
**PhD in Information Technology and Electrical Engineering**

**Università degli Studi di Napoli Federico II**

# PhD Student: Davide Fiore

**XXIX Cycle**

**Training and Research Activities Report – Third Year**

**Tutor: Mario di Bernardo**

## 1. Information

I received on 18/12/2014 the Laurea Magistrale cum laude in Ingegneria dell'Automazione from University of Naples "Federico II". Currently I'm a 3rd year PhD student of the XXIX cycle in ITEE.

Fellowship type: Fondo Sostegno ai Giovani - FSGDIS

Tutor: Prof. Mario di Bernardo

## 2. Study and Training activities

- **Courses**
  - "*Introduction to stochastic hybrid dynamical systems*" (3.75 CFU)
    Lecturer: Andrew Teel, University of Santa Barbara
- **Seminars**
  - *"Information and Entropy Flow in Stochastic Control"*
    Lecturer: Professor Sanjoy Mitter, MIT
    Date: 07.10.2016 - 1h
  - *"Neuronal network analyses: premises, promises and uncertainties"*
    Lecturer: Tomas van Pottelbergh, University of Cambridge
    Date: 17.10.2016 - 1h
  - *"Event-based control"*
    Lecturer: Luka Ribar, University of Cambridge
    Date: 24.10.2016 - 1h
  - *"Hard limits on robust control over delayed and quantized communication channels with applications to sensorimotor control"*
    Lecturer: Thiago Burghi, University of Cambridge
    Date: 31.10.2016 - 1h
  - *"Semidefinite approximations of matrix logarithm"*
    Lecturer: Hamza Fawzi, University of Cambridge
    Date: 03.11.2016 - 1h
  - *"Information centrality and ordering of nodes for accuracy in noisy decision-making networks"*
    Lecturer: Marko Seslija, University of Cambridge
    Date: 07.11.2016 - 1h
  - *"Controllability and stabilizability of piecewise affine dynamical systems"*
    Lecturer: Kanat Camlibel, University of Groningen
    Date: 10.11.2016 - 1h
  - *"Models of central pattern generators for quadruped locomotion"*
    Lecturer: Ilario Cirillo, University of Cambridge
    Date: 14.11.2016 - 1h
  - *"Bayesian Optimization for Accelerated Exploration of Chemical Space"*
    Lecturer: José Miguel Hernández Lobato, University of Cambridge
    Date: 17.11.2016 - 1h
  - *"On structure preserving H-infinity optimal control"*
    Lecturer: Professor Anders Rantzer, Lund University
    Date: 23.11.2016 - 1h

- *"Substrate Enzyme-Sequestration in Multisite Protein Phosphorylation - Introducing WCDD M-matrices in designing stationary probability distributions "*
  Lecturer: Andreas Petrides, University of Cambridge
  Date: 24.11.2016 - 1h

- *"Sloppiness and Emergent Theories in Physics, Biology, and Beyond"*
  Lecturer: Cyrus Mostajeran, University of Cambridge
  Date: 26.01.2017 - 1h

- *"On the geometry of maximum entropy problems"*
  Lecturer: Michele Pavon, Università di Padova
  Date: 26.01.2017 - 1h

- *"Robust transport over networks "*
  Lecturer: Michele Pavon, Università di Padova
  Date: 06.02.2017 - 1h

- *"A Control Systems Perspective on Supercapacitor Modelling and Design"*
  Lecturer: Ross Drummond, University of Oxford
  Date: 09.02.2017 - 1h

- *"IBM Cognitive Computing: Challenges and Opportunities in Building an Artificial Intelligence Platform for Business"*
  Lecturer: Pietro Leo, IBM
  Date: 17.02.2017 - 2h

- *"Cognitive Computing and da Vinci robot: Research Proposals and Discussions"*
  Lecturer: Paolo Maresca, Università di Napoli Federico II
  Date: 17.02.2017 - 1h

**3. Research activity**

- **Title:**

  Contraction analysis of switched systems with applications to control and observer design

- **Research description:**

  In many control problems, such as tracking and regulation, observer design, coordination and synchronization, it is more natural to describe the stability problem in terms of the asymptotic convergence of trajectories with respect to one another rather than towards some attractor. That is, instead of studying the Lyapunov stability of some nominal solution, we are more interested to analyze the incremental stability among solutions [1].
  Several approaches to derive sufficient conditions for a system to be incrementally stable have been presented in the literature, among these contraction analysis has been shown to be particularly effective [2], [3], [4]. A nonlinear system is said to be *contracting* if initial conditions or temporary state perturbations are forgotten exponentially fast, implying exponential convergence of system trajectories towards each other and consequently towards a steady-state solution which is determined only by the input.

  As the number of applications based on the use of switched and hybrid models increases, it is becoming increasingly important to characterize convergence and incremental stability of systems and networks modelled by ODEs with time-dependent or state-dependent *discontinuities*. Unfortunately, most of the results available in the literature on both incremental stability and contraction analysis assume *continuous differentiability* of the system or network under investigation. Only few results deal with the problem of

investigating incremental stability of piecewise-smooth (PWS), switched or hybrid dynamical systems.

In our recent work [5], we extended contraction analysis to the class of switched dynamical systems modelled by ODEs with discontinuous right-hand sides (or Filippov systems [6]). By using results on regularization of switched dynamical systems based on the singular perturbation theory [7], we derived sufficient conditions for convergence of any two trajectories of the Filippov system between each other within some region of interest. Specifically, a bimodal Filippov system is contracting in a certain set if both modes of the system are contracting with respect the same norm and the difference of the two modes evaluated at the switching manifold satisfies an additional condition. We then applied these conditions to the study of different classes of Filippov systems including piecewise smooth (PWS) systems, piecewise affine (PWA) systems and relay feedback systems. Furthermore, we showed that these conditions allow the system to be studied in metrics other than the Euclidean norm. The theoretical results have been illustrated by numerical simulations on a set of representative examples that confirm their effectiveness and ease of application.

Then, using the novel theoretical conditions derived, we proposed a control design strategy [8] to incrementally stabilize a class of smooth nonlinear systems using switched control actions, and we presented conditions for the design of state observers [9] for a large class of nonlinear switched systems including those exhibiting sliding motion.

However, the previous conditions require the switched system to be contracting during *both* flow and switching, excluding from the analysis those systems that contracts only during either one. To overcome this further limitation, in collaboration with prof. Rodolphe Sepulchre and Dr. Fulvio Forni, we made use of the more general and flexible tools of Finsler-Lyapunov functions [10] and Lyapunov stability theory for hybrid systems [11]. This allowed us to analyze flow and switching separately, and to finally formulate a more general contraction analysis based on Finsler-Lyapunov functions.

[1] D. Angeli, *"A Lyapunov approach to incremental stability properties",* IEEE Transactions on Automatic Control, vol. 47, no. 3, pp. 410-421, 2002

[2] W. Lohmiller, J.J.E. Slotine, *"On contraction analysis for nonlinear systems",* Automatica, vol. 34, no. 6, pp. 638-696, 1998

[3] G. Russo, M. di Bernardo, E.D. Sontag, *"Global entrainment of transcriptional systems to periodic inputs"*, PLoS computational biology, vol. 6, no. 4, p. e1000739, 2010

[4] W. Wang, J.J.E. Slotine, *"On partial contraction analysis for coupled nonlinear oscillators"*, Biological cybernetics, vol. 92, no. 1, pp. 38-53, 2005

[5] D. Fiore, S.J. Hogan, M. di Bernardo, "*Contraction analysis of switched systems via regularization*", Automatica, vol. 73, pp. 279-288, 2016

[6] V.I. Utkin, *Sliding modes in control and optimization*, Springer-Verlag, Berlin, 1992

[7] J. Sotomayor, M.A. Teixeira, *"Regularization of discontinuous vector fields",* International Conference on Differential Equations, Lisbon, 1996

[8] M. di Bernardo, D. Fiore, "*Switching control for incremental stabilization of nonlinear systems via contraction theory*", in Proceedings of the 2016 European Control Conference (ECC'2016)

[9] D. Fiore, M. Coraggio, M. di Bernardo, *"Observer design for piecewise smooth and switched systems via contraction theory"*, submitted to *IFAC World Congress 2017*

[10] F. Forni, R. Sepulchre, *"A differential Lyapunov framework for contraction analysis",* IEEE Transactions on Automatic Control, vol. 59, no. 3, pp. 614-628, 2014

[11] R. Goebel, R.G. Sanfelice, A.R. Teel, *Hybrid Dynamical Systems: modeling, stability, and robustness,* Princeton University Press, 2012

- **Collaborations:**
  - Prof. Rodolphe Sepulchre
    Department of Engineering
    University of Cambridge - UK
  - Dr. Fulvio Forni
    Department of Engineering
    University of Cambridge - UK

**4. Products**

- **Publications**

**i. Already published:**

- D. Fiore, S.J. Hogan, M. di Bernardo, *"Contraction analysis of switched systems via regularization"*, published as Regular paper on *Automatica* http://dx.doi.org/10.1016/j.automatica.2016.06.028
- M. di Bernardo, D. Fiore, "*Switching control for incremental stabilization of nonlinear systems via contraction theory*", in Proceeding of 2016 European Control Conference (ECC'2016)
  https://doi.org/10.1109/ECC.2016.7810594

**ii. Submitted:**

- D. Fiore, M. Coraggio, M. di Bernardo, *"Observer design for piecewise smooth and switched systems via contraction theory"*, submitted to *IFAC World Congress 2017* on 08.11.2016
  https://arxiv.org/abs/1611.02518

**iii. In preparation:**

- D. Fiore, G. Russo, M. di Bernardo, *"Exploiting nodes symmetries to control synchronization and consensus patterns in multiagent systems"*
  https://arxiv.org/abs/1603.00322
- Fiore, Forni, Sepulchre, di Bernardo, "*Differential analysis of piecewise smooth systems*"

**5. Conferences and Seminars**

- European Control Conference 2016 (ECC'2016)
  Aalborg (Denmark) – 29.06.2016-01.07.2016
  One (1) conference paper was presented in the "Switched Systems" session
- Co-Chair of "Switched Systems" session at European Control Conference 2016 (ECC'2016)

Seminars made:

- "Contraction analysis of switched systems"
  Internal research group seminar
  University of Cambridge (UK) – 10.10.2016

**6. Activity abroad**

- One period of research at the Department of Engineering of University of Cambridge (UK) to collaborate with Prof. Rodolphe Sepulchre and Dr. Fulvio Forni.

From 06.10.2016 to 10.02.2017 (4 months)

**7. Tutorship**

- Assistant for exercises of the Laurea course “Controlli automatici” (Cod. 02826), held by Prof. Mario di Bernardo, 13 hours.
- Assistant for exercises of the Laurea Magistrale course “Dinamica e Controllo Non Lineare” (Cod. 17066), held by Prof. Mario di Bernardo, 6 hours.

**Student: Davide Fiore** **Tutor: Mario di Bernardo** **Cycle XXIX**

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| | Credits year 1 | | | | | | | Credits year 2 | | | | | | | Credits year 3 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 bimonth | 2 bimonth | 3 bimonth | 4 bimonth | 5 bimonth | 6 bimonth | **Summary** | 1 bimonth | 2 bimonth | 3 bimonth | 4 bimonth | 5 bimonth | 6 bimonth | **Summary** | 1 bimonth | 2 bimonth | 3 bimonth | 4 bimonth | 5 bimonth | 6 bimonth | **Summary** | **Total** | **Check** |
| **Modules** | 0 | 13 | 3 | 3 | 0 | 0 | **19** | 7 | 0 | 0 | 0 | 0 | 0 | **7** | 0 | 3.75 | 0 | 0 | 0 | 0 | **0** | **29.75** | **30-70** |
| **Seminars** | 1 | 1 | 0 | 0.2 | 1.4 | 1 | **4.6** | 0.4 | 0.8 | 0 | 0 | 0 | 0.4 | **1.6** | 0 | 0 | 0 | 0.8 | 1.4 | 1.4 | **3.6** | **9.8** | **10-30** |
| **Research** | 9 | 0 | 6 | 7 | 10 | 9 | **41** | 9 | 8 | 10 | 8 | 8 | 5.8 | **48.8** | 9 | 6 | 9 | 8 | 9 | 9.65 | **50.65** | **140.45** | **80-140** |
| | 10 | 14 | 9 | 10.2 | 11.4 | 10 | **64.6** | 16.4 | 8.8 | 10 | 8 | 8 | 6.2 | **57.4** | 9 | 9.8 | 9 | 8.8 | 10.4 | 11.05 | **54.25** | **180** | **180** |