Distributed Intelligent Systems

WS 2015-2016

Instructor: Alcherio Martinoli

Guest lecturers: Bahar Haghighat, Ali Marjovi

Teaching assistants: Bahar Haghighat (head TA), Ali Marjovi, Zeynab Talebpour, Alicja Wasik

Support staff: Alexander Bahr, Iñaki Navarro, José Nuno Pereira, Felix Schill (specific tasks and course projects); Florian Maushart (all labs); David Mansolino (Webots and e-puck support)

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

1 Credits and Workload

Distributed Intelligent Systems 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 *Distributed Intelligent Systems* will be about 150 h over the whole semester. The approximate breakdown of the workload is 60 h for lecture attendance and exam preparation, 45 h for exercises (lab attendance and verification tests, preparation time included), and 45 h for carrying out, documenting, and defending a course project.

2 Grade

The final grade for *Distributed Intelligent Systems* will take into account the performance in the final written exam as well as in the exercises and the course project. The final written exam will last 180 minutes and will involve multiple topics covered during the course (lecture, exercises, and primary handouts). 60% of the grade will be acquired during the semester, based on the performances in the lab verification tests (30%, average of the two tests) as well as in the course project (30%, specific evaluation coefficients for this effort will be communicated in a timely fashion). 40% of the grade will be based on the performance in the final exam.

3 Reading

Distributed Intelligent Systems does not follow a specific course book. Weekly reading material will be exclusively made available in electronic format, downloadable from the lecture website (student area on the Moodle server), typically the week before a given lecture and exercise session. Access to this material will be limited to people enrolled in the class and controlled via username and password. Most of this material is copyrighted and therefore it should exclusively be used for course purposes.

For this edition, the reading material has been classified in primary and secondary reading. Primary reading material will be covered to large extent during the lecture: it represents therefore a good complement to slides. On average, the primary reading material will consist of about 35 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

Lecture will be given with the help of a LCD projector and a black board, when appropriate. *Preliminary* lecture notes will be available on the course web site *possibly shortly before* a given lecture (Monday evening), in PDF format. No e-mail notification will be send for such posting operation. *Definitive* lecture notes will be available *after a given lecture* in a timely fashion, with an e-mail notification through the Moodle forum.

5 Labs and Verification Tests

Each week, with the exception of the first week (lecture only) and the last week of the semester (dedicated to the course project presentations), there will be either a 3 hour lab (see course outline below) or verification test. The course will involve in total 10 lab assignments and 2 lab verification tests (in the computer room). Solutions for lab assignments will be distributed a few days after a given exercise session. A lab verification test will include material covered in the previous laboratory sessions (first 6 exercises for the first verification test and last 4 for the second one). The submitted solutions of the lab verification tests will be reviewed individually and will be available for download on the Moodle server in timely fashion (up to three weeks after a given lab verification test). Possible discussions of grading and evaluation should take place during office hours of the TAs and *not* during the lab sessions.

The assignment of labs will be made available at the beginning of the week of a given laboratory session via the Moodle server, in pdf format. At the beginning of each lab session, a mini-tutorial of typically 5-10 minutes will be given by the main designer of the lab exercise. The corresponding slides will be made available on the exercise page after the lab session.

No specific office hours of individual TAs will be posted but requests of meeting with a TA (including a meeting in the computer room) can be submitted anytime using the course e-mail list (dis-ta@groupes.epfl.ch).

6 Course Project

Distributed Intelligent Systems involves a 45h course project (this includes reading, implementation, reporting, oral defense of the project, and reviewing the report of another student team). Students will choose a project from a list of approved topics to be distributed during the sixth week. Projects will be carried out in groups of three (default) or two (if needed) students belonging as much as possible to different teaching sections or programs. Each of the team members will have to defend part of the project in front of the audience. Every project will be supervised by at least one Teaching Assistant or Support Staff member. Definitive assignment of course projects will be communicated during the seventh week, based on the preferences expressed by the students. Students will be expected to contact their project supervisor as soon as possible to begin planning their work schedule.

Around the end of the eighth week and the beginning of the ninth week, an official kick-off tutorial will be organized by each project supervisor to his or her teams of students. Course projects are aligned with the course schedule during the semester and commonly structured. Project supervisors will set specific milestones for their teams to ensure timely progress. Further details on this work plan will be available in a timely fashion.

Each student will also be asked to serve as a reviewer for another student project and invited to ask questions during the defense session. Reviewers will receive the technical report of another team one or two days before their defense.

The final course project report will be due by the thirteen week of the semester while the oral defense of the project will happen during the last week of the semester, as much as possible during lecture and exercise hours of the course but possibly also outside these time windows (possibly until Friday December 18), depending on the number of student teams in the course. Additional details about the project defense and reporting will be distributed in timely fashion.

7 Collaboration Policy

Unless otherwise noted, students can collaborate with their fellow students on the lab assignments, have to work individually during lab verification tests and final written exam, and are encouraged to efficiently collaborate during the course projects.

8 Course Syllabus

WEEK 1 – September 15 and 16

Lecture – 5 h (Tue in GC C3 30 and Wed in GR C0 01)
Organization meeting, timetable. Overview of the course. Introduction to Swarm Intelligence (SI) and key principles (e.g., self-organization, stigmergy), natural and artificial examples, computational and embedded SI. 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 Salesman 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.

No exercises

WEEK 2 – September 22 and 23

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. 2 (pp. 25-46).

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

WEEK 3 – September 29 and 30

Lecture – 2 h; guest lecturer: Ali Marjovi
Introduction to mobile robotics: basic hardware and software concepts centered around the differential drive vehicle used in the course (e-puck) and the high-fidelity 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, a high-fidelity robotic simulator. E-copies of the Webots user manual will be available.

WEEK 4 – October 6 and 7

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), Ch. 5 (pp. 181-200).

Secondary
- Maybeck P. S. “Stochastic Models, Estimation, and Control”, Academic press, 1979, Ch. 1 (pp.1-16).

Lab 3 – 3 h

Introduction to the e-puck robot. Illustrate key concepts of the course for basic behavior using different reactive control architectures (Artificial Neural Network, linear Braitenberg, behavior-based, rule-based). Simple localization algorithms based on odometry. An e-copy of a simple e-puck manual will be made available to the students.

WEEK 5 – October 13 and 14

Lecture – 2 h
Collective movements in natural societies; focus on flocking phenomena. Collective movements in artificial systems: Reynolds' virtual agents (Boids) and experiments with multi-robot systems (flocking, formation). Graph-based distributed control for continuous consensus algorithms (spatial rendez-vous, formation).

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

Secondary
- 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.
- Balch T. and Arkin T. C., "Behavior-Based Formation Control for Multirobots 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 – 3 h
Multi-robot localization, coordinated and collective movements in a point-simulator (Matlab) and Webots.

WEEK 6 – October 20 and 21

Lecture – 2h; guest lecturer: Bahar Haghighat
Division of labor and task-allocation mechanisms: threshold-based algorithms, market-based algorithms and comparisons between the two algorithmic classes.

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).

Secondary

- 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.
- 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 5 – 3 h
Multi-robot systems coordination using market-based and threshold-based algorithms using Webots/point-simulator.

Course project
Distribution of course project list.

WEEK 7 – October 27 and 28

Lecture – 2 h
An introduction to wireless sensor networks; discrete consensus algorithms (collective decisions).

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.
- Cianci C., Raemy X., Pugh J., and Martinoli A., "Communication in a Swarm of Miniature Robots: The e-puck as an Educational Tool for Swarm Robotics". *Proc. of the SAB 2006 Workshop on Swarm Robotics*, September-October 2006, Rome, Italy. Lecture Notes in Computer Science (2007), Vol. 4433, pp. 103-115.

Secondary
- Cianci C., Pugh J, and Martinoli A. "Exploration of an Incremental Suite of Microscopic Models for Acoustic Event Monitoring Using a Robotic Sensor Network". *Proc. of the 2008 IEEE Int. Conf. on Robotics and Automation,* May 2008, Pasadena, U.S.A., pp. 3290-3295.

Lab 6 – 3h
Introduction to Mica-z sensor nodes. Simulated (Webots with NS-3 plugin) and real (e-puck and Mica-z) sensor and actuator networks: networking static sensor nodes with mobile robots for performing collective decisions.

Course project
Collection of student project preferences and definitive assignment of course projects to students.

WEEK 8 – November 3 and 4

Lecture – 2 h
Introduction to multi-level modeling techniques (underlying theoretical framework, levels, assumptions, principles). Linear and nonlinear modeling case studies.

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.

Lab verification test 1 – 3 h

In the computer room; subject: lab 1 to 6.

Course project

Course project kick-off tutorial (organized separately for each project topic) in the second half of the week.

WEEK 9 – November 10 and 11

Lecture – 2 h

Calibration of model parameters. Additional selected multi-level modeling case studies. Combined modeling and machine-learning methods for control optimization; diversity and specialization metrics.

Reading

Primary

- 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.
- 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

- Nembrini J., Winfield A., and Melhuish C., "Minimalist Coherent Swarming of Wireless Networked Autonomous Mobile Robots". *Proc. of the Seventh Int. Conf. on Simulation of Adaptive Behavior*, 2002, Edinburgh, UK, pp. 273–282.
- 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.
- Winfield A. F. T., Liu W., Nembrini J., and Martinoli A., "Modelling a Wireless Connected Swarm of Mobile Robots. Special issue on Swarm Robotics, Winfield A. F. T. and Sahin E., editors, *Swarm Intelligence Journal*, 2(2-4): 241-266, 2008.

Lab 7 – 3 h

Multi-level modeling of distributed robotic systems.

Course project

Course project kick-off tutorial (organized separately for each project topic) in the first half of the week.

WEEK 10 –November 17 and 18

Lecture – 2 h
Introduction to unsupervised multi-agent machine-learning techniques for automatic design and optimization: terminology and classification, Particle Swarm Optimization (PSO), performance comparison with Genetic Algorithms. Application of machine-learning techniques to automatic control design and optimization of single-robot systems. Noisy and expensive optimization problems; noise-resistant algorithms.

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.
- 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.

Secondary
- Poli R., Kennedy J., and Blackwell T., "Particle Swarm Optimization: An Overview". *Swarm Intelligence Journal,* **1**(1): 33-57, 2007.
- 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 8 – 3 h
Particle Swarm Optimization: application to benchmark functions and control shaping for single robot (in simulation).

WEEK 11 – November 25 and 26

Lecture – 2 h
Application of machine-learning techniques 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). Advanced techniques for expensive and noisy optimization problems.

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.

Lab 9 – 2 h
Particle Swarm Optimization application to noisy problems: benchmark functions and multi-robot problems.

WEEK 12 - December 1 and 2

Lecture – 2 h
Distributed sensing using sensor networks: energy efficiency and mobility.

Reading
Primary

- 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.
- 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.
- Lochmatter T. and Martinoli A., "Tracking Odor Plumes in a Laminar Wind Field with Bio-inspired Algorithms". *Proc. of the Eleventh Int. Symp. Experimental Robotics*, July 2008, Athens, Greece, Springer Tracts in Advanced Robotics (2008), Vol. 54, pp. 473-482, 2008.
- J. M. Soares, A. P. Aguiar, A. M. Pascoal, and A. Martinoli, "A Distributed Formation-based Odor Source Localization Algorithm - Design, Implementation, and Wind Tunnel Evaluation," *Proc. IEEE Int. Conf. on Robotics and Automation*, 2015, pp. 1830–1836.

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.
- Hayes A. T., Martinoli A., and Goodman R. M., "Distributed Odor Source Localization". Special Issue on Artificial Olfaction, Nagle H. T., Gardner J. W., and Persaud K., editors, *IEEE Sensors Journal*, 2(3): 260-271, 2002.
- Lochmatter T., Aydın Göl E., Navarro I., and Martinoli A., "A Plume Tracking Algorithm based on Crosswind Formations". *Proc. of the Tenth Int. Symp. on Distributed Autonomous Robotic Systems*, November 2010, Lausanne, Switzerland; Springer Tracts in Advanced Robotics (2013), Vol. 83, pp. 91-102.
- Marjovi A., Arfire A., and Martinoli A., "High Resolution Air Pollution Maps in Urban Environments Using Mobile Sensor Networks". *Proc. of the 2015 IEEE Int. Conf. on Distributed Computing in Sensor Systems*, June 2015, Fortaleza, Brazil, Boston, U.S.A., pp. 11-20.

Lab 10 – 3 h
Distributed sensing with static, mobile, and robotic nodes (implementation in Webots).

WEEK 13 – December 8 and 9

Lecture – 2 h
Self-aggregation and self-assembling in natural and artificial systems. General take-home messages of the course.

Reading

Primary

- Correll N. and Martinoli A., “Modeling and Designing Self-Organized Aggregation in a Swarm of Miniature Robots”. Special issue on Stochasticity in Robotics and Biological Systems, Asada H. H. and Kumar V. editors, *Int. Journal of Robotics Research*, 30(5): 615-626, 2011.
- Halloy J., Sempo G., Caprari G., Rivault C., Asadpour M., Tâche F., Saïd I., Durier V., Canonge S., Amé J.M., Detrain C., Correll N., Martinoli A., Mondada F., Siegwart R. R., and Deneubourg J. L. “Social integration of robots in groups of cockroaches to control self-organized choices”. *Science*, 318(5853): 1155-1158, 2007.
- Mermoud G., Mastrangeli M., Upadhyay U., and Martinoli A., “Real-Time Automated Modeling and Control of Self-Assembling Systems”. *Proc. of the 2012 IEEE Int. Conf. on Robotics and Automation*, May 2012, Saint Paul, MN, U.S.A., pp. 4266-4273.

Secondary

- G. Whitesides and B. Grzybowski. “Self-assembly at all scales”. *Science*, 295(5564): 2418-2421, 2002.
- Rubenstein M., Cornejo A., and Nagpal R., “Programmable Self-Assembly in a Thousand-Robot Swarm”. *Science* 345 (6198): 795-799, 2014.

Lab verification test 2 – 2.5 h
In the computer room; subject: lab 7 to 10.

Discussion with students – 0.5 h (in GR C0 01)
Discussion with the students based on SAC and Moodle feedback.

Course project
Submission of final report of the course project by the end of the week.

WEEK 14 – December 16 and 17

Lecture
None.

Reading
None.

Lab
None.

Course project
Defense course project: lecture, lab time and as much as appropriate in the whole last week of the semester.