COLLOQUIA DOCTORALIA 2018

PhD in Information Technology

Computer Science and Engineering
Electronics
Systems and Control
Telecommunications
PHD SCHOOL OF POLITECNICO DI MILANO

The Doctoral (PhD) degree is the highest academic degree awarded. The Doctoral Program of Politecnico di Milano is a 3-year program aiming to develop the professional competence to carry out high level research in manufacturing and service companies, public bodies and universities. The Doctoral Programs provide a selected number of highly qualified graduates, endowed with a solid preparation and keen intellectual curiosity, with the opportunity to acquire a high degree of professional expertise in specific scientific, technological, social and economic fields. PhD graduates are not only capable of carrying out research projects but develop, during their period of study, new knowledge on scientific frontiers that can be immediately applied in professional activities. Doctoral Programs have existed at Politecnico di Milano since they were first introduced in 1985. In 2018 PhD titles have been awarded for the XXX cycle of the Program. The School of Doctoral Programs coordinates the 19 Doctoral Degree Programs of Politecnico di Milano in the areas of Engineering, Architecture and Industrial Design. It ensures the quality of the Degree Programs and promotes their development.

PHD COURSE IN INFORMATION TECHNOLOGY

The PhD course in Information Technology is hosted at the Dipartimento di Elettronica, Informazione e Bioingegneria (DEIB) and is part of the Polimi PhD School. It is a significant program in size with about 19% of the total number of PhD students in the School. It offers advanced training and research activity in four wide research areas: Computer Science and Engineering, Electronics, System and Control, Telecommunications.

Nowadays these fields of research are of enormous scientific and technical interest to both industry, governmental organizations, and to the society in general. The doctorate opens interesting possibilities of extended study and participation in high level research in information technologies that include hardware and software, automatic control, electronic components and systems, instruments, telecommunication networks, decision support systems. Scientific collaboration of DEIB with prestigious research institutes in Europe, the United States and elsewhere, facilitates the entrance into the world of international research through meetings with scientists and visits to foreign laboratories. Intense industrial collaboration of DEIB in applied research allows the doctoral student to become acquainted with the activities of technologically advanced companies, thus acquiring the necessary elements for an informed choice between a career in industrial research and in universities.

The PhD Course in Information Technology enrolls every year about 60 students, mostly supported by scholarships from public institutions and private companies. Once admitted, each PhD student chooses a research advisor that will guide the research activity, and a professor of the Doctoral Board as a tutor. Study activities consist of courses and individually guided study. Advanced courses (in English) offered by DEIB professors bring the attendants to the frontiers of knowledge in those sectors where DEIB’s research is most active. These are integrated by courses offered by the School which give the possibility to develop general skills. Specific courses on relevant subjects are offered to PhD students also by national and international schools.
DEIB’s scientific activities are distributed along many research lines and organized in six areas: Bioengineering, Computer Science and Engineering, Electrical Engineering, Electronics, Systems and Control, and Telecommunications. The Phd Program in Information Technologies deals with four of these six areas.

A wide range of research topics is pursued, distributed over five strong research lines: Advanced Software Architectures and Methodologies; Artificial Intelligence and Robotics; Data, Web, and Society; Information Systems; and System Architectures. System and software reconfigurability, self-adaptivity, autonomy, pervasive Internet-of-Things, service computing, information and knowledge management and discovery, multimedia applications, sustainable ICT, human-machine interaction, autonomous robotics, artificial intelligence, machine learning, and advanced computing architectures are the basic themes addressed by the area and are the ground for the development of future ICT systems. Moreover, our vision pursues the strategic aim to conceive, favor, and support a new penetration wave of computer science and engineering in society, also carrying out research oriented towards concrete applications that allow the interdisciplinary development of innovative services and products.

The scientific roots of DEIB research activities in Electronics date back to 1957 when Emilio Gatti was appointed first Italian Chair of Electronics. Following his vision, Electronics research at DEIB has always been carried out through a balanced mix of theoretical analysis and experimental activities. Nowadays, the Electronics labs cover 1,400 sq.m of floor space and are well equipped with state-of-the-art instrumentation for the electrical characterization of nanoelectronic and optoelectronic devices, sensors, MEMs and integrated circuits. A facility for the design and manufacture of application boards and systems is also available. The research activities are organized according to six major research lines: Digital Systems, Electron Devices, Electronic-Circuit Design, Radiation Detectors, Single-Photon Detectors and Applications, and Smart Microsystems and Microsystems.

The teaching and research activities of this area concern various fields related to control-system science and engineering, industrial automation, systems theory, environmental systems, ecology, and operations research. Despite the rich variety of topics, both theoretical and application-oriented, a unifying system level viewpoint is generally adopted, which enables the analysis, the management, and the design of complex systems, through the powerful theoretical tools of mathematical modeling. The area is organized according to five research lines: Control Systems, Dynamics of Complex Systems, Operations Research and Discrete Optimization, Planning and Management of Environmental Systems, and Robotics and Industrial Automation.

Subsequent courses, organized especially for the doctorate will bring the student to the frontiers of knowledge in sectors where DEIB’s research is most active. Other relevant courses are offered annually by various national and international schools. The participation in local and external courses supplies the necessary knowledge to approach research problems in the most serious and competitive way.

All research is conducted under the guidance of a scientific supervisor. The student will, throughout the three-year period, publicly illustrate both his/her studies and research results to DEIB’s professors and colleagues, and to audiences of international scientific conferences. In doing this, the student will develop a capacity for public speaking as well as improving his/her ability of oral and written communication.
INTRODUCTION

PHD program in information technology

ELECTRONICS
SYSTEMS & CONTROL

TELECOMMUNICATIONS

COLLOQUIA DOCTORALIA 2018

COMPUTER SCIENCE & ENGINEERING

PHD IN IT - THE NUMBERS

Academic year 2018 - XXXI, XXXII, XXXIII cycles
PhD students enrolled in the Program: 183 including 40 foreign students

184 Research assistants
99 Associate professors
70 Full professors
67 Assistant professors
43 Tech and Administration staff
14 CNR
47 Bio PhD students
63 Assistant professors
38 System and controls
46 Electronics
66 Computer science

EMPLOYMENT AFTER PHD DEGREE

Professional skills and positions achieved by graduated doctors
A doctorate in Information Technology gives access to the highest levels of scientific research in the fields of Computer Science and Engineering, Electronics, Systems and Control and Telecommunications. According to the personal skills and the circumstances, those who have achieved a PhD can approach an academic or industrial career in Italy or elsewhere.

Every year Politecnico di Milano and neighbor universities make post-doctorate positions available oriented towards research and teaching. In recent years the positions, and their number, offered in our disciplines have usually fulfilled the expectations of the best PhD graduates. As a result of the experience gained during the triennium, in seminary courses, conferences and other education activities, the research graduate is also qualified to undertake teaching activities.

The practice of communicating and working in English, as well as the knowledge of the academic world, acquired during visits and stays abroad, qualifies the PhD graduate for positions offered by the best European and American universities, and generally by all technologically advanced institutions.

As proof of the interest shown by companies, many grants for graduate students at DEIB have been founded by important industrial groups, with the aim of promoting research in fields of their interest. Those aiming for a research career in industry must be aware that the globalization of the economy has led to industrial research centres often being localized in other countries, and organized into intercontinental research structures that impose great mobility on the researchers themselves.

Finally, openings are available in service sectors (e.g. transport planning, natural and human resource management), in important engineering firms, in the technical services of government and EU bodies, in international institutions.

From data collected by Polimi Career Service about PhD Graduated in 2015 and 2016, we have a picture of their occupation in 2017. They collected 80 answers from the 103 contacted graduates in information technology (77.7%). 100% of them has a job. 36.25% works in a foreign country. The distribution of the occupied graduates is reported on the left.

The average income of graduates in Information Technology at Politecnico, with 2318 euro/month, is among the highest average incomes of all the Politecnico’s graduates in the monitored period (1-2 years after graduation date).
Perspective candidates may be enrolled in the PhD Program without limits of age and citizenship. Admission is based on the skills and attitude toward scientific speculation. The majority of the candidates may be supported by scholarships, but candidates without financial support may be admitted as well, provided that positions are available.

The call for positions is published once a year by the PhD School of the Politecnico di Milano. The 2018 call for the PhD in Information Technology had a number of open positions in the following research areas:

- Computer Science and Engineering
- Electronics
- Systems and Control
- Telecommunications

Basic requirements for PhD admission

Five years of education at the University level are required. English language of certified level (please refer to the call for further details).

Doctoral positions in partnership with companies: Executive PhD Program

In order to promote interaction and integration between university research and the growth and innovation of companies, the Doctoral School of the Politecnico di Milano may stipulate specific agreements in partnership with external institutions (Executive PhD) to admit industry employees as students to the program.

Scholarships

The number of admitted students depends on the number of available scholarships. Scholarships are granted from the Ministry for University and Research, from Politecnico, from companies or from the Department, based on research project funds. A number of 35 scholarships was available for 2018 admissions.
The attainment of the PhD title in Information Technology requires a study and research activity of at least three years equivalent to full time study, research and development of PhD thesis. All the activities aim at:

- creating the starting knowledge common to the PhD Program;
- examining the basic research issues (problems, theories, research methods) which represent the founding element of the PhD Program and which identify clearly its cultural position;
- deepening in a specialist way some research issues connected with the problems developed in the thesis.

Educational Activity

The PhD in Information Technology foresees 25 credits from PhD level courses. Among the 25 credits, at least 10 credits have to be acquired through PhD courses characterizing the PhD program in Information Technology (held by DEIB Professors or foreign Professors visiting DEIB), at least 10 credits from PhD School Courses on transversal skills and 5 or less credits may be taken from external PhD courses, e.g. from other PhD programs, from Summer Schools, and so on. Each PhD candidate has to submit his study plan, he will have the opportunity to review it periodically in order to adapt it to every possible change of the training offer or to needs motivated by the development of his study plan. The study plan is approved by the Coordinator of the PhD Program, according to the modalities established by the Board of Professors of the PhD Program itself. All the mentioned courses have to foresee an evaluation for the PhD student to let him acquire the corresponding credits. Other activities like attendance of seminars, of PhD courses without evaluation, of workshops, conferences, and similar, contribute to create the curriculum of the PhD student. Participation in local and external courses provides advanced knowledge and give the students the necessary training for addressing research issues in a professional and competitive way. Should it be necessary to fill in any gap from their previous training, PhD students may attend preparatory courses which are normally chosen among the wide choice of graduate courses in Information Technology offered at Politecnico di Milano. Lessons are in English, except when indicated otherwise. At least one path thoroughly in English language is foreseen in the PhD Program. During the three years students are often required to give talks in front of foreign professors or to attend international scientific conferences and present the results of their research. PhD students are thus led to develop their ability for public speaking and improve their communication skills, in both writing and speech. All activities related to courses (attendance/evaluation) have to be completed within the second year of the program. At the end of each year, an evaluation of the PhD candidate is foreseen to continue the program. The evaluation of the 3rd year includes also the admission to the final examination. The final examination, held by a commission including also external members, allows the achievement of the PhD title.

Development of the research and of the PhD thesis

The Program foresees that the candidate is devoted to the research activity in a continuous way, following the lead of his/her Supervisor and of the Board of Professor. In the third year the candidate should be devoted entirely to the research and to the development of the PhD thesis.

The aim of the PhD Program is the development in the candidates of a research-oriented mindset, with expertise and skills in a specific research topic. To develop a research-oriented mindset, the candidates have to acquire the capability of problem-solving in complex context, included a deep analysis of the problem, the identification of an original solution and the capability of evaluating a solution and its applicability in given contexts. These skills provide the PhD candidates with major opportunities of development in their research both in the academic field and in public and private organisations.

The main objective is the development of an original research contribution which has to contribute to increase the knowledge in the research field of the candidate. Besides, it has to be coherent with the research topics developed in the Department.

Research and study work is predominantly individual, but students are strongly encouraged to participate in the DEIB’s research groups. Projects are often awarded external funding by industrial companies or research programs by the European Community, or other research agencies. Many projects are carried out jointly with other European institutions or companies. Every PhD student is granted the necessary resources (PC, connection to the internet, scientific computing and library services, etc.) so that they may access documentation and communicate. Furthermore, there are scientific laboratories at
DEIB and the research laboratories pertaining to the consortium structures (in particular, Ce-friel) and to the CNR are also available for the PhD students. Joint scientific research projects, both national and international, with academic and industrial institutes and laboratories are very intense.

The original research has to be submitted through a PhD thesis which should document a solid knowledge in the chosen area, present original contributions, and demonstrate appropriate ability in the individual work and in the presentation of the results. Normally during the first year the topic and the general objectives of the research are identified. Subsequently, the necessary scientific background knowledge has to be acquired more in depth through an extensive work of bibliographic study and analysis of international research.

Finally, during the third year, the research yields its results, which must be a significant progress beyond the state-of-the-art.

The PhD research is developed under the guidance of a Supervisor, who supports the candidate in the setting-out and in the everyday activities regarding the development of the thesis. The Supervisor does not have to be a member of the Professors Board and can also belong to an institution different from Politecnico di Milano. The Supervisor can be supported by one or more co-Supervisors.

The scientific quality of the work is guaranteed by the thesis supervisor's assistance, the daily exchanges with the other research project participants, and by the periodical seminars. PhD students learn how to promote their own research and disseminate their results to the scientific community. While working on the thesis, it is recommended for PhD students to get in touch with laboratories abroad, where they may spend part of their three-year course of study. They can thus compare scientific points of view and get to know other ways of thinking and operating at universities or industrial laboratories.

In the same way, it is highly recommended that students participate in national and international conferences, in order to learn how to promote their own research, and to get new stimuli from the comparison with other work. Meeting people and fostering professional relations are important aspects for the students' future career. The thesis body is an organized and accurate collection of the comparisons, the experimental or theoretical studies, the original results and the projects that have been worked on during the research period. The ability to write an effective scientific piece of work thus complements the attitude to research the student has given proof of by obtaining valid and original results.

The final evaluation of the thesis by the commission marks the final step of the PhD study course with a qualified assessment. More precisely, the process of writing the thesis evolves along the following steps:

- the submission of the thesis outline within the first year;
- the intermediate results to present each year;
- the final discussion.

The thesis body is an organized and accurate collection of the comparisons, the experimental or theoretical studies, the original results and the projects that have been worked on during the research period. The ability to write an effective scientific piece of work thus complements the attitude to research the student has given proof of by obtaining valid and original results.

The final evaluation of the thesis by the commission marks the final step of the PhD study course with a qualified assessment. More precisely, the process of writing the thesis evolves along the following steps:

- the submission of the thesis outline within the first year;
- the intermediate results to present each year;
- the final discussion.
### COURSES

**Computer Science and Engineering**

- Advanced Topics on Heterogeneous System Architectures
- Automated Verification of Timed systems
- Business Process Management
- Data and Results Visualization
- Deep Learning: Theory, Techniques and Applications
- Designing Interaction
- Image Classifications: Modern Approaches
- Integration and Computational Analysis of Genomic Information
- Parallel Computing Using MPI and Openmp

**Electronics**

- Advanced Mems Gyroscopes
- Microcontrollers for Embedded Systems
- Organic Electronics: Principles, Devices and Applications
- Signal Integrity in Very High Speed Digital Circuits
- Single Photon Detectors For Advanced Scientific and Consumer Applications

**Systems and Control**

- Constrained Numerical Optimization with Control Applications - Theory and Algorithms
- Cooperative and Non Cooperative Optimization and Control
- Model Predictive Control
- Object-oriented Modelling and Simulation
- Sliding Mode Control Theory and Applications

**Telecommunications**

- Advanced Topics in Music Informatics
- Machine Learning Methods for Communication networks and system
- Molecular and Nanoscale Communication
- Network Traffic Measurement and Analysis
- Statistical Signal Processing

---

**2018**

- Beyond CMOS Computing
- Digital Circuits and Systems for DSP and FPGA-Based Processing
- Embedded Sensor Systems
- High Resolution Electronic Measurements in Nano-Bio Science
- Nuclear Microelectronics

**2019**

- Data-driven Approaches to Uncertain Optimization: Theory and Applications
- Feedback Control for Computing Systems
- Hybrid Systems
- Nonlinear System Identification
- Stochastic Programming

---

**2016**

- Advanced Topics in Reconfigurable FP GA-Based Systems Design
- Advanced Topics in Computer Security
- Advances in Deep Learning with Applications in Text and Image Processing
- Complex Networks
- Concurrent Object-Oriented programming
- Data and Information Quality
- Formal Languages and Automata to Model Complex Structures: Two-Dimensional and Operator Precedence Languages
- Genomning Computing
- Intelligent Multagent Systems
- Internet Economics
- Learning Sparse Representations for Image and Signal Modeling
- Stream and Complex Event Processing in the Big Data Era
- Virtual and Mixed Reality
COURSES HELD BY FOREIGN LECTURERS DURING THE LAST FIVE YEARS

Advanced topics on computational complexity
Prof. Miltersen Peter Bro - Aarhus University Denmark

Big Data Analysis Methods for Knowledge Discovery
Prof. Norberto Díaz-Díaz - School of Engineering, Universidad Pablo de Olavide, Sevilla (Spain)
Prof. Mark D. Robinson - Institute of Molecular Life Sciences, University of Zurich (Swiss)
Prof. Osmar R. Zaiane - University of Alberta (Canada)

Robust Optimization and Network Design
Prof. Arie Koster - Department of Mathematics, RWTH Aachen University (Germany)

Online Big Data Analytics and Applications
Prof. Yannis Papakonstantinou - University of California (San Diego),

Robust control of MIMO and time-delay systems : an LMI approach
Prof. Oliver Sename - GRENOBLE INP, Grenoble Institute of Technology

Switching control for positive systems with applications
Prof. Richard Middleton - The University of Newcastle (Australia)

Sparse Representations: Theory and Applications
Dr. Brendt Wohlberg - Los Alamos National Laboratory (USA)

Foundations of Data Exchange and Integration
Prof. Leopoldo Bertossi - Carleton University, School of Computer Science

A Top-Down Introduction to Information-Centric Networking
Prof. Giovanna Carofiglio - Bell Labs, Alcatel-Lucent
Prof. Luca Muscariello - Orange Labs, France Telecom

Optimization models for communication network design
Prof. Michał Pióro

Semantic Technologies
Prof. Alfo Gliozzo - IBM

Network Programming Languages
Prof. Robert Soule - Università della Svizzera Italiana (USI)

Integer Programming and Scheduling
Prof. Helena Ramalhinho Lourenço - Universitat Pompeu Fabra (Barcelona, Spain)

Internet Economics
Prof. Carmine Ventre - Teesside University (UK)

Practical Software Verification with Autoproof
Prof. Bertrand Meyer - ETH Zurich

DATA OF PHD IT INTERNATIONALIZATION

- **Foreign students**
  - Cycles: XXXI - XXXII - XXXIII

- **Periods of study and research abroad**
  - Percentage of last cycle PhD students that went abroad during their doctoral studies (38/65)

- **Average length of the stays**
  - 40% 69 months 5 months
Politecnico di Milano has signed cooperation agreements with important institutions, which further motivates the internationalization of research. These agreements offer PhD students the possibility to experience academic exchanges such as Double PhD Program, joint Doctorate, and the participation in international networks. For example, the Double PhD Program enables the students to perform coordinated doctoral studies while attending both Universities, by spending equal amounts of time in the premises of both sites, to write a dissertation jointly guided by faculty members from both Universities, and to obtain the doctoral degree from each University by completing a dissertation and defense, complying with the quality standards for doctoral studies at both Universities. Currently the following agreements are in place:

- Agreement for double doctorate with Shanghai Jiao Tong University (P.R. China);
- Agreement for double doctorate with Universidade de Lisboa, Instituto Tecnico Superior (Portogallo);
- Agreement for co-supervision of a doctoral Thesis between Politecnico di Milano and Ecole Polytechnique de Montreal – Canada.

Other international collaborations:

- Cooperation agreement with “Escuela superior Politecnica del Litoral” (Ecuador) for admission of Doctoral candidates;
- Erasmus mundus Programs;
- Other mobility programs:
  - Innovative Training Networks (ITN) - Marie Curie Actions;
  - Mobility ConfaP Italy (Brazil) – with Brazil;
  - China Scholarship Council (CSC) – with China;

Other international collaborations:

- Agreement for double doctorate with Qa'tar University;
- Agreement for double doctorate with Shanghai Jiao Tong University (P.R. China);
- Agreement for double doctorate with Universidade de Lisboa, Instituto Tecnico Superior (Portogallo);
- Agreement for co-supervision of a doctoral Thesis between Politecnico di Milano and Ecole Polytechnique de Montreal – Canada.

Results achieved by PhD students

Publications in 2017

Publication of results at international level is encouraged by the PhD Program, since the presentation of the results to the national and international research communities provide an optimal forum for students to discuss research results, to get feedback, and to validate the achieved results.

An average of papers published for each PhD student at the end of their third year is provided below:

In addition to international journals and conferences, dissemination of results is also achieved through book chapters and publications at the national level. The total number of publications by PhD students at the end of their third year are listed in the following table.
Awards to PhD students
Each year students receive awards for their scientific activities. In particular, two students from the PhD Program are awarded the Chorafas Foundation Scholarship. The award is proposed by the PhD Board and usually accepted by the Chorafas Foundation.

The awards received by the students in the last three years are listed below:

2016
Chorafas Foundation Award: Stefano Ambrogio, Matteo Pirotta
Best Junior Carassa Award 2016: Andrea Annoni
CPSWEEK Best PhD Forum Presentation Award: Naveed Anwar
Ericsson Innovation Award – 3rd place: Saleem Shahid
iEMSs 2016 Student Best Presentation Award: Francesca Recanati
IEEE CAS DAY 2016 Best Poster Award: Giacomo Gervasoni
IEEE PRIME 2016 Golden Leaf Award: Dmytro Cherniak
IEEE RNDM 2016 Best Paper Award: Ali Hmaity
IEEE WACV Best paper Award 2016: Andrea Romanoni
XILINX Open Hardware 2016 Award for PhD FPGA Category: Giuseppe Natale

2017
17th International Conference on Web Engineering Best Student Paper Award: Carlo Bernaschina
IEEE Computer Society Italy Section Chapter 2016 PhD Thesis Award: Amir Hossein Ashouri
Maxeler Open Dataflow Design Competition 2017: Emanuele Del Sozzo, Marcello Pogliani
CASE Best Paper Award: Marouan Mizmizi
Young Researcher Award of the International Hydropower Association (IHA): Rafael Schmitt
Chorafas Award: Rafael Schmitt, Abdurrahman Kaitoua
2017 Microsoft AI for Earth Azure Research award: Frajberg Darian
Innovation Design Contest 2017 - 3rd place: Ragani Andrea
XILINX Open Hardware PhD Award 2017: Del Sozzo Emanuele, Ra-bozzi Marco
IFAC Young Author Prize: Deori Luca
Premio Francesco Carassa 2017: Bernardini Alberto

2018
ACM CHI2018 PhD Student Best Paper Award - 3rd place: Gelsomini Mirko
IEEE SSP 2018 Best Student Paper Award: Brambilla Mattia
IEEE Inertial 2018 Best Student Paper Award: Marra Cristiano Rocco
Outstanding Student Paper Award per Cristiano Marra: Marra Cristiano Rocco
Chorafas: Giuseppe De Nittis, Alessandro Falsone

The Dipartimento di Elettronica, Informazione e Bioingegneria (DEIB) is one of the largest European ICT departments. With nearly 1000 members, researchers, collaborators, PhD students, technical and administrative staff, the Department is a vital institution capable of promoting education, fundamental and applied research, and technology transfer to companies. Research is the main focus of DEIB, pursued according to the highest international quality standards. The six department sections cluster consolidated competences in systems and control, computer science and engineering, electronics, telecommunications, bioengineering and electrical engineering. They have a broad network of partnerships with the best international institutions, which makes the Department one of the fundamental players in the worldwide scenario of scientific and technological innovation.

DEIB’s research environment also includes the industrial consortium CEFRIEL and several spin-offs.

The research activity
The Dipartimento di Elettronica, Informazione e Bioingegneria (DEIB) pursues ambitious research, educational and societal goals: to be at the cutting edge of research, generating innovative ideas, gaining international recognition, exploiting the synergy among researchers from different Information and Communication Technology (ICT) areas and from other disciplines.
The DEIB research is in continuity with the past but also pointing to new directions; its guidelines are:

> maintain a focus on long-term, basic and visionary research, funded by agencies and initiatives such as ERC, FET, EU Flagships, or PRIN at national level;

> enhance the involvement in medium-to-short-term research focusing mainly on those projects that transfer cutting-edge research results to improve products and services;

> enhance the involvement in interdisciplinary research, opening to collaborations with other departments and institutions. Such trend is fully in line with the Horizon 2020 framework program of the European Community, and focuses on a variety of challenges, from supporting the ageing society, to improving transportation, to addressing the climate change to supporting energy-aware society, and to strengthening education, cultural heritage and entertainment;

> support and contribute to the innovation processes of industries, public administrations, and the society in general, by understanding needs and problems, analyzing and interpreting market opportunities and challenges, identifying technological trends and directions, providing expertise and methods to design and develop disruptive solutions.

To address these complex issues, DEIB will also exploit the partnership with CEFRIEL and with the spinoffs and startups that have been created over the past years.

The quality of research is also witnessed by the high number of DEIB members that participate in the scientific boards of prestigious international journals, conferences and research associations.

---

**MAIN RESEARCH LINES**

**Bioengineering**

Analysis of biological systems and e-health
Biological and Biomechanical Engineering
Technologies for diagnosis, therapy and rehabilitation

**Electronics**

Digital systems
Electronic devices
Electronic circuit design
Radiation detectors and applications
Single-photon detectors and applications
Smart microsensors and microsystems

**Computer Science and Engineering**

Advanced software architectures and methodologies
Artificial intelligence and robotics
Data, web, and society
Information systems
System architectures

**Electrical Engineering**

Optical measurements and laser instrumentation
Electromagnetic compatibility
Electrical and electronic measurements
Electric Power Systems and Power Electronics
Circuits and systems: theory and applications

**Systems and Control**

Control systems
Dynamics of complex systems
Operations research and discrete optimization
Planning and management of environmental systems
Robotics and industrial automation

**Telecommunications**

Applied electromagnetics
Information transmission
Networking
Remote sensing
Signal processing for multimedia and telecommunications
PHD THERSES AWARDED IN 2018

Askarpour Mehrnoosh - Safer-HCR: a methodology for safety assessment through formal verification in human-robot collaboration
Banfi Iacopo - Multirobot exploration of communication-restricted environments
Bellotti Giovanni - Silicon drift detectors and readout electronics for high throughput spectroscopy applications
Bhatti Naveed Anwar - System support for transiently-powered embedded sensing systems
Brankovic Aida - Distributed randomized model selection for non-linear identification and supervised machine learning
Busnelli Fabio - Stability control and analysis of two-wheeled vehicles out of plane dynamics
Ceccarelli Francesco - Development of custom-technology single-photon avalanche diode arrays for high-performance applications
Cesarini Matteo - Fully printed organic imagers on flexible substrates for large area applications and novel radiation detectors
Colombo Tommaso - Analysis and design of suspension control systems for off-highway vehicles
Continella Andrea - Defending from financially-motivated software abuses
Cogetti Giulia - Development of scintillation detectors based on silicon photomultipliers for high-energy gamma-ray applications
De Nittis Giuseppe - Patrolling adversarial environments exploiting an alarm system
Di Federico Alessandro - Compiler techniques for binary analysis and hardening
Falsone Alessandro - Distributed decision making with application to energy systems
Fezzardi Pietro - Discrepancy analysis: a methodology for automated bug detection in hardware designs generated with high-level synthesis
Gelsomini Mirco - Empowering interactive technologies for children with neuro-developmental disorder and their caregivers
Geronazzo Angela - Smart buildings: a methodological approach to data design, analysis and exploitation
Grande Andrea - Design of ultra-fast frontend electronics for new pixel detectors for the European XFEL
Hmaity Ali - Reliability strategies for next generation cloud networks
Khosronejad Misagh - Study of level measurement pulse radar systems
Laudato Mario - Study of novel devices for crosspoint memory and neuromorphic applications
Leanza Antonio - Decorrelation phenomena in a geosynchronous synthetic aperture radar: theory, techniques and performance
Libutti Simone - Multcore resource management: a horizontal perspective
Lusardi Nicola - Advanced methods techniques and digital architectures for high performance timing of events
Mansouri Aida - Nanofabrication and characterization of high-performance graphene field-effect transistors
Mason Emanuele - Beyond full rationality: modeling tradeoff dynamics in multi-objective water management
Meddouri Soufiane - Robust control of autonomous system for wind electrical generators
Minotti Paolo - Towards fully-integrated frequency-modulated MEMS gyroscopes
Morosi Jacopo - Phase-coded brillouin optical correlation domain analysis for fast and highly-resolved distributed strain and temperature monitoring
Pagani Alessio - Algorithms and methods for the design and development of intelligent, content aware and sustainable mobility services
Paladino Stefano - A learning approach for pricing in e-commerce scenario
Parigi Polverini Matteo - Novel contributions to robot force control for industrial manipulators
Peronio Pietro - Time-correlated-single-photon-counting systems: challenging the limits
Peserico Nicola - Integrated optical platform for biosensor applications
Pinciroli Riccardo - Energy efficiency in large data-centers using performance evaluation techniques
Pollok Alexander Joseph - Modelling and control of aircraft environmental control systems
Quarta Davide - Embedded system security: attacks, impacts & defenses
Quattrociocchi Giovanni - Fast and fine-grained elastic resource provisioning for modern software systems
Rallo Gianmarco - Robustness in data-driven control: theory and automotive applications
Recanati Francesca - Sustainable design and management of agroecosystems-integrating optimization techniques to support decision-making
Resnati Davide - Physical modeling of nanoscale NAND Flash Memory reliability
Roselli Federico - Vehicle dynamics planning and control for safety and comfort in autonomous cars
Sacak Basak - Optimal kinodynamic planning for autonomous vehicles
Santagno Francesco - Feature-based analysis and synthesis of violin timbre
Shahid Saleem - Design and implementation of microwave and terahertz material characterization methods
Zhang Xinglong - Hierarchical and multilayer control structures based on MPC for large-scale systems
ADVISORY BOARD

Industrial Referees 2018/2019
Mario Caironi, IIT
Luigi Cicchese, Concept Reply
Cristina Cremonesi, The European Ambrosetti
Massimo Crisci, European Space Agency
Alessandro Ferrretti, Tre-Alamira
Giuseppe Foglianza, MCE Srl
Bruno Garavelli, Xnext s.r.l.
Alessandro Grossi, Micron Semiconductor Italia Srl
Renato Lombardi, Huawei Technologies
Renato Marchi, Gruppo PAM
Giorgio Parladori, SM Optics s.r.l.
Enrico Ragani, ABB S.p.A.
Piercarlo Ravasio, Prospera
Beatrice Rossi, STMicroelectronics
Domenico Rossi, STMicroelectronics
Carlo Sandroni, RSE S.p.A.
Massimo Valla, TIM
Luisa Venturini, Vodafone Italy
Stefano Verzura, Huawei Technologies
Roberto Villa, IBM Italy

BOARD OF PROFESSORS

1. Andrea Bonarini (Chair PhD)
2. Cesare Alippi
3. Francesco Amigoni
4. Luca Bascetta
5. Giuseppe Bertuccio
6. Cristiana Bolchini (Vice Chair CSE)
7. Paolo Bolzern (Vice Chair S&C)
8. Andrea Castelletti
9. Matteo Cesana (Vice Chair TEL)
10. Fabio Dercole
11. Lorenzo Fagiano
12. Giancarlo Ferrigno
13. Carlo Fiorini
14. Simone Garatti
15. Nicola Gatti
16. Angelo Geraci (Vice Chair ELE)
17. Paolo Martelli
18. Raffaella Mirandola
19. Andrea Monti Guarnieri
20. Barbara Pernici
21. Matteo Pradella
22. Ivan Rech
23. Carlo Riva
24. Alessandro Sottocornola Spinelli
25. Letizia Tanca
26. Massimo Tornatore
INTRODUCTION

PHD program in information technology

ELECTRONICS
SYSTEMS & CONTROL
TELECOMMUNICATIONS

COLLOQUIA DOCTORALIA 2018

COMPUTER SCIENCE & ENGINEERING

PHD SCHOOL
OF POLITECNICO
DI MILANO

THESIS ABSTRACTS
SAFER-HRC: A METHODOLOGY FOR SAFETY ASSESSMENT THROUGH FORMAL VERIFICATION IN HUMAN-ROBOT COLLABORATION

Askarpour Mehrnoosh

Robots usually function in workspaces divided (e.g., by fences) from those of human operators. However, novel robotic and cyber-physical systems have evolved in size and functionality to include the collaboration with human operators within common workspaces. This new application field is often referred to as Human-Robot Collaboration (HRC) and is increasingly prominent in people's lives and in industrial domains, for example in manufacturing applications. However, HRC raises new challenges to guarantee system safety, due to the presence of operators. Close proximity and frequent physical contacts between operators and robots, and intrinsic non-determinism in operators' behavior make it difficult for safety assessors and analysts to cope with the dynamism of collaborative applications. Yet, formal verification techniques can help in this regard through the exhaustive state-space exploration of system models, which can identify unwanted situations early in the development process. In fact, this thesis proposes to use formal verification techniques for analyzing risks in HRC, through a methodology, which is compatible with well-known standards in the area of collaborative robotics. The generic model contains a nondeterministic formal model of operator behavior, which captures the hazardous situations resulting from human errors. This method has an iterative and incremental nature, and allows safety engineers to refine their designs until all plausible erroneous behaviors are considered and mitigated. Finally, this thesis introduces a toolsupported approach for the automated generation of formal models from a semiformal language, in particular UML. The tool prototype is based on Papyrus UML modeler that provides mechanisms to allow safety engineers, who are typically not experts in formal methods, to automatically generate and formally verify logical models from an UML-based notation, which is more attuned with their background.
MULTIROBOT EXPLORATION OF COMMUNICATION-RESTRICTED ENVIRONMENTS

Bonfi Iacopo

In the last two decades, research in mobile robotics has shown that exploiting a team of cooperative robots can be a valid alternative to the employment human operators in carrying out repetitive, difficult, or hazardous tasks. Applications like warehouse management, information gathering, search and rescue, and patrolling are some representative examples. Such teams of robots operating in the same environment to achieve common goals are customarily referred to as multirobot systems.

From a general perspective, different challenges are involved in the deployment of a multirobot system for a particular application: these range from the choice (or development) of appropriate robotic platforms to deal with low-level issues (sensing and actuation) to the development of decision-theoretic planning tools aimed at enabling the robots to accomplish the assigned tasks with the required autonomy. In the context of mobile robotics, decisions happening at the highest levels of abstraction imply the definition of a navigation strategy, which specifies high-level directives for driving the robots in an environment to achieve some goals, like visiting the most “interesting” locations.

This thesis is concerned with the development of novel navigation strategies for teams of autonomous mobile robots in the context of a particular kind of information gathering task, namely, the exploration of unknown environments. In a nutshell, the problem that the robots have to face in this context is the following. Imagine some robots placed at the entrance of an unknown environment, as shown in Figure 1. They are equipped with sensors able to perceive their surroundings (e.g., laser range scanners and/or cameras) and can communicate with their teammates and, possibly, with a supervising control station either by means of an ad hoc network, or through a pre-deployed communication infrastructure. In the context of “plain” map building, the objective of the exploring robots is simple: construct a representation (map) of the unknown environment in an efficient way. However, if we think of search and rescue applications, map building is only functional to enabling the robots to find as many victims as possible in a short period of time.

Throughout the years, several efforts have been devoted to study coordinated multirobot exploration strategies assuming that communication is possible between any two locations. However, this is a reasonable assumption only in a very limited number of real settings. In fact, real operational conditions may require to deploy a team of robots only equipped with local limited-range communication modules: for instance, think of a search and rescue mission in a collapsed building, where the pre-existing WiFi infrastructure has been destroyed. Methodologies and techniques to devise multirobot systems for effective exploration in presence of communication constraints, despite their remarkable practical relevance, have not yet reached a level of maturity comparable to that of their “ideal” counterparts. Therefore, our work aims at proving the current state-of-the-art in multirobot exploration of communication-restricted environments by addressing some of its key challenges that, to the best of our knowledge, are still unsolved. The main contributions of the thesis can be summarized as follows.

First, we provide a general framework for modeling multirobot exploration in presence of communication constraints, where we theoretically justify some modeling choices regarding the construction of robots’ paths by means of an original theorem concerning the intractability of time-optimal multirobot path planning even on 2D grid graphs with holes (a typical environment discretization used in mobile robotics).

Second, we present a novel exploration strategy operating under what we call recurrent connectivity constraints to a fixed base station, which are often imposed in search and rescue settings. In short, our strategy enforces the robots to be connected with the base station each time they gather new information from the exploration frontiers. By allowing to submit new plans to arbitrary groups of robots, provided that they are “ready” (informally, they have sent all the required data to the base station), we are able to obtain a good trade-off between rapidity of the mapping process and situational awareness at the base station. Plans prescribe the robots to reach locations from which new information on the environment can be acquired and locations that form a relay chain with the base station, according to the predicted presence of communication links.

Third, we study a possible approach to overcome the widespread adoption in the literature of overly conservative or unrealistic assumptions on the robots’ communication capabilities by proposing coordinated navigation strategies aimed at mapping the unknown communication features of a (fully or partially) known environment. These strategies work by collecting samples for building a Gaussian Process (GP) representing a map of the signal strength between any two locations of the environment. Such maps can then be used to infer the existence of communication links in a non-conservative, yet reliable, way. Being specifically designed for an online setting, our strategies for building communication maps could be employed along with several multirobot exploration strategies presented in the literature by simply pairing a first team of exploring robots with an additional dedicated team. However, nothing prevents their use also for building communication maps for applications when the environment is fully known in advance, such as surveillance.

Finally, we propose an algorithmic framework for computing and handling the execution of backup plans aimed at dealing with the absence of predicted communication links in generic multirobot information gathering missions (hence including exploration as a particular case). In particular, we formalize what we call the multirobot reconnection problem, study its computational complexity, and provide optimal and heuristic algorithms for practical settings. These algorithms can be used to improve the robustness of all the information gathering strategies which exploit predictions of the availability of a communication link between two locations (including ours) which, in general, could be affected by false-positives.

Figure 1: Six robots ready to explore an unknown environment.
SYSTEM SUPPORT FOR TRANSIENTLY-POWERED EMBEDDED SENSING SYSTEMS

Bhatti Naveed Anwar

Transiently powered embedded systems are becoming popular because of their self-sustainable, no maintenance and easily deployable nature. However, there is an intrinsic challenge with these systems: they can be unpredictably interrupted, as energy harvesting by no means can ensure a predictable supply of energy. Reboots will frequently happen, which translates into a waste of resources, including energy, as applications need to re-initialize and re-acquire the state. As a result, the overall performance inevitably suffers. To allow an application to cross the boundaries of periods of energy unavailability, prior solutions, either save only a portion of program memory (avoiding the heap) limiting developers to employ sophisticated programmatic techniques, or resort to hardware modifications by replacing SRAM with FRAM, that may not only impact cost but also processing speed.

This thesis aims to design software techniques for transiently-powered embedded devices, allowing an application to make progress, with a minimum possible energy spent on saving the system state and without resorting to hardware modifications. In the first part of the thesis, we present the detailed analysis of the existing energy harvesting and wireless energy transfer solutions for wireless sensor networks (WSNs). We define desirable properties, classify existing solutions, and argue about their applicability in different deployment environments. Later, we conduct a comprehensive survey of the state of the art for transiently-powered embedded systems. We discuss challenges, define goals and classify transiently-powered embedded system solutions into different categories based on the techniques they use to ensure forward progress of the application.

In the second part of the thesis, we develop three different techniques for saving system state quickly and in an energy-efficient manner, exploiting different properties of non-volatile memory. Key to their efficiency is the way the state information is organized on non-volatile memory. Our results, through extensive simulation, crucially indicate that there is no ‘one-size-fits-all’ solution. It is the application’s memory characteristics that will make one technique preferable over another. A detailed evaluation results also lead us to design an additional technique, DICE, which, instead of reading non-volatile memory to compute changes in the system state, avoids reading non-volatile memory to ensure forward progress of the application, but also helps existing system support complete a given workload with better energy efficiency and reduced execution latency.

Finally, we present HarvOS that decides when to save the system state by looking at the worst-case energy cost required to reach the next opportunity to save system state, depending on the program structure as represented in the control flow graph. HarvOS allows the system to make an informed decision, at every opportunity to save system state, on whether to continue with the normal execution or save the system state.

Our evaluation indicates that HarvOS allows transiently-powered embedded systems to complete a given workload with 68% fewer restarts, compared to existing literature.

DEFENDING FROM FINANCIALLY-MOTIVATED SOFTWARE ABUSES

Continella Andrea

Software is involved in every aspect of our world, from our homes to large enterprises, and, in particular, it manages our data. As a consequence, software abuses can drastically impact our lives, for instance causing substantial financial losses or affecting people’s privacy. This raised the attention of cybercriminals, who found in this scenario a lucrative business. In fact, in the past twenty years the motivation behind the cybercriminals’ modus operandi has changed. No longer searching only for notoriety and fame, they have turned their attention to financial gain. Indeed malicious software, “malware,” is one of the most dangerous Internet threats nowadays. In this dissertation, we detail our research on the analysis and detection of the current software abuses, with the aim of defending users from such threats.

In particular, we concentrate on three main threats, which caused billion dollars losses in the past years. First, we focus on information-stealing malware, also known as “banking Trojans,” a class of malware that steals victims’ private information (e.g., banking credentials) by taking control of the victims’ browser — Man in the Browser attacks. Second, we focus on ransomware, another class of malware that encrypts victims’ files, preventing legitimate access until a ransom is paid. Third, we focus on mobile privacy leaks. Mobile apps collect a wealth of users’ private information, which is particularly attractive. In fact, cybervinicians are known to sell users’ private information on the underground markets, and advertisement libraries massively gather such data to illicitly increase their profits.

In the aforementioned threat landscape, our main research area focuses on financially-motivated software abuses. In particular, we focus on generic approaches to detect these malicious activities and protect users from such threats. Our contributions focus on the mitigation of three main threats that have been widely spread and caused billion dollars losses: banking Trojans, ransomware, mobile privacy leaks.

Banking Trojans Analysis and Detection. Banking Trojans can be detected by static signatures that precisely identify malicious binaries. However, this approach is not generic and strongly depends on the implementation details of the malware sample. In addition, new families and new versions of such Trojans are constantly released. For these reasons, we propose a novel, generic, and effective approach to analyze and
detect the common behavior of this malware. Modern Trojans are in fact equipped with a common functionality, called WebInject, used by cybercriminals to silently modify web pages.

We proposed a tool, Prometheus, that, based on web-page differential analysis, characterizes WebInject mechanisms in an implementation-independent fashion, without needing a-priori knowledge about the API hooking method used by the malware, and generates robust, behavioral signatures of the WebInject behavior.

• We combined the web page differential analysis with a memory forensics inspection technique to validate the generated signatures.

• We performed experiments on a dataset of real, active Trojans, and provided insights from a data analysis point of view (i.e., classification of the URLs where injections occur typically) that is used for validating our approach.

• We developed a prototype tool, Iris, that leverages the signatures produced by Prometheus to check, on the client side, whether a web page is rendered on an infected machine.

Protection from Ransomware Attacks. Preventive and reactive security measures can only partially mitigate the damage caused by modern ransomware attacks. In fact, pure-detection approaches (e.g., sandboxes or pipelines) are not sufficient, because, when luck allows a sample to be isolated and analyzed, it is already too late for several users. We believe that a forward-looking solution is to equip modern operating systems with generic, practical self-healing capabilities against this serious threat. In summary:

• We proposed a tool, Prometheus, that, based on web-page differential analysis, characterizes WebInject mechanisms in an implementation-independent fashion, without needing a-priori knowledge about the API hooking method used by the malware, and generates robust, behavioral signatures of the WebInject behavior.

• We implemented these approaches in ShieldFS as a drop-in, Windows kernel module that we showed capable of successfully protecting from current ransomware attacks.

Mobile Privacy Leaks Detection. Despite significant effort from the research community in developing privacy leak detection tools, it is still unclear whether apps and ad libraries can hide the fact that they are leaking private information. In fact, all existing analysis tools have limitations: data flow tracking suffers from imprecisions; on the other hand, network traffic analysis cannot handle encryption or custom encoding. We propose a new approach that is not affected by such limitations, and it is also resilient to obfuscation techniques, such as encoding, encryption, or any other kind of transformation performed on private information before it is leaked. In summary:

• We developed a prototype tool, Agrigento, that performs root cause analysis of nondeterminism in the network behavior of Android apps.

• We showed that, in most cases, non-determinism in network behavior can be explained and eliminated. This key insight makes privacy leak detection through differential black-box analysis practical.

• The results of our empirical study provide new insights into how modern apps use custom encoding and obfuscation techniques to stealthily leak private information and to evade existing approaches.

• We proposed an approach that makes a modern filesystem resilient to malicious encryption, by dynamically reverting the effects of ransomware attacks.

Physical security is one of the most important challenges of our times. Due to the terrible events happened in the last decades all around the world, especially nowadays in Europe, novel techniques and methods are being developed to face new threats and dangers. But security means also helping people and saving lives, e.g., detecting and rescuing desperate migrants trying to cross the Mediterranean Sea.

Algorithmic Game Theory allows us to scientifically investigate these phenomena, modeling such interactions as mathematical problems and designing suitable algorithms to deal with these threats. When patrolling large environments or infrastructures, a crucial issue is to guarantee some level of protection to each area without being able to constantly surveil them. A common countermeasure is the usage of cheap but wide-ranged sensors, able to detect malicious events that may occur. In this thesis, we propose the first Security Game model with the presence of an alarm system able to trigger alarm signals, which carry the information about targets that can be under attack. Specifically, we focus on the exploitation of such information to improve the effectiveness of patrolling strategies. The dissertation is structured in three parts, according to the research lines along which the contributions are developed.

Uncertainties of the alarm system. First, we study the uncertainties that may affect the alarm system. We start considering the scenario in which the Defender can control a single patroller and the alarm system is affected by spatial uncertainty, i.e., the signal sent to the Defender communicates that something suspicious is happening in an area, without specifying the exact location. We divide the problem into two phases: signal response and patrolling. For the signal response phase, we provide a complexity analysis and design two exact algorithms and two approximation algorithms. We show that, without false positives and missed detections, the best patrolling strategy reduces to stay in a place, wait for a signal, and respond to it at best. Then, we introduce a significant positive missed detection rate, i.e., no alarm signal is generated even though an attack is occurring. This scenario is in favor of the Attacker, who can exploit such flaw in the alarm system. This is why such new element puts the problem in a different perspective and requires a new approach to be solved. We deeply analyze security games in which the alarm system is both characterized by detection uncertainty and spatial imperfection, tackling the challenge of designing tractable algorithms for real-life scenarios. In particular, we show that standing still and waiting for a signal is no more the best response, and provide the Defender with the best patrolling strategy to move her resource. We prove that Markovian strategies are arbitrarily worse than optimal non-Markovian ones, and thus we resort to a deterministic approach.

A coordinated defense and multiple attacks. The second direction we investigate is the dimension of the problem, namely, the number of resources both the Defender and the Attacker...
PHD program in information technology

...with the number of resources. We prove that the problem of finding the best Defender’s strategy, when the number of defensive resources is given, is hard. We also show that the problem of finding the minimum number of resources assuring non-null protection to every target cannot be approximated in polynomial time within a constant factor on arbitrary graphs. We design an algorithm to find the best strategy to respond to any alarm signal once an allocation of resources in the environment is given, according to different degrees of coordination among the resources, each described by an adversarial team game with different forms of strategies.

Then, we investigate the opportunities the Attacker can take when she can perform multiple attacks, simultaneously or sequentially. The challenge is due to the high interaction level among the players, e.g., the Attacker can use resources to make the patroller move away from some valuable targets and, subsequently, she can attack those targets. When the number of resources is a fixed parameter, the problem admits an algorithm capable of finding the strategies on the equilibrium path, requiring polynomial time in the size of the graph. Conversely, we show that there is no algorithm requiring polynomial time in the number of Attacker’s resources, even in the simplified case in which the Attacker uses all her resources simultaneously. Unfortunately, computing the equilibrium strategies requires the knowledge on the number of Attacker’s resources. Since it is unlikely to have this information, we study the robustness of a Defender’s strategy when the guess such number, evaluating the worst-case inefficiency of this strategy, showing that can be arbitrary even when the guess is a wrong estimate—both over and under—for just a single resource. Furthermore, we investigate the use of online algorithms to adopt when no information is available to the Defender.

er. We provide a tight upper bound over the competitive factor when non-stochastic online algorithms are used, and we show that the factor can be improved by resorting to randomization. Facing the unknown. Finally, we introduce the notion of uncertainty in the type of the Attacker. We tackle the problem of facing an unknown adversary, whose profile is just known to be in a list of possible profiles. Here, a different approach is required: we learn the profile of the Attacker and exploit such information to prevent possible future attacks. We show that state-of-the-art bandit and expert algorithms suffer from a linear and logarithmic regret, respectively, in the length of the time horizon. Thus, we present two novel approaches, bridging together game-theoretical techniques and online learning tools. In the first approach, the Defender has a belief about the follower and updates it during the game, and we provide a finite-time analysis showing that the regret of the algorithm is constant in the length of the time horizon. In the second approach, the learning policy is driven by the estimated expected regret and is based on a backward induction procedure. We provide a thorough experimental evaluation in concrete security settings, comparing our algorithms with the main algorithms available in the state of the art of the online learning field and showing that our approaches provide a remarkable improvement in terms of expected pseudo-regret minimization.

Despite the growing popularity of interpreted or byte-compiled languages, C/C++ and other languages targeting native code are still dominantly used for system programming. Programs compiled to native code present a set of challenges compared to alternatives. In particular, in this work we focus on how they can be efficiently analyzed, how existing security measures (known as binary hardening techniques) perform, and how new ones can be introduced to secure features that have received little attention.

We propose rev.ng a binary analysis framework based on QEMU, a popular dynamic binary translator and emulator, and LLVM, a mature and flexible compiler framework. rev.ng can easily handle a large number of architectures and features a set of analyses to recover basic blocks locations, function boundaries and prototypes in an architecture- and ABI-independent way. rev.ng can be used for instrumentation, debugging, decompilation, retrofitting of security features and many more purposes. Our prototype encompasses about 17 kSLOC of C++ code and has been publicly released under a Free Software license.

The core component of rev.ng is revamb: a static binary translator which can accurately identify all the basic blocks, and, in particular, the targets of indirect jumps for switch statements. Along this work, we will make heavy use of analysis techniques popular in the compiler literature, such as Monotone Frameworks, to recover an accurate control-flow graph, identify function boundaries and the number and location of function arguments and return values.

We will also discuss how rev.ng can handle native dynamic libraries, how it can be easily employed for instrumentation purposes, how it can be extended to handle even more architectures and how its performance compares to tools with analogous purposes such as QEMU, Valgrind, Pin and angr.
DISCREPANCY ANALYSIS: A METHODOLOGY FOR AUTOMATED BUG DETECTION IN HARDWARE DESIGNS GENERATED WITH HIGH-LEVEL SYNTHESIS

Fezzardi Pietro

Field Programmable Gate Arrays (FPGA) are steadily becoming more appealing in computing. They provide reconfigurability and flexibility like software, while guaranteeing low power consumption and massive parallelism close to what is possible with Application Specific Integrated Circuits. This is very promising in the current general struggle to find new paradigms that can cope with the end of Moore’s Law. For these reasons, FPGAs are not under investigation just for prototyping, but they are increasingly used in datacenters, High-Performance Computing and irregular parallel applications. One of the main obstacles to the adoption of such devices is that the skillset necessary to program them effectively is very broad. Digital circuits designers are harder to find than software engineers, and the development of a dedicated digital circuit to execute a given task usually requires considerably more time than a software implementation of the same functionality. FPGAs are traditionally programmed using so called Hardware Description Languages (HDL), that allow designers to describe every component of the digital electronics that compose the system. For their nature, HDLs are very tightly related to the underlying devices and electronics, forcing designers to focus at the same time on the low-level details of the electronics and on the high-level algorithmic level of their implementations. This close relationship with the underlying hardware also means that the same HDL design cannot be easily ported from an FPGA device to another, without significant modifications. These three components – scarceness of skilled engineers, languages that place multiple heavy responsibilities on the shoulders of designers, and lack of portability of hardware designs – clearly represent a scalability problem that has to be overcome to enable FPGA computing to really go mainstream.

In recent years, a promising approach in this field that has received much attention is High-Level Synthesis (HLS). The main insight behind High-Level Synthesis is that the key to removing all the obstacles to FPGA design is to use a high-level software programming language, instead of HDL, as a starting point for hardware synthesis. This approach software engineers could start programming FPGAs, ignoring the details of the underlying electronic designs to focus on algorithms, while at the same time creating designs that are easily portable on new devices. Today, many different academic and commercial tools are able to generate HDL design starting from a variety of programming languages: C, C++, Java, Python, Haskell, Erlang, and many others. However, the most common and well supported by FPGA vendors are C and C++. These languages are at an higher level compared to HDL and allow designers to write portable code, while still giving programmers the capability to control low-level details that might be relevant in hardware. Moreover, C and C++ are the basis of a large number of standard libraries and programming language extensions for HPC and multithreading, like POSIX threads (pthreads), OpenMP, OpenCL, and CUDA. Commercial HLS tools and academic projects often provide support for High-Level Synthesis starting from these multi-threaded language extensions, providing programmers with familiar tools to easily exploit the massive physical parallelism available on FPGAs. These solutions are also seen as a promising trend to provide well-known programming paradigms for FPGAs in the cloud.

However, for a programming paradigm to succeed, there is more to be taken care of besides the programming language. One of the fundamental aspects that will determine the success or the failure of High-Level Synthesis in the long term is the ecosystem of development and verification tools that will be built around it. Indeed, in hardware design, testing and verification typically constitute a significant portion of the whole effort for a project. Another important factor is the support for the integration of multiple components in System-on-Chip (SoC) design. These components can be either generated with HLS, hand-written by designers, or provided as Intellectual Property (IP) blocks by third-parties. According to ITRS prediction future SoC architectures will be characterized by heavy reuse (more than 90% by 2020) of IP blocks for reducing design cost and time-to-market. To increase productivity and tackle design complexity, designers will need to raise the abstraction level and use Electronic System Level (ESL) methodologies based on High-Level Synthesis to automatically generate and integrate the IP descriptions in a suitable HDL design. This will result in a proliferation of IP vendors specialized in the optimization of specific functionalities, while system designers will focus on the integration of the different components, posing new threats for the design and verification of complex architectures. At the same time HLS compilers are growing in complexity, adding more optimizations passes to generate more efficient accelerators in term of frequency, area, or power consumption. This complexity is hidden to users and managed by the tools, but it can become a real burden during testing, debugging and verification. Given that in SoC design up to more than 50% of the overall time can be spent on verification, the risk is that the speedup HLS gives to development could be negatively compensated by a slowdown in testing and debugging. HDL generated by HLS is not intended to be human-friendly, because that is not the purpose of HLS. This may become a problem if the HLS users are software engineers with little previous exposure to HDL and to hardware design.

In order to avoid this risk, or even to improve the testing and debugging experience as much as the development phase has been improved, it is critical for High-Level Synthesis tools to integrate techniques and workflows to also manage verification. In particular, the tools need to keep track of the additional complexity introduced and managed by HLS during the design stage, in order to be able to reason about it later during verification, helping users to unravel the details of what went wrong in case of bugs. In this way, it is possible to extend the support that these tools give to the designers beyond implementation phase, up to the testing, debugging and verification steps. This thesis describes the definition, implementation, and evaluation of a methodology for automated bug detection, called Discrepancy Analysis, targeted at hardware designs generated with High-Level Synthesis. Discrepancy Analysis is based on a notion of equivalence between the execution of the hardware generated with High-Level Synthesis and the execution of the software obtained from the original high-level source code used to generate that hardware. Using this notion of equivalence, the thesis describes how to compare automatically the two executions, and how to detect and isolate the first mismatch if present. All these operations are executed without human interaction, relieving users from the time-consuming and error-prone tasks to select the necessary signals for debugging, analyzing the signal traces to identify the malfunction, and backtracking it to the original high-level source code.

The methodology is tightly integrated with the High-Level Synthesis process. As a consequence, it supports all compiler optimizations available during High-Level Synthesis. This coupling with the High-Level Synthesis tool also allows to automatically select in the generated designs the signals necessary for automated bug detection. Despite the tight coupling with the High-Level Synthesis tool, the discussion is kept as general as possible and only relies on common features.
that are present in all the known commercial and academic tools. The thesis also describes two extensions of Discrepancy Analysis: one to support automated bug detection in hardware generated with High-Level Synthesis of multi-threaded code; one to support automated bug detection on pointers and memory accesses.

Two bug detection flows based on Discrepancy Analysis are presented. The first is based on simulation of the hardware at the Register Transfer Level and performs the automated bug detection process offline after execution. The second flow is for on-chip bug detection. The generated hardware is instrumented with dedicated checker components, that analyze the execution on the fly, halting the circuit if a mismatch occurs and notifying it to users. Both the debug flows have been implemented and tested with BAMBU, an open source research framework for High-Level Synthesis developed at Politecnico di Milano.

The results have been evaluated in terms of performance, coverage, and other advantages brought to the overall debugging experience, like the considerable reduction of the size of the waveforms files that can be achieved with a heuristic for automated signal selection. This evaluation showed Discrepancy Analysis to be fast, accurate, and effective in identifying several different classes of bugs, coming from the original high-level code, from external libraries of components, and even subtle bugs injected by the High-Level Synthesis tool itself. A thorough and extensive analysis of these classes of bugs has been carried on, both on the baseline version and on the presented extensions for multithreaded code, for pointers, and for on-chip debugging. The technique used to compress the execution traces for On-Chip Discrepancy Analysis, based on Efficient Path Profiling, also showed reductions of the memory consumption necessary for on-chip debugging up to 95% compared to previous state-of-the-art.

Neuro-Developmental Disorder (NDD) is an umbrella term for a group of disorders arising during the developmental period that is characterized by severe and often co-occurring deficits in the cognitive, social, communicative, motor, behavioral and emotional spheres. In this regard, the use of digital interactive technology is considered as a promising approach that does not replace current therapies but can be incorporated into them and support caregivers in their daily routine.

Disability nowadays no longer means a condition, an incapacity, or lack that belongs to a body, but rather a product of the interactions between self, society, body, and the variety of interactions from political economies to personal and socio-economical commitments that they engender. From a socio-economical point of view, the rapid growth of these technological resources requires a carefully planned response by health institutions and their administrators.

In addition to relevant staff development and training, this response urges to address the cost of technological resources applicable; the individuals’ unique needs with which those resources will be most useful; the benefits and risks of using them; the methods for preparing care-givers (clinicians and families) to accept, adopt and appropriate these resources; and an organizational commitment to empirically evaluating their effectiveness and utility.

This work addresses the previous issues by developing the “Empowerment Framework”, a framework that offers a space so that health institutions, administrators, clinicians, educators, parents and eventually external stakeholders can contribute in it. Using the framework, they will get access to:

- A broad set of evidence-based design guidelines, carefully organized by interaction paradigm and category, informed by the literature and by the experience gained through the years;
- A portable, accessible, modular and scalable software platform that will enable them to collaborate with partners in designing, developing, configuring, evaluating and sharing the activities through the web, building a new model of social crowd-sourcing;
- A psycho-pedagogical model of intervention for teachers, parents and novice care-givers; co-developed with specialists and informed by macro-psychological theories and many technologically-based studies;
- Adoption and sustainability guidelines to provide administrators and care-givers with the information they need to integrate and expand the use of technologies in their contexts.

Over the last decades, through many policies and efforts, public awareness of NDD has become widespread, especially for children in the Autism Spectrum Disorder. NDD includes a wide umbrella of disabilities and unique abilities. This highly prevalent condition presents itself in a wide variety of ways, engendering interest from a vast array of professional care-givers, researchers, and other stakeholders. Thus, peo-
people interested in NDD and those with specific backgrounds in medicine, biology, genetics, psychology, education, physiology, speech, language, and technologies alike have become interested in the use of technologies to support these individuals.

The media attention to children with NDD, their teachers and families has fueled what some may consider to be a tech bubble in the NDD space. myriad applications and devices, many of which have not been rigorously tested. Therefore, more and more researchers are working to find evidence of the efficacy of these technologies though, in an environment in which families and educators may be desperate to try new therapies, before their early intervention support runs out, waiting for research evidence may not be desirable. Thus, there is currently a great opportunity to build on early research and commercial successes, contribute to evidence-based practices, and develop holistic empirically grounded interventions.

This thesis is my echo to this opportunity, an attempt to build a framework to sustain the entire community to do their best, eventually enabling the entire community to do their best, eventually enabling the ecosystem thus empowering dynamic operation strategies. Nonetheless, it introduces the need to master the heterogeneous, multi-facet data collected from the building ecosystem and to effectively exploit it. This challenge requires to address data quality issues, by designing ad-hoc processing approaches and to develop effective analysis methods able to support the discovery of useful knowledge and to enhance results interpretation. Nonetheless, data harvested from the building ecosystem represents a unique opportunity to develop new methods to address data quality issues, such as timeliness and consistency, and to design new analysis approaches, oriented to solve challenges concerning energy efficiency, occupants’ comfort assessment and improvement, building control and fault detection.

In this context, there is an evident quest to define a methodological framework that identifies the main choices that are available in designing a monitoring and exploitation process, possible alternatives for each identified choice and their expected effects on the collected data. These choices need to be evaluated with respect to the goals of the monitoring activity. However, except for the broad guidelines provided by ASHRAE, there is no recommendation to support the design of monitoring campaigns and the process is typically planned and deployed on the basis of experience of domain experts and/or off-the-shelf kits, thus making each building a stand-alone, unique case. Hence, case studies in literature adopt customized solutions and the description usually focus on innovative aspects rather than discussing the monitoring solution, which, however, has an impact on the data exploration process and its results. The main contribution of this thesis is the in-

During the last decades, improving energy efficiency in buildings has risen as an important societal issue and research area, motivated by a pressing quest to design, develop and implement effective and affordable energy demand reduction strategies. The ultimate goal is to optimize the trade-off between energy consumption and the occupants’ comfort, aiming at reducing the high-energy demand and carbon footprint without compromising the occupants’ quality of life. In this perspective, current research trends focus on Information and Communication Technologies (ICT) to enhance energy efficiency in buildings and communities.

Buildings, especially existing, non-residential ones, and occupants are the two key elements of the stated problem, to be opportunely monitored, dynamically controlled and made aware in order to pursue the desired optimization goal. In this context, ICT supports the following challenges: it empowers the adoption of Building Management Systems (BMSs) and Energy Management Systems (EMs), equipped with sensors and actuators, with the mission to optimize the available resources and operational goals thus improving occupants comfort while saving energy; it enables the integration between building systems, e.g., lighting, ventilation, Heating Ventilation And Cooling (HVAC) systems; it supports the collection and storage of real-time information, e.g., indoor conditions, energy consumption, as well as the modeling of information about the building and its systems, e.g., constructive features, sensor positions, system technical details; and it contributes to the definition of an integrated infrastructure useful to extract from the available heterogeneous, multi-facet data the information needed to provide an overarching picture of the building ecosystem thus empowering dynamic operation strategies. Nonetheless, it introduces the need to master the heterogeneous, multi-facet data collected from the building ecosystem and to effectively exploit it. This challenge requires to address data quality issues, by designing ad-hoc processing approaches and to develop effective analysis methods able to support the discovery of useful knowledge and to enhance results interpretation. Nonetheless, data harvested from the building ecosystem represents a unique opportunity to develop new methods to address data quality issues, such as timeliness and consistency, and to design new analysis approaches, oriented to solve challenges concerning energy efficiency, occupants’ comfort assessment and improvement, building control and fault detection.

In this context, there is an evident quest to define a methodological framework that identifies the main choices that are available in designing a monitoring and exploitation process, possible alternatives for each identified choice and their expected effects on the collected data. These choices need to be evaluated with respect to the goals of the monitoring activity. However, except for the broad guidelines provided by ASHRAE, there is no recommendation to support the design of monitoring campaigns and the process is typically planned and deployed on the basis of experience of domain experts and/or off-the-shelf kits, thus making each building a stand-alone, unique case. Hence, case studies in literature adopt customized solutions and the description usually focus on innovative aspects rather than discussing the monitoring solution, which, however, has an impact on the data exploration process and its results. The main contribution of this thesis is the in-
MULTICORE RESOURCE MANAGEMENT: A HORIZONTAL PERSPECTIVE

Libutti Simone

The end of Dennard's scaling has been one of the most disruptive events occurring in the evolution of computing platforms. In order to cope with the subsequent increase in chips power density, hardware designers have progressively moved towards solutions that leverage the concepts of parallelism and heterogeneity. As a consequence, modern architectures feature an increasing number of shared computational resources that are power-hungry, can possibly be different in nature, and can be concurrently used by multiple applications.

This increasing hardware complexity has in turn affected the software stack: task scheduling and mapping have become challenging problems due to the need of maximizing the performance of applications while minimizing power, temperature, and contention on the shared resources.

This dissertation directly tackles the above mentioned problem. In particular, we address resource management from a horizontal perspective, trying to identify the challenges and solutions that pertain the increasingly blurred area between high-end embedded and High Performance Computing (HPC) systems.

At operating system level, we studied how the Linux Control Groups (cgroups) perform CPU time allocation in Linux-based systems. In particular, we analyzed how the cgroups cpu controller limits bandwidth. We discovered that, in certain scenarios, the CPU bandwidth that is effectively exploited by the applications could potentially be not only lower than the expected one, but also notably higher, which may cause troubles in multi-application scenarios.

Then, we dealt with application characterization. In particular, we employed Design Space Exploration techniques to characterize resource usage and energy consumption of applications. Experimental results shown that, by exploiting the characterization information to suitably map applications, the resource manager is indeed able to optimize scheduling decisions. We also showed that, in order to maximize the Quality of Service (QoS) that can be squeezed out from the available resources, applications need to constantly update their software parameters in order to continuously adapt them to the system status.

We then studied the benefits that come from allowing a system-wide resource manager and an application-specific auto-tuner to work in a synergistic way. The main idea behind that study is that, whereas resource managers allocate resources to applications according to precise and known system-wide optimization goals, they are often unaware of what applications really need. We tackled this problem by moving part of the management complexity to the applications side: each application relies on an application-specific auto-tuner, i.e., a component that is specifically configured for the target application and is able to tune the application software parameters at runtime in order to make it comply with its QoS goal despite a runtime-variable resource availability.

In order to better exploit the capabilities of multi-core processors, we then added another degree of complexity: heterogeneity. We specifically addressed big.LITTLE architectures, i.e., processors that feature two clusters of cores: a performing and power-hungry one (big), and a slower and power-efficient one (little). The two clusters share the same Instruction Set Architecture; therefore, threads can be migrated between the two clusters during runtime. This, in turn, allows operative systems to exploit the trade-off between performance and power consumption. We studied how to dynamically migrate threads among the big and little clusters in order to maximize the usage of the big cluster while...
minimizing the performance losses that are induced by resource contention. We did so by introducing the concept of stakes function, which represents the trade-off between exclusive allocation and sharing of resources in multi-core processors. We introduced a co-scheduling policy that exploits stakes functions as a metric to take co-scheduling decisions on heterogeneous processors.

Then, we used the two clusters of cores as a heterogeneous OpenCL device. In this context, we presented a mechanism that forces the OpenCL runtime to view the big.LITTLE processor as a custom set of heterogeneous devices instead of viewing it as a single device.

Finally, we dealt with distributed systems, mainly focusing on High Performance Computing. In those scenarios, the objectives of resource management are typically different from those of embedded systems. In particular, resource management techniques for HPC mostly focus on minimizing power consumption and thermal hot-spots, detecting and counteracting faults and aging-induced performance variability, and exploiting heterogeneous accelerators.

First of all, we performed and interesting study of how the freeze/restore-based process migration of MPI applications, which is usually performed at node granularity to address faults, can be made fine-grained in order to migrate only parts of the application on a different computing node. The outcome of this study was the development of the mig framework, an OpenMPI module that allows MPI applications—or even just a subset of their processes—to be migrated from an HPC node to another one without requiring developers to change their applications’ code nor performing intrusive changes to the OpenMPI framework.

Then, we focused on the node-level optimization of distributed computation. We presented a resource management approach that exploits the trade-off between power consumption and performance when migrating HPC applications that must comply with runtime-variable QoS requirements. We applied an adaptive performance-aware execution model in the context of a real scientific application domain on a multicore HPC system. The approach is based on the concept of “resource minimization via late termination”. That is, we minimize the amount of resources that the applications can use so that they are barely able to comply with their QoS requirements. The unused resources can be therefore used to perform system-wide optimizations such as minimizing power consumption or isolating faulty parts of the system.

The final step towards a performance, quality and power aware (but yet homogeneous) HPC resource management consisted in designing a feedback-based and partially decentralized resource management approach that allowed applications to comply with their QoS goals while minimizing resource usage; minimizing the negative effects of faults-induced performance variability; and leveling the temperature throughout the available computing cores, so that hot-spots are avoided and the effects of temperature on Mean Time To Failure are equally balanced on the cores.

To conclude this dissertation, we presented our “work in progress” in the context of the MANGO European Project, which aims at performing the first steps towards an unified runtime management support for deeply heterogeneous HPC systems. We discussed the goals, requirements and solutions for an HPC software stack that targets deeply heterogeneous architectures composed of both general purpose nodes and a variety of accelerators. In particular, we proposed to employ a combination of resource management techniques to control the allocation of computing units and memory resources to different applications under QoS requirements; and a low-level runtime support to provide a minimum common base among different accelerators, thus allowing functional portability of applications and an easier porting of high-level programming models on the different accelerators.

During our work, we extensively used, modified and extended the Barbeque Run-Time Resource Manager, which is an Open-Source manager developed at Politecnico di Milano. You can find our contributions to this framework at https://bitbucket.org/bosp/barbeque.

The quantity of data generated by public transport agencies, users and public transport oriented applications is constantly growing. This information is not fully exploited though, especially in the public transports field: just a few of the existing applications make use of this information and no service is able to offer a dynamic, real-time, individually-customized interaction. Aim of this thesis is to provide the necessary infrastructure to enable the development of innovative, context-aware services and applications in the field of the public transportation. A set of methods and tools has been designed to create the structures and the information required. These instruments have been integrated in a general framework able to reconstruct and update in real-time the public mobility state. The public mobility state can be defined as the intersection of three state dimensions:

- The public transport network state represents the current position of each means and by their equations of motion;
- The road network state represents the current state (i.e., travel speed, traffic flows, congestion) of the roads in a given area;
- The users state is composed by the position of the traveling users (e.g., gathered using a smartphone application), their destination and, when on a vehicle, the matching with the means of transport they are traveling on.

These three states are not directly obtainable, thus they have been reconstructed using publicly available data, such as open data, transport means timetables, actual arrival times upon each stop and users’ GPS position. Each state has been elaborated in a different conceptual module and, together with the data fusion module and the API server module, they compose what in this thesis is defined as the Public Mobility Platform. The Public Mobility Platform manages all the information regarding the public mobility, the vehicles, the traveling users, the state of the transportation network and road network. This platform enables the design of user oriented planning and assistance services increasing the perceived quality of the public transport service and offering a better travel experience, reducing travelling time and improving perceived comfort, even in case of disruptions.

Furthermore, this innovative platform can also supply public transport agencies with detailed information such as number of traveling passengers, commutation times and routes. The platform is composed of several modules, each of which deals with a conceptual task. The public transport network reconstruction module is designed to reconstruct the position and the estimated motion laws of all the means of transportation in a given area, using information typically available, such as estimated time of arrival of the vehicles at the stations. This module uses a state-based Bayesian approach for the reconstruction of the transit state system from the limited publicly available knowledge. The proposed general approach has proved to be effective both in reconstructing the state of the network and in exploiting it to predict the position of the public transport vehicles in the near future, also in the presence of various real world kinds of noise, such as information blackouts. The user contextualization module integrates the location of users in the reconstructed public mobility state in order to estimate when the users are on a vehicle. Obtaining this information poses two main challenges. The first challenge concern the travel state of the us-
ers, that is when they are actually on the vehicle or not (e.g., they are just walking on the street close to a bus). The second challenge revolves around the association of these generic users to the vehicle they are riding, taking into account noise, limited precision of the sensors available (e.g., GPS, accelerometers) and possible presence of multiple means of transport in the same area. The proposed solution is based on a Particle Filter, a model that includes the probability for each user to be on a selected vehicle. The system has proved to be effective in presence of noisy data and to identify correctly when the users are actually on a vehicle or not. Thanks to underlying model, this approach is also convincing in the identification of the specific vehicle each agent is traveling on. The road network reconstruction module, through a knowledge discovery method that processes the real-time position of the car sharing vehicles available, estimates interesting metrics, such as travel time, congestions and vehicles flows at different times and in different days. The estimation of the road network state does not require any dedicated sensor or probe, instead it uses only information (historical and in real-time) about the car sharing vehicles movements during the day. This approach is used to reconstruct the road network in the cities where other services (with dedicated resources) are not available and can be used, as an additional source, to improve the accuracy of road network state in the cities where other services are already available. The reconstructed road network state can be provided to external applications and used to estimate the best routes for the private public transport services (e.g., car sharing). Moreover, this state is integrated with the public mobility state in order to improve the speed accuracy of the vehicles that travel on roads shared with the private transportation. A further module, the network features classification module, is designed to predict urban mobility scenarios and to explain them. The main topic is relative to the private public transportation (e.g., taxis and car sharing) and includes two main techniques based on explainable deep learning: the first one is focused on the design of interpretable deep neural networks, using neural sub-networks to represent engineered input features. These sub-network are used to explain how these features determine the predictions. The second technique revolves around the representation of geographical informations about travels using road graph and features selection. An ad hoc simulator has been developed to test the set of methods and tools and the Public Mobility Platform. The accuracy and the robustness of the approach have been demonstrated, even in case of missing data, extremely inaccurate GPS position of the users and unlikely corner cases. Afterwards, a working implementation of this platform has been developed for the city of Milan and, in collaboration with TIM Joint Open Lab, it has been evaluated, proving to have excellent performances even in real case scenarios. Nevertheless, the system is generalizable and can be deployed in other cities easily adjusted to the real-time data available. Summarizing, an innovative platform that enables interesting innovative public transport services is proposed. From a user point of view, the public transport applications can shift from a planning paradigm to an assistance one, where information is provided during the whole trip and not just before the beginning. These new applications can provide the maximum precision and accuracy considering the context of the users (e.g., the estimated time of arrival is constantly updated, taking into account the precise means the users are traveling on, they can play context-aware games and share news with the other passengers). From the transit agencies perspective, it is possible to evaluate metrics valuable to duly assess service quality, such as the number of connections taken, mean waiting times at connections and commutation time. If adequate relevant information is available to travel agencies in real time, the new generation of transport services could dynamically adjust service parameters, and immediately assess the effects, in order to dynamically improve service quality in closed-loop fashion.

A LEARNING APPROACH FOR PRICING IN E-COMMERCE SCENARIO

Paladino Stefano

Over the past few years, there has been a significant increase in the use of e-commerce websites. Thanks to technological progress and the massive adoption of e-commerce, almost everything can be bought online, from groceries and clothing to holiday packages and cars. Market research shows that the one of e-commerce is a market with a global value of more than two trillion USD, and it will even grow in the future. Online markets have many features that can be exploited by vendors, thus, with the advent of e-commerce, a number of new strategies became possible. For instance, prices can be easily adjusted without incurring in any cost, while, in traditional markets, price changes would often induce costs, since a new catalog had to be printed or price tags had to be replaced. Furthermore, in online markets it is possible to access historical data without substantial costs, making it easier for vendors to study customers’ behavior in order to make more accurate and informed decisions.

With the spread of e-commerce, metasearch engines began to arise as well. These tools are so named as they conduct searches across multiple independent e-commerce and they aggregate the results, to allow customers to evaluate and compare the offers for a product more clearly. The scenario of online selling of travel products is a noteworthy example in which the role of metasearch engines is acquiring a great importance. In this scenario, we have Online Travel Agencies (OTAs) which provide online booking facilities for flight tickets, hotels and other travel-related services to customers. Some of the most famous OTAs are lastminute.com, Expedia and eDreams. Metasearch engines have emerged in this field as a response to the need of users to compare offerings without having to consult each OTA individually. The most famous metasearch engines are websites such as Skyscanner, Google Flights or Kayak. Their relevance has been increasing in recent years, and market analysis for the US shows that travelers, when asked about their last flight trips, were almost equally likely to have consulted metasearch engines websites, with roughly three-quarters of the total doing so.

Our work investigates the pricing problem in the setting of online sales of digital goods from the point of view of an e-commerce, such as an OTA, selling its products in a metasearch environment. Metasearch engines send a lot of traffic, then resulting in sales, to OTAs’ websites. From the data of one of the major European OTA, we saw that more than a half of the profits are made from the sales on metasearch engines. Thus, this scenario presents a great profitability, but also a number of characteristics which makes the problem very challenging. We have a vast catalog of items to price. We have almost no information about our customers since they do not directly use our websites but they go on metasearch engines, which actually act as middlemen: they send a lot of traffic to OTAs’ websites, but they give OTAs very few information about customers’ behavior and purchasing history. Furthermore, most users perform searches without the actual intent of buying but only for informational purposes, generating a huge amount of searches performed every day, but with only few of them converting into bookings. Another difficulty arises from the non-stationarity of the environment, since we have seasonal effects on the market and we have a lot of competitors which impact on the non-stationarity of the environment by changing their marketing strategies. All these characteristics make the problem of finding the optimal pricing strategy really complex and with a lot of variables to take into account. It is tough for a human operator to tackle this computational burden, considering...
all the facets of the problem. In our work, we study the problem of finding the pricing strategy that maximizes the expected profit of an e-commerce. We design an automatic pricing system which uses clustering techniques to partition the catalog in contexts of items sharing similar features, and online learning techniques to learn the optimal price of each context.

First, we tackle the clustering problem by learning from historical data collected by recording the interactions with customers. We focus on the Learning from Logged Bandit Feedback (LLBF) setting. Commonly, the logs generated by the interaction between the system and a user present the structure of a sequential decision process: basing on a context, the system takes an action from a set of possible choices and, afterwards, the user provides the system with a feedback, in terms of reward. The peculiarity of this setting is that the feedback, as it happens in bandit settings, is only on the chosen action showed to the user, while no information is available about other possible actions. Some approaches had been proposed to address this problem, but they lack in some of the fundamental characteristics that make an algorithm suitable for practical purposes. Indeed, they did not provide a clear interpretability of the final model since there is no direct method to infer those features that most influence the resulting model. Moreover, in economics scenarios, the proposed algorithm should be as risk-averse as possible, but most of the theoretical guarantees available in literature are provided in terms of average value. Finally, existing approaches usually require knowledge of the behavior of the user and assume it to be stationary, which is rarely met in practice in microeconomics scenarios. We propose a novel algorithm, whose goal is to solve all the mentioned drawbacks of the literature approaches. The algorithm we propose can learn a risk-averse policy to maximize the expected profit and make use of statistical lower confidence bounds to build a decision tree, which provides both a decisional tool over future samples and an instrument to highlight the features that influence the profit the most.

Then, we study algorithms to learn the optimal policy to follow in each context to find the price that maximizes the expected profit. We study online learning techniques, in particular the Multi-Armed Bandit (MAB) ones, which have been widely studied in literature and provided evidence to be effective also in real-world scenarios. MAB problems have been tackled with two distinct approaches, the frequentist and the Bayesian ones. The goal of a frequentist algorithm is to achieve the best parameter-dependent performance, and the expected mean rewards corresponding to the arms are considered as unknown deterministic quantities. Conversely, in the Bayesian approach, each arm is characterized by a distribution corresponding to the arm parameter. Even if it is possible to use existing general-purpose algorithms to solve our problem, by exploiting the pricing structure we can improve the performance of the classical algorithms. More specifically, we exploit the monotonicity of the conversion rate in the price and the a priori information e-commerce sellers have about the customers’ behavior and the maximum conversion rate. To the best of our knowledge, these two properties have never been studied before. Furthermore, we tackle both stationary and non-stationary settings, as already done in literature. Finally, we study the property of unimodality over the expected profit. We present algorithms exploiting one or more of these features at the same time, also providing theoretical guarantees for the proposed methods.

These are the techniques we used to design an automatic pricing system, deployed in collaboration with one of the major Online Travel Agencies in Europe. The two problems of clustering and online learning algorithms are interconnected and continuously communicating: the data generated from the interaction of the users with our MAB algorithms are collected and passed through our LLBF algorithm to update the contexts model and improve the performance of the system.

Data-centers power consumption is one of the greatest issues that IT organizations must face. Indeed, to enable future expansions, it is necessary to take under control the energy related costs. The U.S. data-centers energy consumption will be 73 billion kWh in 2020. Although it is estimated to increase only by 4% with respect to 2014, it is still an important problem, if considering that the worldwide amount of energy consumed for data-centers in 2014 has been estimated to be 270 TWh. Moreover, even if large data-centers have made great improvements in energy efficiency, small and medium data-centers – that are generally used in medical, retail, office, and education sectors – are difficult to monitor and may affect the global energy consumption trend due to their wide diffusion. Besides being a huge cost for every IT company, the energy high demand of data-centers has also an environmental impact due to the emission of large quantities of greenhouse gases. Indeed, according to the literature, data-centers are estimated to be responsible for 2% to 10% of global CO2 emissions and the U.S. Environmental Protection Agency estimated that 67.9 million metric tons of CO2 have been released in the atmosphere in 2011 by IT industry.

For these reasons, the reduction of data-centers energy consumption is crucial when new infrastructures and applications are developed. Reducing energy consumption allows IT companies to increase their revenues in several different ways: lowering the electricity bill, thus letting the company save several money; reducing the carbon tax the organization must pay when the CO2 emitted by their infrastructure exceeds some thresholds; the governments may also apply some credit and cap-and-trade systems in order to limit the data-centers CO2 production. For instance, when a business exceeds allowed carbon dioxide emission levels, it must purchase either credits or carbon offsets from the market – usually, less polluting companies – to be permitted to keep on working and producing CO2. Due to its relevance for IT organizations, the data-centers energy consumption problem has been largely studied by scientists from industry and academia. Many different techniques have been proposed, such as frameworks and tools to directly reduce the energy consumption of a server, or scheduling strategies to better allocate the incoming requests, thus being able to turn off unused resources. Nonetheless, several efforts are still required in order to further improve the available techniques and introduce new approaches. The main problems studied in this thesis are described in the following.

Power models. Over the years, several techniques and strategies have been proposed in literature in order to improve the data-centers energy efficiency. However, most of the proposals require a suitable power model that can estimate the power consumption of the system starting from simple system parameters, such as the utilization of its resources. Especially when the techniques considered are based on results that exhibit a non-linear behavior, the accuracy of the power consumption model is of paramount importance to correctly identify the optimal system configurations that can achieve the target performance with the lowest possible power budget. The typical use of analytic expressions for the power computation is the inclusion of energy characterization in models of the system defined using suitable formalisms, e.g., queuing networks, Petri nets, Markov chains. Taking into account widespread commercial power reduction techniques, like dynamic voltage/frequency
can provide a more detailed power consumption expressions that can be used to obtain more accurate estimates. Unfortunately, the available power models either do not consider these power-saving features, or do not account for both of them at the same time.

In this thesis, a model to estimate the power consumption of a multi-core CPU, when both DVFS and SMT, is proposed. It needs some parameters that may be easily derived from operational and machine characteristics and some calibrating coefficients that must be derived from the experiments.

Multi-class workloads. The available techniques and metrics proposed to reduce power consumption through the application of efficient load control strategies rarely take into consideration the multi-class nature of system workloads, i.e., jobs with different characteristics and behavior. However, this type of workloads may be composed by a mix of jobs that saturates different resources, thus it is an important system's feature which may be exploited in order to increase the utilization of each resource and decreasing the idle period of a server. Indeed, a scheduler that accounts for the mix of requests in execution could make the system work with an optimal mix. This way, the utilization of each server increases and the system's energy consumption decreases, since a strong relationship between a server power consumption and its CPU utilization has been proven in literature.

However, the available power metrics analyze the power consumption of a data-center assuming it is processing only a single class of job. This assumption may decrease the accuracy of the power/energy metrics and, in the worst case, also make the user take a sub-optimal decision about the strategy that should be adopted.

To address this problem, a new energy metric and Pool depletion systems paradigm have been proposed. The former is exploited to evaluate the performance of energy saving strategies in a multi-class environment, the latter lets the users consider a system made of a pool of heterogeneous tasks that must be depleted in the shortest time by machines with finite capacity.

Epistemic uncertainty. When a model is adopted to study a physical system, its input parameters are usually estimated from observations. The value of the parameters is not the exact one since it is derived from a finite number of samples. For this reason, the input parameters of the model are assessed with uncertainty and are stochastic. Those input parameters become input random variables with a probability density function. Thus, the model does not return an exact value, but some stochastic results with a confidence interval. Differently from aleatory uncertainty – that has been largely considered in literature and that is due to the natural variations of the physical phenomenon modeled – epistemic uncertainty is introduced into the model by a lack of knowledge (i.e., finite number of observations) and needs to be propagated to the output. Albeit in the former case the uncertainty is reduced improving the model itself, in the latter one it may be curtailed by collecting a larger amount of samples for a more accurate input parameters estimation. In this thesis, epistemic uncertainty propagation is studied for M/M/1 queues and power consumption models.

Other systems and applications. Energy consumption has become such an important problem also due to the wide diffusion of portable devices (e.g., smartphones, sensors, etc.). Indeed, they are usually powered by a battery with a short lifetime, thus it is important to efficiently manage power and energy requirements in order to extend their life. In other words, reducing energy consumption is fundamental when dealing with mobile devices to increase the lifetime of their battery, differently from the data-centers case where energy efficiency is crucial to increase the companies revenues. For these reasons, analyzing energy consumption in small devices to make their lifetime longer is another important feature that may be enabled by power models. In particular, the case of Mobile CrowdSensing – a contribution based paradigm involving mobile devices in pervasive application deployment and operation – is studied in this thesis.

EMBEDDED SYSTEM SECURITY: ATTACKS, IMPACTS & DEFENSES

Quarta Davide

Embedded systems are nowadays ubiquitous: smartphones, home appliances, medical devices, Industrial Control Systems (ICS). These devices, often display a common subset of characteristics: limited processing power, limited available power, physical exposure, remoteness and unmanned operation, and network connectivity. Such characteristics create venues for peculiar attacks: we focus on software attacks, and in particular those stemming from the interconnection of a particular kind of device, Industrial Robot. Regarding defenses, we focus instead on mitigations to the aforementioned attacks, and strategies to strive for a more secure future of the industrial robotics ecosystem.

In the context of the Industry 4.0 revolution, these devices are interconnected, with other industrial robots, and more in general with other Internet-of-Things devices (e.g., sensors, actuators, tools), and collaborate with human to shorten production times, and reduce costs. This revolution is bringing industrial robots closer to the forefront. The improvements in the way industrial robots work and communicate unlock new venues for attacks.

On the one hand industrial devices are designed according to strict safety standards in order to work in rough conditions, and to guarantee the safety of the human operator. On the other hand industrial robots are also designed to provide extreme flexibility and adaptability to different necessities, this is required both by the Industry 4.0 concept, but also by the very same definition of an industrial robot which needs to be a multi-purpose manipulator.

Embedded systems have grown in complexity over time, and likewise, their interconnections and communication primitives, the ubiquitousness of these devices calls for more attention to their security, and to the security problems arising from their interconnection.

The Mirai botnet incident is an excellent example of what happens when IoT systems, once designed to be not remotely accessible, and not interconnected, are exposed to external networks. The Mirai botnet was composed mostly of IoT devices, and grew up to include a whopping 600k of infected devices. It’s nevertheless easy to find many instances of security incidents in the embedded system world, in particular, the ICS environment in which embedded devices (e.g., controllers, sensors, actuators) are displaying peculiar challenges in securing them have seen an increased attention by researchers in the last few years.

The dissertation explores also defensive aspects: in particular we focused on the software security of a specific class of embedded systems, Industrial Robots, by exploring attacks and the extent of the impact of such attacks, moving later to discussing mitigations and the role of standards in the security Cyber-Physical Systems (CPS). Moreover we propose a system to obtain transparent execution of arbitrary code in a TEE environment while achieving code confidentiality and being easy to use.

To the best of our knowledge, there is no systematic analysis of the attack surface and of the impact of attacks against industrial robots enabled by software vulnerabilities and architectural flaws.

In this chapter, we systematically analyze the feasibility of attacking a modern industrial robot by exploring concrete attack vectors that, when exploited, can subvert the interaction between a robot and the surrounding environment, thereby violating its basic requirements. In other words, we wonder to what extent, starting from the exploitation of the “cyber” components of a robot, an attacker can affect the physical environment. To answer this question, we propose a domain-specific attacker model, discuss how certain combinations of software vulnerabilities enable classes of attacks unique to industrial robots (e.g., circumventing safety measures, impairing the precision of movements), and evalu-
In the last decade the increasing number of connected devices, the rise of cloud computing and the explosion of the size and velocity of data changed and shaped the requirements, the development process and the architectures of software systems. Nowadays, for example, web applications are deployed and executed into the cloud, and single monolithic deployments are split in many modular services to individually develop and manage functionalities. Moreover special purpose frameworks for parallel batch processing are emerging to cope with large amounts of data. One of the challenges to be addressed on these software systems is how to provision and optimize resources to meet a varying demand such as fluctuating workloads, unpredictable peaks of traffic, and unexpected changes that are increasingly common phenomena. Without taking care of these contingencies, service providers struggle in satisfying functional and non-functional requirements, usually defined in SLAs (Service Level Agreements). To avoid resource saturation and unresponsiveness, users dissatisfaction and unnecessary costs, the provisioning of resources must be elastic, that means being capable of automatically adapt to changes in the execution environment that could affect the quality of service perceived by the users. Therefore resources allocated to a system should match as closely as possible the demand. One of the key metrics that captures the quality of a service of a system is the speed of answer that is often the subject of non-functional requirements defined in SLAs as a constraints over the time to answer one or more requests. Moreover the elastic provisioning of resources must be automatic to be less error prone and to reduce the complexity of managing the services at runtime. For this reason, elasticity can be materialized in autonomic systems whose behavior can change automatically according to the state of the system itself and of the environment. State of the art solutions focus on the control of software systems deployed in the cloud by changing the number of allocated virtual machines using mainly heavyweight techniques such as optimization problems or delegating to the system administrators part of the adaptation process (i.e., rule-based approaches). Moreover virtual machines are relatively slow to be provisioned (around six minutes on average) and only available in fixed configurations limiting how fast and precise the adaptation could be. This thesis aims to study, analyze and evaluate novel technologies and models that enable the creation of lightweight, autonomous, fine-grained and fast elastic resource provisioning for modern software systems. Its main contribution is the technique used to plan and react the control actions. It mixes containers, a lightweight virtualization technology that enables the fast and fine-grained elasticity, and control theory that provides a lightweight theoretical foundation for controlling these systems. Containers can be provisioned in seconds and re-configured in milliseconds while control theory enables the computation of next allocations in constant amount of time. In the solution we used gray-box controllers: they capture just the main characteristics of the controlled system abstracting away many implementation details. We applied this methodology to two real-world scenarios: web and big-data applications. For the first area we present EcoWare, an autonomic system that allows containerized web-applications to scale their resources both at the VM level and at the container level. Furthermore, applications can combine this infrastructural adaptation with higher level (such as middleware or application layer) adaptation actions. The experiments show that our planner outperforms Amazon’s Auto-Scaling by 78% on average without containers;
and that the introduction of containers allows us to improve by yet another 46% on average. Instead, xSpark is dedicated to the control of big-data batch applications. This type of systems manipulate huge quantities of data and users are often interested in quantifying and constraining the execution times (deadlines) for completing single runs. xSpark is a novel container-based extension to the Spark framework that exploits container technology to provide extremely fine-grained resource allocation. While vanilla Spark does not allow users to constrain deadlines, xSpark allows that and allocates required resources accordingly at runtime. The evaluation on four well-known benchmark applications witnesses that xSpark was able to use less resources than native Spark and complete the executions with a less than 2% error in terms of set deadlines. Since this work mainly focuses on CPU allocation, future works include the support in the adaptation process of more resource types such as memory, storage and networking. Moreover the approach could be extended to handle the simultaneous control of web and big-data applications in heterogeneous cluster. Finally we plan to apply a similar methodology to new areas such as the Internet of Things and Fog computing.
SILICON DRIFT DETECTORS AND READOUT ELECTRONICS FOR HIGH THROUGHPUT SPECTROSCOPY APPLICATIONS

Bellotti Giovanni

X-ray Absorption Fine Structure (XAFS) spectroscopy studies the absorption coefficient of materials in the region close to the absorption edges. After-edge oscillations of the absorption coefficient contain information about the chemical and physical structure that surrounds the excited atom. Fluorescence mode XAFS spectroscopy makes it possible to obtain the XAFS for thick or very diluted samples measuring their emission spectrum that, in the dilute limit, is proportional to the absorption. In this technique, the sample is excited by a beam of photons, whose energy can be finely tuned using a monochromator. The energy of the beam is changed at small steps starting in the region immediately before the absorption edge and ending 1 keV after it. The fluorescence produced by the sample is acquired by an X-ray radiation detector. Solid State Detectors (SSDs) are generally used for XAFS as they guarantee high energy discrimination.

Among SSDs, the best performances in terms of count rate and energy resolution are provided by Silicon Drift Detectors (SDDs). SDDs, that have been introduced by E. Gatti and P. Rehak in 1983, are characterized by a signal-charge collecting electrode with a very low capacitance, independent from the device active area. These detectors have the high energy resolution required by the applications (in a 55-Fe spectrum, the Ka line should have a FWHM < 200 eV) to distinguish among the different spectral lines of interest. As in SSDs each photon is revealed independently and its processing takes a finite amount of time, there is a finite dead time after each pulse in which the detector is not able to acquire another pulse. This sets a limit on the maximum count rate the detector can achieve. Synchrotron beamlines are experiencing in these years an increment in brilliance (i.e. in fluorescence flux) that asks for an improvement of the existing detectors in terms of count rate. My doctoral activity took place in the framework of the ARDESIA experiment. ARDESIA (ARray of DEtectors for Synchrotron radiation Applications) is an experimental project funded by the INFN National Scientific Committee V, whose goal is the realization of an X-ray spectrometer for synchrotron experiments based on arrays of SDDs. The spectrometer has been designed and manufactured in all its parts, from the detection module to the mechanical structure and the readout electronics. ARDESIA detection unit is the main building block of a flexible and adaptable platform for high-count rate high-energy resolution soft X-rays spectroscopy. It is composed by a monolithic array of 4 SDDs, with an area of 5×5 mm² each, read by a 4-channel CUBE preamplifier. The SDD arrays are manufactured by Fondazione Bruno Kessler (FBK, Trento, Italy). The window of the SDDs is characterized by a thin dielectric layer and a very shallow junction that optimize the collection efficiency of carriers generated close to the surface. The SDDs are produced with a low-leakage process, that keeps the leakage current at room temperature lower than 200 pA/cm², making it possible to obtain good energy resolution even at relatively high temperatures. CUBE CMOS charge preamplifier is connected to the SDD’s anode through chip-to-chip wire bonding. The high transconductance of the input MOSFET makes this technology suitable for high-count rate applications. The detection unit has an area of 16×16 mm² and a fully modular structure. Multiple units can be arranged together without dead space among them. The detection unit has an energy resolu-
Recent years have seen the rise of Single-Photon Avalanche Diodes (SPADs) as the solid-state alternative to Photo Multiplier Tubes (PMTs) in many Single-Photon Counting (SPC) and Time-Correlated Single-Photon Counting (TCSPC) applications: high Photon Detection Efficiency (PDE), compactness, high reliability and the compatibility with the fabrication of detector arrays are just few of the main advantages of SPADs. Furthermore, silicon custom technologies have widely contributed to obtain large-area detectors, with excellent performance in terms of Dark Count Rate (DCR), afterpulsing probability, time jitter and detection efficiency over the visible range and up to 1-3 keV wavelength. In particular, a significant breakthrough was the introduction of the Red-Enhanced SPAD (RE-SPAD), the first SPAD able to attain a remarkable PDE in the near infrared range (e.g. 40% at a wavelength of 800 nm), while maintaining a good time jitter of less than 100 ps FWHM. These features have been already proven to be crucial in single-photon applications like single-molecule Förster Resonant Energy Transfer (smFRET), a powerful tool used to study the conformation of diverse biomolecules, like proteins, nucleic acids, etc. Nevertheless, this application suffers from long measurement times, strongly limiting the time scale on which the biological phenomena can be observed.

Multi-spot excitation/detection schemes are a promising way to increase the throughput of single-molecule analysis, but this requires the use of a complex setup in which a suitable SPAD array has to be employed. The main focus of this doctoral work was the development of high-performance RE-SPAD arrays, using silicon custom technologies. The first prototypes of RE-SPAD arrays (Fig. 1) have been fabricated at the Cornell Nanoscale Science and Technology Facility (CNF) and part of my work was focused on the experimental characterization of these devices, aimed both at quantifying their performance and at understanding their behaviour. This led to some significant results. In particular, with the new experimental set-ups (both wafer-level and chip-level) that I designed I was able to demonstrate that the electrical isolation has been fully recovered by means of deep trenches, with no detrimental effect on the detector DCR. Furthermore, I showed also that additional n+ structures implemented in the deep trenches are sufficient to inhibit the direct optical crosstalk between pixels. Therefore, deep Phosphorus diffusion is no longer needed, with obvious advantages in terms of compactness and thermal budget. Overall, these results demonstrate that RE-SPAD arrays can be employed in photon counting applications with the same performance of single-pixel devices. A 32x1 RE-SPAD array has been exploited in the development of the first complete RE photon detection module, able to attain a PDE as high as 70% at 650 nm; this module is currently employed in a multi-spot smFRET set-up, in the context of a fruitful collaboration with the University of California, Los Angeles (UCLA). Even though the attained results are remarkable, the current design suffers some important limitations. Indeed, the onset of the edge breakdown strongly limits the applicable excess bias and, in order to overcome this, a guard ring structure is present in each pixel. Unfortunately, the possibility to increase the operating overvoltage
comes at the expenses of an increased complexity in the biasing of the device and in a reduction of the attainable fill factor. Both these limitations prevent the fabrication of dense arrays and completely preclude the scaling toward arrays with thousands of pixels. Therefore, with my PhD work I propose a new design, that resorts to a high-energy Boron implantation to obtain at the same time a fully optimized electric field profile and a higher edge-breakdown voltage. Furthermore, I also show how both standard and RE detectors can greatly benefit from the use of a standard Phosphorus implantation instead of a predeposition, both in terms of PDF and temporal response. Detectors with the new design will be fabricated and experimentally investigated in the next months, in order to verify the predicted results and to exclude any detrimental effect on the device noise of both the new technological approaches.

A second important contribution that I gave was on the experimental characterization of standard SPADs belonging to the previous generation and fabricated by the National Research Council of Italy - Institute for Microelectronics and Microsystems (IMM-CNR sez. Bologna). These devices allowed me to participate in the development of a complete detection module based on a 8x8 standard SPAD array, getting acquainted also with the issues that are typical of the system integration. In particular, the module has been envisioned also for use in an alternative operating mode, that combines the output coming from the 64 pixels in order to enhance the maximum count rate to more than 2 Gcps, to provide photon-number resolving capabilities and to extend the dynamic range to 141 dB, a value higher than reported so far in literature. In particular, this value is currently limited by the speed at which the Active Quenching Circuits (AQC) can be operated and by the presence of some high-DCR SPADs in the array. To the aim of investigating the future perspective of the 8x8 array, I also developed a detection head based on a low-noise, single-pixel SPAD, operated with a new AQC able to attain a dead time as low as 8.3 ns. The result was the best dynamic range ever reported for a SPAD: 152 dB, that can become even higher if this configuration is employed in a parallel module like the aforementioned one. Furthermore, I studied also the effect of the introduction of a n+ epitaxial layer on timing performance: thanks to the reduction of the parasitic elements, the jitter shows a strong reduction of the dependence on the detection threshold. This opens new prospects in the design of high-threshold detection systems with a high number of pixels and reduced electrical crosstalk among them.

In the last decades organic semiconductors have gained considerable interest in electronics because of their mechanical compliance and flexibility, the possibility of being processed and deposited via solution in ambient conditions, and to be chemically engineered in their optical properties. The prospect of depositing these materials adopting additive techniques derived from the graphical arts represents a fundamental asset for these emerging electronic technologies. As an example, inkjet printing, screen printing, roll-to-roll coating and other methods show compatibility with a wide selection of substrates, are upward scalable and thus capable of addressing large area deposition, and are compatible with already assessed industrial processes. Interestingly, these deposition techniques can now be used to deposit an increasing amount of different inorganic materials, which have complementary properties and enlarge the possibilities for printed devices. A novel concept of cheap, entirely printed “intelligent” system could become a game changer in numerous applications, paving the way to cost-effective solutions that were not even thinkable before. Examples can be envisioned in smart packaging, electronic skin, large-area scanning for border and customs security, diagnostic imaging, smart packaging, point-of-care disposable systems and wearable technology. In the field of light-sensing or light emitting applications, organic semiconductors are particularly promising for their outstanding absorption coefficients and luminescence in the visible range. Organic LED-based screens and lighting systems are now integrated with standard technology, gaining outstanding market share. Moreover, significant improvements were recently demonstrated in the field of organic, solution processed solar cells. Solution processed inorganics, in turn, become decisive when detecting higher energy photons, showing remarkable performances. The focus of this work is the development of entirely printed opto-electronic systems and devices for large area imaging and radiation detection, using fully scalable, low material waste techniques that retain all the aforementioned (actual and potential) advantages. The main adopted techniques are inkjet printing and screen printing. After an introductory chapter, where a summary of the fabrication techniques and an overview of the state of art of fully-printed photodetectors are presented, this document is organized in two parts. The first part focuses on fully-inkjet printed organic devices developed on flexible substrates. Chapter 2 investigates process optimization for performance reproducibility and yield in inkjet-printed vertical photodiodes. In these devices, photon to charge transduction is exerted by stacked organic photodetectors with PEDOT:PSS semitransparent contacts and P3HT:PCBM active layer. The bottom contact is functionalized by printing amine rich polymers to adjust the electrode workfunction. In this study, it is found that the most crucial process step to obtain reproducible, well performing devices is the printing of the nanometer thin interlayer used as a surface modifier for the bottom electrode. Tuning solution composition, deposition parameters, and ambient relative humidity for the deposition of this layer, an enhanced process control, yield and performance is achieved for devices, paving the way for the results described in the next chapter. A new technique to improve top contact coverage on the underlying hydrophobic active layer is also discussed. In chapter 3 the fabrication and functionality of a fully inkjet-printed organi-
ic imager on flexible polyethylene naphthalate is demonstrated. Large area image sensors are much attractive for indirect X-ray imaging, but a fully-printed prototype has not been demonstrated yet. The most common choice for the addressing element of a passive pixel, viz. a transistor, requires the integration of the transistor process and of the photodetector process, which turns out to be non-trivial in the fully printed approach. To overcome this issue, an alternative scheme is adopted, with a diode as an addressing element. The developed scheme and its critical parameters are studied in order to optimize performance. The performances of the pixel are compared to the requirements for indirect X-ray imaging, showing noteworthy results. Printed imager prototypes on flexible substrates, reaching 8 x 8 (64 pixels) dimension, only limited by the capability of the developed custom readout system, are proven capable of reconstructing letter patterns. These results are a strong suggestion of the possibility to apply this technique to develop true low cost, large-area scanners.

The second part of the thesis concerns printed inorganic based devices for ultraviolet and gamma detection. In chapter 4 a novel kind of simple, low-voltage, printed ultraviolet detector is presented. In contrast to photodetectors based on simple charge pair photogeneration, here information is stored in a property of the material, exploiting a property of titanium dioxide, namely UV light-induced conductance switching. This effect grants devices a number of peculiarities. The first presented version of the detector has a vertical structure developed by sandwiching the screen printed active material between a top metal contact and a bottom semi-transparent contact on glass. For this detector, a process tunable memory effect is demonstrated, which could enable its use in a smart monitoring tag for light sensitive goods. The work was brought further by demonstrating imagers as simple crossbars with no need for addressing elements, in prototypical 5 x 5 arrays on glass, potentially useful for forensic reflective imaging. UV detectors were also implemented in a fully-inkjet printed, lateral configuration on flexible PEN substrates. This second implementation is a suitable candidate for whole-day sunlight exposure monitoring for skin protection. A peculiar effect is also discovered in the lateral implementation, when the active material is mixed with PEDOT:PSS. This last version of the devices shows a reverse current response to UV light, and provides a markedly faster time response and a high current switching against small amounts of dose. Chapter 5 presents preliminary tests performed on printed vertical titanium dioxide sensors, demonstrating their capability to directly sense gamma radiation. Furthermore, a strong, induced sensibilization to the visible range of light, absent in non irradiated devices, is observed after exposure. The presented results will be object of further studies. Possible strategies towards further optimization of devices for their use in gamma dosimetry are discussed.

The Dissertation represents a new challenge of Silicon PhotoMultiplier (SiPM) application to high-energy gamma-ray detection with scintillators in nuclear physics experiments and Prompt Gamma Imaging (PGI) in proton therapy. Although SiPMs are considered a promising alternative to the PhotoMultiplier Tubes (PMTs) in many medical imaging applications, more efforts are mandatory to introduce SiPM technology also into the field of high-energy gamma-ray detection. The main challenges are linked to the high energy range, within saturation effects can be present, and the need of several units to cover the large area of detection required by the applications. Therefore, an optimization of the detector and the front-end electronics is mandatory to face the high energy range and to get high spectroscopic performances and imaging capability comparable to that measured with PMTs. In this context, aim of the Dissertation is to develop an innovative multichannel spectrometer and imaging module based on scintillators and SiPMs which can be innovative for the two high-energy applications.

The SiPM-based detection module has been designed with a modular structure to be compatible, except for the scintillator and the photodetector array, for both nuclear physics and PGI applications. The photodetector chosen for nuclear physics experiments, where monolithic and large (>1”) LaBr3:Ce scintillators are used, is composed by NUV-HD SiPMs (FBK, Trento, Italy). This SiPM shows high PhotoDetection Efficiency (PDE > 45% at 380 nm), low Dark Count Rate (DCR < 100 kcps/mm2) and small microcell size (30 x 30 um2), allowing to improve the energy resolution and the dynamic range. The SiPM module consists of an array of 5 by 6 SiPMs, each one having an active area of 6 x 6 mm2. The single array is used for the 1” x 1” crystal readout and it is assembled in a 2 x 2 format to read the 2” x 2” scintillator. On the other hand, the photodetector for PGI applications has a pixelated geometry, which is a possible solution to decrease the count rate/pixel requirements thanks to the detector segmentation. The photodetector for PGI applications is produced in RGB-HD SiPM technology (FBK, Trento, Italy) and designed to improve the linearity at high energies thanks to a smaller microcell size. The photodetector is composed by an array of 8 x 8 SiPMs: a single SiPM has an active area of 4 x 4 mm2, 15 x 15 um2 microcells, for a total of 70000 microcells/SiPM. Each SiPM is coupled 1:1 to a 4 x 4 x 22 mm3 LYSO crystal. In both photodetector geometries, signals are processed by two ASICs, improving the compactness of the system, and acquired by an external Data AcQuisition system (DAQ). Moreover, the module also implements a real-time stabilization of the SiPM gain for the gain drift with temperature. The ASIC chip used in this prototype is ANGUS, a 36-channel front-end ASIC in standard CMOS 0.35 um technology. Although it cannot provide a suitable dynamic range for a nuclear physics experiments up to tens of MeV because it was developed for low-energy applications, it has allowed to test the nuclear physics detection module up to 1.3 MeV. This has been enough to fulfill the primary objective of the work, i.e. the comparison between SiPM and PMT performances for LaBr3:Ce readout. A current filter has been designed on the PGI detection module, which has allowed to decrease the input current of the chip to acquire up to 13 MeV of gamma-ray energy, with the drawback of the introduction of more variability on the readout channels. This modi-
An experimental characterization of the two photodetector modules has been then performed in terms of spectroscopic performance and position sensitivity. The gamma-ray response linearity and energy resolution of the first and second LaBr₃:Ce crystals readout in an energy range of 122 keV to 1.33 MeV is presented. The energy resolution achieved with the NUV-HD SiPMs shows a significant improvement over earlier works and nearly matches the resolution obtained using a super bialkali PMT (Hamamatsu R6233-100). In fact, a 3.19 ± 0.01% FWHM at 662 keV was obtained at a room temperature of 30°C with SiPM readout, similar to the measured 3.07 ± 0.03% FWHM at 62keV achieved coupling the same crystal to the Hamamatsu R6233-100 PMT. For the first crystal an energy resolution of 3.70 ± 0.01% FWHM was measured with SiPMs at 662 keV, as slightly worse performance with respect to the second detector due to an inferior crystal. This assumption was confirmed by the 3.57 ± 0.04% FWHM energy resolution measured at 662 keV with the same scintillator coupled to the same Super Bialkali PMT. An analysis of the energy resolution terms based on the measurements performed communicates an important achievement in development of SiPMs for scintillator readout, demonstrating, for the first time in literature, the equivalence between SiPM and PMT for high-resolution spectroscopy. The experimental characterization of the second LaBr₃:Ce detection module in terms of position sensitivity is also performed, because it is another fundamental requirement to correctly the Doppler broadening in nuclear physics experiments. A spatial coherence has been successfully demonstrated and a preliminary 2 cm spatial resolution has been estimated with the centroid method for image reconstruction. Although at the time of writing it was not possible to perform beam measurements in a proton therapy facility, the reported experimental results demonstrate that the designed photodetection module is suitable also for future prompt gammas detection. Spectroscopic measurements between up to 1.3 MeV show a satisfactory energy resolution of 13%, 9% and 8% FWHM at 662 keV, 1173 keV and 1333 keV, respectively. Results are the same of the state-of-the-art PGI gamma camera, and it is correct to assume that they would allow an accurate energy calibration of the system, and, consequently, a correct setting of the two energy thresholds within reconstruct the prompt gammas profile. Moreover, an adequate position sensitivity necessary for profile reconstruction, coherent with the pixel dimension of 4 mm, has been proved. Finally, thanks to the use of a LED setup which simulates the absorption of gamma-rays from 800 keV to 13 MeV, the module shows a proper response in the energy range of the application. Future activities will include the test of the SiPM-based photodetection module in the energy range of nuclear physics experiments to make a compete comparison in terms of achievable performances and linearity with PMT-based readout. Moreover, a characterization in a proton therapy facility is necessary. In order to make successful these measurements, there are two aspects that need to be considered for future improvements of the prototype: the design of an ASIC for high dynamic range for nuclear physics experiments and the development of a fast electronics to face the high count rate required by the next-generation accelerators which are spreading in proton therapy facilities.
PHD program in information technology

one of the DEPFET-based solution. This goal has been achieved by forcing the input PMOSFET, which is not equipped by an intrinsic non-linear gain like the DEPFET, to operate in a non-linear mode with a signal compression induced by the signal itself. A simple way to achieve this mechanism is to put a resistor in series with the PMOSFET and connect the other side of the resistor to the virtual ground of the filter. Based on the same idea, a second prototype has been designed to improve both the compression behavior and noise performance of the Front-End (FE). In particular, thanks to the introduction of an NMOSFET as non-linear resistor and the inclusion of three input branches, the dynamic range has been increased from 500 photons of the previous prototype up to 2800 photons at 1 keV.

The use of the FE in matrix application, like the 64x64 channels of the DSSC project, urged the study on the yield and robustness of the circuit from power supply fluctuations and crosstalk between pixels. For these scope, in my research, the design, realization and testing of new Mini-SDD front-ends has been discussed. Both open loop and closed loop solutions have been demonstrated through both analytical evaluation and experimental characterization. All the solutions have been designed to keep the same filter, ADC and memory as in the DEPFET sensor scheme. A bulk control circuit to correct the chip to chip process variations of the open-loop non-linear FE has been presented. The circuit is capable to stabilize the FE response in matrix application like the 64x64 (F2) channels ASIC.

In linear mode, the CSA cannot achieve the single photon resolution and a large dynamic range at the same time. To reach this target a CSA with gain compression mechanism has been also studied. The circuit exploits in the feedback network a non-linear PMOS. Furthermore, to couple the CSA with following FCF filter a voltage to current converter has been introduced. During the programming phase a negative feedback has been designed to fix the CSA output at the same voltage as the filter virtual ground before the burst phase of the European XFEL. The mechanism exploits the output stage of the CSA. The FE has been integrated in the 64x64 (F2) channels ASIC.

Nowadays, the amount of digital information is increasing exponentially due to the large diffusion of consumer electronics. All over the world an ever-growing number of people has the possibility to purchase smartphones and tablets able to save a large amount of photo, video, music and applications in a single portable device. This social phenomenon has caused an enormous request of non-volatile memories capable to store a high quantity of data in a very small volume, maintaining the stored information even without power supply. In the last ten years the Flash technology has been the leader in the non-volatile memory market, but has now reached the scaling limits and the most important semiconductor companies have to face crucial issues related to atomic doping and charge trapping. Moreover, the Von Neumann bottleneck leads to require a memory able to reduce latency time during CPU operations, combining the high-performance of SRAM and DRAM and high density of Flash Technology and HDD.

This circuit is a CSA with gain compression mechanism for promising candidate among the emerging technologies, like image learning, pattern recognition and decision exhibiting high cost for Boolean CMOS processors, while, for human brain, they represent elementary processes. In this scenario, the development of new devices designed specifically for neuromorphic computing could enable high density and low power networks in order to properly operate learning and recognition tasks. For this reason, different industrial and academic institutions are looking for promising candidate among the emerging technologies that could offer the best properties to mimic synaptic behavior in our brain.

Nowadays the most developed technologies for both crosspoint memory application and neuromorphic computing are represented by phase change memory (PCM) and metal-oxide resistive switching memory, commonly known as RRAM. In last years these devices have reached mature technology and outstanding feature in terms of fast switching and high endurance for PCM and low power and low-cost fabrication for RRAM, paving the way for future Storage Class Memory (SCM) with huge market opportunities. In addition, intrinsic variability for RRAM and gradual set transition for PCM, which represents constraints in storage memory application, could result in key strength for neuromorphic network synapses. This doctoral dissertation will

HIGH ORDER MODULATION & MULTIPLE ACCESS IN WIRELESS NETWORKS

We present a theoretical framework to analyze the performance and capacity of high order multiple access schemes, such as MPSK and QAM, in wireless communication systems. The proposed approach allows to generalize the analysis to arbitrary codes and to determine the achievable rate of a given modulation scheme as a function of the channel conditions.

The key idea is to exploit the properties of the Fourier transform to express the channel capacity as an integral over the frequency domain. This integral can be evaluated numerically to obtain the achievable rate of the system. The theoretical framework is applied to analyze the performance of high order multiple access schemes in different scenarios, including fading channels and interference-limited environments. The results show that high order modulation can achieve significant improvements in terms of spectral efficiency and capacity compared to lower order schemes.

Furthermore, the proposed approach enables to explore the trade-offs between the number of transmit antennas and the order of the modulating scheme. The analysis reveals that, depending on the channel conditions, it can be beneficial to use a lower order modulation with a larger number of transmit antennas or to increase the modulation order with a smaller number of antennas, in order to optimize the spectral efficiency and capacity of the wireless system.

In summary, the theoretical framework presented in this work provides a powerful tool to analyze and design high order multiple access schemes for wireless communication systems, enabling to achieve high spectral efficiency and capacity in different scenarios.
be focused on Silicon-based selector devices and emerging memories (PCM and RRAM). The work describes working principles, physical understanding and innovative applications in the field of crosspoint memory and neuromorphic computation. The electrical characterization carried out on these different devices has played a fundamental role in this aim, providing the starting point for physical understanding and modeling and paving the way for design and implementation of neuromorphic hardware for pattern learning and recognition.

**ADVANCED METHODS TECHNIQUES AND DIGITAL ARCHITECTURES FOR HIGH PERFORMANCE TIMING OF EVENTS**

Lusardi Nicola

The precise measurement of time intervals is a primary goal in a growing number of applications and the challenge to achieve increasingly higher resolutions than ever is a main topic of research. In this sense, Time-of-Flight measurements and Time-Correlated Photon Counting are two milestones. Since the intrinsic resolution of the sensors used today is in the order of tens of picoseconds, the measurement systems must guarantee performance at least of this order. The choice of making digital a part or the totality of the measurement electronic systems exploits well-known advantages from the adaptivity, to the versatile calibration, to the easiness of implementation of powerful processing algorithms with lower power consumption, and area occupation with respect to the equivalent analog solutions.

The last generation of digital programmable devices as Field Programmable Gate Arrays (FPGAs) and System-of-Chips (SoCs) has made possible the implementation of high-accuracy Time-to-Digital Converter (TDC) architectures with performance comparable with ASIC realizations. In this way, all the well-known advantages of using programmable devices are exploited, such as totally tunable characteristics, easiness of portability, reduced time-to-market, lower migration cost from one generation of technology to another, just to name a few. This has to be done always keeping on foreground the maximum functional performance.

The dissemination of experiments in which high-performance timing measurements become increasingly important, is triggering the development of new versatile instruments, especially digital. Moreover, the concept of high-performance is not only related to resolution and precision but also indicates other features like high full-scale-range, high acquisition rate, multi-channel operation mode, real-time processing, flexibility, modularity and, last but not least, low time-to-market and implementation costs. We present a new fully configurable system whose structure is a hardware, firmware and software bundle for high-performance timing measures in experiments where high-performance time resolving is a primary request.

Figure 1 shows the schematic structure of the whole system. The hardware is a custom Printed Circuit Board (PCB) that is composed of an analog front-end allowing the acquisition up to 16 simultaneously time events, FPGA processing unit, various communication modules (e.g. USB 3.0 and Ethernet links), and a software that runs on a generic computer. For each channel, the input acquisition stage is a programmable threshold comparator that converts the analog input pulses (0-3.3V) in digital signals with timing jitter less than 7 ps r.m.s. The user can set the programmable threshold with resolution of 50 µV by means of two 16 bits 8-channels I2C programmable DACs.

The FPGA module is a TE0712-02-200-2C provided by Trenz Electronic that hosts an industrial 28-nm programmable Xilinx Artix-7 XC7A200T. The core of the firmware part into the programmable logic is a multi-channel Tapped-Delay-Line Time-to-Digital Converter (TDL-TDC) that is organized as a HDL IP-Core Module (TDC IP-Core) compatible over all Xilinx Serie-7 FPGAs and SoCs. Tab.I returns a synoptic view of achievable performance.

The TDC IP-Core is characterized by an area saving structure and is composed of 16 independent channels implemented in the FPGA. Each channel has average resolution of 250fs and hardware full-scale-range of 9.45s. The pre-
cision, without front-end, is lower than 9.7 ps r.m.s. per single channel that means a global precision less than 12 ps r.m.s. per single channel. Each channel implements an 8th-order Super Wave Union sub-interpolation over the 22222 ps delay-lines that performs the time-to-digital conversion; that achieves a measurement resolution that is 8-time lower than the propagation delay between adjacent taps. In order to extend the hardware full-scale range up to 9.45 s, the Nutt-interpolation has been implemented. In this way, the measurement of the time interval between beginning and end of the interval is composed of a coarse part and a fine contribution from the TDL. We have verified that no detrimental effects of crosstalk among channels are detectable.

The system is composed by firmware-software components, whose synergy maximizes real-time performance of the instrument. The firmware is organized as a daisy chain bus with high grade of modularity, where the TDC IP-Core reads and writes data and, in parallel, other modules perform real-time data processing. A time tagging read-out module is implemented by default that extends the hardware full-scale range thanks to software flexibility. Moreover, the user can implement more histogram-makers in hardware and level-zero trigger modules. The hardware histogram-maker creates a 215 bins real-time histogram from the time difference between two input channels in a program-defined time interval selected by the user, whereas the level-zero trigger stores the measurement that starts and stops with a programmable pattern in a defined time window within the full-scale-range set.

This instrument is being used in several national (2) and international (5) research activities, among which a review of some as examples is presented. Moreover, the most significant achievements accomplished during the activity are attested by 39 international publications (8 on journal), of which 13 as first author and 1 single name submission.

Figure 1: Schematic description of the hardware/firmware/software bundle.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Channels</td>
<td>16</td>
</tr>
<tr>
<td>TDC clock frequency</td>
<td>450 MHz</td>
</tr>
<tr>
<td>System frequency</td>
<td>100 MHz</td>
</tr>
<tr>
<td>Decoding/Calibration Hardware in FPGA</td>
<td>1 per channel</td>
</tr>
<tr>
<td>Device Occupation per Channel</td>
<td>948 Slices, 54kbit BRAM, 1 DSP48E1s</td>
</tr>
<tr>
<td>Maximum Rate per Channel</td>
<td>45 MHz</td>
</tr>
<tr>
<td>Processing Latency</td>
<td>110 ns</td>
</tr>
<tr>
<td>Channel Resolution</td>
<td>250 fs</td>
</tr>
<tr>
<td>Channel Precision</td>
<td>&lt;9.7 ps r.m.s.</td>
</tr>
<tr>
<td>Full-Scale-Range</td>
<td>9.45 s</td>
</tr>
<tr>
<td>Channel Crosstalk</td>
<td>No spurious measure on idles and active channels</td>
</tr>
<tr>
<td>Precision Crosstalk Influence</td>
<td>&lt;3 ps r.m.s. on active channels</td>
</tr>
<tr>
<td>Maximum Non-Linearity-Error</td>
<td>&lt;4.2 ps</td>
</tr>
<tr>
<td>Voltage Drift Influence</td>
<td>No detectable</td>
</tr>
<tr>
<td>Temperature Drift Influence</td>
<td>1 ps/°C without Peltier</td>
</tr>
</tbody>
</table>
The unique electrical, thermal, and physical properties of graphene have attracted research interest both from the electronics and materials science communities. Scaling limitations in conventional silicon technology, pushed the technology market to investigate new materials. Graphene, with exceptionally high mobility and being cheap, flexible, transparent and a true 2D material, gained much attention in the field of nanotechnology. Among industrial applications of graphene, flexible electronics is one of the most promising. In graphene, the mobility is at least two orders of magnitude higher with respect to materials used inorganic electronics. However, fabrication of an entirely flexible electronic device (including batteries and contacts) is still technologically challenging. Moreover, graphene could be an excellent material for the implementation of various sensors due to its large surface to volume ratio, excellent carrier mobility, high thermal and electrical conductivity, and unique optical properties. pH sensors, environmental contamination sensors as well as strain and pressure sensors are the most developed applications of graphene-based sensor technologies. Graphene could also be used as a material for energy generation and storage. The idea of flexible power storage and supercapacitors could be revolutionary in wearable and flexible electronics. Since the discovery of graphene in 2004, graphene electronics have made significant improvements. Many devices from single transistors to more complex analog and digital circuits have been demonstrated. However, along with progress, the physical limitations of graphene have become more evident. The dominant part of this work concerns nanofabrication and characterization of graphene field effect transistors (GFETs) for high frequency applications. Using GFETs as building blocks, more complex devices were demonstrated, such as graphene inverters. The general applications of graphene are summarized below.

Figure 1: Summary of graphene applications in electronics

During this work the main limiting factors in RF graphene applications were diagnosed and then optimized. Some of these factors are: Contact resistance $R_c$, access resistance $R_A$, and gate resistance $R_G$. Transfer length method (TLM) devices were fabricated to investigate the contact resistance in graphene. Different metals such as Au, Ni and Pd have been tested to obtain metal contacts with graphene with the lowest contact resistance. Among the various metals tested, pure gold with $R_c=190\ \Omega \mu m$ exhibited the lowest contact resistance with graphene. Further studies on contact resistance showed that the contact geometry could affect the contact resistance. By etching holes in the graphene channel below the contacts, the edge of contact between graphene and metal contact was increased. This resulted in an outstanding decrease in device contact resistance. The lowest contact resistance achieved in TLM devices with a holey pure Au contacts was $R_c = 24\ \Omega \mu m$.

The access resistance was minimized by using T-gate and self-aligned layouts in which the source-gate and drain-gate distances in the GFETs were minimized. These adjustments were applied to RF GFET to test and characterize their performance at high frequencies. S-parameter measurements were performed on GFETs and a small signal model was designed and optimized within a frequency range of 10 MHz to 50 GHz using advance design systems (ADS). The model shows very good agreement with S-parameter measurements. From S-parameter measurements, RF FOMs were also extracted, revealing an exceptionally high $f_{max}/f_t$ ratio above 3. Moreover, outstanding intrinsic gain $Av > 30\ \text{dB}$ (in GFETs with channel width, $W = 10 \ \mu m$ and gate length, $L = 1 \ \mu m$) and high [S21] $> 12.5\ \text{dB}$ (in GFETs with $W = 100 \ \mu m$, $L = 1.1 \ \mu m$) were extracted from S-parameters, which outperformed GFETs. The maximum cut-off frequency $f_t = 13\ \text{GHz}$ and maximum frequency of oscillation $f_{max} = 27\ \text{GHz}$ were measured in GFETs with holey contacts (with $W = 10 \ \mu m$, $L = 1 \ \mu m$). Thanks to ADS, the parasitic and intrinsic components of the GFET small signal model were de-embedded to characterize their influence on FOMs of GFETs. From these analyses it has been found that the gate resistance $R_G$ is the main limiting factor suppressing $f_{max}$. Measured $f_{max}$ in GFETs with $R_G$ was 17.7 GHz and after deembedding $R_G$, $f_{max}$ grew to 32.3 GHz. Further improvements were seen by passivating graphene by hexagonal Boron Nitride, the improvements in quality of the oxide-graphene interface, and by utilizing smooth and charge-trap free substrates.

Figure 2: Contact resistant results with holey and standard contacts. The contact resistance was decreased by introduction of holes. Different metals were included in this investigation. The lowest contact resistance was obtained with holey pure Au contacts, $R_c = 24.5 \ \Omega \mu m$.

Figure 3: Extracted $f_{max}$ and $f_t$ from S-parameter measurements performed on GFETs with various $W$ and $L$. The plot shows the maximum $f_{max}$ and $f_t$ regarding to each device. The largest $f_{max}$ and $f_t$ are marked by circles.
Producing cheap and stable vibratory MEMS gyroscopes that do not require expensive and time-consuming calibration procedures has proven to be extremely challenging, due to the dependence of the scale factor (or sensitivity) of the sensor on fabrication imperfections and environmental changes (e.g., temperature variations). Conventional microgyrosopes, commonly operated as amplitude-modulated (AM) systems, are very sensitive to the accuracy of the drive设施建设 and the sensor modes, and to the electronic gains in the sense readout chain. The result is a significant scale factor variability over both (i) off-line unavoidable process spreads, and (ii) online variations of the ambient temperature and humidity. For manufacturers, a large amount of the cost of consumer-grade MEMS gyroscopes is thus given by expensive calibration routines: (i) the scale factor must be tuned on every sample at the rate table, and (ii) its dependence across the temperature/humidity operating range must be measured on a representative number of samples, to apply digital compensation. Resulting performance limitations, e.g., the residual scale factor drifts due to imperfect calibration, generally preclude their widespread adoption in applications, making an integrated electronic design not trivial. A custom low-power, low-phase-noise integrated circuit was then developed, this breaks the symmetry of the vibration pattern, increasing the complexity of both the mechanical design and the control electronics. Within this thesis, both yaw- and pitch-rate, analog-output sensing systems based on Lissajous frequency modulation are experimentally demonstrated for the first time, by coupling the developed integrated circuit with two novel micromachined structures fabricated with a 24-μm-thick industrial process. In operation, both gyroscopes show a repeatable and stable scale factor, with less than 0.55% of part-to-part variability, obtained without any calibration, and 35 ppm/° C of variability over a 25° to 70° C temperature range, outdoing an order of magnitude the performance of state-of-the-art amplitude-modulated solutions. The whole system achieves a 10-mdps/√Hz resolution with a ±2000 dps full-scale range and a 50-Hz sensing bandwidth. The design of a frequency-digitizing circuit, required to provide a digital-output sensor, is also reported, but not experimented. As a conclusive remark, a thorough system-level performance comparison between the proposed architecture and conventional amplitude-modulated MEMS gyroscopes is carried out, aimed at highlighting both the advantages and the disadvantages of such an approach.
TIME-CORRELATED-SINGLE-PHOTON-COUNTING SYSTEMS: CHALLENGING THE LIMITS

Peronio Pietro

The analysis of optical signals by means of Single-Photon Avalanche Diodes (SPADs) has undergone a huge spread in recent years, thanks to the achieved ultimate sensitivity, which raised the interest of several applications from different fields, both scientific and industrial. For instance, systems featuring single-photon detectors are effectively employed for Fluorescence Lifetime Imaging Microscopy (FLIM) and Forster Resonance Energy Transfer (FRET) in life science, for Laser Imaging Detection and Ranging (LIDAR) in remote object sensing and for Quantum Key Distribution (QKD) in quantum cryptography.

Besides providing single-photon sensitivity, SPADs can also detect the arrival time of photons with a jitter as low as few tens of picoseconds. These two features are combined by Time-Correlated Single Photon Counting (TCSPC), which is a very efficient technique for measuring weak and fast periodic signals. The remarkable timing precision that is achievable made TCSPC be acknowledged as the gold standard for FLIM and spread it in the life science field in general. Despite the remarkable sensitivity and timing precision that TCSPC can achieve, this technique intrinsically suffers for a relative “long” measurement time, due to the fact that the measured number of photons is not high enough for some FLIM applications. To this aim, I developed a USB 3.0 connection, since it is wide spread, and an Ethernet 10G link, for the most demanding applications, like High Content Screening (HCS), to deal with the data transfer and sustain the generated throughput. As for the software processing, it is a crucial part of the system, because when running at full speed, the 10-Gbps throughput that is generated cannot be stored onto an external SSD, otherwise the storing capacity would limit the measurement duration. Conversely, it is of utmost importance that the software receives the data and directly extracts the desired information. To this aim, a collaboration has started with another research group at Politecnico di Milano, to develop a custom technology. The main goal of this work was to analyze the main issues that affect the design of large TCSPC instruments in order to find possible solutions. In the presented system, the detector array is directly connected to the smart router, which selects five fired detectors at each excitation cycle and connects them to five acquisition chains containing the fast TACs. The communication with the PC is handled through the implemented USB 3.0 connection and the Ethernet 10G link, whereas the presented custom interface manages the communication with the microscope. This system is meant to fully exploit the bandwidth of the data link toward the PC and maximize the utilization of the acquisition chains. As already mentioned, the designed instrument is only a technological step toward the development of large multichannel TCSPC systems; indeed, when a faster data link toward the PC is enabled, also larger systems will be developed.

The proposed solution can either receive the synchronization signals from the microscope or provide it with the properly phased signals. I implemented some of the developed solutions on a 32-channel complete TCSPC system to test and validate them. The instrument, which features state-of-the-art performance, has been employed on a research project to distinguish various stages of aggregation of alpha synuclein (aSyn) in cells, which is a small, natively unstructured protein that can aggregate into insoluble structures that are toxic to neurons, a phenomenon closely linked to the pathology of Parkinson’s disease. The system should enable the direct measurement of the efficacy of aggregation-inhibiting drugs. The results obtained from the testing of the 32-channel system were state of the art and showed that a break of the trade-off was effectively feasible. These premises pushed me toward the design of advanced TCSPC systems that could feature a higher and higher number of channels. As a first technological step on this way, I worked on a 32x32 instrument whose main core is a SPAD array developed exploiting a custom technology. The main goal of this work was to analyze the main issues that affect the design of large TCSPC instruments in order to find possible solutions. In the presented system, the detector array is directly connected to the smart router, which selects five fired detectors at each excitation cycle and connects them to five acquisition chains containing the fast TACs. The communication with the PC is handled through the implemented USB 3.0 connection and the Ethernet 10G link, whereas the presented custom interface manages the communication with the microscope. This system is meant to fully exploit the bandwidth of the data link toward the PC and maximize the utilization of the acquisition chains. As already mentioned, the designed instrument is only a technological step toward the development of large multichannel TCSPC systems; indeed, when a faster data link toward the PC is enabled, also larger systems will be developed.

The proposed solution can either receive the synchronization signals from the microscope or provide it with the properly phased signals. I implemented some of the developed solutions on a 32-channel complete TCSPC system to test and validate them. The instrument, which features state-of-the-art performance, has been employed on a research project to distinguish various stages of aggregation of alpha synuclein (aSyn) in cells, which is a small, natively unstructured protein that can aggregate into insoluble structures that are toxic to neurons, a phenomenon closely linked to the pathology of Parkinson’s disease. The system should enable the direct measurement of the efficacy of aggregation-inhibiting drugs. The results obtained from the testing of the 32-channel system were state of the art and showed that a break of the trade-off was effectively feasible. These premises pushed me toward the design of advanced TCSPC systems that could feature a higher and higher number of channels. As a first technological step on this way, I worked on a 32x32 instrument whose main core is a SPAD array developed exploiting a custom technology. The main goal of this work was to analyze the main issues that affect the design of large TCSPC instruments in order to find possible solutions. In the presented system, the detector array is directly connected to the smart router, which selects five fired detectors at each excitation cycle and connects them to five acquisition chains containing the fast TACs. The communication with the PC is handled through the implemented USB 3.0 connection and the Ethernet 10G link, whereas the presented custom interface manages the communication with the microscope. This system is meant to fully exploit the bandwidth of the data link toward the PC and maximize the utilization of the acquisition chains. As already mentioned, the designed instrument is only a technological step toward the development of large multichannel TCSPC systems; indeed, when a faster data link toward the PC is enabled, also larger systems will be developed.

The proposed solution can either receive the synchronization signals from the microscope or provide it with the properly phased signals. I implemented some of the developed solutions on a 32-channel complete TCSPC system to test and validate them. The instrument, which features state-of-the-art performance, has been employed on a research project to distinguish various stages of aggregation of alpha synuclein (aSyn) in cells, which is a small, natively unstructured protein that can aggregate into insoluble structures that are toxic to neurons, a phenomenon closely linked to the pathology of Parkinson’s disease. The system should enable the direct measurement of the efficacy of aggregation-inhibiting drugs. The results obtained from the testing of the 32-channel system were state of the art and showed that a break of the trade-off was effectively feasible. These premises pushed me toward the design of advanced TCSPC systems that could feature a higher and higher number of channels. As a first technological step on this way, I worked on a 32x32 instrument whose main core is a SPAD array developed exploiting a custom technology. The main goal of this work was to analyze the main issues that affect the design of large TCSPC instruments in order to find possible solutions. In the presented system, the detector array is directly connected to the smart router, which selects five fired detectors at each excitation cycle and connects them to five acquisition chains containing the fast TACs. The communication with the PC is handled through the implemented USB 3.0 connection and the Ethernet 10G link, whereas the presented custom interface manages the communication with the microscope. This system is meant to fully exploit the bandwidth of the data link toward the PC and maximize the utilization of the acquisition chains. As already mentioned, the designed instrument is only a technological step toward the development of large multichannel TCSPC systems; indeed, when a faster data link toward the PC is enabled, also larger systems will be developed.

The proposed solution can either receive the synchronization signals from the microscope or provide it with the properly phased signals. I implemented some of the developed solutions on a 32-channel complete TCSPC system to test and validate them. The instrument, which features state-of-the-art performance, has been employed on a research project to distinguish various stages of aggregation of alpha synuclein (aSyn) in cells, which is a small, natively unstructured protein that can aggregate into insoluble structures that are toxic to neurons, a phenomenon closely linked to the pathology of Parkinson’s disease. The system should enable the direct measurement of the efficacy of aggregation-inhibiting drugs. The results obtained from the testing of the 32-channel system were state of the art and showed that a break of the trade-off was effectively feasible. These premises pushed me toward the design of advanced TCSPC systems that could feature a higher and higher number of channels. As a first technological step on this way, I worked on a 32x32 instrument whose main core is a SPAD array developed exploiting a custom technology. The main goal of this work was to analyze the main issues that affect the design of large TCSPC instruments in order to find possible solutions. In the presented system, the detector array is directly connected to the smart router, which selects five fired detectors at each excitation cycle and connects them to five acquisition chains containing the fast TACs. The communication with the PC is handled through the implemented USB 3.0 connection and the Ethernet 10G link, whereas the presented custom interface manages the communication with the microscope. This system is meant to fully exploit the bandwidth of the data link toward the PC and maximize the utilization of the acquisition chains. As already mentioned, the designed instrument is only a technological step toward the development of large multichannel TCSPC systems; indeed, when a faster data link toward the PC is enabled, also larger systems will be developed.
PHD program in information technology
in NAND Flash memory arrays and their mode-
the reliability issues related to VT instabilities
three years of Ph.D. program was focused on
The research activity carried out during the
First, a comprehensive experimental investi-
gation of the VT instabilities coming from cy-
cling-induced charge trapping/ detrapping in
planar NAND Flash memory arrays was per-
formed, allowing to extract the main features of
the phenomenon, such as its variability along a
memory page and its dependences on the main
array operating conditions. These included the
dependence on retention temperature, which
highlighted a thermal activation of the detrapp-
ing process around 1.1eV, confirming previ-
sous observations, and the impact of the cycling
dose, which revealed a non-negligible amount
of charge detrapping occurring even in fresh,
i.e. uncycled, arrays. Moreover, results regard-
ing the impact of cell VT were found to be in
contrast with the current microscopic pictures
for charge detrapping, demanding a review of
PHYSICAL MODELING OF NANOSCALE NAND FLASH MEMORY RELIABILITY
Resnati Davide
The research activity carried out during the
time three years of Ph.D. program was focused on
the reliability issues related to VT instabilities
in NAND Flash memory arrays and their mode-
ing, with the aim of developing predictive tools
able to reproduce the cell behavior in presence of
these phenomena and to assess their impact on
the array operation.

The statistical distribution of RTN-induced VT shifts in 3-D NAND arrays was also found to
be markedly dependent on temperature, with a
dominant role played by the change in the am-
pitude of the VT shift induced by single RTN
traps. This was explained in terms of nonuni-
formities of inversion charge density between
the grain centers and the grain boundaries,
which increase at lower temperatures and make
the grain boundaries a stronger bottleneck for
current conduction.

The statistical distribution of RTN-induced VT shifts in 3-D NAND arrays is dictated by the presence of potential barriers
formed by charge carriers trapped in the highly
defective grain boundaries delimiting crystal-
line domains.

As a Monte Carlo simulation was then shown to
reproduce this effect, where the simulated cell VT
was determined by a simple program and verify
algorithm together with employing established
models for RTN dynamics.

Finally, the attention was focused on the impact
of temperature on the main parameters con-
trolling the operation of NAND arrays, Davide Resnati - Supervisor: Prof. Christian Monzio Compagnoni with a comparison between planar
NAND arrays and modern three-dimensional
(3-D) NAND arrays, representing the state-of-
the-art of Flash technology.

The temperature effects were addressed by in-
vestigating the temperature dependence of three
main parameters, namely cell VT, the
string saturation current and the amplitude of
RTN fluctuations. The differences between the
temperature behavior of these parameters in
the two technologies are particularly interesting
considering that 3-D NAND strings are realized
with polycrystalline silicon, in place of the
conventional monocrystalline silicon substrate
of planar NAND strings.

The work showed that the string saturation cur-
rent in 3-D strings has a positive activation en-
ergy Ea, as opposite to the negative Ea of the pla-
nar case. The positive Ea in 3-D NAND strings
is dictated by the presence of potential barriers
formed by charge carriers trapped in the highly
defective grain boundaries delimiting crystal-
line domains.

The practical impact of the VT shifts introduced
by all the discussed mechanisms consists in the
increased width of the VT distributions, result-
ning in the insurgence of read errors. The work
highlighted how charge detrapping is more rel-
vant on high VT levels, implying that in MLC/
TLC architectures the most critical read opera-
tion is the one at the highest read voltage. The
highest VT distribution, as a matter of fact, will
have the most pronounced detrapping induced
negative tail after a data retention period. At a
controller level, the resulting increase of the bit
error rate can be alleviated by optimally shifting
the read levels to compensate the shifts of the
VT distribution tails.

Conversely, RTN was shown to have no rele-
vant VT level dependence and consequently it
affects all the VT distributions in the same
fashion. Moreover, RTN-induced VT shifts are
relevant in determining the width of the time-0
VT distribution, that is the distribution imme-
diately after the program operation. Despite the
reduced magnitude of RTN-induced VT shift in
3-D NAND cells with respect to planar NAND
cells, RTN is still an important source of read
errors, especially in architectures storing 3 or
more bits per cell, where very tight time-0 VT
distributions are required. Considering the tem-
perature dependence of RTN observed in 3-D
NAND, this represents a stronger constraint at
lower operating temperature, leading to a worse
time-0 VT placement and to increased bit error
rates.

In conclusion, the research work provided an
in-depth analysis of the reliability issues of mod-
ern NAND Flash technologies coming from
phenomenon impacting the stability of cell VT,
addressing both planar and 3-D architectures.
The experimental and modeling efforts which
focused on cycling-induced charge trapping/de-
trapping and RTN fluctuations in planar NAND
arrays represent a great improvement in the
understanding of the phenomenon and in the
ability to predict its impact on memory arrays
in realistic operating conditions.

The practical impact of the VT shifts introduced
by all the discussed mechanisms consists in the
increased width of the VT distributions, result-
ning in the insurgence of read errors. The work
highlighted how charge detrapping is more rel-
vant on high VT levels, implying that in MLC/
TLC architectures the most critical read opera-
tion is the one at the highest read voltage. The
highest VT distribution, as a matter of fact, will
have the most pronounced detrapping induced
negative tail after a data retention period. At a
controller level, the resulting increase of the bit
error rate can be alleviated by optimally shifting
the read levels to compensate the shifts of the
VT distribution tails.

Conversely, RTN was shown to have no rele-
vant VT level dependence and consequently it
affects all the VT distributions in the same
fashion. Moreover, RTN-induced VT shifts are
relevant in determining the width of the time-0
VT distribution, that is the distribution imme-
diately after the program operation. Despite the
reduced magnitude of RTN-induced VT shift in
3-D NAND cells with respect to planar NAND
cells, RTN is still an important source of read
errors, especially in architectures storing 3 or
more bits per cell, where very tight time-0 VT
distributions are required. Considering the tem-
perature dependence of RTN observed in 3-D
NAND, this represents a stronger constraint at
lower operating temperature, leading to a worse
time-0 VT placement and to increased bit error
rates.

In conclusion, the research work provided an
in-depth analysis of the reliability issues of mod-
ern NAND Flash technologies coming from
phenomenon impacting the stability of cell VT,
addressing both planar and 3-D architectures.
The experimental and modeling efforts which
focused on cycling-induced charge trapping/de-
trapping and RTN fluctuations in planar NAND
arrays represent a great improvement in the
understanding of the phenomenon and in the
ability to predict its impact on memory arrays
in realistic operating conditions.
INTRODUCTION

PHD program in information technology
ELECTRONICS
SYSTEMS & CONTROL
TELECOMMUNICATIONS

COLLOQUIA DOCTORALIA 2018

COMPUTER SCIENCE & ENGINEERING

88 89

SYSTEMS AND CONTROL

Branković Aida
Busnelli Fabio
Colombo Tommaso
Falsone Alessandro
Mason Emanuele
Meddouri Soufiane
Pengi Polverini Matteo
Pollok Alexander Josef
Rallo Gianmarco
Recanati Francesca
Roselli Federico
Sakcak Basak
Zhang Xinglong

DISTRIBUTED RANDOMIZED MODEL SELECTION FOR NON-LINEAR IDENTIFICATION AND SUPERVISED MACHINE LEARNING

Branković Aida

Today thousands of variables or features are often used in classification problems. It is therefore crucial to select the most relevant ones in order to obtain robust, reliable, and easily interpretable models, not to mention storage space and classification time issues. Feature Selection (FS) aims precisely at selecting features that allow a good discrimination among samples of different classes. Suitable criteria are required to remove irrelevant and redundant features. Similar issues are encountered in nonlinear identification. For example when identifying polynomial NARMAX models from data one is faced with the task of selecting the most appropriate model structure to represent the underlying system. This task, denoted Model Structure Selection (MSS), is akin to FS.

Both mentioned tasks configure combinatorial optimization problems aiming at selecting the combination of features or model terms that result in the most accurate classifier or model. The objective of this thesis is to investigate the possibility of employing some recent randomized techniques, originally developed in the nonlinear identification area, to FS problems, and to extend those techniques in both contexts, in order to deal with large-size problems. Indeed, the difficulty of these subset selection techniques increases rapidly with the size, given the exponential complexity of the underlying combinatorial problems.

The first outcome of the research is a novel classification approach (denoted RFSC, for Randomized Feature Selection and Classification), adapted from the nonlinear model identification framework, which jointly addresses the feature selection and classifier design tasks. The classifier is constructed as a polynomial expansion of the original features and a selection process is applied to find the relevant model terms. The selection method progressively refines a probability distribution defined on the model structure space, by extracting sample models from the current distribution and using the aggregate information obtained from the evaluation of the population of models to reinforce the probability of extracting the most important terms. The performance of the RFSC was found to be quite satisfactory on small/medium size problems.

To address large size problems, a distributed scheme is here proposed, which employs a vertical partitioning on the features and operates the selection in parallel on different feature subsets. The method alternates the parallel selection phase with a partial information exchange among the different processors, which reinforces the probability that promising terms be selected. The proposed scheme is applicable to both nonlinear identification and FS problems and in both frameworks it resulted in significant improvements in performance and efficiency. Moreover, the method has a tendency to produce small models, easily amenable to interpretation. While capable of addressing much larger problems than the non-distributed approach developed previously, the distributed scheme was found to be ineffective when dealing with extra-large search spaces (as are encountered, e.g., with micro-arrays), due to computational issues associated with parameter estimation and classifier design. An alternative version of the distributed scheme was then developed to target micro-arrays in particular, which employs a non-parametric multivariate filter algorithm and population extraction using the distance correlation index (dCor) as a criterion.

Finally, while analyzing the behavior of the RFSC, it was noticed that structurally different
INTRODUCTION

PHD program in information technology

ELECTRONICS
SYSTEMS & CONTROL
TELECOMMUNICATIONS

COLLOQUIA DOCTORALIA 2018

COMPUTER SCIENCE & ENGINEERING

classifiers may result in equivalent performance due to the discrete nature of the 0 - 1 loss function in classification problems. The randomized characteristic of the RFSC was then exploited to generate ensembles of classifiers. In most cases the results demonstrate an improved accuracy when ensembles of classifiers are employed with respect to the ‘single classifier’ case.

All proposed methods have been evaluated and compared to other well-known FS and MSS methods on standard benchmarks for classification/nonlinear identification problems. The results show the effectiveness of the proposed methods with respect to competitor methods both in terms of prediction accuracy and model complexity.

STABILITY CONTROL AND ANALYSIS OF TWO-WHEELED VEHICLES OUT OF PLANE DYNAMICS

Busnelli Fabio

This thesis deals with the study and the design of a semi-active stability control of out-of-plane dynamics for two-wheeled vehicles. The thesis is divided in three parts: the first part is devoted to introduce two-wheeled vehicle dynamic, together with the actuators and sensors commonly installed on production motorcycle; the second part is focused on the implementation of a multi-body model, the design of semi-active stability control algorithm and the design of an optimal steering damping for handling purpose; the third part deals with the estimation of the side-slip angle for two-wheeled vehicles.

The control design problem considered in the second part correspond to two different problems:

- stability control system based on semi-active steering damper, in particular based on an electro-hydraulic steering damper;
- optimal steering damping design to enhance handling of the motorbike when the vehicle is not affected by stability issues.

In the third part the side-slip estimation problem is carried out and two approaches are considered: a kinematic based estimator and a black-box approach, based on an artificial Neural Network, are analyzed and tested. Both the problems, the control design algorithm and the side-slip estimation, are firstly studied in a simulation environment and then their efficacy is tested with an equipped motorbike.

At first a dynamic multi-body model has been developed. The model has been used to make sensitivity respect to longitudinal speed, rolling angle, longitudinal acceleration and steering damping coefficient. Special focus of sensitivity is given to the out-of-plane modes of weave and wobble. Validity of the model is confirmed by the fact the similar conclusions are given by multi-body models presented in the literature. Furthermore, the model parameters have been identified by means of an optimization procedure based on experimental data, where modes of interest have been excited. The most interesting results from the control viewpoint is given by the sensitivity to the steering damper coefficient. It turned out that when the steering damper coefficient increases weave mode is worse damped while wobble mode is better damped. The control algorithm developed in this work faced and solved this trade off with the algorithm presented in the next chapter. Results given by the simulation are exploited to develop the control algorithm implemented and tested to improve stability and handling. The key feature of the algorithm is given by the Mode Detection algorithm that processes the steering damping signal to determine whether a mode is exited or not. When a mode is exited the Mode Detection algorithm defines which mode is excited and optimally damp in a closed loop fashion the oscillations. In the case no oscillations are detected an open loop control, or adaptive control, is engaged to allow the driver the best handling of the motorbike. Both the stability control algorithm and the adaptive control strategy have been studied and analyzed in simulation to find the optimal strategy respect to the given objective. In the first case the objective is to optimally damp the oscillations to avoid instability issues, while handling objective is to require to the driver the minimum force to accomplish a curve. To prove the results experimental tests have been carried out. The effectiveness of the stability control is presented through ad-hoc experiments that excite weave and wobble modes. At last, adaptive control experiments are carried out and drivers’ feedback confirm the efficacy of the strategy. Stability of motorbikes are strictly related with the side slip angle, but its measure it is critical. This work presents a black-box method to estimate the
sideslip angle of a powered two wheeled vehicle. In particular the approach exploits the neural network framework to identify a non linear static relation between the available signal and the sideslip angle. The training data are achieved exploiting the most common on-board signals. Moreover, it is shown which are the most significant signals for the sideslip estimation. It has presented how the neural network has been designed and proves its effectiveness both in simulation and through real experimental data. Simulation is carried out with the multi-body simulator BikeSim. Several kind of manoeuvres have been simulated as well as several test manoeuvres have been used to verify the network effectiveness. This is has been achieved by defining different handling conditions changing both the speed profiles and the road conditions (bank percentage of the curves). Results shown that the RMS estimation error of the side slip angle never exceed 0.63 degrees. This results has been improved when the roll and steering angle are included to train the network: in these cases the RMS estimation error drops respectively at 0.12 degrees and 0.07 degrees. Finally, a sensitivity analysis respect to the signals of a 6-axis IMU confirms that the most significant axis for the sideslip estimation is the roll rate. In the literature, sideslip estimation requires a model, therefore the proposed approach overcomes the following main issues: define a proper model that can be used to design the estimator and identify the parameters of the model. This is not straightforward because parameters that are usually needed i.e. cornering stiffness are not trivial to identify and may vary a lot depending on the road and tire conditions. At last, a kinematic approach for sideslip estimation is presented. The method was developed for four-wheeled vehicles, where the sideslip is referred to CoG of the vehicle and the kinematic model is given by one point moving in a 2D space. In this work, kinematic relations have used to be able to write the 3D kinematic of the motorbike in a 2D space. This is possible because measures of acceleration of the motorbike, angular velocities and attitude angles are usually available on modern motorbikes equipped with sensors like inertial platforms. The validity of this approach is shown in simulation and the sideslip has been estimated with an RMS error of about 0.1 degrees. Moreover, the designed observer confirmed it efficacy with a completely different circuit, and sensitivity analysis has been carried respect to the sensor positioning and road banking. The last sensitivity showed that the estimation error rapidly increases when road banking is unknown, leading to an absolute error of 90 % with 30 % of road banking. At last, a stability analysis has been done through the Lyapunov theory because the observer depends on different parameters. The results of the stability analysis showed that stability is guaranteed when these parameters are positive and bounded.

The study, design and control of vehicle vertical dynamics is one of the most important themes in vehicle design as it radically influences the driving experience. Commonly two objectives are considered for suspensions design: the driver’s comfort and the tires road holding. The first one is the suspension capability of filtering the road asperities, reducing the accelerations the driver perceives. The second one is suspension ability to maximize the vertical contact forces between the vehicle’s tires and the ground, guaranteeing the best grip. The vehicle’s suspension’s parameters are designed to match these two objectives. Anyway, it is well known that passive suspensions have intrinsic limits that, even considering one goal per time, do not allow to optimize the performances in all conditions. For example, considering the comfort objective, it is known that in common road vehicles a large damping guarantees better attenuation of the body resonance, while a low damping provides a better high frequency filtering. To overcome the limits of passive suspensions, in the last decades, controllable electronic suspension systems have been widely studied and used in the automotive and motorcycles field. According to literature electronically controlled suspension systems be ideally classified depending on the control variable, the control bandwidth and the power request. The most commonly used electronic suspension classes are:

• Load leveling suspensions: this kind of suspensions has the capability of generating a desired quasi-static vertical force in order to balance the load forces acting on the suspension. It can be considered as an active suspension with very slow dynamics (<0.05 Hz) and its main purpose is to control the suspension equilibrium point at a desired position, rejecting the disturbances caused by load variations. The power request for a light road vehicle usually is some hundreds of watts. This kind of technology is usually found on passenger transportation vehicles (e.g. buses) which present large load variations, and luxury cars, where changing the height can be used to decrease the air drag consumption while driving, and to help the passengers exit from the car when it is parked. Not much in literature is present on load leveling control.

• Active damping suspensions: this class features a controllable shock absorber whose damping can be varied run-time. Depending on their bandwidth they are called adaptive suspensions (0.5-5 Hz) or semi-active suspensions (10-50 Hz). As the control variable is the suspension damping, no energy can be introduced in the system. Semi-active suspensions technology is without doubt the most used and studied class of electronically controlled suspensions as it is considered the best compromise between energy consumption and control performances. Wide literature is present about semi-active suspension control systems, for both comfort and road-holding control. They are widely used in luxury cars and motorcycles to guarantee the best possible comfort and driving feeling, controlling the vertical dynamics along its complete bandwidth.

• Active suspensions: this kind of suspension presents a large bandwidth linear actuator which can fastly generate a vertical force along the suspension in order to control the all the vehicle vertical dynamics. Depending on the bandwidth it can be internally classified as slow active (1-5 Hz) or fully active (20-30Hz). The actuator can be in parallel of two passive spring and shock absorbers or can totally substitute the passive hardware. This class of suspension is the most performing in terms of vertical dynamics controllability, and therefore can bring mayor benefits for both comfort and road holding. Anyway, due to its large power demand (1-10 kW), their
usage on commercial vehicles has been limited. They have been used on F1 cars for some years, until they were banned in the early 1990s.

Most of literature and development about these electronic suspensions systems has been driven by the great “research engine” of the automotive field, which led and economically supported the research, innovation and application of electronic suspensions systems was the vertical dynamics of road vehicles, and problems related to them.

Anyway, the evolution of electronic control systems has recently started to affect also off-highway vehicles, in particular agricultural machines. In this context, the interest in vehicle vertical dynamics control is continuously growing due to its mayor potential impact on driving experience. Furthermore off-highway vehicles present different critical issues w.r.t classical road vehicles, which makes this theme even more interesting. In particular:

• Driver’s long term health: off-highway vehicles are driven for long periods of time (even entire days) on very rough where the driver is subjected to large accelerations and suspension oscillations. In these conditions reducing the vibrations perceived by the driver is not only related to comfort, but also to driver’s long term health, and therefore it becomes a mayor suspension objective.

• End-stroke impact: vehicle’s suspensions presents very large oscillations due to high level of roughness of off-roads ground profiles. This radically increases the risk of impacting the suspension end-stop which has two main drawbacks: first it would dramatically deteriorate the driver’s comfort, second it may damage the suspension hardware. For this reason, controlling the suspension such as the end-stroke risk is minimized becomes fundamental.

• Steep slopes and load variations: in off-road driving, very steep slopes can be encountered. In this conditions the suspension is subjected to large slow varying load transfers which can get the suspension equilibrium point in a very asymmetrical position w.r.t suspension limits, increasing the possibility of impacting the end-stop. Furthermore, working vehicles such as agricultural machines, are often loaded of ballast and large weights which have the same effect on the suspension. It is therefore clear that a load-leveling suspension systems becomes fundamental in this field, and a proper control system design is necessary.

Between the many off-highway vehicles, agricultural machines are of mayor interest because: they present complex non-standard vertical dynamics w.r.t to other off-road vehicles; they are used in such a wide range of road conditions and environments that they present all the previously cited critical issues; finally, as the introduction of electronic suspension systems in the agricultural field is relatively recent, not much literature is present. In fact, some research can be found about the analysis and control of agricultural vehicles vertical dynamics, but there is still much space for investigation and innovation. In particular, problems related to load leveling control design and end-stroke avoidance control, at the best of author’s knowledge has not been properly covered and present many open issues. This thesis work is focused on the analysis, modelling and control of agricultural vehicles’ vertical dynamics and the application of load-leveling and semi-active electronic suspension technologies to them. This is done through the analysis of case studies related to the control of the cabin and front axle suspension system, which are the most classical suspension configurations that are found in tractors. All the analysis and proposed control systems focus on the driver’s comfort, which is previously described is of mayor interest in this field.

This thesis addresses decision making problems in systems composed of multiple agents with computation capabilities, which can communicate with their neighbors and aim at optimizing performance, subject to some coupling in their decisions. Our focus is on problems that can be formulated as a mathematical program involving decision variables, objective functions, and constraints of the agents.

Centralized solutions of the global optimization program pose several difficulties, ranging from being computationally intensive to forcing agents to disclose their local information to some central unit. This calls for distributed resolution strategies exploiting the agents computation and communication capabilities. Throughout the thesis, we focus on different global optimization problems, which are all characterized by a decomposable structure, but present a feature that couples the agents decisions. More precisely, we consider structures characterized by an objective function that is the sum of the local objective functions, with the agents decisions possibly subject to local constraints, and a coupling element given by either a common decision variable or some network-wide constraint. For each global problem, a distributed algorithm is introduced, which consists of an iterative procedure where agents solve a local optimization problem, share their decisions with their neighbors, and repeat the process based on the received information. The algorithms are introduced first for the deterministic case, and then extended to account for the presence of uncertainty affecting the agents locally and/or globally; and combinatorial complexity, as we address the case of discrete decision variables.

We introduce the problem of decision making in multi-agent systems motivating the interest in this research area through some relevant applications in the energy system domain. We then describe the thesis structure and synthesize its contribution.

We propose a new distributed algorithm for solving convex global optimization programs over time-varying networks, where the agents have to agree on a common decision vector. In contrast with other approaches in the literature, we are able to handle the case when agents have different local constraint sets and we relax some regularity assumptions regarding their local cost functions. The proposed procedure is tested on the power allocation problem in cellular networks, where the agents are the base stations serving mobile users within a cell, the common decision vector is the power to be assigned to the mobile users, and the base stations aim at maximizing the throughput of the entire network while accounting for local power limitations and minimizing the interferences among users sharing the same transmission channel.

Simulations show that the proposed approach avoids oscillatory behaviors of the tentative solution across iterations, in contrast with an alternative approach in the literature.

DISTRIBUTED DECISION MAKING WITH APPLICATION TO ENERGY SYSTEMS

Falsone Alessandro

This thesis pose several difficulties, ranging from being computationally intensive to forcing agents to disclose their local information to some central unit. This calls for distributed resolution strategies exploiting the agents computation and communication capabilities. Throughout the thesis, we focus on different global optimization problems, which are all characterized by a decomposable structure, but present a feature that couples the agents decisions. More precisely, we consider structures characterized by an objective function that is the sum of the local objective functions, with the agents decisions possibly subject to local constraints, and a coupling element given by either a common decision variable or some network-wide constraint. For each global problem, a distributed algorithm is introduced, which consists of an iterative procedure where agents solve a local optimization problem, share their decisions with their neighbors, and repeat the process based on the received information. The algorithms are introduced first for the deterministic case, and then extended to account for the presence of uncertainty affecting the agents locally and/or globally; and combinatorial complexity, as we address the case of discrete decision variables.

We introduce the problem of decision making in multi-agent systems motivating the interest in this research area through some relevant applications in the energy system domain. We then describe the thesis structure and synthesize its contribution.

We propose a new distributed algorithm for solving convex global optimization programs over time-varying networks, where the agents have to agree on a common decision vector. In contrast with other approaches in the literature, we are able to handle the case when agents have different local constraint sets and we relax some regularity assumptions regarding their local cost functions. The proposed procedure is tested on the power allocation problem in cellular networks, where the agents are the base stations serving mobile users within a cell, the common decision vector is the power to be assigned to the mobile users, and the base stations aim at maximizing the throughput of the entire network while accounting for local power limitations and minimizing the interferences among users sharing the same transmission channel.

Simulations show that the proposed approach avoids oscillatory behaviors of the tentative solution across iterations, in contrast with an alternative approach in the literature.
We exploit dual decomposition together with the algorithm developed in Chapter 2 for the solution of convex programs, where the agents local decision variables and a network-wide constraint. In contrast with other approaches in the literature, we achieve optimality of both the dual and the original decision variables. Our approach requires a lower amount of information to be exchanged and no prior coordination among the agents regarding the computation of a specific strictly feasible candidate solution. The proposed algorithm is tested on the plug-in electric vehicles charging problem, where the vehicles are the agents, the coupling constraint is given by the network power limits, and the objective is to set the overnight charging schedule of each vehicle so as to ensure a desired battery state of charge for the morning after while minimizing the cost of the electricity. An interesting feature of the approach is that feasibility of the solution is preserved when some permanent failure of the communication network occurs, causing the communication graph not to be connected anymore.

We consider the linear case of the set-up of Chapter 3, i.e., separable objective function with local decision variables and a coupling constraint, but allow some decision variables to take integer values. This results in a (non-convex) mixed integer linear program which involves the whole network. Inspired by a recent work in the literature, we propose a decentralized algorithm that is able to compute, in a finite number of iterations, a solution that is feasible for the global problem, with precise guarantees regarding its suboptimality level. Decentralized schemes require the presence of a central unit, which however is typically required to perform some simple sorting and coordination tasks only. In our set-up the central unit is in charge of gathering some information about the agents contribution to the coupling constraint and updating the associated dual variable. The proposed approach is tested on an integer version of the plug-in electric vehicles charging problem, where the vehicles can charge and discharge their battery, but they cannot set the charging rate, which is fixed. At the end of the chapter we suggest a possible way to derive a distributed version of the algorithm.

We revisit the problems introduced in Chapters 2 and 3 treating the case in which the agents are affected by uncertainty. We develop a sample-based approach to decision making that guarantees convergence to a solution that is feasible for almost all uncertainty instances except for a predefined fraction. The key novel feature of our approach is that agents use a finite number of uncertainty realizations, which can be available locally and do not need to be exchanged with the other agents, thus preserving the private nature of the agents local dataset and avoiding to overload the communication links. Compared to other approaches in the literature, we are able to provide guarantees for a finite number of samples, as opposed to asymptotic guarantees in the number of samples; we do not need any description of the uncertainty, as we rely only on samples; and we are able to take into account correlation of the uncertainty affecting the overall multi-agent system using only the agents local information. The developed techniques are tested on the energy management problem of a building cooling district. All buildings in the district are connected to a common chilled water circuit through which they can exchange cooling energy. Each building has to guarantee a certain thermal comfort for its occupants and, to this end, it can decide to produce cooling energy with its own chiller plant or to draw energy from the cooling network. The goal consists in minimizing the overall electrical energy cost of the district while accounting for the uncertainty in each building cooling energy demand, which is characterized through a (private) dataset of past cooling energy demand profiles per building.

We draw some conclusion, illustrate future research directions, and briefly describe other interesting results that we developed and are related in terms of methodology or application to the thesis, but do not really fit its main topic.

Anthropocene denotes the scale and intensity of the anthropic influence on natural processes and ecosystems. Recent trends in the scientific literature on natural resources acknowledge this issue by putting forward the concept of Coupled Human-Natural System (CHNS). It denotes systems where the human and natural components are so entangled that a correct assessment of system resilience or sustainability require a comprehensive study of both parts. Within the human component, a crucial role is played by decision making, which mediates human interactions at the various levels of system governance, ranging from institutional to operational decisions that directly impact the natural resource. Modeling of decision making has been a daunting challenge for researchers. However, they developed various approaches, among which the normative approach.

In the normative approach, it is assumed that an agent’s decisions seek to rationally achieve a certain goal. The rationality hypothesis enabled a plethora of theoretical studies in various fields, e.g., economics, or optimal control theory, which supported the broad adoption of this modeling approach to provide prescriptive solutions. However, the same hypothesis has been strongly criticized on the basis of empirical evidence of behavior deviations. In particular, full rationality has thwarted modelers’ efforts to deal with systems operated for multiple objectives.

In these systems, the operating policy has to balance multiple goals, by reflecting the preferences of the decision maker and/or of the stakeholders. Another issue arises from the time dynamics of the tradeoff and preferences that are unlikely to remain stationary but are instead adjusted in response to various changes. Triggers of the change may be exogenous influences that modify the conditions at the system boundary, or extreme events, such as floods or droughts, originated by the inherent variability within the system.

The objective of this thesis is to advance algorithms adopting the normative approach to develop behavioral models of system operators. The proposed algorithms are able to cope with tradeoffs among multiple objectives, and with the time evolution of preferences. A first effort has been devoted to formalize the modeling of multiple objectives by recognizing the inherent uncertainty in their formulation. This leads us to adopt the idea of rival framings, each representing a set of objectives formulations, to rationalize the search for the candidate set of objective functions that represents the operator of the modeled system.

On this premise, we then propose two different algorithms to identify the tradeoff among the multiple objectives that best represents the historical operations in the modeled CHNS. The first algorithm adopts Inverse Reinforcement Learning to efficiently identify a set of weights that measure the preferences of the system operator as they can be presumed by a time series of system operations. This algorithm is able to achieve high quality, above 0.9 goodness-of-fit, in a synthetic application. We also applied it to a real case study, effectively improving the operator’s behavioral model with respect to single-objective counterparts. Moreover, we were able to quantify the effect of an exogenous transition on the system in terms of change in the weights of operating objectives.

We also developed a second algorithm for tradeoff identification, inspired by multi-agent negotiation protocols, called Set-based Egocentric Concession protocol (SEC). Operator’s be-
behavioral models identified with this algorithm prove to be accurate, as we tested on a synthetic case study. Moreover, SEC identifies the tradeoff as a function of a set of parameters, named attitudes, that can be used to model tradeoff evolution in time. To this end, we propose an autoregressive model of attitude evolution driven by the recent system performance as they reflect the extreme variability of the system, e.g., in terms of droughts and floods. We found this model a promising start to explain the evolution of the tradeoff of a time series of decisions with dynamic preferences, developed for the synthetic case study. More significantly, we framed the testing of the proposed model of preference evolution in a scientific approach that has significant implications for the construction of reliable projections of the future evolutions of CHNS.

Facing the exhaustion of fossil energy resources and environmental problems caused by the exploitation of these resources, other alternative energy resources have been and should be developed. One alternative is to use renewable energy resources, which however show natural fluctuations of the main source. These energies include wind power which represents a huge resource with more than 54 GW of power installed across the global market in 2016, its capacity has expanded rapidly to 486.8 GW, cumulative capacity grew by 12.6%. All wind turbines installed worldwide by mid-2015 can generate 4% of the world’s electricity demand. Faced problems and limitations on the development of wind farms

The production of electricity from wind energy is facing a significant increase, nowadays we mainly build wind farms of high power and high efficiency, since the first wind farm established in 1980, the technology is widely developed with a legislative and tariff framework which has been set up for the development. In order to better explore the effectiveness of the wind energy production, the wind farms are usually installed in rural sites, or in off-shore where we can make the most of open spaces and windy. Nevertheless, there are few inhabitants and little electricity consumption there. So the problems of transmission of electricity over long distances become very meaningful. We need a great investment for cables, pylons, and loss during transport is relatively important, which can reach 10%. In addition, till now we do not have a good and effective storage system, especially for long term storage system. In this context, it's important to consider the possibility of development of the small production units near to the users. Moreover, the existence of big towers and wind effects caused by buildings offer favorable conditions for installing small wind turbines in cities. Indeed, they are increasingly popular for autonomous operations to ensure supply of isolated sites.

The present thesis deals with the study, control and performance improvement of a chain of wind energy conversion into electrical energy in autonomous operation, including a storage system based on a flywheel. It concerns a study, design, implementing and comparison of different control schemes with different control techniques applied to stand alone wind system for variable speed wind turbine with saturated induction generator. Based on Field Oriented Control (FOC) principle, fuzzy logic control technique (FLC), Lyapunov-Based control and Model Predictive Control (MPC) have been proposed with different strategies and situations. Namely MPC based single model, Switched MPC and Adaptive MPC strategies have been performed, the same switched principal strategy also was adopted for the Lyapunov control, where the switching strategy is based on different models according to different situations of the model in several working points. The linearized models are obtained by means of identification around equilibrium point procedure. A special variable-step smoothing technique was introduced as well which provides good performances in various situations, the effectiveness of the developed control schemes is evaluated through several comparisons with traditional control techniques in different situations and scenarios. The above mentioned studies require the modeling of the different parts of the studied system and the determination of the different parameters needed for the control. In particular, the nonlinear model of the generator which takes the saturation effect into account of the magnetic circuit is represented by means of variable inductance. It is approximated with a polynomial.
function of degree 12. Using the saturated model of the induction generator allows the study of the system with good accuracy. Due to the significant fluctuations of the wind as well as the load, which introduce an unbalance between the power production and the power needed by the load, that can cause different control problems to the system, an extension of system has been validated by introducing a storage system using flywheel, in order to improve the electric quality and contribute in the ancillary service. The flywheel is then connected by means of an induction machine which is operating as motor and generator for storing and retrieving energy respectively. The mechanical part based on a wind turbine and gearbox have been modelled as well and connected to the saturated induction generator model considered in the system, where a suitable control technique has been designed, using an optimal torque control (OTC) to track the maximum power point (MPP) of the wind turbine. An interesting association and control of the whole system (wind turbine, generator and the storage system) have been achieved with good and improved performance of the wind conversion system, in terms of DC bus voltage control, and the control of the power delivered by the wind and required by the load, regardless the different disturbances and parameters uncertainties of the system. The results presented in this thesis are very interesting and relate to subject that continues to generate research in terms of effective control of a device with non-linear characteristics combined with uncertainties on the value of the quantities identified. The approaches adopted in the thesis are relevant in the sense that the adopted control algorithms are introduced and applied in order of increasing complexity while showing their contributions in the control, more and more effective of the DC voltage at the output of the rectifier.

Control of robot interaction with the environment, generally referred to as robot force control, is required to face the inadequacy of pure motion control for the successful execution of those robot tasks involving contact with a surface. Widely popular since the early 1980s, research on force control algorithms employing a conventional (single arm) robot has gradually lost its appeal during the last decade, despite the growing employment of robots in finishing and machining operations would strongly benefit from increased controllers’ performance. At the same time, the recent diffusion of new industrial robotic platforms, like light-weight dual-arm robots, has driven research on robot force control towards the execution of complex and dexterous robotic tasks, such as bimanual automated assembly. In this regard, the research findings described in this thesis cover two main areas of robot control: performance improvement in implicit force control for traditional industrial robots and force controlled bimanual assembly through constraint-based trajectory generation for dual-arm robots.

Performance in Implicit Force Control. Implicit force control is a force regulation approach developed for position controlled industrial robots, typically required in robotic polishing, deburring and machining. It is based on an external force control loop, closed around the inner robot positioning system. Improving the performance of this controller with the novel tools developed in this thesis is one of our targets. Two requirements for an improved control performance have been introduced and addressed: fast convergence speed with absence of force overshoots and avoidance of environment modeling and identification. Experimental validation has been performed on the COMAU Smart Six robot, a 6 degrees-of-freedom position controlled industrial manipulator manufactured by COMAU, see Fig. 1.

In order to achieve the first performance requirement, a constrained control approach has been developed which extends the so-called invariance control by exploiting set invariance conditions for output regulation purposes. By introducing a constraint on the regulation error, it is possible to derive a control law that achieves fast converge speed and absence of output overshoots with respect to the reference, by means of set invariance and Lyapunov stability conditions. The proposed control law, formulated for single-input single-output systems and extended to multi-input multi-output systems, has been applied to the implicit force control problem and experimentally validated. Controller robustness to compliance uncertainties has been addressed first in an adaptive fashion, and later by exploiting robust set invariance for a smooth convergence to the force reference. With respect to the second performance requirement, a mixed data-driven and model-based control approach has been proposed. A model-based feedback loop (accounting for the robot configuration-dependent joint and link compliance) aims at making the robot-en-
environment system entirely depending on the unknown environment transfer function, while a data-driven PID controller, tuned with the Virtual Reference Feedback Tuning Algorithm (VRFT), is responsible for the force regulation. A hierarchical architecture is further proposed to enhance the control performance, in terms of a high bandwidth of the closed-loop system with avoidance of force overshoots. The introduction of a high bandwidth of the closed-loop system to enhance the control performance, in terms of a high bandwidth of the closed-loop system with avoidance of force overshoots. The introduced data-driven/model-based controller, is combined with an outer Model Predictive Controller (MPC) acting as reference governor to select on-line the optimal reference to the inner closed-loop system.

**Force Controlled Bimanual Assembly**

The redundancy, dexterity and inherent compliance of bimanual light-weight robotic systems, commonly referred to as Cobots, naturally motivate their employment in autonomous assembly operations, e.g. insertion, folding, capping/tapping. However, while the lower inertia combined with the compliant structure of this type of robots provides an intrinsic degree of safety towards manipulated objects, which is beneficial in assembly operations, the consequent lower position accuracy makes the application of force control algorithms even more crucial for a successful task execution compared to traditional industrial (single-arm) robots. As an additional trade-off, the dexterity of a dual-arm system (allowing for the execution of tasks with an increased level of complexity compared to traditional positioning tasks) and its kinematic redundancy (enabling the simultaneous execution of multiple tasks with a given order of priority) introduce additional constraints on the planning problem of a robot trajectory. Based on these considerations, it becomes clear that, when a bimanual light-weight manipulator is employed to perform an assembly task, real-time constrained-based trajectory generation and force control are crucial elements for a successful task execution. To this end, bimanual robotic assembly is treated in this thesis as an equivalent constraint-based trajectory-generation control problem fulfilling the typical force control requirements involved in assembly operations, i.e. a compliant robot motion and a robust bounding of the interaction force. Estimation of the contact force/torque further enables sensorless execution of the assembly process. The validity of the proposed control approach is experimentally validated on a bimanual assembly use case involving both a peg-in-hole insertion and a cap rotation task, performed with the ABB YuMi dual-arm robot, see Fig. 2 and Fig. 3.

**Virtual Reference Feedback Tuning Algorithm**

A hierarchical architecture is further proposed (VRFT), is responsible for the force regulation. The introduction of a high bandwidth of the closed-loop system to enhance the control performance, in terms of a high bandwidth of the closed-loop system with avoidance of force overshoots. The introduced data-driven/model-based controller, is combined with an outer Model Predictive Controller (MPC) acting as reference governor to select on-line the optimal reference to the inner closed-loop system.

**Unseen by the passengers, aircraft environmental control systems are complex thermodynamic systems, requiring a large quantity of power.** The tasks of designing, modelling, optimising and controlling all these systems lead to what degrees of freedom to the respective expert, and typically require many design loops to arrive at satisfactory results. This thesis contributes to the state of the art.

**Multiple aspects of this process.**

In aircraft Environmental Control Systems (ECS), Limit Cycle Oscillations (LCO) can occur. Those are problematic since the life expectancy of the ECS is affected. Using an Equation-based object-oriented modelling language (EOOML), a complete, detailed and dynamic simulation model of an ECS. This model includes the Engine Bleed-Air system (EBAS), the air conditioning pack, the cabin and ducting dynamics as well as the recirculation system. Using simulations, it is shown that LCO occurring in ECS cannot be explained by Helmholtz resonance effects. (Fig. 2)

To further investigate the cause of the LCO electromechanical valves - as used in EBAS - are modelled in more detail, using the Lund-Gre nobly-friction model. Using this model, LCO in aircraft ECS are predicted for the first time. (Fig 3).

Several control strategies are devised, implemented and evaluated against this model. A strategy based on a combination of feed-forward control, feed-back control and online tuning of the integral action outperforms all other candidates. A 46% reduction of the developed
Robustness in Data-Driven Control: Theory and Automotive Applications

Rallo Gianmarco

Model-based design represents a standard practice in industrial control. According to this concept, a model of the plant is identified from data or developed from first principles and then used to design a feedback controller satisfying some closed-loop requirements. Unfortunately, the resulting feedback controller is not necessarily optimal when connected to the plant, as it is designed using information about the model of the plant to control. In particular, the closed-loop performance is limited by modeling errors, which are typically due to incomplete knowledge of parameters or inappropriate “a-priori” model structure selection. In fact, a model suitable for control design needs to be both simple and reliable and the best trade-off is not easy to find. Moreover, a good model describing the main dynamics of a system may not be the best for control. Standard model-based design is in fact an indirect data-driven procedure, in that the controller is derived from a model, which in turn is usually derived or refined using experimental data. An alternative is represented by “data-to-controller” algorithms. According to these approaches, only the final control cost is taken into account and the controller is directly obtained from experimental data without first deriving a model of the system. This feature may lead to a significant performance improvement in many practical situations. Several direct data-driven controller tuning techniques have been proposed, both iterative and noniterative. The advantages provided by data-driven control strategies are evident. The control design phase is much faster and more effective and the problem of undermodeling is avoided since no model of the plant is needed. For the same reason, direct approaches are suitable when the knowledge of the physics of the plant is poor or if the modeling cost is high due to the complexity of the system to control, as for automotive applications. Moreover, the structure of the controller designed according to direct strategies does not depend on the structure of the model. Therefore, the parameters of the controller structure are directly optimized from data and the reduction phase is unnecessary. There are also drawbacks when dealing with data-driven control approaches. First, without the model of the plant it is not possible to check closed-loop performance before implementing the control law. Moreover (as is the case with indirect model-based strategies) direct methods are limited by real-world uncertainties that act at different stages of the design process and could limit the applicability of these techniques. Strictly speaking, a problem of robustness – in a broad sense – arises in this field. The following list helps to tidily provide an insight into the possible causes of direct approaches effectiveness reduction.

- Robust controller design. When linear controllers are designed for real-world plants, a prescribed level of robustness is necessarily required. Although this problem has been thoroughly addressed in the model-based literature, it currently represents a challenge for data-driven control approaches. In fact, the classical concept of robustness, i.e., the one meant for indirect methods, can be seen as the capability of handling model uncertainties or model parameters variations throughout the controller design procedure and, for this reason, it strongly depends on the employed system representation. On the other hand, data-driven strategies exclusively rely on experimental data and there are no model uncertainties to deal with. However, the robustness property is here directly related to the plant under control (e.g., cope with system dynamics variations or changing operating condition) rather than on its mathematical description. This difference contributes to
highlight the potentiality of direct strategies but research efforts are needed in order to explore such a new and promising perspective.

- Robust closed-loop reference matching. If the selected fixed-order controller structure does not allow to match the reference model closed-loop behaviour, the data-driven parameters optimization provides a biased result. This problem can be tackled within the controller design phase by means of tuning a suitable prefiler. However, a non-optimal controller structure selection may emphasize direct approaches robustness problems.

- Data uncertainty. Experimental data are inevitably affected by measurement noise, which is one of the main causes of uncertainty for direct methods. The detrimental effect of the noise must be addressed during the controller design phase but this task is not trivial without exploiting a model of the system to control. Moreover, a closed-loop stability certificate can be derived from the same batch of data used for the controller tuning. This assessment is extremely useful for safety-critical applications. However, existing criteria need to be conservative for dealing with the effect of the noise but when the data-driven stability condition is not satisfied the designer has to lower tracking performance requirements. Lastly, a robustness problem arises also for what concerns closed-loop stability assessment procedures, which must consider system variations.

- Experiment design. The design of the experiment (i.e., determining the input sequence to use for feeding the plant and gather data) is crucial for both system identification and direct controller tuning frameworks. While several contributions can be found in the “identification for control” literature, it is still necessary to explore experiment design for data-driven approaches.

The overall aim of this work is to extend the effectiveness of noniterative direct methodologies for control system design by proposing solutions for counteracting part of the above listed limitations. Addressing these critical points allows to fully compare data-driven techniques to indirect approaches, therefore it could be possible for the control engineer to be free of choosing the most suitable method for a given application. The present study aims attention at time-domain approaches and it mainly concerns the linear framework. The focus on noniterative data-driven strategies, which allow to design a ready-to-use controller from a single batch of data, is motivated by their lower experimental cost combined with a null on-line computational effort that make these approaches more appealing/easy-to-use with respect to the iterative ones. Furthermore, assessing or improving the robustness for the iterative techniques requires additional experiments devoted to gather information at each iteration.

Among all the noniterative techniques, the Virtual Reference Feedback Tuning (VRFT) method represents the main strategy exploited for the analysis proposed in this work (this technique was developed at Politecnico di Milano). Within this framework, linear-in-the-parameters controllers, like PIDs, can be rapidly designed and possibly recalibrated with new experiments. Automotive applications can serve as an important benchmark for direct techniques, given the complexity of the systems usually involved. In this thesis, the novel robust VRFT technique is successfully applied to a vehicle lateral dynamic control problem. Lastly, this work proposes also an open-loop data-driven control strategy, motivated by a particular automotive case-study that involves Electric Parking Brake systems, which extends the effectiveness of direct approaches to feedforward control problems.

Sustainability in the agri-food sector is key in the global development context defined by the Agenda 2030 and the 17 Sustainable Development Goals. The presence of nutritional, economic, and environmental goals, which are all directly or indirectly interlinked and are often conflicting, makes food systems complex and further challenges our capacity to achieve overall sustainability standards. Moreover, promising approaches to increase agri-food sustainability, such as agroecology and multi-functional agriculture, highly differ from the currently widespread intensive agricultural practices based on monocultures, both for planning and management choices. Appropriate mathematical tools and quantitative assessment methods are needed to explore the complexity of agricultural systems, and ultimately support actors in the food sector in the transition towards more sustainable agri-food practices via informed decisions. This being the context, the goal of this thesis is to design quantitative tools to support farmers, researchers, associations, NGOs, and other actors and decision makers in the agri-food sector to develop more sustainable agricultural systems, with a focus on multi-species agroecosystems. The work carried out during this research has been divided into three stages, ranging from knowledge acquisition to the optimized design of agroecosystems. The first step is two-fold: it includes (i) understanding the predominant biological components and processes of an agroecosystem, and (ii) developing a mathematical model of the system. The second step consists in the investigation of the sustainability concept, and of how it can be put into operation to assess agroecosystems. Finally, the last step aims at integrating models and sustainability assessments into an optimization problem to provide a decision support tool to help develop ‘more’ sustainable agroecosystems. The first outcome of this thesis is a crop dynamic model that simulates agroecosystems, including mechanisms of competition for limited resources, and it is flexible enough to describe both monoculture and multi-species systems (Figure 1).

The development process behind the model and the model itself allowed to understand the functioning of agroecosystems and to highlight the main processes and components involved. It ultimately aims to support the comparison of alternative agroecosystems, characterized by different species composition and biodiversity levels (e.g., monoculture vs. agro-forestry) from an ecosystem services perspective. Secondly, we develop a comprehensive and multi-spatial scale sustainability assessment framework for agricultural systems (Figure 2), including a set of quantitative indicators covering the three dimensions of sustainability (i.e., environmental, economic, and social one, the latter being focused on nutrition), and we test it onto the assessment of domestic food production in the Gaza Strip. The framework definition and its application supported the understanding of how the sustainability concept can be put into operation to quantitatively assess food systems. Focusing on the environmental sphere of sustainability, we investigated how the consumption and depletion of natural resources, the impacts on the environment and on the functioning of ecosystems due to food production can be assessed through the Life Cycle Assessment (LCA) and Ecosystem Services (ESs) Assessment methods. On the
The automotive industry is rapidly evolving and the advent of fully autonomous cars seems every day closer. The problem of autonomous driving has been widely discussed in the academic environment in the last decades and it covers many fields of the Information Technology from the sensing to the control. This research work is focused on the main aspects related to the control of vehicle dynamics. The main control systems developed so far in the automotive field aimed to improve the driving experience or help the driver in the most challenging maneuvers. With the advent of fully autonomous cars these features will lose their value, but two factors will gain significant importance: comfort and safety. Since several studies conclude that the most of car accidents are caused by human mistakes, safety has become the main driver for autonomous drive development. This research aims to improve these two important requirements by controlling the vehicle dynamics in case of emergency situations and in very uncomfortable scenarios. High speed driving and emergency maneuvers mainly excites the longitudinal and lateral vehicle dynamics. Lateral dynamics control is the most challenging problem when dealing with quick maneuvers like an obstacle avoidance. The trajectory preview plays an important role in this case and most of the works in the literature exploit this feature using the Model Predictive Control (or other optimization based techniques). While these techniques give the possibility of considering the future reference trajectory and the nonlinearities of the system, it is not suitable for sudden obstacle avoidance due to the high computational time especially when cheap hardware has to be used. In this work two path tracking methods for accurate tracking of high speed and emergency maneuvers are developed. The proposed algorithms exploit the preview without asking an excessive computational burden and without the need of lateral speed measure that is often unavailable. Another important issue in emergency maneuvers is the planning of the avoidance trajectories: the most of the approaches in the literature don’t consider the path tracking control dynamics that becomes fundamental in case of quick maneuvers. Moreover the planning must be completed as fast as possible not to risk to make the avoidance unfeasible. The approach presented in this work is based on the characteristics of the best performing controller between the two developed to guarantee feasibility and optimality in the path generation. The standard presence of “preview sensors” like cameras in self-driving cars can become useful also in case of driving on particularly uncomfortable scenarios, for example in presence of potholes and bumps. A vehicle equipped with stereo cameras is used to experimentally explore the possibilities of having preview information about the presence of a bump/obstacle. Depending on the available information two comfort oriented control strategies are designed. The experimental analysis and validation was performed with a vehicle made available by the European Honda Research Department.

Lateral Control. Two control techniques have been developed for high-speed/highly-dynamic driving exploiting the preview. To deal with non-linearity introduced by the variation of longitudinal speed, the system is considered as a LPV system, where the speed is a low varying parameter.

• Look-ahead based LPV control: it consists in a self-scheduled H-infinity controller. The objective is to control 2 variables: the lateral error with respect to the reference trajectory at the CoG of the vehicle and the first derivative of a look-ahead error defined as the distance between a virtual point on the same longitudinal
Motion planning is one of the most important factors affecting the functioning of an autonomous vehicle and aims to find a collision-free motion guiding the vehicle from an initial configuration to a final one. In particular, kinodynamic motion planning addresses this very issue, taking also into account the dynamics of the system so that the resulting solution would be executable by the vehicle. For most applications, the solution to the trajectory planning problem has to satisfy some desirable properties; e.g., reaching the goal in minimum time by minimizing the energy consumption or by maximizing the safety. These requirements shift the focus from finding any feasible trajectory to finding the optimal trajectory for a given objective function. This thesis addresses the optimal motion planning problem with a strong emphasis on inclusion of the underlying realistic dynamic system as an object of the planning. The proposed approaches consider arbitrary dynamics without imposing strong restrictions on their characteristics. Furthermore, the motion planning problem is also widened to encompass some particular aspects such as the role of the topology on the generated trajectories and constraints imposed by the landmarks. The problem of optimal kinodynamic motion planning is addressed, using important classes of motion planning algorithms: the exact approach and the sampling based approach. The former looks for a solution in the continuous state space, while the latter samples this space redefining it as a graph where nodes are connected via edges representing local trajectories between sampled states. The optimality for a sampling based planner is achieved once all the nodes are connected to the underlying graph representation optimally, possibly rewiring the graph by testing connections within a neighborhood. The same strategy applies to kinodynamic planning as well, with the additional difficulty that when optimality is required, connecting two nodes involves solving a two point boundary value problem (TPBVP), which is computationally challenging especially when dealing with complex dynamics, such as for non-holonomic systems, in presence of actuation constraints. To this end, this thesis contributes with a new optimality algorithm (RRT*_MP) that samples the state space in a grid representation and generates a tree of trajectories using a database of motion primitives. Therefore, the computationally intensive part of solving for a TPBVP is carried to the preliminary phase of database generation by alleviating the computational load during planning. This represents a promising result for online applications, especially in dynamic environments where the planner has to generate a new trajectory in response to changes in the environment. Furthermore, it allows to compute the true cost-to-go in order to guide the expansion of the tree, improving the convergence properties. The algorithm is proven to be asymptotically optimal as the grid resolution goes to zero and number of nodes goes to infinity. The (sub)optimality caused by the gridding can be tuned to compromise between the size of the database and this performance degradation. Planning with topology constraints has gained an increasing attention in the recent years. Other than obtaining a collision free trajectory that minimizes a selected objective, one might be interested in how the resulting trajectory avoids the obstacles. This interest a number of fields in the robotics and autonomous vehicle applications, ranging from avoiding dangerous zones, coordinating multiple agents for better exploration, following rules on how to avoid obstacles. Furthermore, other than imposing some rules about how to avoid the obstacles, it is also possible to use the topology information for obtaining a number of distinct good trajectories or for decomposing the otherwise complex trajectory.
Over the last decades, the complexity of systems is continuously increasing due to economic reasons and technological advances. It is known that the centralized Model Predictive Control (MPC) solutions for such large-scale systems might result in unacceptable control performance due to various factors, such as high dimension of the system, computation efficiency and communication bandwidth. Moreover, centralized controllers are not scalable and difficult to maintain. For these reasons, in the last twenty years, decentralized and distributed MPC algorithms have been developed with a number of local problems solved in parallel to achieve global or local objectives. An alternative to decentralized and distributed control consists in the use of hierarchical control structures based on MPC. This approach is very powerful especially for control of systems with separable fast and slow dynamics, for the coordination of subsystems and when it is required to consider different objectives in the long term and regulation problems in the short term. This Thesis addresses the theoretical development of hierarchical and multilayer control algorithms based on MPC for large-scale systems. In Chapter 2, we develop a two-layer control structure for the coordination of independent linear dynamic systems with input and joint output constraints. At the higher layer, a reduced order dynamic model of the system's components is used to state and solve an economic MPC algorithm in a long time scale. The outcomes of this layer are the components of the control variables to be held constant over the long sampling periods. At the lower layer, decentralized MPC controllers, one for each subsystem, are implemented in a shorter time scale and according to a shrinking horizon strategy to compensate for the model inaccuracies at the high level. The overall convergence, recursive feasibility, as well as the fulfillment of the joint constraints, are obtained under mild assumptions. A fully scalable hierarchical control scheme for coordination of similar independent systems with joint output and input constraints is presented in Chapter 3. Differently from Chapter 2, a scalable low-dimensional model mapping the common input to the collective output is used at the high layer, this model is easily determined from the impulse responses of the subsystems. The outcome of the high layer is the value of the common input to be held constant and to be distributed among the subsystems based on a specific weight associated with each subsystem. This approach allows to modify the system configuration with time varying weights, in terms of the contribution provided by any subsystem to the overall system performance, and to implement plug-and-play operations. The recursive feasibility is guaranteed also during plug-in and plug-out operations, and the overall convergence of the system output to the set-point is proven. Finally, in Chapter 4, we extend the hierarchical control structure to large-scale interconnected systems. At the higher layer, a robust centralized MPC algorithm based on a reduced order dynamic model optimizes a long-term performance index, while at the lower layer local MPC regulators, are designed for the full order models of the subsystems to refine the control action computed at the higher layer. The recursive feasibility and robustness of the two layer algorithm are guaranteed and the overall convergence of the state to the steady state is fully discussed. Several simulation examples are reported to show the effectiveness of all the proposed algorithms.
This work addresses the network reliability challenges of cloud-based services with special focus on two specific use-cases. The former considers the resiliency of Cloud Service Providers (CSPs), which exploit cloud networks to provide ubiquitous access to contents, while the latter concerns Infrastructure Providers (InPs) and targets the case where Network Functions (NFs) are implemented as software modules and run in virtualized environment, spread across the network.

This dissertation is motivated by the growing need of resiliency in cloud-based networks. In particular, as the Internet is shifting from being an end-to-end communication model, to an end-to-content communication model, CSPs are investigating novel resiliency mechanisms to maintain the service continuity, especially in case of disaster-based failures. In case of such widespread failures, CSPs might not be able to guarantee the Network Connectivity (i.e., the reachability of all nodes from any node in the network). Hence, researchers proposed the concept of Content Connectivity (i.e., the reachability of the content/service from any node in the network) that can be satisfied even if the CSP’s virtual network is disconnected. On the other hand, the increase of cloud-based service adoption urges InPs to investigate new strategies to contrast the competition of CSPs and keep stable profit margins. In this context, Network Function Virtualization (NFV) was proposed as a new architectural paradigm to improve the flexibility of network service provisioning, reduce Capital Expenditure (CapEx) and Operational Expenditure (OpEx) and decrease the time to market.

Figure 1 shows a detailed overview of this set-up running on top of a cloud-based infrastructure. The figure illustrates also the clear separation between CSP and InP domains. In particular, the CSP handles the virtualization of applications and management of hardware clusters that can be whether centralized or distributed across the edge of network (i.e., edge computing). NFV can revolutionize how InPs design their infrastructure by leveraging virtualization to separate software instances from hardware appliances, and decoupling functionalities from locations for faster service provisioning. NFV supports the instantiation of Virtual Network Functions (VNFs) through software virtualization techniques and runs them on Commercial-Off-The-Shelf (COTS) hardware. Hence, the virtualization of network functions opens the way to the provisioning of new services without the installation of new equipment. NFV simplifies service deployment by exploiting the concept of service chaining: a Service Chain (SC) is a sequential concatenation of VNFs and/or hardware appliances to provide a specific Internet service (e.g., VoIP, Web Service, etc.) to the users. However, deploying NFV solutions in operational networks require solving multiple issues related to performance, availability, security and survivability. One important key design in an NFV framework is the ability of the NFV-Manage and Orchestration (NFV-MANO) component to ensure service continuity. Such objective translates into many requirements that the Network Function Virtualization Infrastructure (NFVI) must satisfy, among which resiliency and geo-redundancy requirements, which are the focus of this work.

In light of the above, this dissertation is motivated by the growing need of resiliency in cloud-based networks. In particular, as the Internet is shifting from being an end-to-end communication model, to an end-to-content communication model, CSPs are investigating novel resiliency mechanisms to maintain the service continuity, especially in case of disaster-based failures. In case of such widespread failures, CSPs might not be able to guarantee the Network Connectivity (i.e., the reachability of all nodes from any node in the network). Hence,
researchers proposed the concept of Content Connectivity (i.e., the reachability of the content/service from any node in the network) that can be satisfied even if the CSP’s virtual network is disconnected. On the other hand, the increase of cloud-based service adoption urges InPs to investigate new strategies to contrast the competition of CSPs and keep stable profit margins. In this context, Network Function Virtualization (NFV) was proposed as a new architectural paradigm to improve the flexibility of network service provisioning, reduce Capital Expenditure (CapEx) and Operational Expenditure (OpEx) and decrease the time to market.

**Thesis contribution.** In this dissertation, we address some open challenges in the resiliency of next-generation cloud-based networks. The main contributions of this thesis work are as follows:

- **New optimization models and heuristic algorithms** to evaluate the potential power savings introduced by the combination of multiple power reduction strategies in protected IP-over-WDM networks, with focus on dynamic traffic conditions.

- **New optimization model and heuristic algorithms** to evaluate the potential power savings introduced by the combination of multiple power reduction strategies in protected IP-over-WDM networks, with focus on dynamic traffic conditions.

Figure 1: Network virtualization and cloud-based services with separation between Cloud Service Provider (CSP) and Infrastructure Provider (InfP)

- **New optimization models and heuristic algorithms** to evaluate the potential power savings introduced by the combination of multiple power reduction strategies in protected IP-over-WDM networks, with focus on dynamic traffic conditions.

- **New optimization models and heuristic algorithms** to evaluate the potential power savings introduced by the combination of multiple power reduction strategies in protected IP-over-WDM networks, with focus on dynamic traffic conditions.

- **New optimization models and heuristic algorithms** to evaluate the potential power savings introduced by the combination of multiple power reduction strategies in protected IP-over-WDM networks, with focus on dynamic traffic conditions.

Figure 2: Proposed technical solutions, area of application and paper organization

**Figure 2** summarizes the overall contributions and shows their respective area of application in a cloud network. Three out of the four proposed contributions are applied in core networks, while the fourth is applied in metro networks. The contributions in Chapters 3, 4 and 5 benefit to the InP, while our contribution in Chapter 2 assumes that the CSP and InP constitute a single provider, which corresponds to the case where an InP has its proper Cloud infrastructure and hence can play the role of a CSP as well (e.g., Vodafone).

The technical benefits of radar as a level measurement technique are clear. Radar provides a non-contact sensor that is virtually unaffected by changes in process temperature, pressure or the gas and vapor composition within vessel. In addition, the measurement accuracy is unaffected by changes in density, conductivity and dielectric constant of the product being measured or by air movement above the product. These benefits have become more significant to the process industry since the advent of low costs, high performance, two wire loop powered radar level transmitters. This breakthrough, in the summer of 1997, produced an unprecedented boom in the use of non-contact microwave radar transmitters for liquids and solids process level application. Currently, there are two FM-CW and Pulse radar techniques in common use for level measurement applications. Design theory for both types of radars are well known, while the developing process can be a challenge and usually requires original techniques to experimentally verify the operational performance of the radars. In radar technology, to make a contribution in developing process of front-end RF circuits, it is required to have competitive system with the performance and cost of radar systems in use today.

The major objective of the dissertation was to design and fabricate a front-end RF system for level measurement pulse radars in order to push the radar capability a step further by higher frequencies (K-band). Since radar design techniques are well-known theoretically, challenges of the work were under experimental phase. The aim was achieved while there were limits regarding budget, available components, laboratory instruments and etc. The front-end microwave module took advantage of smaller size, low cost and ease of fabrication in comparison with many other level measurement radars. Each block of the system (oscillator, filter, mixer, directional coupler, antenna) was individually designed and realized and the simulation and measurement results were reported. All blocks came together and form the front-end microwave module circuit. The microwave module circuit as a section of level measurement pulse radar device went under a real case scenario test to measure distance and results were presented. As long as compactness of electronic devices is requested, the antenna designer is pushed to reduce the antenna size as well. Planar antennas are widely used in variety of applications due to their compact shape, light weight, less complexity, low cost and ease of implementation and integration with microwave integrated circuits. Despite these significant advantages, planar antennas suffer low impedance bandwidth, low gain and poor radiation efficiency. However, we have designed and realized two types of novel planar array antennas with high directivity and gain. These two antennas could be used for level measurement process due to their high radiation efficiency in comparison with classic horn antennas which are most common types of antennas used in level measurement applications. Several other research activities that were carried out during the PhD cycle, are listed following.

- **A design method to realize multilayer polarization converter devices in transmission:** The method was validated by realization of two multilayer full cross polarization converter devices. These devices are capable to rotate the polarization 90-degree independently from the direction of the input linear polarization.

- **Design of two perfect linear polarization converter devices in reflection:** These devices are capable to rotate the polarization 90-degree for normal incident waves.

- **Implemented an efficient numerical method in order to use direct mode-matching technique to analyze step-discontinuity in elliptical waveguide:** This method allowed us to improve analysis performance of elliptical-shaped aperture in horn
antennas.
- Design and implementation of a novel dual-band partial reflective surface (PRS) in order to enhance the directivity of a dual-band planar dipole antenna. This periodic structure was effectively enhancing the directivity of the basis antenna, and it took advantages of simplicity, low cost, and ease of fabrication.
- Extraction a novel formula to calculate the effective dielectric constant of a structure consisting of antipodal planar dipole element: This formula was used to study the radiation performance of planar log-periodic dipole array (PLPDA) antennas. Introducing the proposed formula into classic design procedure of log-periodic dipole array antenna allows us to calculate the design parameters of a PLPDA antenna accurately.
- Design and implementation of a novel multi-layered dual-polarized planar antipodal dipole antenna: This antenna allows us to effectively apply polarization diversity technique in WLAN applications. Results illustrated -20dB isolation between ports for 25% bandwidth at 5.5GHz.

DECORRELATION PHENOMENA IN A GEOSYNCHRONOUS SYNTHETIC APERTURE RADAR: THEORY, TECHNIQUES AND PERFORMANCE

Leanza Antonio

Geosynchronous orbit (GEO) Synthetic Aperture Radar is a novel concept which would provide significant potential advantages over the present Low-Earth Orbit (LEO) systems. In particular the nearly-zero inclined GeoSAR would grant the continuous time coverage of the observed sub continental region with 12 hours revisit time, coarse resolution imaging every 20 minutes and high integration gain to compensate the significant spread loss, limiting in this way the required physical antenna size and transmitted power. However the long integration time (minutes to hours) introduces signal decorrelation problems. In this thesis the study of these decorrelation phenomena is tackled, providing analysis, performance evaluations and when possible, methods to counteract their effects on the focused images. After a general description of the main GeoSAR characteristics and potential applications, the nature of the main decorrelating sources is described, along with their respective effects on the Impulse Response Function of the GeoSAR system. In particular two decorrelation sources have been considered, since their contribution is more relevant for the GeoSAR system, namely decorrelating clutter and atmospheric phase noise.

Clutter decorrelation is due to those moving targets that slowly change their electromagnetic response within times comparable to radar observation interval. The phenomenon has been described through different models depending mainly on target type and timescale. Target decorrelation issue has been addressed with the two-fold purpose of analyzing the interferometric coherence for the GeoSAR candidate bands (C and X-band) and studying the moving target decorrelation on the sub-daily timescales comparable to the GeoSAR integration times. The analysis performed on Sentinel-1 (C-band) and Cosmo-Skymed (X-band) image stacks showed that, over vegetated areas, the decorrelation time constant results in the order of several tens of days for the C-band and rapidly falls down below one day in the X-band. The results brought to the conclusion that, to get acceptable performance in high-resolution GeoSAR interferometry over forests or rural areas, C-band is the limit frequency for the single sensor system while the X-band would require a constellation in order to reduce furtherly the revisit. Ground-Based radar Ku-band data have been exploited to evaluate clutter decorrelation from the mid-term (minutes) to long-term (hours). The mid-term observations showed the validity of Billingsley model, even if with significant differences between the predicted and observed parameters. In particular the observed decay rate β values resulted higher. The reason relies in the impact of small targets like leaves or grass, which is more relevant at Ku-band w.r.t. the lower frequencies analyzed by the Billingsley experiment, and the different portion of the spectrum analyzed in the two experiments. The long-term analysis indicated that target decorrelation, at this timescales, is better represented by the exponential model, also adopted for the interferometry. Furthermore these analysis highlighted that decorrelation is not stationary with a wide range of decorrelation time constants. This makes difficult the prediction of the performance in terms of Signal-to-Clutter Ratio which, in general, can be evaluated only in a statistical way. This, along with filling the gap between mid-term and long-term decorrelation behaviours, represents a challenging and interesting issues to address in future works.
PHD program in information technology

Both mid-term and long-term observations evidenced a daily and a seasonal trends that indicates how the performances improves during the night and/or during the cold months. Atmospheric phase noise (APS) is then addressed. In the considered bands, the main contribution is due to troposphere which introduces a delay in the wave travelling time and hence a multiplicative phase noise that depends on the acquisition time and targets position. Its statistical characterization has been exploited to derive a model of the APS affected Focused Impulse Response Function (FIRF) which allows to estimate significant effects such as the peak power loss, the mainlobe widening and the clutter noise originated by the sidelobes spreading. The optimal sub-aperture is then defined which represents the aperture interval that provides the best compromise, in terms of decorrelation, between the temporal and spatial contributions.

Unlike clutter decorrelation, APS decorrelation can be (partially) compensated. Hence it has been proposed a strategy to estimate it and compensate its effects in the focused image. The processing was composed by a sub-apertures interferometric-based estimation followed by a regularized MMSE focusing. The operations were repeated iteratively widening the sub-apertures. Exploiting a Sentinel-1 image and a possible GeoSAR design, a series of simulations have been performed in order to evaluate the proposed processing performance. The results showed significant improvements but limited by the sidelobes clutter, as foreseen by the theory. In fact simulations showed that the final residual decorrelation is comparable with the one observed in the optimal sub-aperture. Jointly analyzing the decorrelation phenomena, an important consideration is that decorrelating clutter noise is scene dependent whereas APS is not. In fact, decorrelating clutter nuisance is absent when urban areas (or stable targets in general) are imaged, no matter what the system frequency is. On the contrary, APS is always present on any kind of scene, even if with variable strength, and its impact significantly depends on the system frequency. For this reason, in the GeoSAR design, the choice of band depends mostly from the APS. According to the analysis performed, C-band would be a suitable solutions for a single-sensor COMSAT-like GeoSAR system (eccentricity = 0.0008). In the X-band (or higher frequency) APS impact becomes critical. However in this case reducing the synthetic aperture time, by the exploitation of a more eccentric orbit or by a multi-sensor system (constellation), could solve the problem and provide good performances.

Monitoring, diagnostic and early warning are becoming key tasks for an efficient management of many industrial processes. Conventional sensing systems are based on electrical devices such as accelerometers, vibrometers, strain-gauges and thermocouples, each one providing point measurements of a single specific parameter. However, optical fiber sensors can now provide an alternative sensing methodology, owing to important advantages such as resistance to harsh environments, absence of electromagnetic interference and small size, which allows them to be directly embedded in the structure to be monitored. A single optical fiber can be used both as the sensing element and the leading cable conveying information back to the receiver, which can thus be placed far away from the monitored area. A further key feature of fiber optic sensors is their capability in providing highly-accurate multi-parameter information on the entire monitored structure in a truly distributed way, thereby replacing, with a single optical cable, a plurality of discrete sensors. From the 80s, distributed fiber optic sensors have been the subject of extensive research. They rely on inelastic scattering phenomena, such as Raman and Brillouin and usually exploit stimulated configurations. When the stimulated backscattering configuration is used, access from both sides of the sensing fiber is required. This way, high signal to noise ratio is guaranteed, allowing for more accurate measurements. Extensive research on Brillouin-based sensing has been carried out continuously throughout the past 40 years, and many different configurations have been proposed, the vast majority of them exploiting the Stimulated Brillouin Scattering (SBS) process. The measurement principle relies on the intrinsic dependence on temperature and strain of the Brillouin Frequency Shift (BFS), that is the frequency detuning between a pump and a probe lightwave, counter-propagating inside the fiber under test (FUT), for which the Brillouin Gain Spectrum (BGS) exhibits a maximum. From the BFS, the strain/temperature distribution along the entire length of the sensing fiber can be inferred. The traditional time-domain based localizations approach (OTDR), which enables to relate information given by the BFS to specific positions on the FUT, allows for spatial resolution which is typically limited to ~1 m by the acoustic-wave response time. Yet, many predictive maintenance applications, such as thermoelectric generation, automotive and power cable manufacturing are now demanding smart diagnostic solutions able to provide a detailed information about temperature and strain distributions on machines, plants or mechanical components with a much better spatial resolution. For these applications the monitored distance might be quite limited, the main focus being more on a high number of sensing points, fast acquisition and cost-effectiveness. In this frame, phase-coded Brillouin Optical Correlation Domain Analysis (phase-BOCDA) can indeed be a potential solution fulfilling these new requirements. However, a few unsolved issues are currently limiting its actual in-field application. This research, starting form a basic phase-coded BOCDA scheme, mainly addresses these issues, proposing and integrating novel hardware and software solutions. At first, a novel two-steps estimation algorithm is applied to remove the background noise – which usually
contributes for more than 90% on the received signal. This approach has proven to be extremely effective, allowing to always recover a good quality BGS from which the BFS can be precisely calculated. Experimental results have proven the ability of phase-BOCDA setup to recover the temperature and strain profiles along the fiber under test with errors always lower than 1 °C and 20 με respectively. Attention has also been given to the typical low measurement speed affecting BOCDA approach. To speed-up the measurement, single slope-assisted and double slope-assisted approaches have been applied for the very first time to a phase-BOCDA scheme. Proof of concept experiments have shown that, while retaining the 2-cm spatial resolution achieved by frequency-scanning method, the measurement time can be effectively reduced by 100 times, this value being limited by the available electronics. In particular, double slope-assisted approach proved to guarantee a higher accuracy also in presence of SBS gain fluctuations and a better sensitivity for small strain values. Finally, polarization issues affecting the efficiency of Brillouin amplification process, and thus reducing the measurement accuracy, have been addressed. Polarization scrambling has emerged as the most hardware-wise solution to avoid polarization fading issues, as it does not require consistent modifications of the BOCDA layout. However, the low scrambling speed ensured by commercial polarization scramblers based on electro-optic components can be a limiting factor when high-speed measurements are required. For this reason, we have investigated and developed a novel all-optical and completely passive device based on polarization chaos nonlinearly excited in an optical fiber through cross polarization interaction between a light wave and its intense backward replica generated by means of an amplified reflective loop. The proposed system can reach scrambling speeds as high as 610 krad/s with a Degree of Polarization (DOP) lower that 2.5%, thus clearly outperforming conventional scramblers. As the main elements involved in the scrambling setup are also required in the BOCDA scheme, a new phase-BOCDA layout has also been proposed, which directly integrates the all-optical scrambling capability.

Figure 1: Example of a 3D BGS measured by phase-Coded BOCDA sensor. FUT sections subject to strain and temperature changes are highlighted.

Figure 2: Different strains measured on an 8-cm strained FUT section.

Figure 3: Different temperatures measured on a 5-m heated FUT section.

Biosensors are essential tools for the daily life of everybody, used in various environments from clinical exams for patients up to control of water quality in distribution sites. There are several technologies available for implementing biosensors, but research in this field is always looking for new solutions, aiming for higher sensitivity, faster responses, wide dynamics range, solution suitable for low cost implementations, etc. The three years of Ph.D. have been mostly dedicated to the research on integrated optics circuits for biosensing application. The field of biosensors is a wide multidisciplinary field regarding different competences to successfully arrive to a prototype. The research has mainly concentrated on the implementation of an innovative, robust, and reliable integrated optical device for the detection of several analytes. The reported activities have been connected within a EU project, a Regional project, a collaboration with companies, and an internal project. Both label-free and label-based approaches have been explored. With label-free assay, the biotransducer has to convert the biological event without the support of any other kind of additional elements or processes. An optical device based on integrated microring resonators, whose resonance wavelength is affected by the presence of analytes over the waveguide has been conceived, realized, and tested. The platform showed important results, for example by detecting Ovalbumin protein (a Ricin A toxin simulant) down to a concentration of 100 PM. Detection of DNA was also achieved, focusing in particular on the functionalization of the microring resonator with a novel method based on Micro-Contact Printing. We decided to move to label-based approach, and in particular to exploit a combination of optical and magnetic approaches, in collaboration with Nanomagnetism for Biology and Spintronics Group (NaBiS) of Prof. R. Bertacco. In our research, we combined the use of magnetic beads as labels with our optical device, exploiting the invasive impact that these beads have on the optical mode. The first results showed an enhancement of the detection limit of almost three orders of magnitude when magnetic beads were used. Following this path, we designed a novel platform that increases the interaction of optical detection and magnetic properties. By the use of an electromagnet, we were able to actually move the beads. The oscillation of the beads induces a variation of the evanescent optical field and hence a fluctuation of the optical phase. If a biological molecule links the beads to the optical device, the oscillation applied to the beads is transformed into a stretch of the molecule itself and can be detected from the output optical power. This opto-magnetic platform has some advantages, the main one is the possibility of an on-off detection, since the signal is revealed just in presence of molecules, magnetic beads, and magnetic field. We tested this platform by using DNA strand to link the optical waveguide to the beads. The results show that the platform works correctly, as the signals matched with the expected values, in particular the stretch constant of the DNA matched with the observed displacement of the beads. A patent was filled to cover this innovative concept. The second path
The timbre of musical instruments is one of the most complex and ambiguous case of study in music research. The lack of a mathematical formulation, the subjectivity of timbre description and the dependency on the data make this property far from being exhaustively understood. Nevertheless, timbre is a very important aspect of music and it is of great interest for manufacturers, musicologists and researchers to be able to analyse and control the sound properties of musical instruments.

Among the others, the sound of the violin received particular interest for decades, due to its complex behaviour and the aura of legend that surrounds the masterpieces of the ancient Cremonese masters - Stradivari, Guarneri, Amati. The violin is a complex instrument made of tens of different pieces and materials and involving non-linear interactions between its components. Researchers correlate acoustical properties, materials and structural behaviour to timbre perception, but many aspects are still unclear.

In this thesis, timbral analysis techniques are studied and applied to the specific case of violins. The choice of this class of instruments depends on different reasons: the aforementioned complexity of the bowed instruments family; the great interest in the manufacturing, music and research communities; and the availability of the remarkable collection of the Violin Museum in Cremona, that includes historical and top-quality contemporary violins. The timbral musical timbre depends both on the physics of sound (low-level perspective) and human perception (high-level perspective). For this reason, this study is conducted at different levels of abstraction. The first level concerns the measurable aspects of the audio signal. The second level is related to how the listener perceives and describes the sound.

This study requires a proper data collection stage. In particular, this stage includes audio recordings, interviews with violin makers and a listening test where the subjects evaluate the timbre of the recorded violins.

First we recorded 50 violins in Cremona including historical instruments from the Violin Museum, top-quality contemporary instruments from the Triennale competition and low-quality violins from the violin making school Istituto Antonio Stradivari. We obtained a considerably large, diverse and unique dataset which is the basis for this study. The recordings include different performances: open strings, single notes, a major scale and six musical excerpts. The interviews have been conducted with the purpose of collecting the words that are typically used to describe the timbre of violins. We interviewed 18 violin makers in Cremona and we collected several descriptors, their meaning and the relations among them.

As for the listening test, the purpose was to annotate each violin in the dataset with a set of numbers describing its timbre. The descriptors collected during the interviews were arranged in pairs (e.g. Dark/Bright) and, for each violin recording and each pair, the subjects were asked to provide a number from 1 to 10.

For what concerns the low-level analysis, the purpose is to investigate measurable properties of the audio signal that timbre relies on. A typical way of analyzing such properties is called feature-based analysis. This approach is often used in Music Information Retrieval (MIR) and it is based on the extraction of many objective quantities from the raw audio (low-level features). These quantities have a low degree of abstraction and are obtained by means of signal processing algorithms.

We define and extract a set of low-level features in order to capture various aspects of violin timbre. Since the literature suggests that the timbral relations between instruments depends on the pitch, we investigate this dependency. The results suggest that the differences between violins change with the played note. This phenomenon

was to improve the resolution in the detection of resonance wavelength shift. In the first experiments, detection of wavelength shifts was performed by spanning a tunable laser source over a certain wavelength range. With this method, achieving a resolution under 10 pm is very critical. To overcome these limitations, we developed an electronic-photonic platform together with STMicroelectronics (STm). The main concept is the locking of a tunable laser to a microring resonator through an electronic feedback loop. In particular, we designed an add-drop microring resonator, whose powers at the output ports are balanced by the tuning of a laser wavelength. In this scheme, biological events will induce a shift of the microring resonance that is tracked by the electrical signal that drive the laser. The platform required a lay activity in collaboration with STm in order to be designed and tested. As results, we were able to distinguish step changes in the wavelength shift down to 9 femtometers, three orders better than state-of-the-art. In conclusion, with this Ph.D. work, we developed optical platforms for biosensing. The obtained results are beyond the state-of-the-art concerning optical biosensors. The close relationship with other research groups and industries have been essential for this path, allowing to generate innovative ideas and concepts. The experimental side of the Ph.D. has been wide and essential, in particular in the Photonic Device Laboratory and in Polifab. The future steps will focus on the integration of the two platforms in a single solution, capable of joining the main features of the both.
The research work is focused on characterization of dielectric materials for microwave and terahertz imaging systems. Novel source antenna designs are proposed and a couple of time domain data inversion techniques are implemented in order to study dielectric material characterization of solid objects. Interaction of electromagnetic waves with materials is studied, where the variation in magnitude and phase of the transmitted and reflected wave has been observed with and without presence of dielectric material for calibration purpose. Different data inversion techniques are developed and tested e.g. Fourier inversion and Bayesian inversion. Time and computation efficiency of the post processing techniques has also been enhanced significantly, by using proprietary code in MATLAB. The dielectric measurement are carried out at PoliMi and UPC Barcelona to validate the results in multiple environments and test benches. The materials tested have dielectric constant in the range of 2 to 12 thickness ranging from 0.5mm to 10mm. Both single and multi-layered materials at different frequency bands i.e; 26-40GHz, 75-110GHz and 915-925GHz are measured during the experiments. The Bayesian inversion method provides a measure of reliability on material properties since, the probability density is calculated and corresponding eigenvectors are plotted to find the confidence on observed parameters over model parameters. The novel horn antenna designs and improved time domain data inversion techniques made in this research, are very useful contribution in the development of latest dielectric measurement and imaging systems. The possible applications of this research are biomedical imaging for detection and diagnoses of cancer, non-destructive testing of structural defects in objects and communication systems with ultra-high data rates.