

10. Lerman K., Martinoli A., and Galstyan A., "A Review of Probabilistic Macroscopic Models for Swarm Robotic Systems". In Sahin E. and Spears W., editors, *Proc. of the SAB 2004 Workshop on Swarm Robotics*, July 2004, Santa Monica, CA, USA. Lecture Notes in Computer Science (2005), Vol. 3342, pp. 143-152.
11. Martinoli A., Easton K., and Agassounon W., "Modeling of Swarm Robotic Systems: A Case Study in Collaborative Distributed Manipulation". Special Issue on Experimental Robotics, Siciliano B., editor, *Int. Journal of Robotics Research*, Vol. 23, No. 4, pp. 415-436, 2004.
12. Agassounon W., Martinoli A., and Easton K., "Macroscopic Modeling of Aggregation Experiments using Embodied Agents in Teams of Constant and Time-Varying Sizes". *Autonomous Robots*, special issue on Swarm Robotics, Dorigo M. and Sahin E., editors, 17(2-3): 163-192, 2004.
13. Li L., Martinoli A., and Abu-Mostafa Y., "Learning and Measuring Specialization in Collaborative Swarm Systems". Special issue on Mathematics and Algorithms of Social Insects, Balch T. and Anderson C., editors, *Adaptive Behavior,* Vol.12, No. 3-4, pp. 199-212, 2004.

4.3.2 Sample questions

- Can you clarify various sources of errors in going up with abstraction (physical -> sub-microscopic -> microscopic-> macroscopic) with the typical implementation we saw in the course (real miniature robots -> Webots -> multi-agent non-spatial -> mean-field ODE).
- Given an arena of a certain area, a certain number of robots, a certain number of behaviors, formulate a macroscopic model for capturing the system dynamics; can you calculate some parameters as a function of other in stationary conditions? How?
- Can you illustrate how the stick-pulling experiment was modeled in its essence (simplified model)? Is this a linear or nonlinear model? What metrics were used for evaluating the performance of the team?
- Can you illustrate how the seed-assembling experiment was modeled? Is this a linear or nonlinear model? What were the modeling difficulties of such case study? What metrics were used for evaluating the performance of the team?
- How does a simple in-line search algorithm work? How many variants do you know? What are advantages and drawbacks of such simple algorithm?
- What is specialization and what is diversity? How can you measure them? What is social entropy? Can you illustrate how it works with an example seen in the course or provided to you (e.g., 1D or 2D)? Do you know an alternative method to measure diversity?

4.4 Platforms, Localization and Distributed Sensing

Keywords: sensors and actuators; control architectures types and taxonomy (e.g., Braitenberg, ANN, behavior-based, motor-schemas, modular vs. sensory-motor control); odometry; feature-based localization; sensor networks principles and applications; power consumption and mobility in sensor networks; robotic sensor networks; gas source localization

4.4.1 Selected handouts

14. Siegwart R. and Nourbakhsh I. R., "Introduction to Autonomous Mobile Robots", MIT Press, 2004, Ch. 3 (pp. 47-53), Ch. 5 (pp. 181-191).

15. Siegwart R. and Nourbakhsh I. R., "Introduction to Autonomous Mobile Robots", MIT Press, 2004, Ch. 5 (pp. pp. 227-233).
16. Maybeck P. S. "Stochastic Models, Estimation, and Control", Academic press, 1979, Ch. 1 (pp.1-16).
17. Barrenetxea G., Ingelrest F., Schaefer G. and Vetterli M., "The Hitchhiker's Guide to Successful Wireless Sensor Network Deployments". *Proc. of the 6th ACM Conference on Embedded Networked Sensor Systems* (SenSys 2008). Raleigh, NC, USA, 5-7 November 2008.
18. Marjovi A., Arfire A., and Martinoli A., "Extending Urban Air Pollution Maps beyond the Coverage of a Mobile Sensor Network: Data Sources, Methods, and Performance Evaluation," *Proc. of the Int. Conf. on Embedded Wireless Systems and Networks*, February 2017, Uppsala, Sweden, pp. 12-23.
19. Soares J. M., Aguiar A. P., Pascoal A. M., and Martinoli A., "A Distributed Formation-based Odor Source Localization Algorithm - Design, Implementation, and Wind Tunnel Evaluation," *Proc. of the IEEE Int. Conf. on Robotics and Automation*, 2015, pp. 1830–1836.
20. Rahbar F. and Martinoli A., "A Distributed Source Term Estimation Algorithm for Multi-Robot Systems", *Proc. of the IEEE Int. Conf. on Robotics and Automation,* May-August 2020, Paris, France, online organization, pp. 5604-5610.

4.4.2 Sample questions

- What classification axes for sensors do you know? Can you give examples in each of the category and explain how these specific sensors work?
- What performance metrics do you know for a sensor? What is the difference between accuracy and precision? How do you calculate them?
- What are the main research issues/challenges in sensor networks? What are the main application domains so far? What are the typical problems encountered in the deployment of WSN in the field?
- What are the key principles for designing a simple, robust and energetically efficient algorithm to gather environmental data with a sensor network?
- What is a Braitenberg vehicle? How does it work?
- What is the difference between a modular and sensor-motor control architecture? Examples?
- Can you tell me how you would build a controller for obstacle avoidance?
- What is the kinematic forward model of a vehicle? How does look like the one for a differential-drive wheel robot? What's useful for? Can you mathematically formulate a kinematic forward model for a differential wheeled vehicle?
- What is odometry? How does it work? What are the assumptions for good odometry? What is the difference between an odometry based on wheel encoders vs. accelerometers? Can you explain the effect of wheel slip on wheel-based odometry?
- What indoor positioning techniques do you know? What main classification axes for positioning systems do you know? Can you give some examples?
- What does it mean feature-based navigation? What is a Kalman filter? What is it good for? Can you explain how it works mathematically in 1D?
- What are the challenges and solution in mobile sensing for gas sensing? What are the challenges and solution in distributed sensing of air quality in urban settings?
- What class of algorithms do you know for solving a gas source localization problem? Can you explain how a source term estimation algorithm works? How can you apply it to a multi-robot system?
- How can you apply a Laplacian-based controller for localizing a gas source? What are advantages and drawbacks of such approach?