

## FINAL REPORT

Student name: Nicoletta Bof

Cycle: 30°

Curriculum: ICT

Supervisor name: Luca Schenato

Thesis title (final): Multi-Agent Distributed Optimization and Estimation over Lossy Networks

### PART 1 - COURSES, CONFERENCES AND MOBILITY

#### Courses for Ph.D. students

- Among the Ph.D. courses offered in Padua, I followed the following ones taking the final examination:
  - Applied Functional Analysis (Prof. G. Pillonetto)
  - Applied Linear Algebra (Prof. G. Picci)
  - Statistical Methods (Prof. L. Finesso)
  - Computational Inverse Problems (Prof. F. Marcuzzi)
- During my Visiting Research period at Stanford University, I attended the following courses (without taking the final examination):
  - Principles of Robotic Autonomy (Prof. M. Pavone)
  - Convex Optimization I (Prof. S. Boyd)
  - Introduction to Optimal Control and Dynamic Programming (Prof. M. Pavone)

#### Summer schools, short courses, tutorials

- SIDRA 2015 PhD Summer School (Bertinoro , July 12th-18th 2015, courses on “Robot Control” and “Underwater Robotics”).
- “The interplay between Big Data and sparsity in control and systems identification” (Paris-Saclay, May 09th-13th 2016, course of the International Graduate School on Control)
- SIDRA 2016 PhD Summer School (Bertinoro, July 11th-16th 2016, courses on “Robust and Constrained Control” and “Distributed Control and its applications”)

#### Seminars

The list of attended seminars can be found at the end of the document

#### Participation to International Conferences and Workshops

- 15th European Control Conference (ECC 2016) in Aalborg, Denmark. During this conference I presented the paper N. Bof, R. Carli, L. Schenato "On the performances of consensus based

versus Lagrangian based algorithms for quadratic cost functions.” Control Conference (ECC), 2016 European. IEEE, 2016.

### **Other learning activities**

- During the academic year 2015-2016 I carried out some tutoring activity for the course “Laboratorio di automatica” (Bachelor Degree in Information Engineering, Prof. Angelo Cenedese). This activity required to arrange some exercises and to help the students solve them.

### **Mobility periods**

- Dates: January 9th 2017 to June 30th 2017.
- Hosting institution: Stanford University (California, USA) under the supervision of Professor Marco Pavone.
- Title: Challenges for Mobility on Demand systems

## **PART 2 - RESEARCH ACTIVITY**

During the PH.D. I focused on the following different themes:

- Output feedback control for Boolean Control Networks (BCNs): the study concerned the output feedback controllability for the interconnection of BCNs (series, parallel, feedback) and also the stabilizability of 2-dimensional BCNs.
- Controllability of complex systems: the controllability of marginally stable systems with a huge number of nodes was studied. In particular, an analysis of the control energy required to control the network was carried out.
- Comparison of the convergence rate for distributed algorithms: an analysis was carried out to compare the convergence rate of Average Consensus, Accelerated Average Consensus, ADMM and Dual Ascent for the minimization of quadratic cost functions. Particular attention was given to relation between convergence rate and the connectivity of the underlying communication network.
- Distributed robust estimation in asynchronous and lossy communication networks: starting from a measurement model  $y = Hx$ , the problem analyzed was the estimation of the quantity  $x$  from measurements  $y$  that are corrupted by gaussian noise but also outliers. This problem was solved minimizing a modified version of the norm 1 of the residuals ( $z = y - Hx$ ). The minimization was carried out using the Block Jacobi algorithm, which is shown to be robust to packet loss and uses an asynchronous protocol. This approach was applied to a localization problem and to voltage estimation in Smart Grids.
- Camera patrolling: the problem studied was the development of an optimal moving strategy for a group of cameras in order to patrol a one dimensional perimeter. After reducing this problem to a partitioning problem, a distributed algorithm was developed which allows each camera to evaluate the optimal part of the perimeter it has to patrol. The developed algorithm is able to work under unreliable communications.
- Making Newton-Raphson Consensus asynchronous and robust to packet losses: in this context, the idea was to widen the applicability of the Newton-Raphson Consensus (NRC), an existing algorithm for the distributed minimization of additively separable functions. In particular, a new version of this algorithms was developed to make the original NRC asynchronous and robust to packet losses. This required the merging of two algorithms for consensus already present in the

literature to obtain an asynchronous and robust average consensus which exponentially converges to the mean.

- Mobility on Demand (MoD) Systems (during the mobility period at Stanford University): in this context part of the research focused on the integration of autonomous MoD systems with electric vehicles (EVs) and the power network, and part on the rebalancing of MoD systems. For the first topic, the aim was to study the effects of the recharging of EVs on the stability of the power network at the distribution level, and to find a good linearization of the power flow equations. The idea was to obtain an easy enough model for the power grid which could be integrated with a model for the autonomous MoD system. This would allow to optimally manage the MoD system minimizing the EVs' charging costs but at the same time guaranteeing the stability of the power grid. The second topic regards the rebalancing problem, i.e. the problem of scheduling the assignment for a groups of rebalancers that have to try to move the cars between stations in order not to leave a station without cars. The idea employed was to model the rebalancing of a MoD system as a Markov Decision Process (MDP) and to solve the problem using an on-line approach. In particular, the studied solution involves Markov Chain Tree Search (MCTS) possibly with Double Progressive Widening.
- Estimation of the Intensity of a Poisson Arrival Process: the problem analyzed was the estimation of the intensity of an arrival Poisson process in a 1-dimensional area. In particular, the area was divided in (possibly overlapping) intervals and the intensity had to be estimated starting from aggregated data of each interval (the number of arrivals in the interval, without the precise position of the arrival). The solution adopted involved a non-parametric approach using Gaussian Kernels.

## PART 3 - PUBLICATIONS

### List of publications on international journals

1. N. Bof, E. Fornasini, M. E. Valcher. "Output Feedback stabilization of Boolean control networks." In Automatica, vol. 57, July 2015. DOI: 10.1060/j.automatica.2015.03.032
2. N. Bof, and G. Baggio, and S. Zampieri. "On the role of network centrality in the controllability of complex networks." IEEE Transactions on Control of Network Systems, vol.4, no. 3, pp. 643-653, September 2017. DOI: 10.1109/TCNS.2016.2550862
3. N. Bof, and R. Carli, and A. Cenedese, and L. Schenato "Asynchronous Distributed Camera Network Patrolling under Unreliable Communication." IEEE Transactions on Automatic Control (2017). DOI: 10.1109/TAC.2017.2703926
4. N. Bof, and R. Carli, and L. Schenato "Is ADMM always faster than Average Consensus?" **provisionally accepted** by Automatica as a Technical Communique
5. M. Todescato, and N. Bof, and G. Cavraro, and R. Carli, and L. Schenato "Generalized Gradient Optimization over Lossy Networks for Partition-Based Estimation." **submitted** to SIAM Journal on Optimization

6. N. Bof, and R. Carli, and G. Notarstefano, and L. Schenato, and D. Varagnolo "Newton-Raphson Consensus under asynchronous and lossy communications for peer-to-peer networks." **submitted** to IEEE Transactions on Automatic Control

**List of publications on conference proceedings**

1. N. Bof, R. Carli, L. Schenato "On the performances of consensus based versus Lagrangian based algorithms for quadratic cost functions." Control Conference (ECC), 2016 European. IEEE, 2016.
2. N. Bof, and M. Todescato, and R. Carli, and L. Schenato "Robust Distributed Estimation for Localization in Lossy Sensor Networks." *IFAC-PapersOnLine* 49.22 (2016): 250-255.
3. N. Bof, R. Carli, L. Schenato "Average Consensus with Asynchronous Updates and Unreliable Communication." 20th IFAC World Congress, July 9-14, 2017, Toulouse Convention Center, Toulouse, France

20/09/2017

Student signature

Nicoletta B.

Supervisor signature

Luca Schenato

## List of seminars

- 3/11/14: Florian Dörfler, ETH Zürich, “Plug and Play Operation of Microgrids”, Automatica Group Seminars
- 14/11/14: José A. Cobos, Technical University of Madrid, “Power Supply Systems for Energy Efficiency”, DEI Distinguished Lecture
- 17/11/14: Arthur Krener, University California Davis, “Filtering of Boundary Value Discrete Time Linear Systems”, Automatica Group Seminars
- 27/11/14: Luigi Colangeli, European Space Agency (ESA), “Rosetta rendez-vous with the 67P/Churyumov-Gerasimenko comet”, DEI Distinguished Lecture series 2014
- 3/03/15: Michele Pavon, Università di Padova “On the geometry of maximum entropy problems”, Automatica Group Seminars
- 15/03/15: Alessandro Farinelli, Università di Verona, “Recent advances on coordination in Multi-Robot Systems”, Automatica Group Seminars
- 23/03/15: Walter Snoeys, PH department, CERN, “How chips helped discover the Higgs boson at CERN”, DEI Distinguished Lecture series 2015
- 27/03/15: Lorenzo Rosasco, Università di Genova, MIT, “Learning with Computational Regularization”, Seminari di Ingegneria dell’Informazione
- 08/04/15: Ulrich Oberst, University of Innsbruck, “Weakly exponentially stable linear time-varying differential behaviors”, Automatica Group Seminars
- 24/04/15: Luigi Palopoli, University di Trento, “When multimedia meets control: use of soft real-time techniques for control design”, Automatica Group Seminars
- 28/04/15: Martin Grötschel, Zuse Institute, Technical University Berlin, “Polyhedra: Their Description and Use”, Colloquia Patavina
- 29/04/15: Gianluca Pollastri, University College Dublin, “Deep architectures and deep learning in chemoinformatics: the prediction of properties and activities of drug-like molecules”
- 25/05/15: Silvio Micali, MIT, “Proofs, Secrets and Computation”, Colloquia Patavina
- 29/05/15: Francesco Ticozzi, Università di Padova, “A walk to symmetrization via a Schrödinger bridge”, Workshop: New challenges in reciprocal processes, Schrödinger bridges
- 03/06/15: Mérouane Debbah, Huawei France R&D Center, “Mathematical Scientific Challenges of 5G”, DEI Distinguished Lecture series 2015
- 09/06/15: Ivar Ekeland, University Paris Dauphine, “Are people rational?”, Colloquia Patavina
- 17/06/15: Michel Verhaegen, Delft University, “Nuclear Norm identification for lumped and distributed systems”, Automatica Group Seminars
- 18/06/15: Rodolphe Sepulchre, Cambridge University, “Do brains compute?”, DEI Distinguished Lecture Series 2015
- 07/07/15: Davide Piovesan, Gannon University, “Human Arm Mechanics: from system identification to neural control”, DEI Colloquia
- 09/07/15: Luca Scardovi, University of Toronto, “From Synchronization Analysis to Synchronization Control of Cellular Networks”, Automatica Group Seminars
- 24/09/15: Kahori Kita, Center for Frontier Medical Engineering, Chiba University, “Development of sensory feedback system for stroke patients with sensory disturbance and neural basis of musicians dystonia”, Seminari di Ingegneria dell’Informazione
- 25/09/15: Pratap Pattnaik, IBM, “Bitcoin, an attempt at a separation of money and state”, DEI Distinguished Lecture series 2015
- 28/09/15: Blaz Zupan, Lubiana University, “Large-scale data fusion”



- 24/09/15: Pierluigi Crescenzi, Università di Firenze, “Fast and Simple Computation of Top-k Closeness Centralities”, Seminari di Ingegneria dell’Informazione
- 25. 30/10/15: Giulio Caravagna, University of Edinburgh, “Algorithmic Methods to Infer the Evolutionary Trajectories in Cancer Progression”
- 3/11/15: Horst Uwe Keller, University of Braunschweig, “From Halley Multicolour Camera on Giotto to OSIRIS on Rosetta: the first and the latest images of cometary nuclei”
- 6/11/15: Fabrizio Luccio, Università di Pisa, “Arithmetic for Rooted Trees”, DEI Colloquia
- 10/12/15: Francesca A. Lisi, Università degli Studi di Bari, “Lovelace Test: Verso macchine creative”, DEI Colloquia
- 18/01/16: Alessandro Abate, University of Oxford, “Formal verification of complex control systems”
- 02/02/2016: “Workshop on neural science” held at DEI
- 31/03/2016: Lucia Pallottino, Università di Pisa, “The Walk-Man humanoid robot: whole- body loco-manipulation planning and control”
- 27/04/2016: Alexandr Aravkin, University of Washington, “Conjugate Interior Point Method for Large-Scale Problems”
- 17/05/2016: Marino Gatto, Politecnico di Torino, “Matematica ed ecologia: le nuove frontiere della modellistica”, Colloquia Patavina
- 18/05/2016: Ujjwal Maulik, Jadavpur University, Kolkata, “Single and Multiobjective clustering”
- 20/05/2016: Kim Listmann, Lab Group Manager, ABB Ladenburg, “Interactive Control & Learning for Robots - What we need and why!”
- 23/05/2016: Luca Zaccarian, Università di Trento, “Static input allocation for reaction wheels desaturation using magnetorquers”
- 25/05/2016: Ananda Chowdhury, Jadavpur University, Kolkata, “Matching, Cut, Connectivity: Graph-theoretic Solutions for Biomedical”
- 6/06/2016: Eli Upfal, Brown University, Providence, “When is Big Data Sufficiently Big? When is it Too Big? Sample Complexity, Uniform Convergence, and Generalization Error”, DEI Colloquia
- 14/06/2016: Oscar Pozzobon, Qascom S.r.l. , Italy, “Galileo Satellite Navigation System: Current status and research opportunities”, DEI Colloquia
- 21/06/2016: M.I. Jordan, University of California, Berkeley, “Computational Thinking, Inferential Thinking and Data Science”, Distinguished Lectures series 2016
- 24/06/2016: Franco P. Preparata, Brown University, “Lo straordinario percorso dell’informatica”, DEI Colloquia
- 24/06/2016: Marcello Pelillo, Ca’ Foscari University, “Grouping Games: Finding Clusters in Graphs, Digraphs and Hypergraphs”, DEI Colloquia
- 20/07/2016: Subhrakanti Dey, Uppsala University, “Sensor Scheduling in Variance Based Event Triggered Estimation with Packet Drops”
- 21/07/2016: Enrico Lovisari, Volvo Cars, “Traffic networks: modelling and control”,
- 19/09/2016: Dante Mantini, KU Leuven, Belgium, “Detecting large-scale brain networks using high-density EEG”, DEI seminars
- 29/09/2016: Maurizio Corbetta, Washington University School of Medicine St.Louis, “Networks: Brain, Health, and Society. ”, Distinguished Lectures series 2016
- 28/10/16: Yukinori Nakamura, Okayama University, Japan “State Estimation via Time-Stamp Information”
- 3/11/16: Kasm Sinan Yldrm, TU Delft, “Research Challenges for Intermittently Powered Wireless Embedded Systems”

- 25/11/16: Andrea Bisoffi, Università di Trento, “Global asymptotic stability of a PID control system with Coulomb friction”
- 18/01/17: Katie Driggs-Campbell, UC Berkeley, “Modeling and control of human-in-the-loop systems with applications to autonomous vehicles”, ASL Lab meetings, Stanford
- 20/01/17: Silvio Savarese, Stanford University, “Seeing objects and People in the 3D world: Visual Intelligence in perspective”, SAIL-Toyota Center Seminar, Stanford
- 8/02/17: Gesualdo Scutari, Purdue University, “In-network Non-convex large scale optimization”, ASL Lab meetings, Stanford
- 8/02/17: Kyunam Kim, UC Berkeley, “On the Locomotion of Spherical Tensegrity Robots for Planetary Exploration Missions”, ASL Lab meeting, Stanford
- 15/02/17: Chang Liu, UC Berkeley, “From Automation to Human-Centric Planning”, ASL Lab meeting, Stanford
- 9/03/17: Panayotis Mertikopoulos, French National Center for Scientific Research-CNRS, “Learning in Games via Reinforcement and Regularization”, ISL Colloquium, Stanford
- 10/03/17: Marcello Romano, Naval Postgraduate School, Monterey, California, “Spacecraft Dynamics, Guidance and Control: analysis, simulations, experimentation”, Space Rendezvous Laboratory (SLAB)
- 10/03/17: Mo Chen, Sylvia Herbert, EECS, UC Berkeley, “High-Dimensional Reachability Analysis: Addressing the ”Curse of Dimensionality” in Verification”, ISL Colloquium, Stanford
- 27/04/17: Wolf Ketter, University of Cologne, “FleetPower: Creating Virtual Power Plants in Sustainable Smart Electricity Markets”, Stanford Smart Grid Seminar
- 11/05/17: Scott Moura, UC Berkeley, “Electric Vehicles in the Smart Grid: Optimization & Control”, Stanford Smart Grid Seminar
- 12/05/17: Ken Goldberg, UC Berkeley, “The New Wave in Robot Grasping”, SAIL-Toyota Center Seminar Series, Stanford
- 17/05/17: Changliu Liu, UC Berkeley, “Designing Robot Behavior in Human-Robot Interactions with Application to Intelli- gent Industrial Co-Robots.”, ASL Lab meetings, Stanford
- 24/05/17: Timothy Barfoot, University of Toronto, “Can a Robot Navigate Using Vision Alone Forever?”, ASL Lab meetings, Stanford
- 17/07/17: Marco Tognon, Analysis and Architecture of Systems (LAAS), Toulouse, “Aerial Physical Interaction by Means of Cables or Bars: Modeling and Control of Tethered Aerial Vehicles”, Automatica Group Seminars
- 6/09/17: Jacques Savoy, Universit di Neuchatel, “Text, Computer, and Style: In the Pursuit of Elena”
- 23/09/17: Chris Van Hoof, Holts Centre/ IMEC, The Netherlands, “Personal Behavioral Technology - Wearables Can Become an Active Contributor to Your Wellbeing”, Distinguished Lectures series 2017

