FINAL REPORT

Student name: Giulia Michieletto
Cycle: XXX
Curriculum: ICT
Supervisor name: Prof. Angelo Cenedese
Thesis title (final): Multi-Agent Systems in Smart Environments - from sensor networks to aerial platform formations

PART 1 - COURSES, CONFERENCES AND MOBILITY

Courses for Ph.D. students

- Computation Inverse Problems (Prof. *Fabio Marcuzzi*)
- Applied Linear Algebra (Prof. *Giorgio Picci*)
- Statistical Methods (Prof. *Lorenzo Finesso*)
- Applied Functional Analysis (Prof. *Gianluigi Pillonetto*)

Summer schools, short courses, tutorials

- **EECI Graduate School on Control**
  Nonlinear Control for Physical Systems - Roger W. Brockett, Alexander L. Fradkov
  (Berlin, 23 - 27/03/2015)
- **SIDRA PhD Summer School**
  Robot Control & Underwater Robotics - Alessandro De Luca, Gianluca Antonelli
  (Bertinoro, 13 - 18/07/2015)

Seminars

First Year

1. 07/11/14: David Yau, *University of Purdue*
   "Cyber-Physical Security in Future Cities",
   TLC Group Seminars
2. *13/11/14:* Florian Dörfler, *ETH Zürich*
   "Plug and Play Operation of Microgrids",
   Automatica Group Seminars
3. *14/11/14:* Josè A. Cobos, *Technical University of Madrid*
   "Power Supply Systems for Energy Efficiency",
   DEI Distinguished Lecture

4. *17/11/14:* Arthur Krener, *UC Davis*
   "Filtering of Boundary Value Discrete Time Linear Systems",
   Automatica Group Seminars

5. *27/11/14:* Luigi Colangeli, *ESA*
   "Rosetta rendez-vous with the 67P/Churyumov-Gerasimenko comet",
   DEI Distinguished Lecture

6. *13/03/15:* Michele Pavon, *University of Padova*
   "On the geometry of maximum entropy problems",
   Automatica Group Seminars

7. *23/03/15:* Walter Snoeys, *PH department, CERN*
   "How chips helped discover the Higgs boson at CERN",
   DEI Distinguished Lecture

8. *08/04/15:* Ulrich Oberst, *University of Innsbruck*
   "Weakly exponentially stable linear time-varying differential behaviors",
   Automatica Group Seminars

9. *24/04/15:* Luigi Palopoli, *University of Trento*
   "When multimedia meets control: use of soft real-time techniques for control design",
   Automatica Group Seminars

10. *28/04/15:* Martin Grötschel, *ZIB Berlin*
    "Polyhedra: Their Description and Use",
    Colloquia Patavina

11. *15/05/15:* Alessandro Farinelli, *University of Verona*
    "Recent advances on coordination in Multi-Robot Systems",
    DEI Seminars *2*

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

13. *29/05/15:* Francesco Ticozzi, *University of Padova*
    "A walk to symmetrization via a Schrödinger bridge",
    Workshop: New challenges in reciprocal processes, Schrödinger bridges...

14. *03/06/15:* Mérouane Debbah, *Huawei France R&D Center*
    "Mathematical Scientific Challenges of 5G",
    DEI Distinguished Lecture

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

16. *07/07/15:* Davide Piovesan, *University of Gannon*
    "Human Arm Mechanics: from system identification to neural control",
    DEI Colloquia

17. *09/07/15:* Luca Scardovi, *University of Toronto*
    "From Synchronization Analysis to Synchronization Control of Cellular Networks",
    Automatica Group Seminars

18. *10/09/15:* Tamer El Batt, *University of Cairo*
"An Information-Theoretic Framework for Opportunistic Social Networks ",
TLC Group Seminars

19. *25/09/15:* Pratap Pattnaik, *IBM*
"Bitcoin, an attempt at a separation of money and state",
DEI Distinguished Lecture

20. *28/09/15:* Balz Zupan, *University of Ljubljana*
"Large-scale data fusion",
DEI Colloquia

21. *30/09/15:* Pierluigi Crescenzi, *University of Firenze*
"Fast and Simple Computation of Top-k Closeness Centralities ",
Informatics Group Seminars

22. *05/10/15:* Jun Miura, *University of Toyohashi*
"Autonomous Mobile Robot Research at Active Intelligent Systems Laboratory, TUT",
Informatics Group Seminars

23. *30/10/15:* Giulio Caravagna, *University of Edinburgh*
"Algorithmic Methods to Infer the Evolutionary Trajectories in Cancer Progression",
Bioengineering Group Seminars

Second Year

1. 06/11/2015: Fabrizio Luccio, *University of Pisa*
"Arithmetic for Rooted Trees",
DEI Colloquia

2. *10/12/2015:* Francesca A. Lisi, *University of Bari*
"Lovelace Test: Verso macchine creative",
DEI Colloquia

3. *19/01/2016:* Alessandro Abate, *University of Oxford*
"Formal verification of complex control systems",
Automatica Group Seminars

4. *17/03/2016:* Gabriel Bustamante, *LAAS*
"Towards information-based feedback control for binaural active localization",
WEekly RObotics MEeting at LAAS

5. *07/04/2016:* Mylène Campana, *LAAS*
"Ballistic motion planning",
WEekly RObotics MEeting at LAAS

6. *26/04/2016:* Marc Renaud, *LAAS*
"Étude des groupes et algèbres de Lie - Lecture 1",
WEekly RObotics MEeting at LAAS

7. *03/05/2016:* Marc Renaud, *LAAS*
"Étude des groupes et algèbres de Lie - Lecture 2",
WEekly RObotics MEeting at LAAS

8. *23/05/2016:* David Hsu, *University of Singapore*
"Robots in Harmony with Humans",
Séminaire du thème robotique at LAAS

9. *25/05/2016:* Marc Renaud, *LAAS*
   "Étude des groupes et algèbres de Lie - Lecture 3",
   WEekly RObotics MEeting at LAAS

10. *27/05/2016:* Marc Renaud, *LAAS*
    "Étude des groupes et algèbres de Lie - Lecture 4",
    WEekly RObotics MEeting at LAAS

11. *30/05/2016:* Stéphan Caron, *LIRMM IDH CNRS*
    "Support Zones for ZMP and multi-contact locomotion",
    WEekly RObotics MEeting at LAAS

12. *30/05/2016:* Quang-Cuong Pham, *Nanyang Technological University*
    " Robotic manipulation with contact and dynamics",
    WEekly RObotics MEeting at LAAS

13. *16/06/2016:* Ruggero Carli, *University of Padova*
    "Coverage Control and Estimation for Gossiping Robotic Networks",
    WEekly RObotics MEeting at LAAS

14. *23/06/2016:* Markus Ryll, *LAAS*
    "Design and Control of Fully-actuated Aerial Robots",
    WEekly RObotics MEeting at LAAS

15. *04/07/2016:* Marcello Pelillo, *University of Venezia*
    "Grouping Games: Finding Clusters in Graphs, Digraphs and Hypergraphs",
    DEI Colloquia

16. *14/07/2016:* Seth Lloyd, *MIT Boston*
    "Dialogue on the Quantum Revolution",
    DEI Distinguished Lectures

17. *20/07/2016:* Subhrakanti Dey, *Uppsala University*
    "Sensor Scheduling in Variance Based Event Triggered Estimation with Packet Drops",
    Automatica Group Seminars

18. *21/07/2016:* Enrico Lovisari, *Volvo Cars*
    "Traffic networks: modelling and control",
    Automatica Group Seminars

19. *29/09/2016:* Paolo Frasca, *CNRS*
    "The observability radius of network systems",
    MAC Group Seminars at LAAS

20. *06/10/2016:* Pierrick Kosh, *LAAS*
    "Managing Environment Models in Multi-Robot Teams",
    WEekly RObotics MEeting at LAAS

Third Year

1. 03/11/2016: Joseph Mirabel, *LAAS*
   "Humanoid Path Planner: a new software platform for constrained motion planning",
   WEekly RObotics MEeting at LAAS

2. *25/11/2016:* Andrea Bisoffi, *University of Trento*
   "Global asymptotic stability of a PID control system with Coulomb friction",
   Automatica DEI Seminars

3. *30/11/2016:* Pablo Millan Gata, *Universidad Loyola Andalucía*
   "Distributed estimation techniques for networked systems",
   LAAS MAC group seminars

4. *01/12/2016:* Riccardo Spica, *CNRS, Rennes*
   "Active visual estimation for single and multiple robot systems",
   WEekly RObotics MEeting at LAAS

5. *01/12/2016:* Antonino Sferlazza, *University of Palermo*
   "A Hybrid Observer for Linear Systems with Asynchronous Discrete-Time Measurements",
   LAAS MAC group seminars

6. *07/12/2016:* Martin Saska, *Czech Technical University*
   "Teams of closely cooperating micro aerial vehicles",
   WEekly RObotics MEeting at LAAS *4*

7. *13/01/2017:* Gabriele Buondonno, *DIAG, University of Rome*
   "Numerical algorithms for elastic actuators and environment interaction",
   WEekly RObotics MEeting at LAAS

8. *24/01/2017:* Fabrice Mayran de Chamisso, *CEA*
   "Lifelong Exploratory Navigation: Integrating Planning, Navigation and SLAM in partially or completely uncharted environments",
   WEekly RObotics MEeting at LAAS

9. *05/04/2017:* Giulia Prando, *DEI*
   "Deep Learning - Lecture 1",
   Automatica Group Seminars

10. *26/04/2017:* Giulia Prando, *DEI*
    "Deep Learning - Lecture 2",
    Automatica Group Seminars

11. *03/05/2017:* John Hauser, *University of Colorado at Boulder*
    "Trajectory Exploration for Aggressive Maneuvering ",
    Automatica Group Seminars

12. *17/05/2017:* Giulia Prando, *DEI*
    "Deep Learning - Lecture 3",
    Automatica Group Seminars

13. *12/05/2017:* Alberto Sangiovanni Vincentelli, *University of Berkeley*
    "Is Technology Transfer a Dream or a Reality?",
    DEI Distinguish Lecture

14. *16/05/2017:* Basilio Gentile, *ETH Zurich*
    "Distributed dynamics to achieve a location equilibrium",
    Automatica Group Seminars

15. *18/05/2017:* Giulio Tononi, *University of Wisconsin*
    "Consciousness: From Theory to Practice",
    DEI Distinguish Lecture

16. *24/05/2017:* Rudi Hackenberg, Enrico Pozzobon, Nils Weiss , *University of OTH Regensburg*
    "Automotive Security in a Connected World",
    Informatics Group Seminars

17. *31/05/2017:* Giulia Prando, *DEI*
"Deep Learning - Lecture 4",
Automatica Group Seminars

18. *17/07/2017:* Marco Tognon, *LAAS*
"Aerial Physical Interaction by Means of Cables or Bars: Modeling and Control of Tethered Aerial Vehicles",
Automatica Group Seminars

19. *07/09/2017:* Jacques Savoy, *University of Neuchatel*
"Text, Computer, and Style: In the Pursuit of Elena",
Informatics Group Seminars

20. *22/09/2017:* Chris Van Hoof, *Holts Centre/ IMEC*
"Personal Behavioral Technology - Wearables Can Become an Active Contributor to Your Wellbeing",
DEI Distinguish Lecture

Participation to International Conferences and Workshops

- Workshop: *Postdoctoral Research in Informatics* (Padova, 08/07/2015)
- Workshop: *ROS (Robot Operating System), un ambiente di programmazione Open Source per la Robotica* (Padova, 12/11/2015)
- Workshop: *Sino-Italian Workshop on Applied Statistics* (Padova, 02/02/2016)
- Workshop: *GIS Micro-Drones* (Toulouse, 04-05/10/2016)
- Workshop: *Co*^{4} *- Control subject to Computational and Communication Constraints* (Toulouse, 26-27/10/2016)
- Workshop: *IMT-LAAS* (Toulouse, 08-09/11/2016)
- CDC Workshop: *Feedback Control of Hybrid Systems* (Las Vegas, USA, 11/12/2016)
- 55th IEEE Conference on Decision and Control (CDC 2016) (Las Vegas, USA, 12-14/12/2016)

Other learning activities

- Tutor Junior activities:

2015-2016 course of *Control Systems Design* (Prof. Angelo Cenedese)
2016-2017 course of *Control Laboratory* (Prof. Luca Schenato)

Mobility periods

Dates: March 2016 - June 2016
September 2016 - February 2017

Hosting institution: LAAS, Toulouse, France (Dott. *Antonio Franchi*)

Title of the activity: Control of Non-conventional Multi-rotor Systems and Rigidity-based Multi-robot Estimation and Control.

PART 2 - RESEARCH ACTIVITY

Wireless Sensor Networks - In industrial automation scenario, the exploitation of wireless sensor networks has shown to provide numerous benefits. Within this context, grouping nodes into local clusters arises as a fundamental tool to enhance the network self-organization capabilities and improve the system autonomicity towards the fulfillment of collective goals. To this reason we have focused on the development of effective clustering strategies specifically tailored for the industrial environment. Differently from other approaches proposed in the literature, we have considered both network decomposition and data clustering, proposing a solution that takes cake of measurements similarity and communication capabilities. Designing both a centralized and a distributed algorithm, we have validated the effectiveness of our approach to detect failures and anomalies.

Multi-Camera Systems - Multi-camera systems integrates a large number of smart visual sensors that interoperate in order to perform some high-level tasks, such as the monitoring and interpretation of the environment or the control of actuators operating in it. The effectiveness of such tasks are significantly affected by the precision of the camera calibration with respect to a reference system, namely on the accuracy in the reconstruction of its absolute pose (position and orientation). We tackle the attitude estimation problem for a camera network in a realistic noisy environment, i.e., the determination of the attitude of each device in the system expressed in a certain global inertial frame exploiting some noisy available measurements derived by the observed scene. The adopted strategy rests up the approach proposed by Tron-Vidal in 2009: it consists in the iterative minimization of a suitable cost function defined over the Riemannian manifold of the rotations. We have faced the estimation problem both in three-dimensional and in two-dimensional space. In the 3D case, motivated by the non-convexity of the considered functional, we have developed a set of initialization methods which can also be used per se as a non-iterative solution, in particular when the noise level is high. For the planar case, instead, we have investigated the relation emerged between the estimate convergence properties and the topology associated to the camera network. In the 2D scenario, we have dealt also with the perimeter patrolling problem, within the border of a certain area is required to be repeatedly monitored by a set of cameras. According to the previous literature, the issue has been recast in a minimization framework whose output is an optimal partition of the perimeter (assumed to be a close curve). The proposed solution, validated in a real environment, takes into account two optimality criteria: the interval time between two consecutive inspection of the same point of the perimeter and the angle of incidence of each camera field of view on the perimeter.

Aerial Platform Formations - Aerial robotics is a fast-growing branch in robotics and the Unmanned Aerial Vehicles (UAVs) are rapidly increasing in popularity. Thanks to their versatility in performing a wide variety of different tasks, autonomous platforms are quickly becoming a mature technology exploited in military, industrial and civil context. Independently from the application, in the real-word scenario, two fundamental properties are generally desirable for the used UAVs, namely the possibility to independently control the position and the attitude of the vehicles and the robustness to the loss of one or more motors. As a consequence, we have first analysed the interplay between the control force and the control moment in a generically tilted multi-rotor platform evaluating the dimension of the freely assignable force space and its relation with the total force space. Then, we have introduced and investigated the concept of static hovering realizability which rests upon the possibility to reject any disturbance torque while counterbalancing the gravity. In this context, we have designed two nonlinear controllers suitable to steer and keep a given platform in constant reference position with constant attitude. The first control solution exploits a state feedback linearization, while the second one is based on

the geometric approach. We have also explored the robustness properties of a family of hexarotors in terms of capability to statically hover after a rotor loss. Finally, we have handled the UAVs formation control, aiming at both stabilizing a given formation and steering it along pre-definite directions. To this aim, we have studied and used the bearing rigidity theory for framework embedded in the three-dimensional Special Euclidean space SE(3).

PART 3 - PUBLICATIONS

List of publications on international journals

J1. A. Cenedese, M. Luvisotto, G. Michieletto. *Distributed Clustering Strategies in Industrial Wireless Sensor Networks.* IEEE Transactions on Industrial Informatics, vol. 13, no. 1, pp. 228-237, Feb. 2017

J2. A. Franchi, P. Robuffo Giordano, G. Michieletto. *Online Leader Selection for Collective Tracking and Formation: the Second Order Case.* IEEE Transactions on Control of Network Systems - [submitted]

J3. G. Michieletto, M. Ryll, A. Franchi. *Fundamental Actuation Properties of Multi-rotors: Force-Moment Decoupling and Fail-safe Robustness.* IEEE Transactions on Robotics - [submitted]

List of publications on conference proceedings

C1. G. Bianchin, A. Cenedese, M. Luvisotto, G. Michieletto. *Distributed Fault Detection in Sensor Networks via Clustering and Consensus.* 54th Conference on Decision and Control (CDC15), pp. 3828–3833, 2015.

C2. G. Belgioioso, A. Cenedese, G. Michieletto. *Distributed partitioning strategies with visual optimization for camera network perimeter patrolling.* 55th Conference on Decision and Control (CDC16), pp. 5912-5917, 2016.

C3. G. Michieletto, A. Cenedese, A. Franchi. *Bearing Rigidity Theory in SE(3).* 55th Conference on Decision and Control (CDC16), pp. 5950-5955, 2016.

C4. G. Michieletto, M. Ryll and A. Franchi. *Control of statically hoverable multi-rotor aerial vehicles and application to rotor-failure robustness for hexarotors.* 2017 IEEE International Conference on Robotics and Automation (ICRA2017), pp. 2747-2752.

C5. G. Michieletto, A. Cenedese, L. Zaccarian, A. Franchi. *Nonlinear Control of Multi-Rotor Aerial Vehicles Based on the Zero-Moment Direction.* IFAC World Congress 2017, Jul 2017, Toulouse, France. 2017.

Padova, 28/09/2017

Student signature

Supervisor signature