Ph.D. School on Information Engineering – University of Padova

FINAL REPORT

Student name: Giacomo Baggio

Cycle: XXX

Supervisor: Prof. Augusto Ferrante

Thesis title: Novel Results on the Factorization and Estimation of Spectral Densities

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PART 1 - COURSES, CONFERENCES AND MOBILITY

Courses

1. Applied Functional Analysis
   PhD course
   Dipartimento di Ingegneria dell'Informazione, Università di Padova
   Nov 2014 – Jan 2015, 7 CFU.

2. Applied Linear Algebra
   PhD course
   Dipartimento di Ingegneria dell'Informazione, Università di Padova
   Mar 2015 – Apr 2015, 5 CFU.

3. Statistical Methods
   PhD course
   Dipartimento di Ingegneria dell'Informazione, Università di Padova
   Apr 2015 – Jun 2015, 6 CFU.

4. Computational Inverse Problems
   PhD course
   Dipartimento di Ingegneria dell'Informazione, Università di Padova
   Feb 2015 – Mar 2015, 4 CFU.

5. Robust Control Reading Club (Part I and II),
   PhD course
   Department of Engineering, University of Cambridge,
   Oct 2015 – Apr 2016, 24 h.

6. Math Classes (Specific Topics in Analysis),
   PhD course
   Department of Engineering, University of Cambridge,
   Oct 2015 – Dec 2015, 10 h.

Summer schools, short courses, tutorials

I attended the SIDRA (Società Italiana Docenti e Ricercatori in Automatica) Summer School held at Bertinoro on 11-16 July 2016, on the topics of "Robust and Constrained Control" and "Distributed Control and its Applications".

Seminars

Seminars attended at the University of Padova:

1. 13/11/14: Florian Dörfler, *ETH Zürich*
   "Plug and Play Operation of Microgrids"
   Automatica Group Seminars

2. 14/11/14: Josè A. Cobos, *Technical Univ. Madrid*
   "Power Supply Systems for Energy Efficiency"
   DEI Distinguished Lecture

3. 17/11/14: Arthur Krener, *Univ. California Davis*
   "Filtering of Boundary Value Discrete Time Linear Systems"
   Automatica Group Seminars

4. 27/11/14: Luigi Colangeli, *European Space Agency (ESA)*
   "Rosetta rendez-vous with the 67P/Churyumov-Gerasimenko comet"
   DEI Distinguished Lecture

5. 28/11/14: Bruno Chiarellotto, *Univ. Padova*
   "Il lavoro e la vita di Alexander Grothendieck"
   Colloquia Patavina

6. 04/12/14: Elisabetta Collini, *Univ. Padova*
   "Quantum mechanics in energy and signal transfer processes"
   DEI Colloquia

7. 13/03/15: Michele Pavon, *Univ. Padova*
   "On the geometry of maximum entropy problems"
   Automatica Group Seminars

8. 23/03/15: Walter Snoeys, *PH department, CERN*
   "How chips helped discover the Higgs boson at CERN"
   DEI Distinguished Lecture

9. 08/04/15: Ulrich Oberst, *Univ. Innsbruck*
   "Weakly exponentially stable linear time-varying differential behaviors"
   Automatica Group Seminars

10. 24/04/15: Luigi Palopoli, *Univ. Trento*
"When multimedia meets control: use of soft real-time techniques for control design"
Automatica Group Seminars

11. 28/04/15: Martin Grötschel, *Zuse Institute, Technical Univ. Berlin*
"Polyhedra: Their Description and Use"
Colloquia Patavina

12. 25/05/15: Silvio Micali, *MIT*
"Proofs, Secrets and Computation"
Colloquia Patavina

13. 29/05/15: Tryphon T. Georgiou, *Univ. Minnesota*
"The Hilbert metric and Schrödinger bridges"
Workshop: New challenges in reciprocal processes, Schrödinger bridges...

14. 29/05/15: Markus Fischer, *Univ. Padova*
"On large deviations for the empirical measures of weakly interacting systems"
Workshop: New challenges in reciprocal processes, Schrödinger bridges...

15. 29/05/15: Francesco Ticozzi, *Univ. Padova*
"A walk to symmetrization via a Schrödinger bridge"
Workshop: New challenges in reciprocal processes, Schrödinger bridges...

16. 03/06/15: Mérouane Debbah, *Huawei France R&D Center*
"Mathematical Scientific Challenges of 5G"
DEI Distinguished Lecture

17. 09/06/15: Ivar Ekeland, *Univ. Paris Dauphine*
"Are people rational?"
Colloquia Patavina

18. 17/06/15: Michel Verhaegen, *Univ. Delft*
"Nuclear Norm identification for lumped and distributed systems"
Automatica Group Seminars

19. 18/06/15: Rodolphe Sepulchre, *Univ. Cambridge*
"Do brains compute?"
DEI Distinguished Lecture

20. 07/07/15: Davide Piovesan, *Univ. Gannon*
"Human Arm Mechanics: from system identification to neural control"
DEI Colloquia

21. 08/07/15: Stefano Ghidoni, *Univ. Padova*
"People pose estimation and re-identification in networks of 2D sensors"
Workshop: Postdoctoral Research in Informatics

22. 08/07/15: Stefano Michieletto, *Univ. Padova*
"Learning techniques from human demonstration through electromyography and vision"
Workshop: Postdoctoral Research in Informatics

23. 08/07/15: Matteo Munaro, *Univ. Padova*
"Robust perception of humans for mobile robots and camera networks"
Workshop: Postdoctoral Research in Informatics

24. 09/07/15: Luca Scardovi, *Univ. Toronto*
"From Synchronization Analysis to Synchronization Control of Cellular Networks"
Automatica Group Seminars

25. 25/09/15: Pratap Pattnaik, *IBM*
"Bitcoin, an attempt at a separation of money and state"
DEI Distinguished Lecture

26. 20/07/16: Subhrakanti Dey, *Uppsala university*
"Sensor Scheduling in Variance Based Event Triggered Estimation with Packet Drops"
Automatica Group Seminars

27. 21/07/16: Enrico Lovisari, *R&D Engineering Department della Volvo Cars, Göteborg*
"Traffic networks: modelling and control"
Automatica Group Seminars

28. 19/09/16: Dante Mantini, *KU Leuven*
"Detecting large-scale brain networks using high-density EEG"
DEI colloquia

29. 29/09/16: Maurizio Corbetta, *Washington University School of Medicine St. Louis / University of Padova*
"Networks: Brain, Health, and Society"
DEI Distinguished Lecture

30. 29/09/16: Damiano Varagnolo, *Luleå University of Technology*
"Modelli di dinamiche del dolore"
Automatica Group Seminars

31. 28/10/16: Yukinori Nakamura, *Okayama University*
"State Estimation via Time-Stamp Information"
Automatica Group Seminars

32. 03/11/16: Kasım Sinan Yıldırım, *TU Delft*
"Research Challenges for Intermittently Powered Wireless Embedded Systems"
Automatica Group Seminars

33. 25/11/16: Andrea Bisoffi, *Università di Trento*
"Global asymptotic stability of a PID control system with Coulomb friction"
Automatica Group Seminars

34. 12/01/17: Michele Scquizzato, *University of Houston*
"Distributed Computation of Large-Scale Graph Problems"
DEI Colloquia

35. 28/02/17: Sandro Zampieri, *Univ. Padova*
"Information transmission in balanced neuronal networks: the role of matrix non-normality"
Neuroscience meetings

36. 02/03/17: Carlo Vittorio Cannistraci, *Technical University Dresden*
"Machine learning and complex networks for precision and systems biomedicine"
DEI Colloquia

37. 05/04/17: Giulia Prando, *Univ. Padova*
"Deep Learning"
Automatica Seminars

38. 07/04/17: Salvatore Anzalone, *Paris 8 University in Saint Denis*
"Socially intelligent robots"
DEI Colloquia

39. 03/05/17: John Hauser, *University of Colorado at Boulder*
"Trajectory Exploration for Aggressive Maneuvering"
Automatica Group Seminars

40. 12/05/17: Alberto Sangiovanni-Vincentelli , *Berkeley University (CA)*
"Is Technology Transfer a Dream or a Reality?"
DEI Distinguished Lecture

41. 15/05/17: Basilio Gentile, *ETH Zürich*
"Distributed dynamics to achieve a location equilibrium"
Automatica Group Seminars

42. 18/05/17: Giulio Tononi, *University of Wisconsin, Madison*
"Consciousness: From Theory to Practice"
DEI Distinguished Lecture

43. 09/06/17: Francesca Boem, *Imperial College London*
"Scalable Methods for Fault-tolerant Control of Large-Scale Systems"
Automatica Group Seminars

44. 16/06/17: Subhrakanti Dey, *Uppsala university*
"Event-triggered remote estimation with packet loss in the presence of an eavesdropper"
Automatica Group Seminars

45. 16/06/17: Mattia Zorzi, *Univ. Padova*
"The Harmonic Analysis of Kernel Functions"
Automatica Group Seminars

46. 21/06/17: Reza Arghandeh, *Florida State University*
"From Data Mining to Knowledge Mining in Smart Infrastructure"
Automatica Group Seminars

47. 21/06/17: Mattia Zorzi, *Univ. Padova*
"Sparse plus low rank network identification: A nonparametric approach"
Automatica Group Seminars

48. 23/06/17: Marco Todescato, *Univ. Padova*
"Efficient Space/Time Learning: Gaussian Regression meets Kalman Filtering"
Automatica Group Seminars

49. 17/07/17: Marco Tognon, *LAAS Toulouse*
"Aerial Physical Interaction by Means of Cables or Bars: Modeling and Control of

Tethered Aerial Vehicles"
Automatica Group Seminars

50. 22/09/17: Chris Van Hoof, *Holts Centre/ IMEC, The Netherlands*
"Personal Behavioral Technology - Wearables Can Become an Active Contributor to Your Wellbeing"
DEI Distinguished Lecture

Seminars attended at the University of Cambridge during visiting period abroad (Oct 2015 – Jun 2016):

1. 08/10/15: Luca Zaccarian, *LAAS-CNRS and University of Trento*
"Input allocation using dynamics: theory and applications"
Control Seminars

2. 16/10/15: Gilbert Strang, *MIT*
"Banded Matrices and Fast Inverses"
Math Seminars

3. 22/10/15: Muhammad Ali Al-Radhawi, *Imperial College London*
"Stability of Reaction Networks: A System-Theoretic Approach"
Control Seminars

4. 29/10/15: Morten Hovd, *Norwegian University of Science and Technology*
"Sum of squares programming for discrete-time non-linear systems - with application to power converters"
Control Seminars

5. 05/11/15: Eric Kerrigan, *Imperial College London*
"Optimal control of wave energy converters"
Control Seminars

6. 12/11/15: Raphaël Jungers, *Université catholique de Louvain*
"Path-complete Lyapunov techniques: when Algebra and Combinatorics meet in Control"
Control Seminars

7. 26/11/15: Stephen Duncan, *University of Oxford*
"Electron beam stabilisation for a synchrotron: An example of the control of spatio-temporal systems"
Control Seminars

8. 14/01/16: Joaquin Carrasco Gomez, *University of Manchester*
"Integral Quadratic Constraint Theorem: A topological separation approach"
Control Seminars

9. 21/01/16: James Anderson, *University of Oxford*
"Decomposition and Structured Model Reduction for Large Scale Systems Analysis"
Control Seminars

10. 4/02/16: Carl Edward Rasmussen, *University of Cambridge*
"Variational Inference in Gaussian Processes for non-linear time series"
Control Seminars

11. 11/02/16: Alessandro Abate, *University of Oxford*
"Computable analysis and control synthesis of complex dynamical systems via formal verification"
Control Seminars

12. 19/02/16: Johannes Schiffer, *University of Leeds*
"Stability and power sharing in microgrids"
Control Seminars

13. 03/03/16: Daniel Limon, *University of Seville*
"Model Predictive Control for changing operation conditions"
Control Seminars

14. 04/03/16: Lorenzo Marconi, *University of Bologna*
"Isolating Invisible Dynamics in the Design of Robust Hybrid Internal Models"
Control Seminars

15. 11/03/16: Vincent Blondel, *Université Catholique de Louvain*
"Communities and privacy in mobile phone social networks"
Control Seminars

16. 14/03/16: Richard Pates, *University of Lund*
"Scalable Design Methods"
Control Seminars

17. 13/04/16: Chun Tung Chou, *University of New South Wales, Australia*
"A Bayesian Approach to Molecular Communication"
Control Seminars

18. 21/04/16: He Kong, *Cranfield University*
"Architectural Issues in the Design of Model Predictive Control: From Centralized to Distributed"
Control Seminars

19. 28/04/16: Muyiwa Olanrewaju, *University of Cambridge*
"Design Considerations for Economic MPC"
Control Seminars

20. 10/05/16: Qing-Chang Zhong, *Illinois Institute of Technology and University of Sheffield*
"Bounded Control that Preserves System Stability and its Applications"
Control Seminars

21. 12/05/16: Andreas Nunnenkamp, *University of Cambridge*
"Quantum control and quantum synchronization"
Control Seminars

22. 26/05/16: Heather Harrington, *University of Oxford*
"Algebraic methods for parameter-free analysis of biochemical networks"
Control Seminars

23. 09/06/16: Emanuele Garone, *Université Libre de Bruxelles*
"It's not MPC! An Explicit Reference Governor for the supervision of constrained nonlinear systems"
Control Seminars

Participation to international conferences and workshops

1. I attended the conference "Division F Conference" held at Clare College, Cambridge (UK), on 3 December 2015 and organized by the Information and Control Engineering (Division F) group of the Department of Engineering of the University of Cambridge.

2. I attended the workshop "Biological Control Across Scales" held at Sidney Sussex College, Cambridge (UK), on 27–28 June 2016 and organized by Prof. Rodolphe Sepulchre. During the workshop I presented a Research Poster.

3. I attended the IFAC (International Federation Automatic Control) 20th World Congress held at Toulouse (France) on 10–14 July 2017. During the conference I delivered two presentations.

Other learning activities

During my visiting period at the Department of Engineering, University of Cambridge, UK (Oct 2015 – Jun 2016), I attended the weekly ERC Meetings organized by Prof. Rodolphe Sepulchre. These meetings consisted of presentations and discussions of topics related to the ERC project "Switchlet: A multi-resolution theory for systems and control across scales". In two of these meetings I delivered presentations involving my research work.

I supervised four groups of students for the course "3F1 Signals & Systems" of the third-year M. Eng. Degree at Department of Engineering, the University of Cambridge. The total amount of supervision hours was 32 h. Each supervision consisted of correcting students' homework and explaining specific course topics to the students.

I supervised the course "Stima e Filtraggio" (Estimation and Filtering) for the Master Degree in "Ingegneria dell'Automazione", at Department of Information Engineering, University of Padova, during the Academic Year 2016–17. The total amount of supervision hours was 20 h. The supervisions consisted of lab sessions on specific topics of the course.

Mobility periods

From 1st October 2015 to 30th June 2016, I spent a Visiting Research Period at the Control Group, Department of Engineering, University of Cambridge (UK), under the supervision of Prof. Rodolphe Sepulchre.

PART 2 - RESEARCH ACTIVITY

During my PhD I mainly worked on the following research topics:

1. *Spectral Factorization.* (In collaboration with A. Ferrante). I analyzed the problem of factoring a discrete-time multivariate rational spectral density. This problem, commonly known under the name of *spectral factorization*, has a long history and is ubiquitous in systems and control theory. I derived a completely general result

for the factorization of such a rational matrix-valued functions in the spirit of a celebrated work by Dante C. Youla. Further, I analyzed the connected problems of uniqueness and parametrization of minimal spectral factors. Such problems are of fundamental importance in stochastic realization theory. The obtained results have been published or submitted for publication in J1, J2, J3.

2. *Spectral Estimation.* (In collaboration with A. Ferrante, R. Sepulchre, B. Zhu). I considered the problem of estimation of spectral densities in the framework introduced by Byrnes, Georgiou, and Lindquist and known under the name of *THREE (Tunable High-REsolution Estimation).* According to this formulation, the problem is recast as a *generalized moment problem* with complexity constraints and includes as special cases some important problems in systems and control theory, e.g. the Nevanlinna–Pick interpolation problem and the covariance extension problem. With reference to this framework this framework, my contributions consist of:

   i) the convergence analysis of an efficient algorithm for the Kullback–Leibler THREE estimation of spectral densities,

   ii) an existence result for a family of parametric multivariate spectral estimators, and

   iii) the definition and analysis of new distances in the space of multivariate spectral densities that feature favourable properties and are in turn connected with a "robust" version of THREE estimation.

   The obtained results have been published or submitted for publication in J4, J5, J6, C1, C2, C3.

3. *Controllability of Complex Networks.* (In collaboration with S. Zampieri, N. Bof). I investigated the problem of steering the state of a large-scale network driven by linear dynamics to a target one. This problem is known as *network controllability* and, in recent years, has attracted increasing attention from the network science and control theory community. I focused on the analysis of the controllability properties, in terms of energy to control the network, for a class of positive networks. In particular, I studied the relation between some measures that quantify the "importance" of nodes in the network (most notably, the PageRank measure) and network controllability. This result has been published in J3.

PART 3 - PUBLICATIONS

List of publications on international journals

J1. G. Baggio, A. Ferrante. "On the Factorization of Rational Discrete-Time Spectral Densities". *IEEE Transactions on Automatic Control.* vol. 61, no. 4, pp. 969-981, Apr. 2016.

ISSN: 0018-9286, DOI: 10.1109/TAC.2015.2446851.

J2. G. Baggio, A. Ferrante. "On Minimal Spectral Factors with Zeros and Poles lying on Prescribed Regions". *IEEE Transactions on Automatic Control.* vol. 61, no. 8, pp. 2251–2255, Aug. 2016.

ISSN: 0018-9286, DOI: 10.1109/TAC.2015.2484330.

J3. N. Bof, G. Baggio, 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, Sept. 2017.

ISSN: 2325-5870, DOI: 10.1109/TCNS.2016.2550862.

J4. G. Baggio, A. Ferrante. "Parametrization of Minimal Spectral Factors of Discrete-Time Spectral Densities". *IEEE Transactions on Automatic Control.* (Submitted), 2017.

J5. G. Baggio. "A Global Convergence Analysis of the Pavon–Ferrante Algorithm for Spectral Estimation". *IEEE Transactions on Automatic Control.* (Submitted), 2017.

J6. G. Baggio, A. Ferrante, R. Sepulchre. "Finslerian Metrics in the Cone of Spectral Densities". *IEEE Transactions on Automatic Control.* (Submitted), 2017.

J7. B. Zhu, G. Baggio. "On the existence of a solution to a spectral estimation problem *à la* Byrnes-Georgiou-Lindquist". *IEEE Transactions on Automatic Control.* (Submitted), 2017.

List of publications on conference proceedings

C1. G. Baggio, R. Sepulchre. "Stochastic Processes: a Behavioral Perspective". *Workshop "Biological Control Across Scales"*, Cambridge, 27-28 June 2016 (Poster Presentation).

C2. G. Baggio, R. Sepulchre. "LTI Stochastic Processes: a Behavioral Perspective". *Proceedings of the IFAC 20th World Congress*, Toulouse, 10-14 July 2017.

C3. G. Baggio. "On the convergence of a matricial fixed-point iteration connected with spectral estimation". *Proceedings of the IFAC 20th World Congress*, Toulouse, 10-14 July 2017.

Student signature

Supervisor signature