Distributed Intelligent Systems SS 2020-2021

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Course Website: https://disal.epfl.ch/teaching/distributed_intelligent_systems/

1 Credits and Workload

Distributed Intelligent Systems (DIS) distributes 5 ECTS. According to the European Commission guidelines, 1 ECTS is equivalent to up to 30 h of workload. Therefore, the total workload for DIS will be about 150 h over the whole semester. The approximate breakdown of the workload is 60 h for lecture attendance and exam preparation, 30 h for exercises (including preparation), and 60 h for carrying out, documenting, and presenting a course project.

2 Grade

The final grade for DIS will take into account the performance in the final oral exam as well as in the course project. Exercises are ungraded but solving them in a thorough and individual way will help the students to be well-prepared for the course project and the final exam. The final oral exam will will involve questions focusing on the different topics covered during the course and the exercises as well on the course project, starting from a short individual presentation of the student. 50% of the grade will be acquired based on the performances in the course project (30% based on the common team work during the semester and 20% based on the part of the oral exam dedicated to the presentation and discussion of the course project). The remaining 50% of the grade will be based on the performance during the final oral exam.

3 Reading

DIS does not follow a specific course book. Weekly reading material will be exclusively made available in electronic format, downloadable from the Moodle server, typically the week before a given lecture and exercise session. Access to this material will be limited to students officially enrolled in the class. Most of this material is copyrighted and therefore it should exclusively be used for course purposes.

The reading material is classified in primary and secondary reading. Primary reading material is covered to large extent during the lecture: it represents therefore a good complement to slides. On average, the primary reading material consists of about 50 single-column pages per week (selected book sections and chapters, conference and journal papers, technical reports). Secondary reading material is only briefly mentioned during the lecture, typically because of one specific aspect complementing the information of the core messages. Availability of this material on Moodle can facilitate curious students to look more into such information. Finally, for students interested in a deeper understanding of specific topics, further tertiary reading pointers are suggested at the end of each lecture notes.

Note that, in any case, the handouts represent a loosely coordinated literature body: some redundancy is possible and their content might not exhaustively discussed in the lecture, although students attending the lecture will get good guidance on the relevance of specific reading material.

4 Lecture Notes

For this edition of the course, lectures will be exclusively held on-line, through Zoom. Recorded lectures will be made available to students in timely fashion. *Preliminary* lecture notes will be available on the course web site *shortly before* a given lecture (typically Monday evening), in PDF format. *Definitive* lecture notes will be available *after a given lecture* in timely fashion, with an e-mail notification through the Moodle forum.

5 Laboratories

The course will involve a total of *eleven* lab exercises (four lasting 3h and seven 2h). All the lab exercises will be ungraded and no points are therefore mentioned on their assignments. The exercises have been designed such as they are doable using exclusively software tools, provided that the corresponding software packages have been downloaded and correctly installed on the personal computers. On-line assistance will be provided during the weekly lab sessions.

The assignment of labs will be made available at latest the day before a given lab session via the Moodle server. At the beginning of each lab session, a mini-tutorial of typically 5-10 minutes will be given by the main designer of the exercise. The corresponding slides will be made available on the Moodle server after the lab session. Official solutions will be distributed for each exercise after a given laboratory session. For the exercises, we encourage the students to take their own personal notes (they will be useful for the course project and the final exam).

Further discussion on specific points of the exercises can happen during on-line office hours. On-line office hours will have to be scheduled upon appointment via the TA mailing list; if appropriate, the Moodle discussion forum will also be leveraged for exercise discussion.

6 Course Project

DIS involves a 60 h course project for each student (this includes reading, implementing, reporting as a team and presenting individually during the exam session). All teaching assistants will serve as project supervisors. The project topic will be identical for all students. Projects will be carried out in groups of *four* (default), three or five (if needed) students, belonging as much as possible to different teaching sections or programs (we aim at aggregating students in a way that at least two different sections or programs are represented in the team). The student teams will be consolidated during Week 5, based on the preferences of the students expressed the week before. During Week 6, a compulsory kick-off session for the implementation of the course projects will be organized. Further details on the final project reporting, carried out by the team and submitted at the end of the semester, will be communicated in timely fashion.

Each of the team members will have to present his or her own contribution in the course project during the final oral exam, in three minutes and based on three slides. However, the follow-up discussion could involve questions on the overall team effort reported at the end of the semester.

On-line weekly assistance for the course project will be available during the lab sessions (1h). If appropriate, some additional office hours at fixed schedule will be made available by the project supervisors. A dedicated slot booking tool will be made available in timely fashion to this purpose. No further assistance for the course project will be provided outside these pre-scheduled hours.

7 Course Syllabus

WEEK 1 – February 23 and 25

Lecture – 5 h (Tue and Thu)
Course organization (credits, workload, logistics) and content overview. Introduction to Swarm Intelligence (SI) and key principles, natural and artificial examples. Foraging, trail laying/following mechanisms. Open-space, multi-source foraging experiments: biological data and microscopic models. From real to virtual ants: Ant System (AS), the first combinatorial optimization algorithm based on ant trail/following principles. Application to a classical operational research problem: the Traveling Salesperson Problem (TSP).

Reading
Primary
- 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. 1 (pp.1-23) and Ch. 2 (pp. 25-36 and 39-56).

Secondary
- Martinoli A., “Collective Complexity out of Individual Simplicity”. Invited book review on "Swarm Intelligence: From Natural to Artificial Systems", by Bonabeau E., Dorigo M., and Theraulaz G. *Artificial Life*, Vol. 7, No. 3, pp. 315-319, 2001.
- Beni G., “From Swarm Intelligence to Swarm Robotics”. In Şahin E. and Spears W., editors, *Proc. of the SAB 2004 Workshop on Swarm Robotics*, Santa Monica, CA, USA, July, 2004. Lecture Notes in Computer Science (2005), Vol. 3342, pp. 1-9.

Lab
Continuation of lecture.

WEEK 2 – March 2 and 4

Lecture – 2 h
From AS to Ant Colony Optimization (ACO). Ant-based algorithms (ABC, Ant-Net) applied to routing in telecommunication networks.

Reading
Primary
- 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. 80-107).

Secondary
- Dorigo M. and Stuetzle T., “Ant Colony Optimization”, MIT Press, 2004, Ch. 1 (pp. 1-24) and Ch. 2 (pp. 25-46).

Lab 1 – 3 h
Trail laying and following mechanisms, emphasizing SI concepts; Ant Colony Optimization.

WEEK 3 – March 9 and 11

Lecture – 2 h
Introduction to mobile robotics: basic concepts centered around the differential drive vehicle used in the course (e-puck) and the high-fidelity, open-source robotic simulator

(Webots). Introduction to control architecture for mobile robots with special focus on reactive control architectures.

Reading
Primary
- Michel O., "Webots: Professional Mobile Robot Simulation". *Int. J. of Advanced Robotic Systems*, **1**: 39-42, 2004.
- Mondada F., Bonani M., Raemy X., Pugh J., Cianci C., Klaptocz A., Magnenat S., Zufferey J.-C., Floreano D., Martinoli A., "The e-puck, a Robot Designed for Education in Engineering". *Proc. of the 9th Conference on Autonomous Robot Systems and Competitions,* May 2009, Castelo Branco, Portugal, Vol.1, pp. 59-65.
- Siegwart R. and Nourbakhsh I. R., "Introduction to Autonomous Mobile Robots", MIT Press, 2004, Ch. 4 (pp. 89-98).

Secondary
- Brooks R., "A Robust Layered Control System for a Mobile Robot". *IEEE Trans. on Robotics and Automation*, **2**(1): 14-23, 1986.
- Arkin R. C., "Motor Schema Based Mobile Robot Navigation". *Int. J. of Robotics Research*, 8(4): 92-112, 1989.

Lab 2 – 3 h
Introduction to Webots, an open-source, high-fidelity robotic simulator.

WEEK 4 – March 16 and 18

Lecture – 2 h
Localization methods in mobile robotics: positioning systems, odometry-based and feature-based localization. Sources of localization uncertainties and corresponding handling methods for mobile robots.

Reading
Primary
- Siegwart R. and Nourbakhsh I. R., "Introduction to Autonomous Mobile Robots", MIT Press, 2004, Ch. 3 (pp. 47-53), Ch. 4 (pp. 145-154).

Lab 3 – 3 h, part I
Localization methods (odometry and feature-based localization) in Webots.

Project
Kick-off of the team building process.

WEEK 5 – March 23 and 25

Lecture – 2 h
Localization methods in mobile robotics: uncertainties in wheel-based odometry, Kalman filters for 2D localization. Collective movements in natural societies; focus on flocking phenomena. Collective movements in artificial systems: Reynolds' virtual agents (Boids).

Reading
Primary
- Siegwart R. and Nourbakhsh I. R., "Introduction to Autonomous Mobile Robots", MIT Press, 2004, Ch. 5 (pp. 181-200).
- Maybeck P. S. "Stochastic Models, Estimation, and Control", Academic press, 1979, Ch. 1 (pp.1-16).

- Reynolds C. W. "Flocks, Herds, and Schools: A Distributed Behavioral Model, in Computer Graphics", *Proc. of SIGGRAPH '87*, 21(4), pp. 25-34, 1987.

Secondary

- Siegwart R. and Nourbakhsh I. R., "Introduction to Autonomous Mobile Robots", MIT Press, 2004, Ch. 5 (212-214; 227-244).

Lab 3 – 1 h, part II
Localization methods (odometry and feature-based localization) in Webots.

Lab 4 – 2 h, part I
Collective movements in Matlab and Webots.

Course project
Consolidation of student teams.

WEEK 6 – March 30 and April 1

Lecture – 2 h
Experiments with multi-robot systems on flocking and formation (behavior-based). Graph-based distributed control for spatial consensus (rendez-vous, formation).

Reading

Primary

- Fredslund J. and Matarić M. J., "A General, Local Algorithm for Robot Formations", *IEEE Transactions on Robotics and Automation,*, special issue on Advances in Multi-Robot Systems, Vol. 18, p.5, pp. 837-846, 2002.
- 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.
- Falconi R., Gowal S., and Martinoli A., "Graph-Based Distributed Control of Non-Holonomic Vehicles Endowed with Local Positioning Information Engaged in Escorting Missions". *Proc. of the 2010 IEEE Int. Conf. on Robotics and Automation*, May 2010, Anchorage, AK, U.S.A., pp. 3207-3214.

Secondary

- Balch T. and Arkin T. C., "Behavior-Based Formation Control for Multirobot Teams". *IEEE Trans. on Robotics and Automation*, 1998, Vol. 14, No. 6, pp. 926-939.
- Pugh J., Raemy X., Favre C., Falconi R., and Martinoli A., "A Fast On-Board Relative Positioning Module for Multi-Robot Systems". Special issue on Mechatronics in Multi-Robot Systems, Chow M.-Y., Chiaverini S., Kitts C., editors, *IEEE Trans. on Mechatronics*, 14(2): 151-162, 2009.
- Ren W., Beard R. W., and Atkins E. M., "A Survey of Consensus Problems in Multi-Agent Coordination", *Proc. of the 2005 American Control conference*, pp. 1859-1864, 2005.

Lab 4 – 2 h, part II
Collective movements in Matlab and Webots.

Course project – 1 h
Kick-off of the course project.

WEEK 7 – April 13 and 15

Lecture – 2 h
Introduction to multi-level modeling techniques (underlying methodological framework, levels, assumptions, principles); linear example; calibration of model parameters.

Reading

Primary

- 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.
- 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.

Secondary

- Correll N. and Martinoli A., "Collective Inspection of Regular Structures using a Swarm of Miniature Robots". In Ang Jr., M.H. and Khatib, O., editors, *Proc. of the Ninth Int. Symp. Experimental Robotics,* June 2004*,* Singapore. Springer Tracts in Advanced Robotics (2006), Vol. 21, pp. 375–385.

Lab 5 – 2 h
Multi-level modeling of distributed robotic systems in (introduction, Matlab and Webots).

Course project – 1 h
Project assistance.

WEEK 8 – April 20 and 22

Lecture – 2 h
Challenging multi-level modeling case studies (distributed seed assembly and collaborative stick-pulling). Combined modeling and machine-learning methods for control optimization; diversity and specialization metrics.

Reading

Primary

- 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.
- 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.

Secondary

- Martinoli A., Ijspeert A. J., and Gambardella L. M., "A Probabilistic Model for Understanding and Comparing Collective Aggregation Mechanisms". In Floreano D., Mondada F., and Nicoud J.-D., editors, *Proc. of the Fifth Europ. Conf. on Artificial Life*, September 1999, Lausanne, Switzerland. Lectures Notes in Artificial Intelligence (1999), Vol. 1674, pp. 575–584.

Lab 6 – 2 h
Multi-level modeling of distributed robotic systems (continuation, Matlab and Webots).

Course project – 1 h
Project assistance.

WEEK 9 – April 27 and 29

Lecture – 2 h
Introduction to machine-learning techniques and metaheuristic optimization: terminology and classification. Particle Swarm Optimization (PSO): algorithm and

performances on benchmark functions. Application of metaheuristic methods to automatic control design and optimization of single-robot systems.

Reading

Primary

- Eberhart R. C. and Kennedy J., "A New Optimizer using Particle Swarm Theory". *Proc. of the Sixth IEEE Int. Symp. Micro Machine and Human Science*, Nagoya, Japan, 1995, pp. 39–43.
- Shi, Y. H., Eberhart, R. C. "A Modified Particle Swarm Optimizer" *Proc. of the IEEE International Conference on Evolutionary Computation,* Anchorage, Alaska, May 1998, pp. 69-73.
- Poli R., Kennedy J., and Blackwell T., "Particle Swarm Optimization: An Overview". *Swarm Intelligence Journal,* **1**(1): 33-57, 2007.
- Pugh J., Zhang Y., and Martinoli A., "Particle Swarm Optimization for Unsupervised Robotic Learning". *Proc. of the Second IEEE Symp. on Swarm Intelligence,* Pasadena, CA, USA, June 2005, pp. 92-99.
- Engelbrecht A. P., "Particle Swarm Optimization: Where Does it Belong?" *Proc. of the Third IEEE Symp. on Swarm Intelligence,* Indianapolis, IN, USA, May 2006, pp. 48-54.

Secondary

- Floreano D. and Mondada F., "Evolution of Homing Navigation in a Real Mobile Robot", *IEEE Trans. on System, Man, and Cybernetics: Part B*, **26**(3): 396-407, 1996.
- Lipson, H., Pollack J. B., "Automatic Design and Manufacture of Artificial Lifeforms", *Nature*, **406**: 974-978, 2000.
- Bongard J., Zykov V., Lipson H. (2006), "Resilient Machines Through Continuous Self-Modeling", *Science* Vol. 314. no. 5802, pp. 1118 – 1121.

Lab 7 – 2 h

Particle Swarm Optimization: application to benchmark functions and control shaping for single robot (SwarmViz, Webots).

Course project – 1 h

Project assistance.

WEEK 10 – May 4 and 6

Lecture – 2 h

Noisy and expensive optimization problems; noise-resistant algorithms. Application of metaheuristic methods to automatic control design and optimization of multi-robot systems. Specific issues for automatic control design and optimization in distributed systems (e.g., credit assignment problem).

Reading

Primary

- Pugh J. and Martinoli A., "Distributed Scalable Multi-Robot Learning using Particle Swarm Optimization". *Swarm Intelligence Journal*, **3**(3): 203-222, 2009.
- 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.
- Di Mario E., Navarro I., and Martinoli A., "Analysis of Fitness Noise in Particle Swarm Optimization: From Robotic Learning to Benchmark Functions". *Proc. of the 2014 IEEE Congress on Evolutionary Computation*, July 2014, Beijing, China, pp. 2785-2792.
- 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.

Secondary

- C. Chen, J. Lin, E. Yücesan, and S. E. Chick, "Simulation Budget Allocation for Further Enhancing the Efficiency of Ordinal Optimization," *Discrete Event Dynamic Systems: Theory and Applications*, pp. 251–270, 2000.
- Di Mario E., Navarro I., and Martinoli A., "Distributed Particle Swarm Optimization using Optimal Computing Budget Allocation for Multi-Robot Learning," in *IEEE Congress on Evolutionary Computation*, 2015, pp. 566–572.

Lab 8 – 2 h
Particle Swarm Optimization application to noisy problems: benchmark functions and multi-robot problems (Webots, Matlab).

Course project – 1 h
Project assistance.

WEEK 11 – May 11

Lecture – 2 h
Division of labor and task-allocation mechanisms: threshold-based algorithms and market-based algorithms; comparison between threshold-based and market-based algorithms.

Reading
Primary
- Stentz A., Dias M. B., "A free market architecture for coordinating multiple robots". Technical report CMU-RI-TR-99-42, Robotics Institute, Carnegie Mellon University, December 1999.
- 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).
- 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.

Secondary
- Dias M. B., Zlot R., Kalra N., and Stentz A., "Market-Based Multirobot Coordination: A Survey and Analysis". *IEEE Proceedings,* 94(7): 1257-1270, 2006.
- Agassounon W. and Martinoli A., "Efficiency and Robustness of Threshold-Based Distributed Allocation Algorithms in Multi-Agent Systems". *Proc. of the First ACM Int. Joint Conf. on Autonomous Agents and Multi-Agent Systems*, July 2002, Bologna, Italy, pp. 1090–1097.

Lab
None (Ascension).

WEEK 12 - May 18 and 20

Lecture – 2 h
Division of labor and task-allocation mechanisms (continuation).

Reading
Same of Week 11.

Lab 9 – 2 h
Multi-robot systems coordination using market-based and threshold-based algorithms using Webots.

Course project – 1 h
Project assistance.

WEEK 13 – May 25 and 27

Lecture – 2 h
Distributed environmental sensing using static sensor networks.

Reading
Primary
- Culler D., Estrin D., and Srivastava M., "Guest Editors' Introduction: Overview of Sensor Networks". *IEEE Computer*, Vol. 37, No. 8, pp.41-49, 2004.
- 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.
- Prorok A., Cianci C. M., and Martinoli A., "Towards Optimally Efficient Field Estimation with Threshold-Based Pruning in Real Robotic Sensor Networks". *Proc. of the 2010 IEEE Int. Conf. on Robotics and Automation*, May 2010, Anchorage, AK, U.S.A, pp. 5453-5459.
- Evans W. C., Bahr A., and Martinoli A., "Evaluating Efficient Data Collection Algorithms for Environmental Sensor Networks". *Proc. of the Tenth Int. Symp. on Distributed Autonomous Robotic Systems*, November 2010, Lausanne, Switzerland; Springer Tracts in Advanced Robotics (2013), Vol. 83, pp. 77-90.

Secondary
- Evans W. C., Bahr A., and Martinoli A., "Distributed Spatiotemporal Suppression for Environmental Data Collection in Real-World Sensor Networks". *Proc. of the 2013 IEEE Int. Conf. on Distributed Computing in Sensor Systems*, May 2013, Boston, U.S.A., pp. 70-79.

Lab 10 – 2 h
Distributed environmental sensing with static and mobile sensor networks (Webots/Matlab).

Course project – 1 h
Project assistance.

WEEK 14 – June 1 and 3
Lecture – 2 h
Distributed environmental sensing using mobile sensor networks. General take home messages of the course. Discussion about student feedback for the course.

Reading
Primary
- 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.
- Arfire A., Marjovi A., and Martinoli A., "Mitigating slow dynamics of low-cost chemical sensors for mobile air quality monitoring sensor networks," *Proc. of the Int. Conf. on Embedded Wireless Systems and Networks*, February 2016, Graz, Austria, pp. 159-167.

Lab
None

Course project – 3 h
Project assistance. Submission of project reports by student teams.