



Chair:
Prof. Carlo Fiorini

DOCTORAL PROGRAM IN INFORMATION TECHNOLOGY

Introduction

The PhD program in Information Technology (IT) goes back to the year 2001, when the two traditional programs in Automation-Computer Engineering and Electronics-Telecommunications were merged. As such, the unified course covers the research interests in four scientific areas, namely Computer Science and Engineering, Electronics, Systems and Control, and Telecommunications. This broad variety of research activities is completely focused in the ICT area, and perfectly corresponds to the core mission of the Dipartimento di Elettronica, Informazione e Bioingegneria (DEIB). However, pursuant the history of the Department, and following the new trends of the modern society, some cross-related research fields are also encouraged, such as ecology, environmental modelling, operations research, and transportation systems. The PhD program in IT is the largest at the Politecnico in terms of number of students. There are more than 60 first year students and about 170 in total. The students are subject to an examination every year to evaluate the progress achieved in their research and course work.

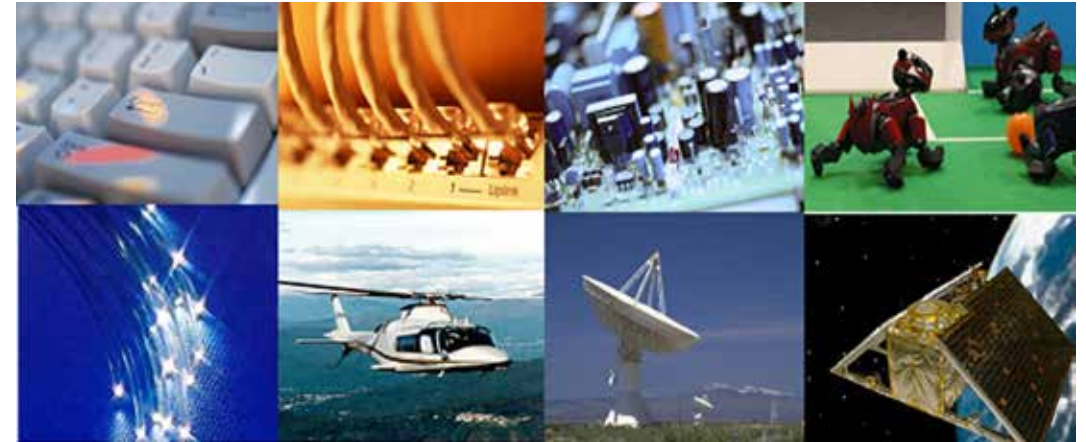
Topics

The research carried out in the Department in the field of Information Technology (including 35 between computing or experimental laboratories) can be subdivided into 4 main areas: *Computer Science and Engineering* (Vice-Coordinator: Prof. Andrea Bonarini): Information systems, Database management, Information design for the web, Methods and applications for interactive multimedia, Embedded systems design and design methodologies, Dependable systems: performance, security and reliability, Autonomous robotics, Artificial intelligence, Computer vision and image analysis, Machine learning, Dependable Evolvable Pervasive Software Engineering, Compiler Technology, Natural Language Processing and Accessibility.

Electronics (Vice-Coordinator: Prof. Angelo Geraci): Circuits and systems: theory and applications, Single-photon detectors and applications, Radiation detectors and low noise electronics, Electronic circuit design, Electron devices.

Systems and Control (Vice-Coordinator: Prof. Carlo Piccardi): Control systems, Robotics and industrial automation, Optical measurements and laser instrumentation, Dynamics of complex system, Planning and management of environmental systems, Operations research and discrete optimization.

Telecommunications (Vice-Coordinator: Andrea Virgilio



Monti Guarnieri): Networking, Applied electromagnetics, Information transmission and radio communications, Optical communications, Wireless and space communications, Remote sensing, Signal processing for multimedia and telecommunications.

Industrial collaborations

Due to its intrinsic technological nature, the PhD curriculum is corroborated by many industrial collaborations. About 25% of the total number of scholarships are funded by industry or by international research projects involving industrial partners. In the school vision, the collaboration between university and industry is ideally based on the challenge of turning invention into technological innovation. This amounts to shaping new technology frontiers and to building a fertile atmosphere for a mixture of world-class research at universities and in private companies. This also amounts to creating a common terrain of friendly culture, to size the risk and to believe in strong basic research. The external referee board is composed by members of public and private companies, working in industry and in applied research. The board is in charge of monitoring the activities of the PhD program and giving suggestions for its development. The board meets once a year to point out the new emerging research areas worth to be investigated and to monitor the visibility of the course in the industrial world. In 2008, the PhD "Alumni Association" was started, that organizes a successful yearly scientific and relational event (PHDAEY).

Educational aspects

The teaching organization and subject of the courses reflect the scientific interests of DEIB faculties. The curricula include a wide choice of courses (about 30 per year), of different nature. The challenge is to promote interdisciplinary research while offering technical advanced courses that spur innovative and cutting edge research. Therefore, particular attention is devoted to help each student to make the best choice according to an internal regulation scheme.

Internationalization

Every year, thanks to specific budget grants available in the Department, at least 10 courses are delivered by foreign professors. Moreover, the PhD program encourages joint curricula through agreements with foreign institutions. At present we count joint agreements for a Double PhD Program with New Jersey Institute of Technology (NJIT) in the electrical and computer engineering disciplines; academic cooperation for a Double Doctoral Degree with the Graduate School of Engineering and Graduate School of Life and Medical Science, Doshisha University, Japan; double PhD Program with Queensland University of Technology, Australia; between DEIB and the Drexel University, Philadelphia, Pennsylvania, USA; Double PhD Program with the University of Western Ontario, Canada; Joint PhD Degree Program between DEIB and Georgia Institute of Technology – Atlanta USA; Agreement for co-supervision of a doctoral Thesis with Ecole

Polytechnique de Montreal – Canada.
The PhD program in Information Technology participates in ICO-NEH (International Curriculum Option of Doctoral), in Erasmus mundus Programs: STRONG-TIES Strengthening Training and Research Through Networking and Globalisation of Teaching in Engineering Studies and GREEN IT for the benefit of civil Society (North Africa – for incoming and outgoing mobility) and a Cooperation agreement with “Escuela superior Politecnica del Litoral” (Ecuador) for admission of Doctoral candidates. Some activities are organized within the Network

of Excellence EURO-NF (Network of the Future) and of ACCM, Austrian Centre of Competence in Mechatronics.

Every year at least 4 fellowships are assigned to foreign students, selected on the basis of their CV and research interest.

Conclusions

It is quite clear that the core mission is to offer an excellent PhD curriculum, through high quality courses, a truly interdisciplinary advanced education, cutting-edge research, and international and industrial collaborations.

ADVISORY BOARD

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Prizes and awards

In 2012 the following awards have been obtained by PhD students:

Chorafas Foundation Award: Luigi Malagò, Ilaria Malanchini

Best Ph.D. in Information Technology Award: Fabio Della Rossa

Health Awareness Award: Matteo Valoriani

Yahoo! 2012 Key Scientific Challenges Programming Award: Sofia Ceppi

IRPS Best Student Paper Award: Carmine Miccoli

SIMULATION, DESIGN AND TESTING OF INGAAS/ INP SINGLE-PHOTON AVALANCHE DIODES

Michele Anti - Supervisor: Alberto Tosi

During the last decades, the interest of the scientific world on Single Photon Avalanche Diodes (SPADs) has increased constantly, mainly because they can detect very low signals and have high timing resolution and detection efficiency. Their good performance made them the best choice for many different applications, from biomedical field to optical testing of VLSI circuit. The research on Single-Photon Avalanche Diodes led to design and manufacture high performance silicon detectors (low dark count rate, high timing resolution, and high detection efficiency). However, there is an increasing request for single-photon detectors for the near-infrared wavelength range ($\lambda > 1 \mu\text{m}$), able to operate at high count rates (i.e. with low afterpulsing) with low dark counts, high detection efficiency, and low time jitter. For this reason the use of materials with lower energy gap, such as the InGaAs compound, has been investigated to design photo-detectors that can detect also longer wavelengths, including 1550 nm that is commonly used in many applications based on optical fibers. Aims of my thesis has been the simulation, design and test of SPADs capable to detect near infrared (NIR) photons. Simulation is done by means of an in-house built tool that integrates mathematical

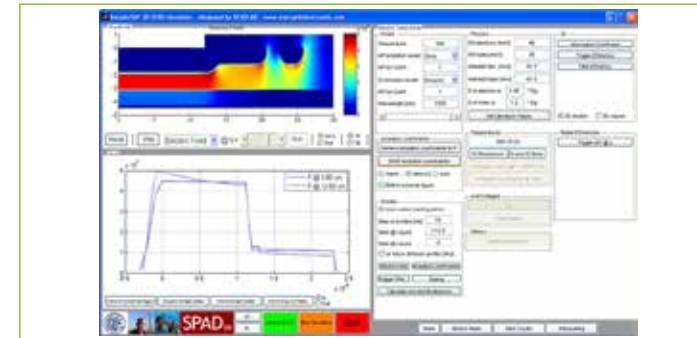
and physical models described in literature with additional modelling developed ex-novo, and exploits such models to optimize the final design of the SPAD. The possibility to design our own masks and the layer structure allowed also to add integrated resistors, an additional component for improving SPAD performances. The initial part of my PhD has been focused on the development of a finite-element-method InGaAs/InP SPAD simulator, able to perform mono-dimensional and bi-dimensional simulations. Other device simulators already available are excellent for 1D, 2D and 3D simulations of electric fields, depleted region extension, carrier concentrations, etc., but they do not give information about the final "detection performance" of the SPAD. The custom SPAD simulator is able to simulate basic SPAD parameters such as electric field profile, breakdown and trigger efficiency, as well as photon detection efficiency, dark count rate and afterpulsing effect for different values of temperature, layers thickness and other parameters. This simulator has demonstrated to be fundamental during the design phase, when we optimized the structure, and the test phase, when we faced some fabrication process issues.

I paid a lot of attention also to simulation speed, since a long calculation time delays the development of the detector, limiting the understanding and solution of possible issues. For this reason I developed a custom mesh generator which refines the grid near the curvature of the diffusions and increases the element dimension in neutral regions, thus reducing the total number of elements simulated. A simple graphical user interface presents to the user all the possible simulations and allows exporting the results in many different formats, either graphically or by text. Physical models used inside the simulator to calculate impact ionization, breakdown, photon detection efficiency and primary dark count rate have been studied in the literature, while models used for afterpulsing characterization have been developed autonomously due to the lack of complete models in previous works. The tight collaboration with the partner fab has started with the zinc diffusion calibration in order to study its dependence on temperature, gas flow and time, and continued during three production runs in order to match the designed SPAD structure and find the best process conditions. Totally me and my colleagues designed two set of masks and hundreds

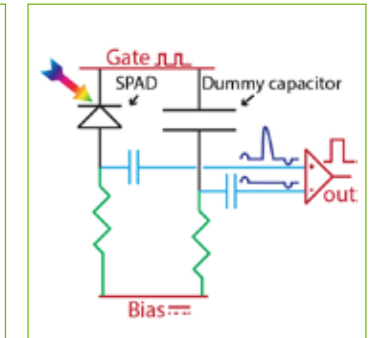
of different SPAD structures to understand the best geometry possible. Moreover we included other devices such as photo-detectors arrays, resistors and transistors. Most of the devices designed and manufactured by the foundry have been tested with our laboratory equipment

of electric fields, which was one of the design targets, resulted in very good temporal response, with a FWHM equal to 66 ps, better than state-of-the-art devices which present a FWHM equal to 121 ps. The good uniformity of electric fields resulted also in a very low

chips, which is more linear and simple than others proposed by different authors, which are either not reliable or require additional process step. Instead, the proposed structure based on patterned Zn diffusion requires little space and no additional fabrication steps. Integrated



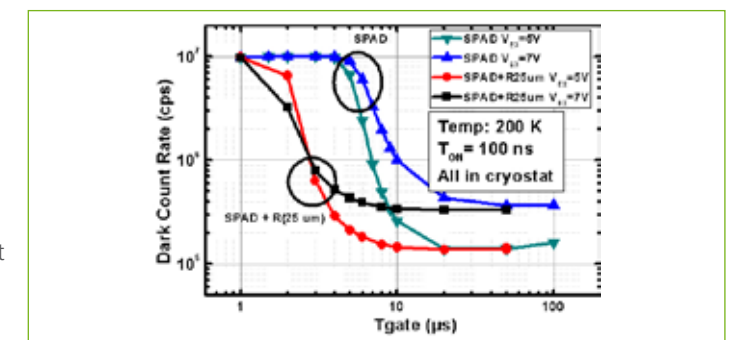
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in order to characterize their SPAD parameters. We have observed a good uniformity in terms of breakdown voltage on devices from the same wafer and between wafers diffused together in the MOCVD reactor, while differences have been observed in wafers with different miscut angles.

We characterized Polimi InGaAs/InP SPADs measuring their breakdown voltage, photon detection efficiency (PDE), primary dark count rate (DCR) and afterpulsing. At $V_{\text{EX}} = 5 \text{ V}$ detection efficiency is over 30% at wavelengths between 900 nm and 1600 nm, comparable to state-of-the-art devices, and is uniform across devices from different wafers. Dark Count Rate is less uniform from wafer to wafer and varies from 10^4 cps to 10^6 cps at $T = 200 \text{ K}$, a bit higher than state-of-the-art devices. The good uniformity



3.

afterpulsing affect, strongly better than state-of-the-art devices.

In this thesis I had also the opportunity to design integrated quenching resistor for improving SPAD performance. More than the device itself, the innovation on this topic is the method used to integrate it inside the

resistors have demonstrated to reduce the afterpulsing effect by at least a factor of 3.

SINGLE-PHOTON DETECTION FOR THE NEAR INFRARED WAVELENGTH RANGE

Andrea Bahgat Shehata - Supervisor: **Alberto Tosi**

In last years, single-photon detection in the near-infrared wavelength range has become more and more important when very faint or ultra-fast optical signals have to be measured. Advanced applications can be found in many fields, such as measurement of fluorescence decays (in physics, chemistry and biology), single molecule detection, characterization of new materials, non-invasive testing of VLSI circuits, single-photon source characterization, fiber optics testing, laser ranging in space and telemetry, quantum cryptography, quantum computing and studies in quantum physics. Different kinds of single-photon detectors have been developed in the past. Among the others, solid-state detectors have the advantage of high reliability and robustness, and they can be very compact and portable. Single-photon avalanche diodes (SPADs) are very sensitive and are characterized by high photon detection efficiency and good time resolution. In order to be sensitive in the near-infrared wavelength range, InGaAs/InP SPADs can be employed. Recently first detection modules based on InGaAs/InP SPADs devices have been developed. The latters, in fact, need a series of circuits in order to be properly exploited and operated. However state-of-

the-art instruments do not allow to configure all operating parameters, and therefore cannot be exploited in many applications. A novel high-end InGaAs/InP single-photon detection module, capable of performing photon counting and photon timing measurements, has been designed and developed to be as flexible as possible, in order to adapt to the different requirements of the near-infrared applications mentioned above. The instrument is composed by a control unit and a detection head, connected by a multipin wideband cable (Fig. 1). In particular three different versions of the control unit has been realized. The first two versions are based on discrete components, while the last one is based on the use of an FPGA, within which some of the sub-circuits of the previous versions have been implemented, together with new functionalities. Through all steps of the design and development the goal was to offer high flexibility of the overall instrument. All main system parameters, in fact, are configurable in a wide range. The SPAD temperature can be set down to 225 K (in order to reduce its dark count rate) by means of a TEC controller, with a resolution better than 0.1 K. The module can either work

with an internally generated trigger or can be synchronized with an external trigger (e.g. with the synchronization output from a laser). In the latter case the electronics accepts any kind of signal level (e.g. CMOS, TTL, ECL) or even a non-standard signal, positive or negative edge-triggered, either periodic or aperiodic, thanks also to the configurable input threshold. The repetition rate of the gate signal can be up to 133 MHz. In the last version of the control unit the circuitry for gate width configuration has been implemented within the FPGA. Different methods to generate programmable delays have been conceived (i.e. multiplexer chain, carry delayer, look-up table internal delay and ring oscillator) and combined together to achieve both dynamic range and resolution. Thanks to a delay auto-calibrator circuitry it has been possible to characterize the different delays to obtain a gate width as close as possible to the one configured by the user. With such implementation gate widths from 1 ns up to 65 ns and from 65 ns up to 1.5 μ s have been achieved, with resolutions respectively of 100 ps and 1 ns. High-speed counters ($f_{MAX} = 250$ MHz) have been implemented within the FPGA, allowing to measure the count rates of signals of interests, such as

the SPAD avalanches, the valid gates applied to the SPAD or the trigger rates. The module can be controlled either from a remote computer by means of an easy-to-use interface developed in LabVIEW environment, or locally, by means of a local user interface, based on a touch-screen LCD display. An extensive experimental characterization has been carried out to test both the electronics and the whole system (electronics + detector), proving outstanding performance, superior with respect to other state-of-the-art single-photon detection modules. In particular an effective afterpulsing reduction was measured thanks to prompt quenching of the avalanche by acting both at the anode and cathode side of the SPAD. Dark count temporal distribution showed excellent flatness inside the gate window, a fundamental requirement for single-photon timing applications, where sensitivity has to be as constant as possible within the gate window in order to avoid distortion in the reconstructed optical waveform. Moreover, the developed instrument is able to work at high repetition rates (up to 133 MHz), thus being exploitable for high count rate applications. Finally, the response of the system to a laser



1. Picture of the InGaAs/InP single-photon detection module

pulse has been characterized, obtaining about 150 ps (FWHM) timing resolution, limited only by the detector, itself. Thanks to these state-of-the-art performance, the developed photon counting module constitutes the enabling technology needed to perform measurements that once were unrealizable. To this aim, different national and international collaborations with other research groups allowed to test the detection system: i) a compact setup for time-resolved diffuse optical spectroscopy up to 1700 nm was developed (for the first time the absorption spectra of collagen was obtained up to 1700 nm using a time-resolved approach); ii) characterization of single-photon sources (demonstrating for the first time in literature room temperature heralded photon source generation from

a silicon nanophotonic chip at telecommunications-band, and demonstrating an extremely low-noise single-photon source based on parametric down-conversion with a periodically-poled lithium niobate crystal).

ENERGY SENSING AND CONTROL FOR THE FUTURE INTERNET OF ENERGY

Antimo Barbato - Supervisor: **Antonio Capone**

Traditional power grids face many challenges that they were not designed and engineered to handle. Firstly, the high correlation among energy demands of customers creates very high peaks in the energy demand. Since electricity grids have little capacity to store energy, power demand and supply must balance at all times. Energy plants capacity is therefore sized to correspond to total demand peaks, driving a major increase of the cost of the infrastructure that is also underutilized during off-peak hours. Another key issue is represented by the increasing decentralization of the power system due to more Renewable Energy Sources (RESs) such as hydroelectric, PhotoVoltaic (PV) and wind. Over the years, renewable energies have experienced a remarkable growth. In the European Union (EU), for example, a total of about 58.8 GW of new power capacity was constructed in 2010 and the renewable share of new power installations was 40%. The increasing diffusion of renewable sources is changing the traditional approach of managing the energy production. In fact, while in the past the energy production was centralized in a small number of large power plants connected to the High Voltage (HV) grid, nowadays there are

an ever-increasing number of medium-small size power plants distributed on Medium and Low Voltage (MV and LV) networks. Moreover, RES units are unable to change their energy injections according to the power system requirements. In this context, the energy dispatching results more difficult than in the past, therefore new instruments are required to ensure the real-time balancing between load and generation. Grid Energy Storage Systems (ESSs) represent one method that the operator of an electrical grid can use to solve problems related to peak loads and to adapt energy production to energy consumption. By most accounts, however, energy storage is still too expensive and inefficient. An alternate approach to grid energy storage is the smart grid in which a communication infrastructure is deployed alongside of the distribution network. The communication infrastructure that connects all distributed network elements, enables exchange of information and therefore makes the grid smart. All data provided by the grid can be used to optimize its efficiency and solve the problems stated above based on Demand Side Management (DSM) methods. DSM is a proactive approach used to modify consumers' demand for energy, over the

long-term, through various methods such as financial incentives and education. The residential sector represents one of the most promising scenarios to use demand side management mechanisms to effectively improve the energy distribution and usage efficiency. Domestic users, in fact, are becoming one of the major contributors to the countries energy balances. Despite the network operation cannot be analyzed without considering the final user perspective, loads, RESs and ESSs management cannot be left to users, since this new difficult task would significantly affect their everyday life. Therefore, an intelligent infrastructure based on Information and Communication Technology (ICT) tools is needed. In this thesis, we propose a framework to manage the energy demand of individual households and small user communities. The goal is to develop hardware and software prototype infrastructures capable of providing advanced tools to residential users in order to make them an active part of future smart grids. In order to support users in managing their energy plan, a novel architecture allowing real-time energy consumption monitoring and control is proposed. The framework proposed in this

thesis, in particular, is a demand side management system for residential users. In order to implement the proposed system we have worked on three specific topics:

- Sensor networks for the smart grid: monitoring systems allow reducing buildings overall energy use and improving the energy efficiency of the grid by providing both power consumption of devices and environmental information (e.g. temperature, users presence, light). Even if the development of sensor networks infrastructures is a research area which has been explored for many years, there are still limitations that prevent the spread of this technology. Sensors energy consumption, in particular, represents a key issue. Energy, in fact, is a critical resource since sensor nodes are often battery powered and it is usually very difficult to recharge or change batteries. For this reason, the sensors energy efficiency problem is considered in this thesis and some efficient solutions are offered. In this field of research, in particular, the following contributions are provided: development of energy efficient Medium Access Control (MAC) and routing protocol metrics to optimize the utilization of sensors batteries and hence increase their lifetime. Regarding the MAC protocol, we propose a receiver oriented Time Division Multiple Access (TDMA) based protocol that is able to dynamically adjust sensors activity periods, according to the network traffic. In this case, energy saving is obtained by reducing the idle listening of sensors. As for the routing protocol, we propose

energy aware routing metrics for the Routing Protocol for Low power and lossy networks (RPL) protocol with the goal of optimizing the utilization of sensors batteries and hence increasing their lifetime.

- Data forecast and users profiling: in order to efficiently plan residential buildings energy use, data provided by sensors have to be processed to extract meaningful and useful information. For this purpose, profiling algorithms have to be introduced. Solutions proposed in the literature, however, have several limitations. For the profiling of energy consumption, for example, these methods allow the assessment only at an aggregate level (homes or buildings), without providing any detail regarding the use of individual household devices. For this reason, in this research area, the following contributions are provided: development of temperature, light and presence learning methods able to profile users preferences; development of algorithms to predict individual household devices consumption and usage.
- Home energy optimization models and heuristics: the whole energy generation and distribution system performance can be improved through DSM mechanisms designed for residential buildings. Solutions proposed in the literature, however, have several limitations. The whole house environment, with loads, generators and batteries, is represented with an oversimplified model and the electric grid efficiency is not explicitly optimized. For this reason, in this research field, the following contributions are

provided: models and heuristics to manage energy loads for both single and multi-users cases, taking into account distributed energy sources and batteries. The home energy management, in particular, is performed in two different steps, offline and online, so that two different kinds of DSM mechanisms are proposed. In the offline scenario, based on predictions on what will happen in the near future (e.g. photovoltaic panels production and users preferences), the DSM defines the optimal energy plan for future periods by scheduling loads, deciding when to buy or sell energy and so on. On the other hand, in the online case, the demand side management has the goal to define in real-time the energy plan of households based on the actual situation of the energy market and on users' needs. Proposed models require some input data such as PV production and users preferences. Regarding users information and preferences, sensor networks and learning mechanisms proposed in this thesis are used to provide these data.

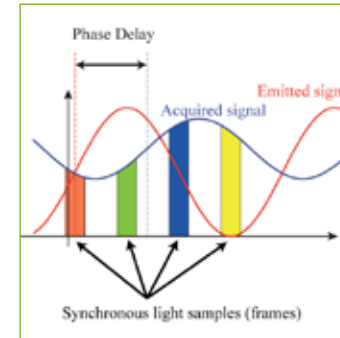
HIGH SPEED SINGLE-PHOTON 3D CAMERAS FOR SAFETY AND SECURITY APPLICATIONS

Simone Bellisai - Supervisor: Franco Zappa

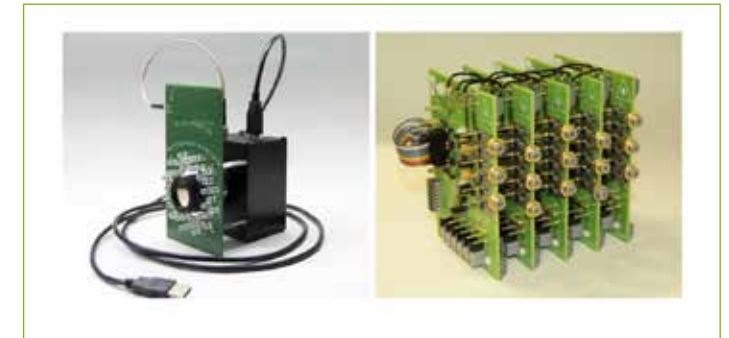
First image acquisitions introduced at the beginning of the XIX Century were based upon chemical reactions, were very slow and the results were not so satisfactory in terms of stability of the process and image quality. Moreover, photographic (or lithographic) techniques were not as widespread as we could think nowadays. But something new was created, one of the greatest technological revolutions of all time, if not equal to the birth of electronics and computers. Imaging technology has made great strides since it's born. The birth of robotics led another great development in imaging research field because new autonomous applications (as for example robotics movement in an unknown area) could be developed; this kind of acquisitions started to requiring the introduction of the last information missing in a normal image: the *depth* information. In recent years, first time-of-flight cameras for the depth measurement in the acquired scene were developed. They were basically based on the distance-to-time conversion. In fact, assuming a photon travelling between the object and the camera, it is possible to measure the distance of the objects pixel by pixel within the image measuring the time interleaved to cover the scene-

camera distance. These systems are based on periodic modulated active illumination; the reflected waveform is compared to the emitted one in order to obtain the phase delay (and hence the distance information) pixel by pixel (as in the scheme of Fig.1). Every aspect of life is accompanied by the technology and the demand of new systems to improve safety and security everywhere drives the Research. In the last decade a great interest around this new kind of electronic systems focuses the Research and the development around the production of new sensors and algorithms to improve the precision and the accuracy of the range-image measurements. This kind of systems is faster and simpler compared to other techniques (i.e. stereography or structured-light acquisition); moreover, the active illumination allows the use in low light environments. Finally, the lower required computing power allows the implementation of a high number of new applications, for example medical aids, autonomous improved surveillance of sensible areas and road safety. While for the former the depth range is very short (up to two meters), for the other two applications it can be much higher, this opening many big issues. Moreover the high speed and the great

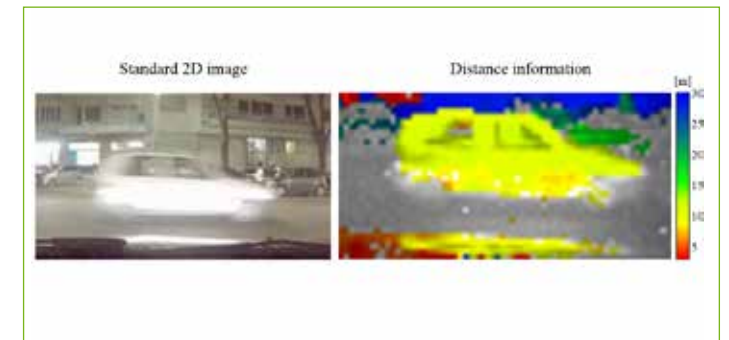
change in the ambient light conditions (from nighttime to very bright daytime) require an accurate analysis, study and development of a complete camera solution. Some novel application can be implemented; for example, the new class of car equipment is focused around the measurements of the spatial occupation of the vehicle itself. Just think to the parking sensor (or parking radar) to "view" around the vehicle during the parking maneuver. With new systems able to detect the obstacles it could be possible to implement algorithms to autonomously move the vehicle, till a standstill when an obstacle is located in front the vehicle. The system should acquire information about the presence of obstacles on the route of the vehicle and predict the relative movements between obstacle and the vehicle, first warning the driver and afterwards taking all adequate decisions to stop the vehicle avoiding the collision. Such a system reduces the peak deceleration suffered by the collision partners during a crash, thus reducing the risks of severe injuries. On the other hand, a number of security applications (including tracking and identification of targets, analysis of crop production, etc.) require high distance measurement devices (for example applications which involve use of an airborne



1. Sinusoidal reflected light compared to the reference signal



2. 3D camera with LED-based illuminator (left) and powerful laser-based illuminator (right)



3. Car passing on the crossing road (left) and its distance measurement (right)

platform, typically an unmanned autonomous vehicle to control and monitor risky areas). Politecnico di Milano is the Coordinator of the FP7 project MiSPiA (Microelectronic Single-Photon 3D Imaging Arrays for low-light high-speed Safety and Security Applications), which aims to the development of new sensors which will be designed to be used in safety and security application. A compact camera ($12 \times 6.5 \times 5 \text{ cm}^3$, shown in Fig.2 left with a low-power LED based illuminator) with external high-performance 20 W peak power LASER-based illumination (Fig. 2 right) is the result of the best technological achievements studied and realized at Politecnico di Milano. The camera is USB-bus-powered and fully PC controlled. The system is able to acquire 3D movies with a frame rate up to 100 fps, while simultaneously

acquiring also 2D movies up to 32,000 fps. In indoor measurements the 3D SPAD-based camera can reach millimeters of resolution with a frame rate up to 100 fps, while in outdoor measurement the resolution is about 25 cm (distance information of a car in a crossroad is shown in Fig. 3) allowing the installation as car anti-collision autonomous systems.

CONTINUOUS-TIME MODEL IDENTIFICATION WITH APPLICATIONS TO ROTORCRAFT DYNAMICS

Marco Bergamasco - Supervisor: **Marco Lovera**

System identification is today a very wide research area, the results of which find application in a very diverse range of fields. While most of the literature on system identification focuses on discrete-time models, in many situations of practical interest (such as, e.g., aircraft and rotorcraft identification) the direct estimation of the parameters of a continuous-time model from sampled input-output data is an important problem per se, for which dedicated methods and tools have to be employed. Moreover, the problem of identifying models under special circumstances which turn out to be critical in discrete-time, such as the identification of stiff systems or the use of nonequidistantly sampled data make it necessary to develop special algorithms that can deal with these cases. The development of identification methods for continuous-time models is a challenge its own, and has been studied extensively. In this thesis continuous-time model identification methods are developed with a special focus on the issues of rotorcraft system identification. Subspace approaches have been mainly studied in the discrete-time domain but in this thesis it will be shown that their charming properties are still valid in the

continuous-time domain.

Subspace model identification

By the late 70s the theory of MIMO linear systems had been completely understood, and yet from a practical point of view black-box identification of MIMO systems remained an issue until the late 80s. The cause for this was the estimation of the structural indices that characterize the parameterizations of MIMO systems, which is tricky and often leads to ill-conditioned numerical problems. Therefore, there was a strongly felt need for simple, possibly suboptimal, procedures bypassing the need for estimating structural indices. Subspace model identification (SMI) methods offered exactly the potential to overcome this difficulty. Classical SMI methods, developed in the early 90s for the estimation of discrete-time models, are the MIMO Output-Error State sPace (MOESP) class of algorithms and the N4SID algorithm. Besides the possibility of dealing with MIMO problems in a simple and natural way, one of the keys to the success of SMI methods in applications is that all the operations performed by subspace algorithms can be implemented with numerically stable and efficient tools from numerical linear algebra.

Not surprisingly, the problem of extending SMI methods to the identification of continuous-time systems has been studied in a number of contributions. Recently a novel approach to the problem of continuous-time SMI has been presented, based on the adoption of orthonormal basis functions to arrive, again, at a MOESP-like data equation for a continuous-time system. The problem of closed-loop SMI has been studied extensively in recent years due to its high relevance for practical applications. The present state-of-the-art is represented by the so-called Predictor-Based Subspace IDentification (PBSID) algorithm which, under suitable assumptions, can provide consistent estimates of the state space matrices for a discrete-time, linear time-invariant system operating under feedback. In the light of the above discussion, the aim of this thesis is to propose novel continuous-time SMI schemes, based on the derivation of PBSID-like algorithms within the all-pass domains and relying, respectively, on Laguerre filtering and Laguerre projections of the sampled input-output data. More in details, the first results of this thesis are the continuous-time predictor based subspace model identification algorithms that consistently estimate continuous-time linear time

invariant system operating in open- or closed-loop. A relevant problem in the engineering field is to design a single control system that guarantees stability and performance requirements for a given plant in many different operating conditions. The gain scheduling technique solves this problem, provided that a suitable model in parameter-dependent form has been derived. This modelling problem can be solved using methods based entirely on identification, i.e., aiming at deriving linear parameter varying (LPV) models for the plant directly from input/output data. In this thesis the problem of the estimation of continuous-time state space LPV models, without a-priori knowledge of the system, will be carried out using a local approach. The identification of the local models will be performed using the continuous-time SMI schemes derived in the first part of the thesis. A downside of the subspace model identification approach to state space model identification is the impossibility to impose a parameterisation to the state space matrices and therefore it is tricky to recover physically-motivated models. In this thesis the problem is formulated as an input-output model matching problem. The solution of the problem is subsequently computing using recent results in non-smooth optimisation techniques.

Rotorcraft model identification

Rotorcraft dynamics is described by the interaction of inertial and aerodynamic forces as well as control forces acting on the

rotor and the airframe. The resulting physical-based model contains a number of uncertain or unknown parameters which are very difficult to determine; for example, fluid dynamics is necessary to describe helicopter motion but the associated mathematical modelling is very complex and is affected by a number of unmeasurable physical parameters, e.g., wake interferences with the empennage and tail rotor. System identification in time and frequency domain has emerged as a viable approach for the estimation of the physical parameters. In helicopter engineering, in the last two decades, frequency-domain system identification has been widely developed, as suggested by the number of contributions in the literature describing the relevant approaches and case studies. In the frequency-domain approach, flight test data is used for the reconstruction of a nonparametric model, i.e., the frequency response data curve that characterizes the input-to-output process at a large number of discrete frequencies. Then, a parametric frequency response curve is matched with the nonparametric model to find the estimates.

Starting from another point of view, time domain system identification has been taken into account for rotorcraft system identification by German Aerospace Center DLR. In the time domain the model is considered in state space form and it is directly matched with the flight test data using least squares and/or maximum likelihood methods. The classical

least squares or maximum likelihood time-domain methods have some drawbacks that are avoided by a subspace approach, e.g., they need estimates of the initial state vector which is a numerical ill-conditioned problem for unstable system, like a helicopter in most of the flight conditions. In most of the flight conditions rotorcraft vehicles are open-loop unstable, therefore the identification algorithm must be able to treat data acquired in closed-loop.

All the above mentioned problems are well solved by a continuous-time closed-loop subspace model identification algorithm. Another characteristic useful in the rotorcraft system identification is that it can merge in a very simple way information from separate data sets into a single state space model. In this thesis a particular attention is given to another common requirement in the rotorcraft model identification, i.e., the model must be physically interpretable or, using the terminology of control theory, a structured one. A solution to this problem will be given thanks to a developed method that allows to transform an unstructured model, for example identified using a subspace algorithm, in a structured one.

EFFICIENT MODELLING AND SIMULATION TECHNIQUES FOR ENERGY-RELATED SYSTEM- LEVEL STUDIES IN BUILDINGS

Marco Bonvini - Supervisor: **Alberto Leva**

It is universally acknowledged that buildings contribute to a very significant extent to the world energy demand. It is also recognised that said contribution can be dramatically reduced by acting along two main – and synergic – directions. The first is to employ better materials, construction techniques, climatisation devices, lighting, appliances, and so forth. The second is to adopt improved control and energy management policies. Needless to say, a huge research effort is nowadays being spent in both directions. In such a scenario, this dissertation deals with the definition and realization of a modelling and simulation paradigm suitable for supporting all the steps of so complex a problem as the design of a new energy efficient building or neighbourhood, and also the refurbishment of an existing one in a view to reducing its energy footprint. As an important peculiarity of the work, it is to be noticed that despite the presented research is said to refer to “buildings” for brevity, in fact the installed plants are considered as well. This makes the obtained results applicable also in other domains, e.g., of industrial nature.

In this respect, it is worth noticing right from the beginning that one of the most significant barriers to energy

efficient building (re)design is that buildings are complex systems, the energy performance of which is affected by the interaction of several parts and phenomena. While the typical design process is tendentially linear and sequential, minimising the energy use requires to optimise the system as a whole, by systematically addressing all the elements that come into play as building form, orientation, envelope, glazing area and a host of interaction and control issues, involving the buildings mechanical and electrical systems.

The design of such complex and heterogeneous systems apparently needs to be supported by computer aided tools. In fact, during the past 50 years, a wide variety of building energy simulation programs have been developed, and some are nowadays commonly in use throughout the building energy community. However, many experts wonder if these tools will be able to address the future needs in an effective way, the main issues being to find a tool capable of effectively addressing the building as whole, and to support the design of buildings, from its early stages to the final realisation, in an orderly and consistent manner.

In recent years, new modelling and simulation techniques have gained interest in the scientific

and professional communities of a variety of fields. These techniques, collectively called Object-oriented Modelling and Simulation (OOMS), are grounded on an equation-based approach, and given their openness to multi-physics problems, they appear to provide a very promising solution in the aforementioned context. The aim of this work is to exploit the OOMS principles so as to provide models – and more in abstracto modelling methodologies – to overcome the main shortcomings of the Energy and Building Performance Simulation tools presently available. As such, the contribution of this dissertation can be summarised as follows.

- It is shown how to use OOMS to represent in a unitary framework phenomena that would otherwise call for different simulation and analysis tools, to the detriment of a coordinated and whole-system, approach. The proposed general ideas are exemplified by addressing and solving (among others) maybe the toughest problem of this type, i.e., the modelling and simulation of large air volumes.
- The same ideas, though differently declined, are shown to be capable of accommodating for a reliable

representation of control systems. In fact, if properly optimised can provide significant energy performance improvements, but such an optimisation is hardly possible if the building and its controls cannot be represented and simulated jointly.

- The principles of OOMS are exploited so as to allow for models of scalable detail level, which permits to tailor the simulation model complexity to any particular study at hand, concentrating on the relevant parts of the system and employing simple – thus computationally fast – descriptions of the rest. It is worth noticing that the possibility of scaling the detail level is highly beneficial also in a view to have the simulation tool follow the entire life cycle of a project.
- Several simulation studies are proposed and discussed, to better explain the presented ideas and to show their actual applicability and potential.

DESIGN OF MEMS MAGNETIC FIELD SENSORS AND READOUT ELECTRONICS

Cesare Buffa - Supervisor: Antonio F. Longoni

While at the beginning MEMS were thought as single sensor or actuator, the present trend sees MEMS to be a combination of functions. Inertial Measurement Units (IMUs) are multi-parameter systems in one single package based on multi-axis MEMS and they play a fundamental role in several fields of applications like navigation units in smart mobile phones and other consumer electronic goods.

Dominant technologies used to integrate magnetic sensing elements in IMUs which are currently on the market are not based on micromachining processes yet. The most common implementations of electronic compasses are based on Hall effect and on anisotropic magneto-resistance (AMR) technologies. Devices based on this latter technology require the deposition of specialized magnetic materials into standard industrial processes, they suffer from magnetic hysteresis and, finally, they are in-plane sensitive only. So, in order to integrate a 3-axis AMR-based magnetometer into an IMU, a vertical assembling for the Z-axis device is required, which has a strong impact on the packaging cost and on the vertical scalability for ultra-thin packages.

Even though Silicon Hall effect sensors avoid problems arising from the integration

of magnetic materials, their power consumption and resolution performance are relatively limited with respect to AMR devices. The research on an alternative approach, Lorentz force based MEMS magnetometers (in particular for the Z-axis element), is encouraged by the possibility to integrate magnetic sensors in the same MEMS technology already used for gyroscopes and accelerometers, so to design a complete 9-axis IMU in a single process.

In this work, Z-axis Lorentz force based magnetometers with driving and readout electronics are presented for consumer applications. Design and optimization of device are reviewed mastering constraints of an industrial MEMS technology (process and packaging) already used for accelerometers and gyroscopes and taking into account the final application in consumer electronics (bandwidth, noise, full scale and linearity). The feasibility of a MEMS based magnetic field sensing system based on a double-chip solution (MEMS + ASIC) is experimentally demonstrated.

This work is part of a collaboration between the Department of Electronics and Information of Politecnico di Milano, Milano, Italy

and the industrial partner STMicroelectronics.

After a brief introduction of the theoretical background necessary for next sections, the first part of this doctoral thesis deals with the design of mechanical elements supported by behavioural and multiphysics simulations. Capacitive readout MEMS and the Lorentz force transduction principle are introduced with the goal of designing a suspended microstructure to detect Z-axis magnetic field. A novel design approach, constrained by project specifications given by the industrial partner, is introduced leading to the design of a very compact mechanical sensing element suitable to be integrated in inertial measurement units (IMUs). The sensitivity of these devices turns out to be independent on the number of sensing cells and the optimized device has an in-plane area occupation of $870\mu\text{m} \times 90\mu\text{m}$. The combination of multi-axis and multi-parameter MEMS in the same technology would result in a very cheap and smart solution for many applications. A behavioural model of the system taking into account also thermomechanical noise, damping effects and electrostatic non-ideal effects is developed using Simulink. Mechanical design

of devices is supported by finite element simulations too. A first generation of devices is implemented using STM ThELMA industrial micromachining process.

The second part of this work deals with electromechanical characterization of fabricated devices to experimentally check that they match desired mechanical properties. A laboratory prototype of an instrument for precise electromechanical characterization of micromachined sensors is designed and implemented achieving a resolution of $\sim 1 \text{ aF}/\text{Hz}$ with a bandwidth up to 100 kHz. In general, a complete mechanical characterization is obtained by measuring the stationary and dynamic response of the suspended part of a MEMS device subject to suitable stimuli. From these tests, main parameters of MEMS devices can be measured or inferred: elastic stiffness, pull-in voltage, mechanical residual offset, resonance frequency and quality factor. According to obtained results, the proposed theory about sensitivity is proved. Measured damping coefficient $b_{\text{area}} = 7.54 \text{ kg}/(\text{sm}^2)$ is approximately 1.3 higher than expected. This is justified by a degassing of package pressure. In order to validate the Lorentz force transduction principle applied to a micromechanical structure in presence of an external magnetic field, a mechanical setup with permanent magnets is built together with the design of driving and readout electronics using discrete components. Driving electronic is based on

an improved Howland current pump with an additional circuit to minimize unwanted electrostatic forces. Readout is based on a transimpedance architecture. A final and more accurate set of magnetic field measurements is performed using *Palm Gauss PG-5G* magnetic field canceller by *Aichi* available in STMicroelectronics laboratories. A measured sensitivity of $150 \mu\text{V}/\mu\text{T}$, in line with the theoretical predictions of $195 \mu\text{V}/\mu\text{T}$ for a gap $g = 2.1 \mu\text{m}$ is measured with designed readout electronics. Differences might result from a process under-etch with respect to the expected one. A resolution of $520 \text{ nT}\cdot\text{mA}/\sqrt{\text{Hz}}$ is measured.

The third part of this doctoral dissertation focuses on system analysis, including considerations about overall noise, power consumption, MEMS modelling in Cadence environment and the design of a VLSI position sense interface. The noise budget set by system specifications about resolution is partitioned between the device intrinsic thermomechanical contribution and electronics noise. As the system is intended for consumer applications and so integrated in portable battery-hungry devices, power consumption plays an important role as well. Available power budget is partitioned among driving circuitry, intrinsic device dissipation due to Joule effect on resistive springs and sensing electronics. In order to better analyse the overall performance and power dissipation from a fully-coupled-system point of view, a detailed magnetometer model has been

integrated directly in the VLSI simulation environment using Verilog-A description language. Indeed, with the hectic miniaturization of technologies and the integration of more and more sensors together with their electronics, fully coupled electro-mechanical simulations become of great interest. Finally, a fully differential transresistance amplifier is implemented using a standard CMOS 150nm process and tested. Magnetic field measurements with system prototype based on a double chips solution achieving a sensitivity of $100 \text{ nV}/\mu\text{T}$ at the output of first amplifier with a feedback resistor of $5 \text{ M}\Omega$. VLSI resolution is set by resistor noise.

Results obtained from this magnetic field sensor prototype are promising towards the direction of integration of an inertial measurement units implemented using a single MEMS process. Further improvements in terms of resolution per unit current consumption and bandwidth can be achieved with technological improvements and with different device operating conditions, getting MEMS magnetometers as competitive as solutions based on other technologies.

DEVELOPMENT OF A GAMMA CAMERA FOR MEDICAL AND NUCLEAR PHYSICS APPLICATIONS

Paolo Busca - Supervisor: Carlo Ettore Fiorini

The basic concept that underlies nuclear medical systems is the injection of a radiotracer into the patient. A radiotracer is a chemical radioactive compound able to bind itself in a precise volume and to emit gamma-rays, providing information on physiological functionalities and their time evolution or on the localization of a pathology, first of all, cancer. A nuclear imaging diagnostic tool can thus be naively described as a camera able to detect gamma-rays in order to form an image correlated to the radiotracer distribution and concentration. This camera, usually called Anger camera, was invented and named after Hal O. Anger in 1958.

Nowadays, microelectronics has made possible advanced signal processing with dedicated ASICs for the readout on an increasing number of channels, in addition computing power allows novel estimation schemes for a deeper analysis of the information carried out by the detector signals. Therefore, modern gamma cameras for medical imaging aim to provide sub-millimetric spatial intrinsic resolution with both extended field of view and depth of interaction capability, higher sensitivity for better signal-to-noise ratio and better energy resolution for multi-radiotracers

acquisitions. Silicon Drift Detectors (SDDs) are relatively recent devices, introduced by E. Gatti and P. Rehak in 1983, which have shown to be competitive photo detectors for the readout of scintillation light, thanks to high quantum efficiency and low electronic noise. Therefore, an Anger camera based on SDDs could represent a gamma-ray imaging device with several potentialities in the fields of medical imaging, above all the possible integration with MRI, thanks to the compatibility of SDDs to magnetic fields.

The aim of my Doctoral activity has been the study, development and extensive use in the field of nuclear medical imaging of the HICAM (High resolution gamma CAMera) camera, a project supported by European Community. HICAM is a compact, light-weighted Anger camera composed of 100 SDDs of 1cm^2 each, in a final $10\times 10\text{cm}^2$ format (Fig. 1). The camera is the largest gamma-ray imager based on SDDs ever developed and represents a flexible device which can be involved in different kinds of applications such as medical imaging and basic physics research thanks to its high spatial resolution in a wide energy range (100 keV – 7 MeV).

In the low energy range, the typical case for medical imaging, HICAM is characterized by a high intrinsic spatial resolution, $< 1\text{mm}$, and high overall spatial resolution, $\sim 2.5\text{mm}@5\text{cm}$, energy resolution $< 20\%@140\text{keV}$. Thanks to its high system performances, clinical trials were performed at Ospedali Riuniti di Bergamo where more than 20 patients were examined. One of the most significant trials was lymphoscintigraphy, used to localize sentinel nodes in breast cancer and melanoma. Three nodes could be clearly distinguished with the third one very close to the injection site, whereas in commercial cameras usually only the bigger node is clearly visible. Also in thyroid scans, HICAM shows superior performances, both the organ shape and the radiotracer distribution were clearly delineated (Fig. 2).

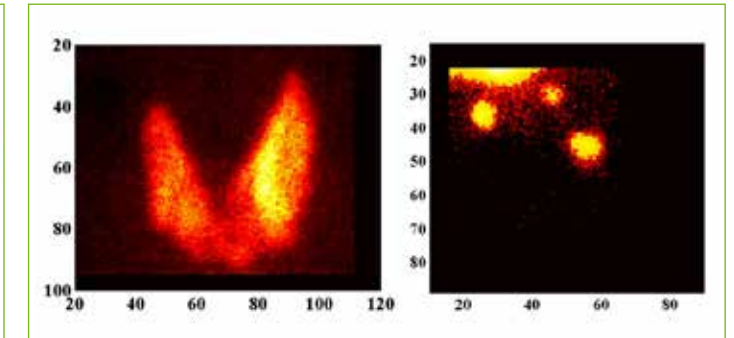
Gamma cameras could, in principle, also be used in high energy applications ($>511\text{keV}$), such as homeland security, astrophysics, nuclear physics research and prompt gamma-ray imaging where spatial resolution can provide further information when combined with energy resolution. High energy imaging is limited mainly because of two reasons: thicker

scintillators, mandatory to stop high energy radiations, spread the signals on the detector plane uniformly, losing the correlation between point of interaction and light distribution. Secondly, high energy γ -rays are absorbed not in a single event, but with multiple hits (Compton

prompt gamma rays (2 to 7 MeV) emitted by a target irradiated by protons. The final objective of our experiment is to assess the feasibility of proton beam range measurements by prompt gamma imaging with a slit camera, and the HICAM camera was chosen for a first prototype.



1. HICAM 10×10 has a global FOV of $12\times 10\text{cm}^2$, using 100 SDDs, aligned in a 10×10 matrix. The fundamental unit of both systems is a single square SDD has an active area of $1\times 1\text{cm}^2$



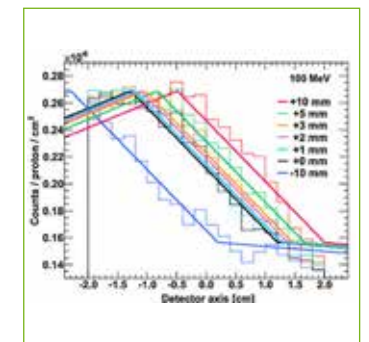
2. Thyroid scan, on the left, is one of the most common exam in nuclear medicine. HICAM can clearly show both the organ shape and the radiotracer distribution. Lymphoscintigraphy on the right, HICAM can detect and delineate three small lymph nodes thanks to its high spatial resolution. Axes in mm

scattering) that degrade the overall spatial information. HICAM exceeds these limitation thanks to its intrinsic resolution and a novel method of least-square estimation for the image reconstruction. The system shows less than 3 mm spatial resolution with a collimated ^{137}Cs source (662 keV) and a 2 cm thick CsI(Tl) scintillator. The crystal has to be covered to enhance light collection, since energy resolution is a primary concern and cannot be neglected. Preliminary results show also depth of interaction capability along with 7% energy resolution.

Although originally designed for low-energy gamma-ray imaging in nuclear medicine, the HICAM camera, suitably modified to image high energy

For the first time, the concept of prompt gamma camera using a slit collimator has been demonstrated, with a 1 mm accuracy in the 100-160 MeV range (Fig. 3).

Thanks to its performances HICAM could be a relevant diagnostic tool for imaging specific locations in adult patients, like brain tumors, breast cancer, thyroid and parathyroid cancer. Due to the compatibility to magnetic fields, a SDD-based camera, has also potential to be used in combination with MRI. Thus, this category of gamma camera opens new and important possibilities for the research and for future projects.



3. Fitted profiles of the acquisitions with the moving target. Each acquisition is 5 min long and corresponds to $7 \cdot 10^{10}$ absorbed protons

DECENTRALIZED MANAGEMENT IN DISTRIBUTED AUTONOMIC SYSTEMS

Nicolò Maria Calcavecchia - Supervisor: **Elisabetta Di Nitto**

Software systems are becoming every day more complex and pervasive. Part of the complexity derives from the fact that they live in highly dynamic environments, where external conditions may vary without notice. The complexity becomes even more critical when dealing with systems composed of a large number of components, distributed over a network. For this reason, it is now becoming clear that computing systems should be able to manage themselves as much as possible, with the aim of minimizing human intervention during their life-cycle.

This thesis focuses on techniques and frameworks that are specifically tailored for decentralized software systems, i.e. systems where distributed elements act without the supervision of a central entity. In particular, our contribution is structured in three main areas. Firstly, we describe a decentralized autonomic framework, the SelfLet, which allows developers to implement decentralized autonomic applications by relying on abstractions such as services, autonomic policies, nodes neighbor relationships etc. Secondly, we present an optimization framework for the SelfLet toolkit able to dynamically assess and predict potential problems

and bottlenecks. By means of predefined adaptation actions, the framework generates a set of candidate actions -- according to the internal state of the SelfLet and the one of its neighbors -- and selects the most appropriate action to actuate.

Finally, we present two adaptation algorithms -- that could be incorporated into the SelfLet framework -- operating on decentralized distributed systems. In particular, the first algorithm -- inspired by the growth behavior found in fungi's roots -- balances the load among nodes of the system despite the continuous sources of external changes (i.e., node failures). The second algorithm, which also includes a load-balancing feature, achieves a resource scaling behavior in a cloud infrastructure context. In particular, the algorithm is able to add or remove computational resources (i.e., nodes in the system) according to the variations observed in the input workload.

INCENTIVE COMPATIBLE REVENUE SHARING MECHANISMS FOR THE FEDERATION OF SERVICES

Sofia Ceppi - Supervisor: Nicola Gatti

Free services are nowadays offered to users through web pages managed by *integrators* who provide multiple services in one location. The atomic services that are federated can be of two types: content, from which no direct profit can be obtained, and advertising, which is the only source of revenue. Thus, since the integrator must make a profit, among her services there must be at least one that provides advertising. Integrators can be of two kinds: those who generate their own information, and those who use information communicated by third parties.

In this thesis we focus on the most general case, i.e., the latter one, and we refer to the third parties as *providers*.

To offer the best service and increase the overall revenue, an integrator must target users by selecting the best services for each of them and those ads that are more likely to be clicked. In order to achieve this, information (i.e., what providers communicate to the integrator) is needed and, since the more information is collected (i.e., the more providers are federated), the better the services offered, an integrator is incentivised to federate also multiple providers that offer the same service. However, this implies that she has to collect the information received and select what to display. The active role of the

integrator in the choice of the services to display makes our problem new, because current integrators, typically, don't operate any selection in presenting information to users. The aim of the thesis is to design a revenue sharing mechanism for the new federation of services described above. To achieve this goal we resort to mechanism design techniques that indicate how to design the rules of a game to get a particular desired outcome. In particular, the problems we want to address are twofold.

The first problem is the design of an auction mechanism for the scenario in which multiple sources of advertising are federated. The mechanism should maximise the overall expected revenue (i.e., it must satisfy the *allocative efficient* property), incentivise the provider to truthfully reveal their information (i.e., it must satisfy the *incentive compatible* property), and guarantee a non-negative revenue to both the integrator and the providers (i.e., it must satisfy the *individual rationality* and *weak budget balance* properties).

Several auctions, called *sponsored search auctions*, are currently extensively used by search engines to define the set of ads to display alongside the search result by auctioning off

slots to advertisers. In particular, a search engine asks advertisers to submit a value that corresponds to the maximum amount they are willing to pay if their corresponding ads are clicked. However, the integrator problem differs fundamentally from the one addressed by classical SSAs for a number of reasons. First, an advertising provider would possess much more accurate information about the quality of an ad than the integrator (since the advertisers interact directly with the provide). Therefore, in order to improve the targetisation of users, the integrator needs to elicit both values and qualities from the providers. Second, ads can be *non-exclusive*, i.e. the same ad can appear in multiple advertising providers, and so the integrator needs to fuse the information collected from different sources. Finally, each provider typically has multiple ads, and so the integrator needs to elicit information about each of these, enabling more strategic manipulation by the provider. This is why we need to design a new auction mechanism. The design of such a mechanism is particularly challenging because ads displayed affect each others' click probability (i.e., there are *allocative externalities*) and because, when one or more advertisers submit a bid to multiple

providers, the revenue of a provider depends also on the information communicated by the other providers (i.e., there are *information externalities*). Due to these critical aspects, we show that there exists no *standard* mechanism (i.e., mechanisms that define the ads' allocation and the providers' payments only on the basis of the communicated information) that satisfies all the desired properties. This is why we focus on *execution-contingent* mechanisms (i.e., mechanisms that compute the payment based on the ads actually clicked). However, even with such mechanisms the results we obtain are not satisfactory. Thus, we turn to consider simplifications of the proposed scenario, and for each of them we design a mechanism. The simplifications focus on restricting the domain (i.e., supposing that externalities do not affect our scenario), and relaxing the mechanism requirements (i.e., when only a subset of desired properties is satisfied). We provide a theoretical evaluation of all the mechanisms proposed and we empirically compare them.

The second problem we aim to address is the design of a redistribution mechanism that compensates all the providers incentivising them to remain in

the federation of services. This problem is challenging, and no redistribution mechanism presented in the literature can be used, because the providers that are federated can belong to different classes. Indeed, the providers federated by the integrator can be of three classes: content-only provider (CP) that communicates only content to the integrator, advertising-only provider (AP) that communicates only advertising, and content and advertising provider (CAP) that communicates both. This heterogeneity necessitates the design of a flexible mechanism that defines different compensation for different classes of provider. We design an efficient truthful mechanism that provides all the actors with a non-negative utility and we prove that, as the number of providers goes to infinity, the revenue collected by the integrator can be completely redistributed. Finally, we empirically evaluate the mechanism proposed. All the empirical evaluations in this thesis are based on the *Yahoo! Webscope A3* dataset.

CONDITIONALLY INDEPENDENT VISUAL SLAM WITH INTEGRATED BUNDLE ADJUSTMENT

Simone Ceriani - Supervisor: Matteo Matteucci

The problem of Simultaneous Localization and Mapping (SLAM) regards the estimation of the pose of an observer (usually a robot) from sensor observations (i.e., local measurements), while creating, at the same time, a consistent map of the observed environment. Visual SLAM aims at the solution of the SLAM problem with the use of visual sensors, i.e., cameras, only; in particular, the problem takes the name of Monocular, Stereo and Trinocular SLAM when, respectively, one, two or three cameras are used, while the term multi-camera SLAM refers to a generic number of cameras. Visual SLAM has become a very attractive and active research field in the last decade due to the richness of the visual percepts coupled with the affordability and the low power consumption of the sensing device. In this thesis we work on the development of a multicamera SLAM system that is able to operate in real time, on large environments and with a generic number of cameras.

The first contribution of this thesis is the development of a generic and modular multi-camera SLAM system based on the well established EKF-SLAM (Extended Kalman Filter SLAM) approach, which uses an EKF as the estimator for the joint

distribution of the observer pose and the environment map. Each camera is treated as an independent system that provides measurements, thus our system operates without any explicit reference to particular geometric constraints among cameras (e.g., the epipolar geometry for the stereo cameras or the trifocal tensor for trinocular vision). This approach guarantees a high level of modularity and flexibility: there are no building constraints on the overlapping of cameras fields of view and sensors can be added or removed at run time with the only requirement of synchronization and relative positioning.

Monocular SLAM is the basic building block of the multi-camera SLAM system we develop and it is treated in the EKF SLAM framework through the use of *parameterizations* of landmarks. A second contribution of this thesis is the review of the different *parameterizations* which allow to treat the initial unknown depth of landmark points perceived by a single camera (a bearing only sensor) in the EKF SLAM framework. This review presents parameterizations from a novel perspective, highlighting the possibility of saving space in the state vector by sharing the common *anchor point* of

landmarks initialized at the same time. This shrewdness, beside increasing the efficiency of the EKF-SLAM, avoids the introduction of singularities in the covariance matrix. During the review of parameterizations, we introduced also two novel parameterizations, named *Framed Homogeneous Point (FHP)* and *Framed Inverse Scale (FIS)*, that extend the concept of anchor point to *anchor frame*. Anchor frames maintain in the filter state the past camera poses representing *milestones* along the trajectory. This gives us the base for the development of further contributions in the thesis. Anchor frame based parameterizations come at the cost of an increased computational complexity in case of FHP parametrization and an approximation on the estimation of the initial viewing ray in case of FIS parametrization.

The EKF-SLAM approach is not directly applicable when the size of the environment the robot (or the observer) is exploring becomes significantly large, since the computational requirements of the basic EKF algorithm increase with quadratic complexity preventing real time performance. To push our system toward real-time performance in very large environments, we rely on a

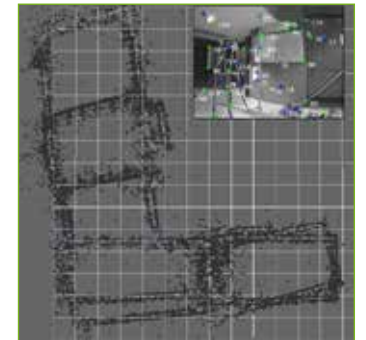
solution already proposed in the literature, the *Conditional Independent Submaps (CI-SLAM)* framework, which allows linear complexity in large maps by decomposing the state into a set of conditional independent submaps. To the best of our knowledge, this framework has never been implemented before apart in the original work. Our implementation, although it does not cover all the features of the original framework, is generic and can be applied with any of the proposed parameterizations, resulting in a module that acts as a *plugin*, i.e., it is added to the multi-camera SLAM system to extend its operability to large maps.

A third contribution comes from the introduction of the *Hybrid Indirect EKF-SLAM* approach; this approach models the SLAM problem in a *indirect form* by representing errors in estimates in the state vector instead of directly representing the values of interest. This approach allows to maintain a local representation of the variables involved in the estimation process, easing, in particular, the representation of rotations. The benefits of the indirect approach regard the state dimension reduction for the frame anchored parameterizations, where quaternions get substituted by rotation vectors, and the proper managing of covariance of rotations, avoiding singularities introduced by quaternions. The Hybrid EKF-SLAM is developed mixing the two classical approaches to the indirect EKF formulation, i.e., the *feedback* approach and the *feedforward* approach; the former is used

for the state vector parts that represents the robot pose while the latter is used for the elements of the environment. Moreover, the Hybrid EKF-SLAM allows to apply the CI-SLAM framework procedures, while a pure feedback approach would have prevented the usage of this powerful submapping technique.

A final contribution is the development of a module that performs a refinement of the EKF state estimates through non linear optimization (i.e., *Bundle Adjustment*) applied on each submap of the CI-SLAM framework; this is possible leveraging on the novel parameterizations based on anchor frames. This module acts as a *plugin* of the whole multi-camera SLAM system, thus it can be used or not, depending on the specific setup. The Bundle Adjustment is performed with a proper formulation of the optimization problem such that the results of the optimization may be reinserted in the EKF, allowing the continuation of the estimation and the propagation of non linear optimization improvement to the EKF machinery. We name the complete system *CIBA-SLAM*, *Conditionally Independent Bundle Adjusted SLAM*.

The system has been tested in simulation and on real data and it has proved to operate in real time on large environments. Figure 1 shows the results of a test performed in an indoor environment with a monocular camera mounted on mobile robot. Such a system can be considered as a milestone towards a deployable



1. Trajectory and map estimated in an indoor environment with a monocular camera applied on a mobile robot

implementation of a modular system able to operate in real time on a real robot, possibly on simple platforms. This motivated us to work on SLAM algorithms based on filtering techniques, although recent trends have moved the research toward pure optimization based strategies. We believe that filter based SLAM has still a role in this research field, especially in the direction of moving from fully fledged multi-core computers to low power embedded system, where high performance parallel processing can not be performed.

EXPLORING THERMAL AND RELIABILITY ASPECTS IN HIGH-PERFORMANCE PROCESSORS

Simone Corbetta - Supervisor: William Fornaciari

Technology scaling, manufacturing advances and enhanced design methodologies have driven the increasing integration capability of CMOS devices. The *International Technology Roadmap for Semiconductors* (ITRS) has shown that sustainable performance increases, since on-state electrical characteristics at scaled nodes benefit from reduced geometry and capacitance. This made it possible for modern chips to host billion transistors, where several different functionalities coexist, and a wide spectrum of applications can be addressed. The constraints for such integration are strict and, most of the time, orthogonal: although performance has been the major driving force in high-performance processors, power consumption cannot be overseen in current technology. Power and performance have to be traded for optimal operation, but the divergence of application requirements poses several challenges in this direction. Increasing power density makes devices hotter and less reliable: experimental results have shown that 50% of failures in IC designs are due to thermal issues. Thus, thermal/reliability metrics are now set aside to the classical power/performance trade-off. In addition, leakage power is becoming the

dominant factor determining the power envelope of a system, still a positive feedback exists between leakage current and temperature: published data from Intel processors confirm that leakage power can account for up to 60% of total chip power consumption. ITRS projections show things going worse with technology advance. All in all, VLSI integration relies on the reliability of the circuits itself, and with technology scaling several failure mechanisms are mining the dependability of the system: mechanisms such as *Negative Bias Temperature Instability* (NBTI), *Time-dependent Oxide Breakdown* (TDDDB) and *Hot-Carrier Injection* (HCI) affect the operation of silicon devices. Although effort is spent at different steps in providing reliable circuits, from material science engineering to circuit design, manufacturing process still introduces a source of variability, and devices experience statistical variation of important electrical characteristics from their nominal values. The interdependence of these and other different aspects is detrimental to the final reliability of any high-performance design. Figure 1 shows the mutual influence of several important quantities on the reliability of the system. Their mutual implication

determines the overall availability and cost of a design. Boxes represent any one of these quantities, and rounded boxes are used to connect the cause to the effect. The final reliability of the system is hereby indicated by means of two ways: considering aging (represented by a threshold voltage shift ΔV_{th}), and temperature accelerated lifetime (MTTF values). Multiple paths go through different blocks, and all of them share process variation, i.e. their nominal initial threshold voltage adheres to a variability model. From process variation, heterogeneous characteristics impact the rate of faults in a given design: hard faults are assumed here to be the most relevant ones in scaled technologies, according to either temperature-related mechanisms of aging.

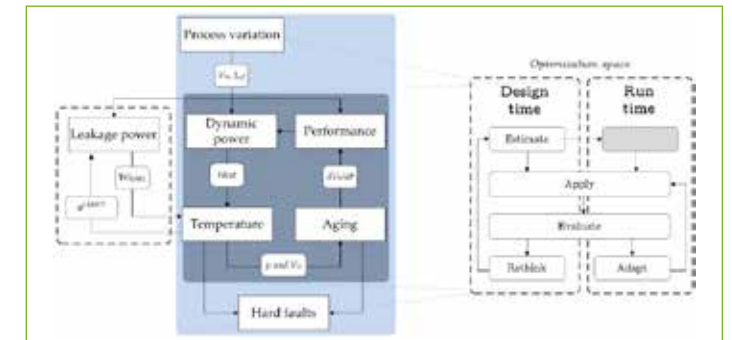
The mutual influence of these parameters brings to two types of variability: "time-0" variability and "dynamic" variability. The former refers to the heterogeneity of electrical characteristics among subsets of the devices, and depends basically on manufacturing technology, although the floorplan and placement decisions might bias the results. The latter class, on the other hand, is driven by dynamically changing operating conditions (e.g., temperature and power).

These are due to performance and power profiles that adapt to the incoming data and processes, as previously sketched. In this context, it is become very challenging to provide a system that is able to meet power/performance and thermal/reliability metrics. The research work is driven by this leitmotif, and solutions are proposed in this direction: design-time optimization covers a limited amount of operating conditions, because of the estimation cost and the inability to predict any application scenario; however, waiting for the real hardware to be available increases the cost of the design and decreases the probability of optimization success. On the other hand, run-time techniques are useful for dynamic adaptation to changing conditions, but their evaluation is laborious. For these reasons, design-time and run-time choices should provide a joint optimization framework, where tools, methodologies and techniques can be evaluated, estimated and optimized. The design-time domain in this context will then provide estimation capabilities of power, performance, thermal and reliability aspects, such that the output from run-time strategies (again, evaluated using design-time methodologies) lead to a closed-loop rethinking of the strategies, to cover a broader optimization space. To this extent, several features that are of utmost importance in the current technology node are addressed in this work:

- **Multi-core processors** – due to the increasing power/performance requirements,

multicore architectures have been proposed as a valid design alternative to drive Moore's law in the nanometer era. Thermal-related issues are of major concerns in these architecture;

- **Reliability and aging** – aging of silicon devices has



1. Mutual influence of power and performance, thermal and reliability.

been demonstrated to be a serious concern, since a time-dependent shift of operating conditions of transistors might lead to performance bottlenecks and, in the worst case, system failure. Among the different failure mechanisms, NBTI is the one of the most serious;

- **Estimation and simulation flows** – design-time analysis is of paramount importance to provide sensible information about the design, at low cost and with little overhead.

Three main important results have been achieved in the proposed research work. A suitable estimation framework, the *Heterogeneous Architectures and Network-on-Chip Design and Simulation* (HANDS), have been proposed: a collection of third-party state-of-the-art tools and in-house developed tools, to address the design-

time estimation of power/performance and thermal/reliability aspects in MPSoC and NoC architectures. Multi-core dynamic thermal management has been supported with appropriate run-time measures and metrics to drive the estimation of the temperature-related bottlenecks, considering the ever growing contribution of thermal coupling among adjacent cores. Last, NBTI mitigation has been achieved in superscalar processors by designing an innovative solution based on power-gating of unused functional units, to trade required reliability with achievable performance.

VEHICLE'S ENERGY ESTIMATION AND OPTIMIZATION VIA INERTIAL MEASUREMENTS

Andrea Corti - Supervisor: **Sergio M. Savaresi**

The transportation sector accounts for 22% of global primary energy use and 27% of global CO₂ emissions. Transport energy demand in developed countries represents the bulk of the world transport energy use with a share of 65%. Nevertheless, the energy used in transport has grown considerably faster in developing countries during the 1971- 2000 period, at an annual rate of 5% compared with 2.1% for developed countries (Price et al., 2008).

The energy consumption of a vehicle directly influences fuel consumption and air pollutant emissions (CO₂, NO_x, PM₁₀, etc.) with both economic and social effect. It is well known that the fuel cost has a deep impact on the world economy, while the Carbon dioxide (CO₂) is the most important components of *greenhouse gases* (GHG). Nowadays, reducing the vehicles' fuel consumption and emissions are two of the main objectives pursued by institutions; the European Commission plan, new cars in Europe may be required by 2015 to meet a strict fleet wide average of 130 grams of carbon dioxide per kilometer driven; the United States is expected to adopt similar CO₂ standards. These ambitious goals may be achieved through the use of alternative

primary energy sources, the development of more efficient powertrains and a broader adoption of electric vehicles. Most of the automotive research in this field foremost focuses on the optimization of powertrain's components, architectures and control strategies. Although these solutions seem promising for the next decades, they will not likely have a big impact in short term. The technology available is not mature enough and the market penetration of alternative vehicles is negligible. Nevertheless human factors and user's modes of transportation have a huge impact both in terms of the vehicle energy consumption and of CO₂ emissions. Previous researches demonstrate that by improving the driving-style, a driver can reduce the vehicle fuel consumption from 5% up to 40%, while CO₂ emissions may be reduced by leveraging the rising interest in public and electric vehicles. This thesis try to take advantages from one of the most pervasive device, the smartphone, to propose several approaches devoted at decreasing fuel consumption and emissions of combustion and electric vehicles by influencing the user behaviour. The main advantage of the approaches proposed in this thesis is that they rely just on inertial measurements,

so they can be directly applied and they can produce a real benefit for the user and for the environment without any additional ad-hoc hardware. In the very first part of the Thesis, we discuss the vehicle energy conversions steps. In particular, we present an analytical parametric model to compute the vehicle consumption from inertial measurements of the vehicle longitudinal dynamic. We therefore show that the overall vehicle fuel consumption and CO₂ emissions depend by the vehicle powertrain and by the upstream process efficiencies. For the sake of clarity, an experimental characterization of electric vehicle efficiencies is carried out. We then analyze the energy estimation achieved with a low sampling-rate dynamic signal. We firstly propose a signal processing methodology to simulate the effect of down-sampling on measured mission profiles. We propose a statistical characterization of the error introduced by the low sampling rate signal using real-data collected by two cars during several days. Experimental results suggest two methodologies to statistically compensate the average and reduce the variance of the energy estimation error. Since most of the remaining parts of the Thesis rely on

smartphone embedded inertial sensor we develop an experimental analysis and evaluation of these sensors measurements. For this aim we carry out an experimental acquisition campaign on urban and extra-urban roads using two vehicles, and comparing four smartphones' measurements with an external reference system. Then, we design a signal processing chain for reducing the signals noise and compensating the device orientation. Finally, we propose a data-fusion algorithm to reconstruct the vehicle longitudinal dynamic and to compute the power consumption. In the last three chapters of the Thesis we propose three innovative application that exploit inertial measurements. First, we design and develop a system able to assess in real-time the driving-style. The system is fully integrated in a smartphone application, which acquires the signals related to the vehicle dynamics (velocity and acceleration) and computes three power-related indexes. The system provides visual feedbacks to the driver who modifies his behavior accordingly. Finally, to experimentally prove the effectiveness the proposed approach we design and carry out an experimental campaign with five volunteers and an

electric car. Experimental results show that the interaction between the driver and the system improves the driving-style and reduces the overall vehicle consumption. Second, we propose a novel method to estimate in real-time the CO₂ emissions related to the user's mode of transportation. We design an algorithm to automatically classify the users mode of transportation in eight classes (car, bus, train, subway, motorcycle, walking, biking, still) using inertial information gathered from smartphone sensors. Since we choose a black-box supervised learning approach we develop a working Android application to collect data for training and validating the model and we design an experimental acquisition campaign with ten anonymous volunteers. Experimental results show that the proposed system is able to identify the mode of transportation with an average accuracy greater than 80%. Third, we propose a methodology to simulate Electric Vehicles (EVs) and Series-Hybrid Electric Vehicles (SHEVs) energy profiles from measured inertial mission profiles. The simulation approach can be applied to several problems. We focus on two examples: obtain reliable EV grid load profiles and determine the optimal sizing for the battery pack and the range-extender

of an SHEV. Examples of the simulation approach and of the two applications are provided with real-data.

PICOSECOND RESOLUTION INTEGRATED ELECTRONICS FOR SINGLE PHOTON DETECTOR ARRAYS

Matteo Carlo Crotti - Supervisor: Ivan Rech

Nowadays the measurement technique of time-correlated single photon counting (TCSPC) is increasingly widespread in a large number of fields, from medicine, to chemistry, to biology and in a large number of applications such as single molecule fluorescence spectroscopy, fluorescence imaging, and laser scanning microscopy.

TCSPC measurements allow the analysis of very fast and weak periodical light waveforms with a resolution of few tens of picoseconds and they basically consist in the detection of a single photon and in the measurement of its arrival time within the period of the analyzed light signal. A basic hypothesis must be satisfied to properly carry out these measurements: in a single period of the light signal the probability to detect more than one photon has to be negligible. Once this hypothesis is verified, after the detection of many photons, the reconstruction of a histogram, based on the measured photon arrival times, is possible. The reconstructed histogram represents the probability distribution function of the photons within the period and hence corresponds to the intensity of the light signal. Nowadays, most of commercial TCSPC systems are focused on single channel applications and,

to design a multidimensional system, the use of multiple parallel acquisition chains is necessary, with very high cost and large occupied area. Nevertheless the development of single photon detector arrays is leading to the design of new multichannel systems, with several parallel acquisition chains, in order to fit the specifics of even more applications, such as fluorescence lifetime imaging and diffuse optical tomography, that need a high number of parallel channels to reduce the overall analysis time; consequently, the cost reduction of the single chain is of utmost importance. Moreover, to develop a densely packed timing array, the reduction of occupied area and of dissipated power is also crucial.

As mentioned before, one of the most important sections in the acquisition chain for TCSPC is the time measurement block; in TCSPC applications three main performance are required in the time measure, in order to reconstruct the analyzed signal without introducing distortions: a high time resolution, in the order of few tens of picoseconds, a low differential non-linearity, of few percents of the histogram channel width and a high measurement rate, in the Megahertz order. Historically, this block has been

implemented in two ways: by means of a time-to-digital converter (TDC) or a time-to-amplitude converter (TAC) followed by an analog-to-digital converter (ADC). Although the employment of a TDC implies a smaller occupied area, the DNL obtainable with this structure is quite high and hence a TAC structure has been chosen, since it allows better performance, even of an order of magnitude, maintaining high resolution and high conversion rate. Moreover, the modern commercial multichannel ADCs with high resolution (14 bit) and high conversion frequency (several tens of MHz) easily allow the development of multichannel systems.

Among the several examples of integrated TAC and TDC reported in literature, two main families can be distinguished: single or few channel structures, that achieve high performance but with large silicon area and high dissipated power and structures with a high number of channels with extremely low silicon area, low power dissipation but poor performance in terms of time resolution and differential non-linearity. Therefore, the development of a new kind of converter, focused both on the performance and on the low cost and low area occupation is necessary.

To meet all the specifics required by TCSPC multidimensional systems a monolithic time-to-amplitude converter in $0.35\mu\text{m}$ Si-Ge BiCMOS technology has been developed and several steps has led to the development of a multi-channel, fully integrated TAC.

The first designed structure consists of a single channel TAC and has been used as a prototype to evaluate the performance and the possibility to enlarge the system to a higher number of channels;. A two channel structure, featuring high performance, comparable with the state-of-art devices has then been developed, to evaluate the crosstalk between the channels and understand the possible interference sources. Based on this circuit, a four channel chip, that can be considered the first step towards a large integrated system, since it presents both high performance and low crosstalk between the integrated channels, has been manufactured. Since the differential non-linearity of modern ADCs is not suitable for TCSPC requirements, the employment of a DNL reduction technique is necessary. To this aim, the dithering technique has been employed; once again, to allow the development of a large number of channels acquisition chain, also the electronic circuits

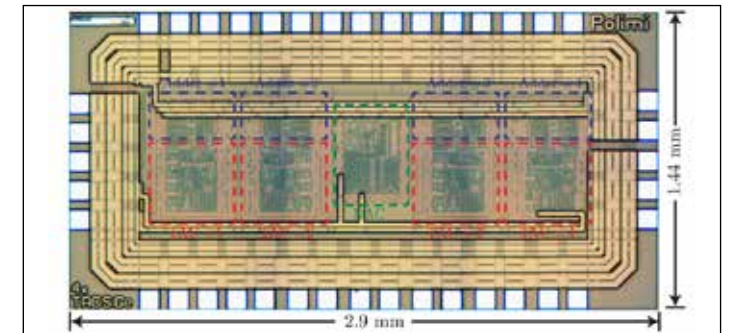


Figure 1. Microphotograph of the integrated circuit including a 4-channel TAC, 4 adder stages and a DAC

necessary to implement this technique (i.e. a D/A converter and an adder stage), have to be integrated with the TAC. Therefore a fully integrated DAC and an adder stage have been designed in the same TAC technology. Finally, a four channel complete system, consisting of 4 independent TAC followed by 4 adder stages and of a shared D/A converter has been designed. This final system presents a variable full scale range, from 12.5ns to 100ns, easily selectable by means of two external connection pads. The integrated circuits features extremely good performance in terms of time resolution (better than 20ps FWHM), differential non-linearity (less than 4% of the time bin width), conversion rate (16MHz) and crosstalk between the channels (negligible

in an actual TCSPC measure). Moreover, the area occupied by the single TAC channel (about 0.25mm^2) and the low dissipated power (less than 50mW) allow the future development of large TCSPC systems featuring both high performance and a large number of parallel acquisition chains.

JOINT DESIGN OF VEHICLE-DYNAMICS AND ENERGY-MANAGEMENT CONTROL STRATEGIES FOR ELECTRIC VEHICLES

Andrea Dardanelli - Supervisor: Sergio M. Savaresi

The urge to quickly and effectively respond to the need of new solutions for safe and green mobility is being recognized world-wide both from public institutions and from the industrial automotive world. In this context, recent efforts converge towards electric vehicles (EVs), which seem to be the most promising technology to achieve the needed reduction of greenhouse gas emissions and to form the basis for new models of urban mobility. However, the limited driving range of EVs represents one of the major psychological barriers in acceptance of green mobility. To overcome this limitation, the thesis advances a novel Energy Management Systems (EMS). The proposed EMS works as a state of charge closed-loop controller for EVs, which aims at reducing the energy consumption on board by actively modifying the driving-style. In particular, the thesis investigates the energy-oriented modeling, identification and control of a prototype light electric two-wheeled vehicle, which is equipped with a dedicated Embedded Control Unit (Gateway ECU) for signal acquisition and control. First, we derive a model of the vehicle. The aim of modeling is twofold. On the one hand we are interested in the longitudinal vehicle dynamics,

seen as the relation between the gas handle opening and the vehicle speed. On the other hand, we develop an energetic model of the vehicle, suitable for sensitivity analysis, identification and control. To this end, we introduce a simple yet effective model of the battery, which can be exploited for the identification and control. Linear and nonlinear versions of the model are presented and thoroughly discussed. We then detail a step-by-step approach to the model identification. First of all, we characterize friction forces and powers. Then, we show how to estimate the motor maps and the wheel-to-battery efficiency, both in traction and regenerative braking conditions, underlining the importance of a proper data filtering and measurements pre-processing. We finally present the battery model identification. Experimental validation results prove the effectiveness of the proposed model and of the identification approach. In order to quantify the energy consumption on-board, we examine the open-loop energetic characteristics of the vehicle. We carry out this analysis based on the spatially-normalized battery discharge, which is a useful indicator of the energetic consumption. We focus on the impact of mass variations, road slopes

and driving-style on energy consumption. The analysis is corroborated by experimental data collected on the vehicle and allows us to highlight the main factors which contribute to drain the battery.

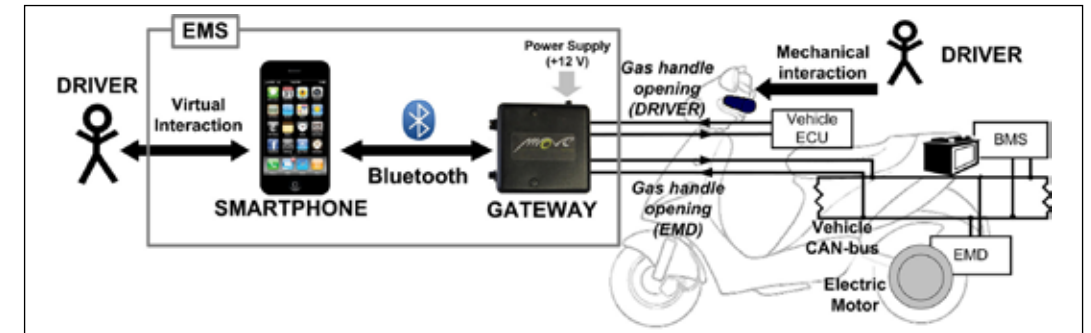
We exploit the identified model of the vehicle and the open-loop characterization of the energy flow for the development of the energy management system. The control algorithm is capable of regulating the battery state of charge by imposing a desired discharge rate. The discharge rate is tracked by means of speed and acceleration controllers (motion controllers), which intervene to control the vehicle dynamics conforming to the high-level energy control policies. The latter are adapted in accordance with the a-priori knowledge of the route, by using cartographic data and road slope information available on the internet.

The proposed control architecture is spatially-distributed and hierarchical, because the control logics are implemented on different devices, which share information through the vehicle CAN-bus and a bluetooth communication channel (see Figure 1). To this end, a smartphone is used as a vehicle-to-driver system and it is equipped within the proposed EMS. Note that mobile devices are attracting more and more

attention as a means to share important information between control systems and users. In order to ease and to enhance the interaction between the driver and the EMS, we leverage on the *Human Machine Interface* (HMI) capabilities of mobile devices. The storage

system on instrumented vehicles. Experimental tests are encouraging and assess the closed-loop performance. We also present an high-level study of the EMS, focusing on the user-side view of the control system. The Human Machine Interface (HMI) of the

real-time constraints, use broadcast networks often based on controller area network (CAN), embedded devices, and have some other characteristics that complicate security. In particular, we propose and successfully implement a security layer that sits on top



1. Overview of the instrumented vehicle

capabilities of mobile devices are also exploited for data logging purposes, but, more importantly, a *smartphone-in-the-loop* architecture is envisioned, as the mobile device is actually part of the proposed control system and runs the high-level control strategies of the EMS. Hence, the system is based on a three-layer architecture, composed of a smartphone that runs the high-level control algorithms, of a gateway ECU that hosts the low-level motion controllers, and of the vehicle electronic control unit that takes care of the actuators control. We believe that the integration of mobile devices on-board of EVs may help (1) to promote EVs diffusion among costumers and (2) to increase the accessibility and usability of the overall control system. We successfully implemented the energy management

EMS is entirely constituted by a dedicated mobile application running on a smartphone. The mobile application must (1) realize an effective system integration, (2) ensure driver-acceptance of the driving-style limitations and (3) reduce range anxiety. A methodical approach to the vehicle-to-driver interface design is thus required. To this end, we provide insight into the implementation structure of the software. Unified Model Language (UML) diagrams and selected screenshots of the application support the discussion. Finally, as security requirements are gaining more and more priority in the automotive research area, we introduce a security framework for the communication between the mobile device and the vehicle. Note that further challenges arise as vehicles have typically

of the Bluetooth standard. Experimental results show that our proposed approach can be applied to real-world cases, because (1) it has very low impact on the (often small) computational resources available on the vehicle and the smartphone, (2) it requires no hardware modifications, and (3) it requires no complex user interactions.

DEVELOPMENT OF ULTRA FAST READ OUT ELECTRONICS FOR THE EUROPEAN X-RAY FREE ELECTRON LASER

Stefano Facchinetti - Supervisor: **Carlo E. Fiorini**

The recent development of Free Electron Lasers (FELs) based on the Self-Amplified Spontaneous Emission technique has allowed a considerable reduction of the emitted wavelength. Nowadays it is possible to provide coherent light pulses in the X and -regime with unprecedented brilliance and short pulse duration. Having laser sources at these wavelengths is beneficial for various applications ranging from medical diagnostic to biology and physical studies. A European X-ray Free Electron Laser (European XFEL) is currently under construction in the Hamburg area, Germany. The first lasing operation is foreseen for 2015. Thanks to the superconducting nature of its linear accelerator this facility will be able to provide the highest repetition rate ever achieved, with X-ray pulses only 220ns apart. The energy range will be tunable between 206.6eV and 12.4keV, corresponding to a wavelength span from 0.1nm to 6nm. The Full Width at Half Maximum of the pulses will be less than 100fs, thus providing an extremely high peak brilliance.

To detect X-ray photons scattered by the samples during experiments several imagers are under development. Among others, the DEPFET Sensor with Signal Compression (DSSC) project aims to provide wide

energy coverage with single photon detection capability. To achieve this result a novel detector structure with a compressive characteristic based on the DEPFET concept is under development at the Max-Planck-Institute Halbleiterlabor (MPI-HLL), Munich. The high gain for small collected charge and the compression for large signals will provide both desired features of single photon detection capability and wide dynamic range. The final imager will be composed of 1024x1024 detectors, each one bump bonded to a dedicated read out channel. Full parallel read out is mandatory due to the high frame rate. Each channel will comprise a fast, low noise analog front end, an 8-bit analog-to-digital converter and a static RAM to store the information in only 200µmx200µm. The aim of my Doctoral activity has been the study, the realization and finally the integration of the analog front end for the DSSC project. To cope with the challenging requirements of high frame rate, very low noise, power consumption and area occupancy a novel filtering architecture has been proposed. The circuit, called Flip Capacitor Filter (FCF), processes directly the current signal of the detector to achieve high frame rates

still providing excellent noise performances. Two correlated measurements per read out cycle can be performed, one of the baseline current before signal arrival and one afterwards. The difference between the two values is obtained by flipping the feedback capacitor in the integrator stage, hence the name of the architecture. In recent years, other circuits based on the current readout approach have been proposed. As an example, VELA (VLSI Electronics for Astronomy) is a multi-channel ASIC developed at Politecnico di Milano that implements a trapezoidal weighting function by means of the Switched Current Technique (SCT). The same filtering technique has also been used as a second stage in ASICs that try to exploit the advantages of the current and voltage readout approaches, like VERITAS. In these chips the signal is initially read out in voltage mode and then converted to a current that can be processed with the SCT. In any case, none of the available solutions was able to fulfill the requirements of the European XFEL, as the DSSC project specifications go beyond any existing instrumentation in terms of speed, noise, area and power consumption. The FCF represents therefore a state-of-the-art circuit in the field of current-based filter architectures,

and besides matching the specific project requirements it can be successfully employed as analog input stage in other spectroscopic experiments. The compliance of the FCF solution to the DSSC project requirements has been demonstrated through both analytical evaluation and experimental characterization. For instance, by careful design of the feedback networks and by regulating the digital signals transitions no charge loss has been noticed due to the flipping phase. The circuit is able to provide an almost ideal trapezoidal shaping with variable gain even at the shortest processing time foreseen of 220ns. The gain can be regulated by acting on the integration time and the number of feedback capacitors in the filter integrating stage. Linearity is sufficiently good to ensure that the first collected photons are placed in the middle of the first ADC bins. The bias component of the detector current is removed by a dedicated current generator to maximize the filter dynamic range. This block is programmable to withstand threshold shifts in the detector after irradiation and mismatches in the DSSC matrix. Two different versions of the current generator have been designed, according to the specifications on the DSSC gain. Both structures are based on 4 bits DAC architectures with pixel wise settings that provide a coarse regulation of the current. Fine matching is obtained by setting the voltage in the active branches by means of a closed loop configuration. In this programming phase

the filter is used as an error amplifier. Measurements on the first version have demonstrated the capability of the current generator to cope with very large current variations. The new version, to be used in the final DSSC pixel, will provide the same current range with the advantage of a simpler architecture, capitalizing on the higher gain foreseen for the detector. Spectroscopic measurements using a ⁵⁵Fe source and a standard type linear detector gave results very close to expectations. A total of less than 50 electrons has been obtained with an integration time of 50ns. The FCF connected to the DEPFET has also been tested with a pulsed laser, to replicate the foreseen operating speed of the future European XFEL. The circuit was able to work at maximum frame rate, and weighting functions similar to that obtained on the FCF alone have been measured. In its final version the FCF circuit, developed in the IBM 130nm CMOS technology, occupies a very small area of 88x84µm². This corresponds to less than 20% of the total DSSC pixel area. Power consumption is limited to about 0.35mW per channel, but still the filter is able to correctly process large current signals comparable to its total current consumption. This result has been obtained by implementing the operational amplifier in the main integrator stage such that it can increase its current capability when needed. Also the reset phase has been carefully studied to obtain a very fast recovery of the system. Initially, a current and a voltage read out filters have been

studied and implemented in the MM1 chip. After measurements on both circuits' prototypes the DSSC collaboration has decided to focus on the FCF solution with its better noise performance, lower power dissipation and simplified sensor design. This decision confirmed the adequacy and quality of the proposed filter architecture. A common test system has been set up which allows for characterization of DSSC test chips comprising 64x64pixels and later full size chips. Several test chips have been realized and fully characterized to assess the figures of merit of the complete read out chain. In particular, the FCF performances match very well what obtained on the dedicated chip submission and the noise of the complete system, from the detector to the ADC, is consistent with the noise of the FCF alone and matches very well the DSSC goals. In conclusion, the analog front end developed during my Doctoral activity fulfills all of the requirements of the DSSC project for which it is designed, and represents one of the fastest current-based analog filters for spectroscopic applications available.

MODEL-BASED VERIFICATION AND ADAPTATION OF SOFTWARE SYSTEMS @RUNTIME

Antonio Filieri - Supervisor: Carlo Ghezzi

Software is the backbone of modern society. Its structure, its development process, and the expectation people place on it have quickly changed since the dawn of Software Engineering, claiming for new directions and new perspectives.

Traditional software engineering processes, starting from the popular *waterfall* model, introduced in the 70s by Winston W. Royce, were mostly focused on how to discipline software development. Their inventors argued that careful requirements analysis could improve quality and avoid costly changes. Avoiding changes was one of the central goals during early years of software engineering, in a time when organizations were monolithic, development centralized, deployment infrastructure well-known and mostly unchangeable, and application domains limited to critical systems, military, and big companies.

Taking a peek at the landscape of software in the past decade, almost none of these assumptions is still in place. Software development, provisioning, and maintenance is decentralized; systems are designed by assembling components developed and operated by third parties;

binding between interfaces and implementations is delayed at run time; infrastructure is often *in the cloud* and may change as quickly as a minute; mobile devices are ubiquitous in everyday life, providing continuous interaction with billions of different users; networks are pervasive and heavily shape software execution.

Today software must change. If it could still be enough in many cases to design applications *for change*, in the near future software will be more and more required to continuously and autonomously adapt in response to unpredictable changes in its environment and goals.

In particular, self-adaptation is a key driver to deal with three challenges of modern software development:

- **Volatility** of requirements, as consequence of the fast transformations of companies and customers
- **Uncertainty** about the effective operative conditions, hard to guess with accuracy at design time
- **Variability** in the behavior of the interacting environment: infrastructure, third party components, and customers.

A second difference between traditional software engineering

and its current evolution concerns the role of *non-functional* requirements, such as reliability, performance, energy consumption, and cost. Customers require the continuous assurance of the agreed quality levels, despite the unpredictable changes the software undergoes. Most of non-functional requirements impose the satisfaction of specific *quantitative properties*, which have to be continuously verified in order to trigger a convenient adaptation process whenever a requirement is violated.

Verification @Runtime.

Continuous verification of quantitative non-functional properties for self-adaptive systems has been the first main focus of this research. Many current works deal with the identification of “unhealthy” conditions that make the software violate its requirements. However, most of them are based on traditional verification techniques that are conceived for design time use and can hardly meet the strict execution time constraints imposed by run time application.

The first verification methodology proposed in this research stands upon two complementary concepts: modeling and monitoring. The

former aims at providing a semantic lens to interpret the data gathered from the running instances of the adaptive system. The latter is in charge of observing and measuring the relevant aspects of both the software and the execution environment and feed the information into the models, keeping them *alive at run time*.

The models considered here describe the behavior of the software, as well as the relevant aspects of the environment, as a stochastic process. Such probabilistic models allow the formalization of a certain degree of uncertainty in the temporal progress of software execution, thus supporting both unsharp assumptions at design time and the intrinsic randomness of physical phenomena.

Models are assumed to capture an updated and consistent abstraction of the running software. They are not considered here as just a many-to-one relation between the real-world phenomena and a set of model elements, but as first class entities that can be used not only to verify the satisfaction of specific requirements, but also as a base for more complex reasoning to support adaptation. Indeed, when the running software no longer satisfies a requirement, a convenient adaptation has to be carried out.

The second methodology is instead based on a syntactic-semantic framework for the definition of incremental verification procedures. These procedures are driven by the syntactic structure of the artifact under analysis (described by a

convenient formal grammar) and are encoded as semantic attributes associated with the production rules of the grammar itself. Incrementality is achieved by coupling the evaluation of semantic attributes with an incremental parsing technique.

This framework is general enough to effectively support the incremental verification of a large number of properties, including quantitative ones.

Model-Based Adaptation.

Software adaptation is the second main focus of this research. Most of the adaptation approaches proposed in the past years are either thought for static environments, when time is not an issue, or only effective in specific domains. Self-adaptive software requires dealing with uncertainty and incomplete information from the system's self and its environment, to correlate local and global decision-making, and to provide scalability as well as formal assurance of the dependability of the adaptation mechanism.

Control theory has established effective mechanisms to make controlled plants behave as expected. Although the similarity with software adaptation is self-evident, most of the attempts to apply control theory to software applications failed because the intrinsic non linearity, the variety of usage profiles, and the interconnection of heterogeneous components make software systems hard to be modeled as a *dynamic system*, i.e. by means of differential equations. As result, the current use of control theory

is limited to specific applications and hard to generalize to large classes of software.

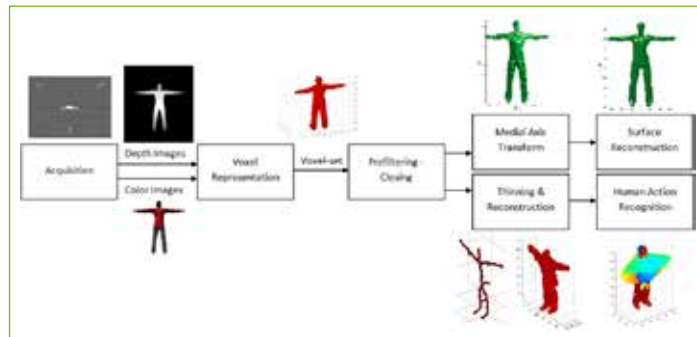
This research tries to change such route. If modeling software as a dynamic system is in general an obstacle, a way to go around it is to derive the differential equations from the abstract behavioral model of the software. This two-step escape has been proved to be effective for all the software whose behavior can be described by a discrete time stochastic Markov model, with rewards, and for most of the goals expressible as the satisfaction of a probabilistic control tree logic assertion. The obtained controllers can also provide formal assurance of their capabilities and notify the unfeasibility of the goal to higher-level decision makers.

A specific control strategy has also been devised for the case of dynamic binding, which is the main enabling technology for self-adaptation of service-oriented applications. The specific issue of dynamic discovering and addition of new services at run time has been considered in proposing a control strategy that joins together the flexibility of the architecture and the formal assurances of its control theory foundation.

ANALYSIS AND CLASSIFICATION OF HUMAN ACTIONS WITH A MULTI-KINECT SYSTEM

Eliana Frigerio - Supervisor: Marco Marcon

This thesis describes an innovative extension of morphological operators: from the analysis and processing of binary images, to the analysis and processing of three dimensional images represented by voxels. These new morphological operators (especially the morphological skeleton extraction and the 3D thinning algorithms) are applied to the analysis and classification of a database of human actions in a predefined vocabulary of gestures. The database is composed by the volumetric reconstructions of sequences of poses performed by one actor in a scene captured with a multi-Kinect system developed in our laboratory (ISPG). We span the entire pipeline from the capturing process (with previously calibrated devices), preprocessing and volume reconstruction, till the topological skeleton extraction, surface representation and classification (Fig. 1). The first part of our research is dedicated to the extraction of volumetric information starting from the acquisition system implemented. The methodologies that we propose are based on Computer Vision theory applied on color images and depth maps simultaneously. In order to obtain a 3D reconstruction of the acquired scene, the devices must be



1. Block diagram of the proposed method for actor representation and human actions classification

calibrated: intrinsic and extrinsic parameters must be known. Points matching between two or more images of a scene shot from different viewpoints is the crucial step to define epipolar geometry between views. The innovative contribution in the process developed is to find robust stereo correspondences for wide baseline acquisitions. We show how the knowledge of the underlying depth map together with a visual snapshot of the scene can greatly improve the robustness of points matching in wide-baseline contexts with respect to the state of the art descriptors. Once the system is completely calibrated, we extract the human silhouette from each color image, we use it to segment the corresponding depth map and we project the depth-pixels into the scene. An intersection of the projected points gives the 3D

volumetric reconstruction of the actor in the scene. Depth maps allow to reconstruct the human body also in its concave parts (using a Visual Hull approach). The use of a 3D reconstruction technique, prior to any analysis or recognition routine, allows the recognition system to work directly on 3D data. Problems like viewpoint dependencies and motion ambiguities are inherently solved.

Frame-by-frame 3D representations of the scene in terms of voxels have been the input data for any other successive analysis and processing. In this thesis we extend the most common 2D morphological operators to 3D. The compact representation of the human body and the analysis of the movements can be addressed with a common framework that, neither

requires any prior information on the reconstructed volume, nor imposes any resolution requirement on the subject under analysis. The only input for morphological operators is a volume of voxels. Information on the volume nature or resolution requirements are related only to the particular application to which the morphological operators are applied, but do not limit the applicability of anyone of the proposed morphological operators. In particular, we extend the morphological skeleton extraction algorithm to 3D and we develop a new 3D thinning algorithm for the computation of an approximation of the topological curve skeleton (briefly defined as a simplified 1D representation of a 3D object without losing relevant information). Our algorithm provides good results, preserves topology, is easy to implement and shows better noise robustness respect to the state of the art methods. We also show that its application improves the performance of our action classification system.

The main methodologies proposed in this thesis are evaluated through a number of simulations and experiments, within the context of human-computer interaction. In particular, we consider two

application scenarios, both with a 3D scene reconstruction system involving a single actor in an indoor scene: Surface Reconstruction and Human Action Recognition. Surface reconstruction of a static 3D human pose is a Computer Vision problem. This work aims to provide a method to reconstruct the actor body surface that is accurate and computationally inexpensive. In particular, using a net of Kinect devices, the resolution is on the order of centimeters and it is too low for many algorithms developed in the literature. However, working with morphological operators, no resolution requirements are imposed. This frees us from the type of devices used for the acquisition. The morphological skeleton extraction algorithm is used for surface rendering as union of balls. This representation is also hierarchically interpretable, a useful property in many applications. Moreover, having the center and radius of each ball (Medial Axis Transform), together with the sampled surface, allows to represent the surface as an iso-surface of a 3D function defined as linear combination of elementary functions with radial support. Automatic classification of sequences of human body movements into a predefined

vocabulary of gestures is a Pattern Recognition Problem. In particular, we investigate how to build spatio-temporal models of human actions that can support categorization and recognition of simple action classes, independently from body position and orientation inside the scene, actor gender and body sizes. The developed 3D thinning algorithm highlights the movement incrementing the similarity between sequences representing the same action, even if performed by actors with different gender or different body structure. The algorithm used for extracting robust stereo-correspondences is also useful to extract motion features that are invariant respect to the actor position and orientation in the scene. The classification shows good results and the improvements using our thinning algorithm are demonstrated by the classification rate.

The solutions proposed in this thesis find potential applications in all the fields that are based on a 3D reconstruction of the scene. In particular they are designed to fit in the area of video security (home care and support), human and computer interaction (with user-friendly interfaces) and immersing video games for example.

ADVANCED METHODOLOGIES AND TECHNIQUES FOR THE OPTIMAL DESIGN OF WIRELESS SENSOR NETWORKS

Paolo Roberto Grassi - Supervisor: **Donatella Sciuto**

In the last two decades, technology advances in chip miniaturization, energy consumption and wireless communication allow the development of revolutionary applications in fields like wearable and ubiquitous computing. The term ubiquitous computing refers to distributed technologies and applications designed to disappear in the environment, allowing the user to unconsciously interact with it. Ubiquitous computing requires small and smart devices deployed in the field of interest with the purpose of sensing valuable physical variables and interact with the users. A large amount of applications has been envisioned to this future in the field of tele-medicine, child care, environmental monitoring, etc. In 2001, the IST Advisory Group (ISTAG) published a white paper that describes what living with Ambient Intelligence (Aml) might be like for ordinary people in 2010. This document includes four user-centric scenarios that envision what technology could do in the future and what could be the role of the user with respect to the Information Technology.

All these scenarios do not define any specific technology rather they are focused on user-machine interaction and applications. Very often they

overlap in many aspects and thus technologies required for Aml could be useful for Smart Cities and so on. In particular, an element is heterogeneity, since different systems will interact each other to provide the user the required service. In Aml, devices like television, washing machine, heating system, security cameras, etc. will actively collaborate. In Smart Cities, a traffic light could need to communicate with a meteorological station. In Ubiquitous Computing, remarkably different devices with substantial hardware differences must communicate each other.

Wireless Sensor Networks

A WSN is an ad-hoc network composed of tiny devices with limited energy and computational resources equipped with sensors to gather physical measures from the environment. A decade of research and applications proved the truth of such statement and their potential in next generation digital systems. A lot of research effort has been spent on Wireless Sensor Networks (WSNs), and many architectures, protocols, programming techniques have been developed. Thanks to this research, today, complex and innovative applications can be developed in challenging

application fields like medical or environmental monitoring.

The increasing complexity of Wireless Sensor Networks (WSNs) is leading towards the deployment of sophisticated networked systems, and the optimal design of WSNs can be a very difficult task in case constraints and requirements are strong. A common WSN node comprises five main components: a processing unit (microcontroller, processor, FPGA, ...), memories (DRAM, SRAM, Flash, ...), sensors and actuators, multiple communication layers (physical radio, MAC, Routing, ...) and a power supply (external power supply, batteries, solar cells, ...).

During the design phase, the cooperation of all these components must be combined to identify the configuration that best fits the design objectives. The rising complexity of WSNs design is also due to the combination of general-purpose architectures (which offer flexibility, but require an optimal configuration in order to behave in an energy efficient way) with ad-hoc radio, MAC and routing layers. The combination of different layers and the large number of configurable hardware and software parameters often generates an extremely large

design space, which requires a powerful CAD algorithm to carry out the exploration.

In the last years, wireless sensor networks (WSNs) are becoming a well-established reality in many different domains, including military applications, environment control, industrial supervision, health monitoring and environmental monitoring. Once retrieved, measures are elaborated and sent over the wireless channel to a sink, where data is stored and used to monitor activities of the area of interest. WSN nodes usually operate in hostile environments with limited energy resources, constrained by the battery capacity, and thus the problem of achieving low power consumption has become one of the main research focuses of research over the last years.

In order to deal with the specific requirements of a given application domain, a WSN has to meet certain performance requirements as well as to guarantee a sufficient lifetime, which are often conflicting goals. The right tradeoff between these two objectives, as well as the prevention of undesired behaviors such as unbalanced performance among the different nodes of the WSN, can be guaranteed by accurately evaluating the network configurations during the design phase. In order to help the designer during the energy-performance tradeoff analysis, many Design Space Exploration (DSE) techniques for WSNs have been proposed in the literature, and most of the classic optimization algorithms can also be adapted to WSNs

with a low effort. However, providing such algorithms with an accurate system-level estimation of the WSN performance is still an open problem, and it is necessary to guide the DSE algorithm to the detection of the Pareto-optimal network configurations.

Motivations and Rationale

Nowadays, Wireless Sensor Network's design requires experts from several application fields such as computer science, electronics, telecommunication, digital signal processing and application-specific competences (medicine, geology, biology, etc.). A collaboration between experts in these fields is required to guarantee an optimal design that respects given constraints and meet desired requirements. This thesis presents a comprehensive study on the design of Wireless Sensor Networks including hardware platform design, network optimization and software partition. Moreover, adaptive techniques are proposed to deal with online real-time events such as interferences. The main contribution of this thesis is a general-purpose design flow for WSN that defines the set and the sequence of processes to follow to obtain the specified design. The proposed design flow is a guideline for the development of automated design tools and design frameworks. The design phase takes several inputs such as the application specification, requirements, constraints, etc. The objective of this thesis is to define how the design process should be done, what can be done automatically and which information are required at each

step of the design flow.

The applicability and effectiveness of the proposed design flow and optimization techniques has been verified and tested through the implementation of a design framework. It includes:

- Automated optimization of the given design;
- Pareto-frontier analysis to detect desired trade-off in a multi-objective scenario;
- Intuitive interface that allow manual design and test of WSNs.

In addition to design-time (offline) analysis and optimization, this thesis presents two techniques for online real-time adaptivity. It does not aim to provide a comprehensive study on online optimization, but show the reader the limits of design-time optimizations and the advantages of online real-time approaches. Please note that design-time optimization are usually more effective than online optimization for two aspects: the ability to define the design, in case of non-optimality, in any aspect (protocols, devices, etc.), and the amount of information during evaluation. However, online real-time optimizations are able to deal with stochastic processes such as faults or interferences effectively.

Design-time and online optimizations must be both considered during the design of a WSN. Reliable and cost-effective design solutions are important factors to ensure success and diffusion of WSN, thus efficient design tools to support the designer in this phase is of extreme important.

TOMOGRAPHIC IMAGING OF THE TROPICAL FOREST IN P-BAND

Dinh Ho Tong Minh - Supervisor: **Fabio Rocca**

The scope of this dissertation is to provide a discussion about the potentials and performances of the Tomographic Phase of the candidate future radar satellite BIOMASS of the European Space Agency. This satellite would host a P-band radar with 6 MHz bandwidth for the remote sensing of natural scenarios, such as agricultural fields, soil surfaces, mountain areas and forests. In the case of forested areas, the object under analysis corresponds to the vertical structure of the trees, to be explored by tomographic techniques. This work can be divided in three parts as follows.

The first part of the dissertation focuses on the problem of biomass estimation in tropical forests. The retrieval of biomass in dense tropical forests using Synthetic Aperture Radar (SAR) images is widely recognized as a challenging task. This is mainly due to the backscatter saturation effect at high biomass values and the ground topography effect. The study presented in this part is an attempt to overcome these problems based on direct three-dimensional imaging of the forest volume, which is possible through multi-baseline SAR tomography.

The second part is dedicated to the ground based array system to complement tomographic

airborne data-set. We proposed an array design which is well suited to study the vertical distribution of forest parameters and their temporal changes. This design has been successfully implemented in October 2011 in Paracou, French Guiana. Concerning short term temporal decorrelation, results indicate that during the day-time the motion of the forest is strong due to wind and temperature changes, whereas it appears to be definitively more stable during night hours. This result suggests that BIOMASS mission performance over tropical forest could be optimized by gathering acquisitions at dawn or dusk time. The coherence values at different forest heights are observed to stay high even after 27 days. This result is critical for the BIOMASS mission because the high temporal coherence after a 27 day is a prerequisite for SAR Polarimetric Interferometry and Tomographic applications in a single satellite configuration.

The final part is to provide performance assessments on the BIOMASS Tomographic Phase. We discuss the impact of temporal decorrelation and ionospheric disturbances affecting SAR images on the quality of BIOMASS tomographic measurements. It is shown that temporal decorrelation

has a more significant impact than ionosphere disturbance. Concerning the temporal decorrelation, the results from studies show that, providing that the revisit times for the tomographic campaigns be 3-4 days as predicted, the problem does not becomes critical.

HIGH DETECTIVITY ARCHITECTURES AND PHOTOCONDUCTION MECHANISMS IN ORGANIC PHOTODETECTORS

Antonio Iacchetti - Supervisor: **Marco Sampietro**

Molecular and polymeric semiconductors are gaining an ever growing interest as materials for electronics. Their unique features allow them to be deposited over unconventional substrates, like low-cost, flexible plastic foils, by means of solution-based techniques easily scalable to address large area depositions; this makes possible to target applications not addressable by standard electronics.

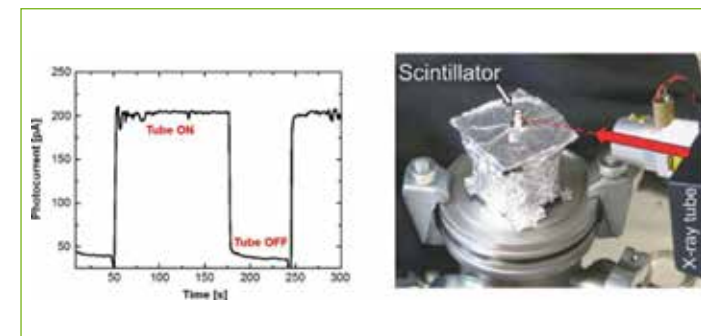
While up to now research has mostly addressed light emissive and light harvesting devices, recently light detection by means of molecular semiconductors have raised considerable interest. Taking advantage of the knowledge already developed in the field of light emitting diodes and organic photovoltaics, and by combining it with a dedicated device design, it is possible to achieve excellent performances, making this technology appealing for commercial development.

When dealing with light detection, one has to maximize the signal to noise ratio, which means that not only the responsivity has to be improved, but also the background noise reduction has to be addressed: this is accounted for by a figure of merit called detectivity. It is within this framework that strategies for the improvement of organic-based light detectors

have been explored in this dissertation. As a first approach, we put the focus on the issue of shot noise produced by dark currents. This is addressed through the implementation of blocking layers. According to a picture where carrier injection from metals represents the dominant leakage source, blocking layers incorporation produced a reduction of dark currents by two orders of magnitude with respect to standard devices. This improvement qualifies organic photodetectors as a viable technology for the field of radiographic acquisition, characterized by strict dark currents constraints. Due to the lack of affordable X-ray focusing optics this is an inherently large area application which can hardly be addressed by inorganic semiconductors, thus making the use of molecular semiconductors very promising. Organic photodiodes were specifically developed to operate in an indirect X-ray acquisition scheme and, thanks to the blocking layers introduction, excellent results could be appreciated from X-ray characterizations; not only we proved the good X-ray detection abilities of such devices, but also radiation hardness was demonstrated. Finally, as organic semiconductors are known to be particularly prone to degradation

in atmospheric conditions, an encapsulation step has been developed, this allowing to appreciate excellent devices stability in air. Secondly we deal with an innovatively approach aimed to responsivity improvement: the property of supramolecular organization peculiar to certain dyes is explored to tailor the absorption coefficient. This results in more selective and higher light absorption with respect to the isolated dye. Thanks to enhanced absorption, thinner photoactive films can be adopted thus limiting both optical and recombination losses. By incorporating J-aggregates of a particular cyanine dye in a planar heterojunction architecture, the first realization of a photodiode exploiting J-aggregates selectivity was demonstrated. Finally, an alternative light detecting device is investigated: the photoconductor. The main advantage introduced by this class of devices is the capability of performing a gain in term of photon quantum conversion. Here a model able to predict photoconductors electrical behavior is developed by adapting a classical photoconductive theory established in the frame of multiple trapping and release transport to a hopping conduction model,

which better fits the case of organic semiconductors. The analytical derivation was followed by the identification of a strategy to assess material physical parameters like exciton dissociation yield, recombination center cross-sectional area, density of states characteristic energy and charge mobility as function of carriers density.



1. (Left) Photocurrent response of the organic photodiode when a coupled CsI(Tl) scintillator is irradiated with X-ray photons. (Right) A picture of the set-up showing the scintillator lying on the photodetector (covered with shielding Al foil) and the X-ray tube

Photocurrent and decay time versus the incident power density in an organic photoconductor with a 6 μm interelectrode spacing ($\lambda = 670 \text{ nm}$)

ENERGY HARVESTING-AWARE DESIGN OF WIRELESS NETWORKS

Fabio Iannello - Supervisor: **Umberto Spagnolini**

Recent advances in low-power electronics and energy-harvesting (EH) technologies enable the design of self-sustained devices that collect part, or all, of the needed energy from the environment. Several systems can take advantage of EH, ranging from portable devices to wireless sensor networks (WSNs). While conventional design for battery-powered systems is mainly concerned with the battery lifetime, a key advantage of EH is that it enables potential perpetual operation of the devices, without requiring maintenance for battery substitutions. However, the inherent unpredictability regarding the amount of energy that can be collected from the environment might cause temporary energy shortages, which might prevent the devices to operate regularly. This uncertainty calls for the development of energy management techniques that are tailored to the EH dynamics. While most previous work on EH-capable systems has focused on energy management for single devices, the main contributions of this dissertation is the analysis and design of medium access control (MAC) protocols for WSNs operated by EH-capable devices. In particular, the dissertation first considers random access MAC protocols

for single-hop EH networks, in which a fusion center collects data from a set of nodes distributed in its surrounding. MAC protocols commonly used in WSNs, such as time division multiple access (TDMA), framed-ALOHA (FA) and dynamic-FA (DFA) are investigated in the presence of EH-capable devices. A new ALOHA-based MAC protocol tailored to EH-networks, referred to as energy group-DFA (EG-DFA), is then proposed. In EG-DFA nodes with similar energy availability are grouped together and access the channel independently from other groups. It is shown that EG-DFA significantly outperforms the DFA protocol. Centralized scheduling-based MAC protocols for single-hop EH-networks with communication resource constraints are considered next. Two main scenarios are addressed, namely: i) nodes exclusively powered via EH; ii) nodes powered by a hybrid energy storage system, which is composed by a non-rechargeable battery and a capacitor charged via EH. For the former case the goal is the maximization of the network throughput, while in the latter the aim is maximizing the lifetime of the non-rechargeable batteries. For both scenarios optimal scheduling policies are derived by assuming different levels of information available

at the fusion center about the energy availability at the nodes. When optimal policies are not derived explicitly, suboptimal policies are proposed and compared with performance upper bounds. Energy management policies for single devices have been investigated as well by focusing on radio frequency identification (RFID) systems, when the latter are operated by enhanced RFID tags with energy harvesting capabilities.

SAR POLARIMETRIC MONITORING BY NATURAL CALIBRATORS

Lorenzo Iannini - Supervisor: **Andrea Monti Guarnieri**

SAR polarimetry offers significant benefits in target characterization and contrast enhancement over traditional single polarization acquisitions. Polarimetric applications obviously demand the preservation of amplitude and phase relationships between the differently polarized channels. The accuracy requirements depend on the specific application and can be honoured through proper monitoring procedures aimed at removing the distortion introduced by the system Transmit/Receive modules and/or by the propagation medium. This process is referred to as external calibration, and can be performed on the natural scene features, on deployed calibrators or on the combination of both. The main research question addressed in this thesis is how the scene information must be collected and processed in order to produce an effective contribution to the polarimetric system monitoring and data calibration activities. In first part of the work an overview on the traditional POLSAR approaches based on the distributed targets (DTs) is introduced. The feasibility related to the estimation of the most acknowledged distortion model, comprising channel imbalances, cross-talks and Faraday rotations in the L/P-Band frequencies,

is explored. The choice of a convenient set of case studies allowed to provide indication on the effectiveness of DT-alone approaches and on the necessity of a calibrated point target (PT). Though it is demonstrated that a full polarimetric calibrator can be achieved only by using a PT, the analysis stresses the fact that significant information on the channel cross-talks and on the imbalance ratio can be nevertheless attained from DTs. The uncertainty on the parameter estimates due to data and model noise sources is assessed both at a theoretical level and on practical techniques. The reader is shown in the end that the poor performance attained by reference algorithms in case of high cross-talk levels or large Faraday rotations can be improved through numerical optimization. An alternative calibration approach which exploits the temporal information provided by multi-image stacks rather than the traditional spatial statistics is then debated. It certainly represents the most innovative contribution of the thesis. The novel methodology is based on the stable natural targets, the so-called Permanent Scatterer (PS). When a sufficient density of PSs can be found within the selected image frame, the PS based technique,

namely PolPSCal, offers a reliable relative calibration solution. More specifically, it returns the differential distortion information with respect to a master image of the stack. The work proceeds then by proposing an encompassing framework for polarimetric system monitoring based on both the spatial and the temporal exploitation of the natural targets. The solution relies exclusively on the in-scene information, and thus it's independent from calibrated reflectors and from other a-priori external information. A generic distortion model has been conceived, so that the approach can be readily tailored to different sensor scenarios, ranging from higher-frequency SARs to lower-frequency acquisitions affected by Faraday rotations. The DT estimates are indeed integrated with the PS differential distortion in order to achieve (up to an absolute radiometric scale factor) an unambiguous temporal monitoring of the system distortion, and therefore a consistent data calibration within the image stack. The performance has been assessed through synthetic simulations and validated on a Fine Quad-Pol Radarsat-2 dataset which comprises 26 images over the Barcelona area, returning an accuracy on the channel

imbalance stability below 0.2 dB and on the cross-talk level < -35 dB, some promising results indeed, that comply with the acknowledged quality requirements for polarimetric SAR systems.

MICROELECTRONIC INSTRUMENTATION FOR MULTI-CHANNEL TIME-CORRELATED SINGLE PHOTON COUNTING

Bojan Marković - Supervisor: **Franco Zappa**

The precise measurement of very short time-intervals is of essential importance in many fields of science, medicine, engineering and industry. Many applications in medicine, biology and chemistry make use of precise time-interval measurements in order to reconstruct very-low intensity fast-changing optical waveforms. In this applications the optical signals are very faint, consisting of just few photons per cycle, thus the discrete nature of the signal itself prohibits analog sampling. Furthermore, in many cases the signals are very fast, therefore a photodetector with very high bandwidth is required if analog sampling is to be employed. To overcome those limitations, the reconstruction of the time-resolved optical waveform is achieved by Time-Correlated Single Photon Counting (TCSPC) technique based on the detections of single photons that compose the optical signal and on the measurement of their time of arrival within the signal period. A single-photon detector, usually a Photomultiplier Tube (PMT) or a Single-Photon Avalanche Diode (SPAD), and a time-measurement device, i.e. a Time-to-Digital Converter (TDC), represent the core of the TCSPC setup. The general requirements of TCSPC setups are very demanding: the time-

measurement precision of the systems has to be very high (tens of picoseconds or less) with very low differential non-linearity (DNL around 1% LSB or less). Several commercial TCSPC modules exist, however, those setups are bulky and consumes a lot of power, thus limiting the number of measurement channels to one or very few. On the other hand, dense arrays of single-photon detectors and time-measurement circuits also exist, however those arrays do not reach nor the resolution nor the linearity required by many TCSPC applications. However, many application would largely benefit from the availability of high-performance compact multi-channel TCSPC systems. The current lack of those systems and their potential to provide important improvements in many fields, such as medicine, biology and chemistry, were the main drivers of this Ph.D. research, setting the main objective of the work: the design and development of high-performance, low-power, compact multi-channel TCSPC instrumentation. The first step in this direction was the design of a new TDC chip capable of reaching very-high performances and with the architecture being easily expandable into an array of TDCs. This is achieved conceiving and architecture

based on global biasing and reference generation electronics and time-measurement circuitry. The compact, 250 μm x 250 μm , area time-measurement circuitry represents the basic building block of the chip and it is the part which can be easily replicated in an multi-channel version, thus representing the measurement channel. On the other hand, the rest of the chip, which is more area consuming, can be shared by all channels. The architecture of the measurement channel is based on a coarse counter and a couple of two-stage interpolators that exploit the cyclic sliding scale technique in order to improve the conversion linearity. The interpolators are based on a new coarse-fine synchronization circuit and a new single-stage Vernier delay loop fine interpolation. Fabricated in a standard cost-effective 0.35 μm CMOS technology the TDC chip reaches a dynamic range of 160 ns, 17.2 ps precision and Differential Non-Linearity better than 0.9% LSB rms. The following step was the development of a compact stand-alone, easily-employable, TDC module having the chip as the core. The instrument reaches timing-precision of 15 psrms (i.e. 36 psFWHM) and conversion Differential Non-Linearity (DNL) better than 1.5% LSBrms,

suitable for demanding TCSPC applications, within a compact 6 cm x 6 cm x 8 cm case and low 3.3 W power consumption. Therefore, the module reaches high-performances with significant improvements in terms of dimensions and power-consumption in respect to the state-of-the-art commercial TCSPC timing-modules. The USB link to the remote PC allows the easy setting of measurement parameters, the fast download of acquired data, and their visualization and storing via an user-friendly software interface, making the module easily employable in any measurement setup.

The final step in demonstrating a compact high-performance multi-channel TCSPC system was the development of a 16x1 linear array chip of SPADs and TDCs and a compact module employing it. The 16x1 array chip integrates 20 μm Single-Photon Avalanche Diodes (SPAD) and 15 bit Time-to-Digital Converters, reaching better than 1% LSB rms DNL, 70 ps FWHM timing precision, with 10 ps LSB and 160 ns full-scale range. Therefore, the array chip reaches high-performances suitable for demanding TCSPC applications and embedded into a compact 6 cm x 6 cm x 10 cm module it represent a state-of-the-art multichannel TCSPC system. Finally, the instruments developed during this Ph.D. thesis, other than providing the state-of-the-arte performances by itself, enable further development and improvements which could provide even more outstanding performances. In particular, the developed TDC module provided high-

performances in much more compact area and with much less power consumption compared to currently available modules, but the four channel module, which is currently in development phase, can even further increase this performance gap. Furthermore, even if the developed 16x1 SPAD + TDC array represent the best multi-channel TCSPC system currently available, a 16x16 SPAD + TDC chip array is being developed, and it has potential to become the milestone for the compact large-multi-channel TCSPC systems. The thesis is organized as follows:

Chapter 1 introduces the main applications of the TCSPC technique which are also the main applications for instruments developed in this work. However, it also present some other applications that could benefit from the results of this research. The second part of the chapter introduces the principle of the TCSPC technique together with a description of required instrumentation and its performances. Chapter 2 presents the design of a TDC architecture capable of reaching high-precision and high-linearity as required by TCSPC technique, together with moderate area occupation per measurement channel. The architecture is based on a coarse counter and a couple of two-stage interpolators that exploit the cyclic sliding scale technique in order to improve the conversion linearity. The interpolators are based on a new coarse-fine synchronization circuit and a new single-stage Vernier delay loop fine interpolation.

Chapter 3 presents a compact, low power time-measurement module having the TDC chip as the core. The module reaches high-performances with significant improvements in terms of dimensions and power-consumption with respect to the state-of-the-art commercial TCSPC timing-modules. Chapter 4 presents the development of a 16x1 linear array chip of SPADs and TDCs and a compact module employing it. The 16x1 array chip integrates 20 μm SPADs and 15 bit TDCs, reaching better than 1% LSB rms DNL, 70 ps FWHM timing precision, with 10 ps LSB and 160 ns full-scale range. Therefore, it represents the state-of-the-art complete (detector plus time-measurement circuit) multi-channel TCSPC system.

PLENACOUSTIC PROCESSING IN THE RAY SPACE: APPLICATIONS TO ACOUSTIC SCENE MODELING AND ANALYSIS

Dejan Marković - Supervisor: Augusto Sarti

The complexity of the tasks that the modern acoustic systems are asked to perform is increasing. At the same time such systems are expected to work in and adapt to acoustically "hostile" environments. In order to address current and future challenges, the new systems need to employ sophisticated audio signal processing algorithms and, at the same time, to interact, exchange information and collaborate with each other, by taking advantage of the presence of devices with integrated loudspeaker and microphone arrays in everyday environments (e.g. surround sound systems, "smart TVs", computers, game consoles, smartphones, etc.). The acoustic measurements that are acquired by different systems in different positions in space need to be collected and organized in a parameter space that exhibits a high degree of regularity and can be accessed and used by different signal processing algorithms. Furthermore, in order to guarantee the necessary operational reliability and robustness, and offer a high-quality user experience, the new acoustic systems need to constantly monitor the hosting environment, adapt to it and predict the effects of their actions within it. In other words, the analysis of acoustic scenes and the modeling of

acoustic propagation should be carried out in a synergistic fashion, i.e. cooperating between the analysis step, which uses the simulation of the soundfield to improve the results of the analysis, and the modeling step, which uses the extracted information about the environment to simulate the soundfield.

In this thesis we address a fairly broad range of current audio signal processing problems through the study, representation, acquisition/construction and use of the plenacoustic data that captures the acoustic scene as "seen" from different points in space. In particular, for the modeling of acoustic propagation, the plenacoustic data takes form of the visibility information that specifies the visibility of geometric objects from generic points in space. This information is used for an efficient and accurate simulation of acoustic propagation in complex environments. As far as the analysis of acoustic scenes is concerned, the plenacoustic data acquired by one or more microphone arrays is represented in form of plenacoustic image that captures the soundfield coming from a given direction at a given point in space. This image carries a great deal of information on the acoustic

scene.

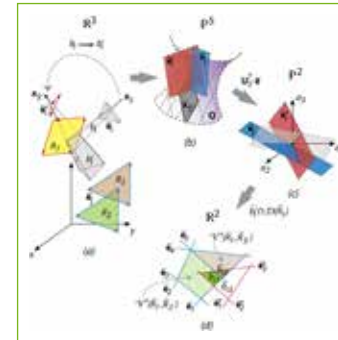
Following the laws of the geometrical acoustics, the plenacoustic data is represented in terms of acoustic rays in a space here referred to as the ray space. The adopted parameterization of the acoustic rays allows both an efficient construction of visibility information and an easy extraction of acoustic features from the acquired plenacoustic images. High regularity and generality make the ray space representation of plenacoustic data suitable for a variety of potential applications.

The applications examined in this dissertation show the validity of the proposed approach for purposes of both modeling of acoustic propagation and analysis of acoustic scenes. In particular, the examined applications follow a specific scenario in which an advanced spatial audio system aimed at reproducing the desired soundfield within a region of space is placed inside an unknown hosting environment. First, an acoustic source probes the environment and the plenacoustic images acquired by a microphone array are examined in order to infer the geometry of the environment. The modeling engine computes the reflective paths between

the source and the array. The modeled paths are then used by the second analysis algorithm that compares them with the acoustic measurements in order to estimate the reflection coefficients of all reflective surfaces in the environment. Given the information on

statistical performance of proposed algorithms are analyzed. However, the potential of the main ideas behind tools developed in this dissertation is not limited just to the presented applications. Efficiency, regularity and generality of the representation, as well as

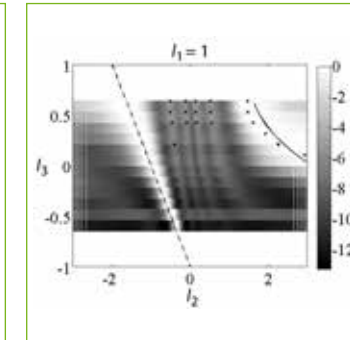
increasingly important topics in the audio signal processing and go far beyond the examined applications. They represent important assets that could be exploited in order to deal with the growing complexity of task that acoustic systems are asked to perform. We believe



1. Fast tracing of acoustic beams using visibility information: (a) reflection of a beam in the 3D geometric space; (b) illustration of the geometric primitives in the ray space (Plucker quadric embedded in a five-dimensional oriented projective space); (c) the projection of the geometric primitives onto the subspace of rays originated from the image source (lies completely on the surface of the ruled Plucker quadric); (d) subdivision into sub-beams is performed by the intersection between the ray space representation of the beam and the visibility diagram of the surface that causes the reflection

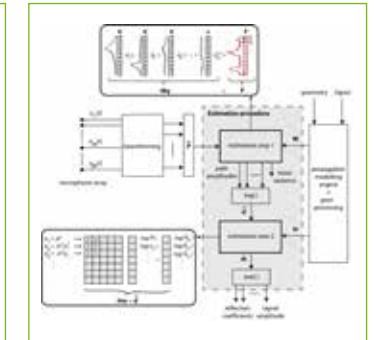
geometry and reflection coefficients of the hosting environment, the modeling engine is used, once again, to model the sound propagation inside such environment. The rendering system uses this information to reproduce the desired soundfield by means of a loudspeaker array while compensating at the same time for the natural reverberation of the hosting environment.

Theoretical aspects, implementation issues and



2. Example of the plenacoustic image in the ray space; plenacoustic imaging turns problems of acoustic analysis in space and time into problems of pattern analysis on images, which can be approached with methods found in the rich literature of pattern analysis, computer vision and multidimensional signal processing; example in figure shows that the contributions of acoustic sources naturally cluster on lines on the plenacoustic image and, therefore, the sources are localized by finding parameters of lines on the image

the perspective of even further availability of inexpensive integrated microphone/loudspeaker arrays in near future, make the proposed tools attractive for a wider range of possible applications including source characterization and separation, wavefield extrapolation, etc. The main ideas that inspired this work, namely environment awareness; collaboration between different spatially distributed systems; and alternating analysis and modeling steps; are becoming



3. Schematic overview of the proposed model-based method for in-situ estimation of sound reflection coefficients in acoustic enclosures

that the approach presented in this work can give a significant contribution to research in the above fields and inspire novel and innovative solutions.

STUDY AND APPLICATION OF RECONSTRUCTION METHODS TO DETERMINE THE INTERACTION POSITION IN GAMMA RAY SCINTILLATION DETECTORS

Alessandro Marone - Supervisor: Carlo E. Fiorini

The main aim of the dissertation was the implementation of reconstruction programs which can be used in medical imaging to improve the spatial resolution along the X-Y axes, to estimate the gamma rays depth of interaction inside a scintillator crystal and to improve the overall energy resolution of the system.

One of the most innovative aspects of the dissertation consists in the fact that the reconstruction programs are based only on simulated data to reproduce the experimental ones. Therefore, no experimental measurements or setups are necessary to train the algorithms created and is possible to estimate the final resolution of a system without the need to implement it beforehand. The critical point in applying this method is directly related to how much the simulated data correctly represent the experimental ones: the better the matching, the better the results obtained in applying the reconstruction methods. Three algorithms were used in the reconstruction:

- The Centroid Method, very fast and simple to implement, however limited in its field of view and reconstruction capability. It is used as a benchmark to evaluate the performances of the other

more advanced reconstruction algorithms.

- The Maximum Likelihood, which is the method that obtains the best results so far with experimental data in terms of field of view and resolution along the X-Y axes. Moreover, it allows also to roughly estimate the depth of interaction and to slightly improve the energy reconstruction.
- The Neural Networks, a method that has been introduced only at the final stage of my doctoral activity, but which has already shown optimal results for reconstructing simulated data without noise, for both X-Y-Z coordinates and energy. This method was firstly applied in our field of interest during the 90's, then for a decade was very seldom used and only in the last years has started being retaken into consideration. The strategy followed in the dissertation development consisted in creating at first a set of programs written in MATLAB® language, for the purpose of simulating the expected behavior of the gamma rays and generated photons inside the scintillator crystal. In these programs, the user can define, through attentively

designed user friendly graphical interfaces, all the crystal characteristics (e.g., sizes, types of coverings and surfaces, parallelepiped or cylindrical crystal, etc.) and how the latter is positioned on an user-defined photodetectors matrix, composed of square or hexagonal photodetectors of given sizes.

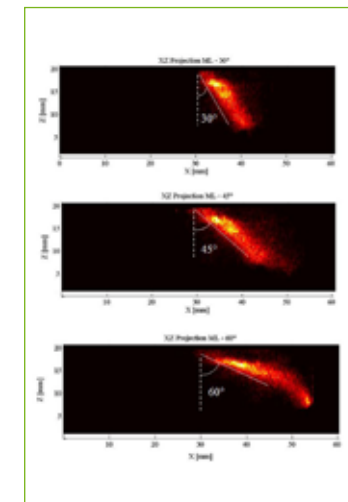
It is therefore possible to simulate different interaction points of the gamma rays inside the scintillator crystal either at given positions or, to better represent their behavior, using GEANT3 software, a program written in FORTRAN and developed by the CERN laboratories, which simulates the interactions of gamma rays with a given energy inside an user-defined material. Subsequently, the behavior of the photons generated inside the scintillator crystal by the gamma ray interaction is simulated with a program, developed by Politecnico di Milano, which takes into account the roughness of the crystal surfaces as well as the coverings applied on these (e.g. black tape, reflective surfaces like Aluminum, etc.). To validate the results obtained, when a simulation of a certain crystal/photodetectors configuration has been made, the data are compared with the experimental ones to see if

the results are matching among each other. Some benchmarks were therefore defined to evaluate this comparison, among them: the number of photodetectors which received photons, the sum of the photons read by all the photodetectors in the matrix and the percentage of photons received by each photodetector respect to the total number of photons counted.

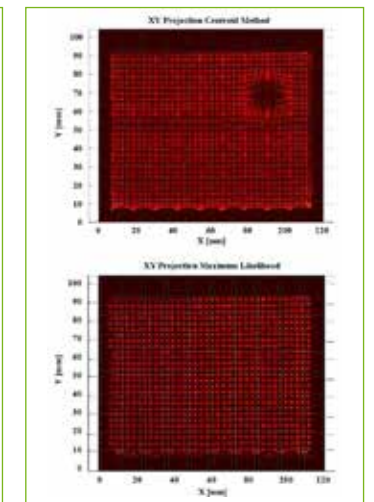
Therefore, if the simulated data "fit" well the experimental ones, the programs implemented, based on the Maximum Likelihood and Neural Networks algorithms, are applied to both the simulated and the experimental data and the outputs are compared with the ones obtained from the Centroid method both for the field of view obtainable and the imaging resolution.

Three experimental setups were considered, moreover highlighting the fact that all the algorithms and programs implemented are very flexible and usable without efforts with different crystals/photodetectors configurations and energies:

- A 5x5 Silicon Drift Detectors (SDDs) matrix coupled with CsI(Tl) crystals of various thickness and surfaces (rough/smooth) and irradiated with a source of ^{137}Cs (incoming gamma rays at 662 keV);



1. Maximum Likelihood reconstructions along the X-Z axes for three 662 keV gamma rays interacting with a CsI(Tl) crystal with different incidence angles: 30°, 45° and 60°



2. Experimental Grid obtained with a 10x10 SDDs matrix. On top, the Centroid reconstruction; on bottom, the Maximum Likelihood one. It is possible to notice that the artifact present in the Centroid Reconstruction due to a broken photodetector is corrected by the Maximum Likelihood algorithm

- A 10x10 SDDs matrix coupled with a CsI(Tl) crystal of 110x90x10 mm³ and irradiated with a $^{99\text{m}}\text{Tc}$ source (140.2 keV);
- A 5x5 SDDs matrix coupled with a CsI(Tl) crystal of 60x50x10 mm³ and irradiated with a $^{99\text{m}}\text{Tc}$ source (140.2 keV). In all the setups, the reconstructions of the X-Y-Z coordinates as well as the energy with the Maximum Likelihood algorithm are shown both for simulated and experimental results, while the Neural

Networks were introduced lately and employed only for the third setup. Among the most interesting results obtained, there are the correct depth of interaction reconstruction using the Maximum Likelihood algorithm of three gamma rays interacting with the CsI(Tl) crystal at different angles (Figure 1) and the capability of the latter to reconstruct correctly the data at low energies (140 keV) also in the presence of a broken photodetector (Figure 2).

DESIGN OF A HIGH-EFFICIENCY WIDEBAND PHASE MODULATOR FOR WIRELESS SYSTEMS

Giovanni Marzin - Supervisor: Andrea L. Lacaita

The communication revolution that has characterized the last decade has focused the interest of the industrial and the academic world in the realization of wireless system more and more powerful (high bit rate) and power-efficient. The introduction of increasingly complex modulation schemes to improve the spectral efficiency and the need of very low-power operation, set new tight requirements on the transmitter. New architecture topology, as the polar and the outphasing transmitter, has been introduced to satisfy the most aggressive requirements and in the last years the first prototypes, realized on a single chip, have been presented.

One of the main issues in the design of a complete transmitter is the realization of a phase modulator, which is at the same time power efficient, wideband and able to perform a tiny phase resolution. At the state of the art, there exists a trade-off between wideband architecture and power efficient architecture and a solution that features both characteristics is a subject of research.

The objective of this thesis is the realization of a wideband phase modulator, which is able to improve the trade off between the desired characteristics and

in particular to extend the use of power efficient phase modulation at wideband and at high resolution. In order to reach this goal, the intensive use of digital architecture, which performs better than the analog counterparts in deep sub-micron CMOS technologies, has been exploited. The main advantage of digital solution is the ability to perform adaptive filter architectures, i.e. calibrations and corrections of the errors caused by the analog parameters, by using simple structures that consume low power and are repeatable. These solutions simplify the design and, as they are portable to the next technology nodes, may potentially reduce the time-to-market.

State of the art architectures are detailed in the thesis by focusing on the limitations of these solutions, and the trade off between power efficiency and wideband, in particular. The two-point modulation technique results the candidate which presents the best compromise between power consumption and jitter performance.

However, to extend this architecture to wideband signal with high phase resolution, many issues arise. In particular the gain and delay mismatch between the two modulation

paths and the nonlinear characteristic of the DCO.

In this thesis the architecture of the wideband phase modulator with the intensive use of an adaptive filter to correct analog errors that preclude the two-point architecture to be a wideband modulator is exploited.

In particular an adaptive filter structure, to compensate the gain and the delay mismatch between the two paths, is presented.

Moreover an adaptive filter technique to improve the linearity of the DCO (realized with a multi-capacitance bank structure in order to save area performing at the same time the required dynamic range) compensating both the mismatch between banks and the mismatch in the same bank is proposed. These solutions leads to the use of the two-point structure as an high efficiency wideband phase modulator.

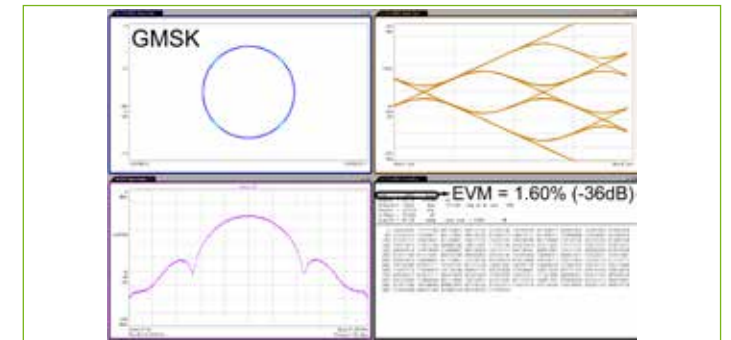
In addition an high efficiency local oscillator (LO), which is the core of the phase modulation, is needed. The LO generates the radio frequency tone and the quality of this signal impact of the overall performances of the system.

The LO is usually implemented as a phase locked loop (PLL) and

in the last decade the digital approach has been widely adopted. The bottleneck of digital PLL is represented by the time to digital converter (TDC), which acts as a phase detector. In fact, this structure presents a trade off between the phase resolution and power consumption. In this thesis, a solution using a single bit TDC, that breaks this trade off and leads to the best FoM jitter noise-power consumption for a PLL to be use as local oscillator, has been reported.

Moreover the novel technique for an automatic bandwidth regulation (ABWC) of the PLL is proposed. In fact the dependence of the loop bandwidth from analog parameters impact on noise performances and cause instability problems. The ABWC estimates the analog parameters involved in the loop bandwidth and compensates the variation with respect to the ideal value acting on the loop gain. The proposed technique works in the background of the common system operation without degrading the PLL noise performance, following in this way any PVT variation of the analog parameter.

Thanks to the adopted solutions, the thesis demonstrates the feasibility of a high-efficiency



1. Measured performance for a 10-Mb/s GMSK modulation: signal constellation, trellis diagram, spectrum of the demodulated signal

wideband phase modulator designed in 65-nm CMOS which is able to produce phase change up to $\pm\pi$ with 10-bit resolution in a single reference cycle of 40MHz. Measured EVM at 3.6GHz is -36 dB for a 10Mb/s GMSK and a 20Mb/s QPSK modulation. Power dissipation is 5mW from a 1.2V voltage supply, leading to a total energy consumption of 0.25nJ/bit. The achieved results demonstrate that the intensive use of digital adaptive filters can lead to a high-efficiency wideband phase modulator which can be used in the most aggressive wireless architecture.

ENERGY-AWARE SERVICE-BASED INFORMATION SYSTEMS

Alexandre Mello Ferreira - Supervisor: Barbara Pernici

The problem of Information Technology energy consumption has gained much attention recently due to the always increasing use of IT both for business and for personal reasons. In particular, data centers are now playing a much more important role in the modern society, where the information is available all the time and everywhere. In parallel with this scenario, governmental institutions have launched many international programs and regulations in order to measure and to reduce energy consumption in many areas, including Information and Communication Technology. In this context, the aim of this thesis is to study energy efficiency issues within data centers from the Information System perspective.

The proposed approach integrates the application and infrastructure capabilities through Business Process co-design, in which the enactment of adaptation mechanisms is aligned with the business process requirements. Based on both energy and quality dimensions of service-based applications, we propose a model based approach and formulate a new constrained optimization problem that takes into consideration over-constrained solutions where

the goal is to obtain the better trade-off between energy consumption and performance. The proposed energy-aware service composition algorithm advances the state-of-the-art by: i) taking into account not only single (average or minimum) values of independent quality and energy metrics but a range of values, while also dependency functions are used in order to express trade-offs between quality and energy metrics, expressed as Key Performance Indicators (KPI) and Green Performance Indicators (GPI); ii) producing a concrete execution plan even if the minimal requirements are over-constrained by accepting a given degree of violations; iii) allowing for the use of non-linear functions in the optimization problem.

However, the comparison of the indicators results should be made with caution, since the values are calculated in different ways or measured following different methods and equipment. Thus, we formally define an indicator and propose an aggregation system, which contribute with: i) the identification and classification in order to enable their aggregation within meaningful clusters called Green Index Functions (GIF); ii) the normalization of indicators

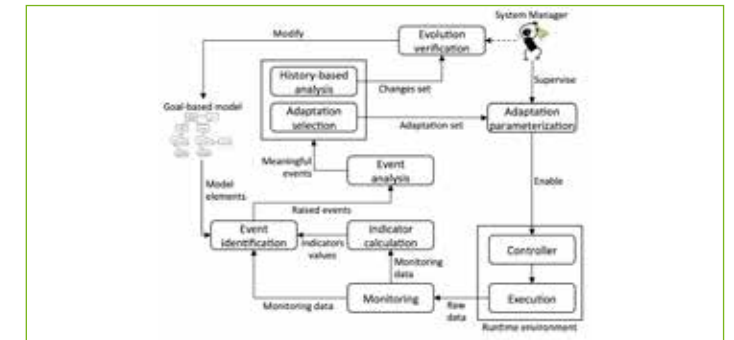
values considering their four different boundaries dimensions, represented by warning and alarming thresholds; and iii) the aggregation metric based on weights and defined in terms of risk management index, which prioritize the most relevant indicators against the system goals fulfillment. Once indicators are defined and their value calculated, the system is able to recognize which ones represent system threats, i.e., can harm the system through indicators violation. The identification of such system threats introduces new complexity boundaries to the model, which needs to be selective in mining the monitored data in order to identify relevant data to support the decision making mechanisms.

In order to put these ideas together we propose a framework in which energy and performance do not always represent opposite objectives, but they are context dependent. Such dependencies are represented as a goal-based model, in which time-based analysis allow the identification of potential system threats and drive the selection of adaptation actions improving global quality and energy indicators. In addition, the framework includes an evolution mechanism that is able to evaluate past decisions

feedback in order to adjust the model according to the current underlying environment.

Figure 1 shows the main elements that compose the proposed framework. First, the *monitoring* system provides raw data about the underlying environment. This information is used to calculate the defined indicators by the *indicator calculation* module. The *event identification* is responsible to verify both monitored variables and indicators values in order to recognize possible situations that represent a threat to the system. This is done according to the system goal-based model defined by GAMES¹ assessment phase. If a threat is identified, the module creates several event occurrences that are analyzed by the *event analysis* module in order to separate the different types of events and, in particular, the ones that require the enactment of adaptation actions (meaningful events). The *adaptation selection* module is responsible to select the adaptation actions that eliminate the system threat without creating new ones. Thus, single actions are aggregated as adaptation actions and send to the *adaptation parameterize* module. In this module the system manager, who is the

¹ <http://www.green-datacenters.eu/>



1. Framework overview

user responsible for the system environment, shall approve or disapprove the adaptation actions and, if approved, he should provide some necessary actions parameters values. In parallel with the *adaptation selection*, the *history-based analysis* module tries to identify possible misleading relationships within the goal-based model that do not provide effective adaptation actions. The output of this module implies a new adaptation attempt, a model modification or both. The model modification comprehends: i) relationships impact labels update, and ii) revelation of unexpected and not yet modeled relationships. The identified model changes are verified by the system manager in the *evolution verification* module in order to ensure the goal-based model soundness.

The benefits of the approach are analyzed in an experimental setting. We use the data from the project testbeds to fill in a simulated environment in which our approach is tested using an eBusiness scenario. The results highlight how our framework can contribute to improve system threats identification, adaptation selection based on feedback loops and impact propagation, and the creation of high-level system goals based on indicators normalization and aggregation.

2D X-RAY IMAGING DETECTORS FOR THE X-RAY FREE-ELECTRON LASER FACILITIES

Davide Mezza - Supervisor: **Andrea Castoldi**

"Creating matter from the vacuum, taking an atomic scale motion picture of a chemical process in a time of a few femtoseconds or unraveling the complex molecular structure of a single protein or virus. These are some of the new exciting experiments that a novel radiation source, the X-ray free-electron laser, will make possible". (C. Pellegrini and J. Stöhr)

My research activity is oriented to the study and development of imaging detectors of the novel X-ray free electron laser sources. The FELs are lasers whose beam characteristics - in particular the high brilliance - open the way to new scientific opportunities in different scientific fields (like medicine, biology, physic, etc.). However in order to fully exploit their properties we need to develop a new suitable instrumentation, and especially the "eye" (detector). The challenge that every scientist who wants to develop such detectors faces, is related to the unique characteristics of these machines and the way these characteristics are reflected at detector level. Just to mention few, the energy range (0.5 up to 20 keV in the case of European XFEL) has an impact on the detector entrance window, radiation tolerance, dynamic range and noise performance

of the detector (also dependent on the experiment). The frame rate (up to 4.5 MHz in the European XFEL case) poses constraints both on the detector and the front-end electronics. The radiation tolerance is one of the main issues for detectors that have to work with hard X-rays (photon energy typically 12 keV and higher). In fact, for these energies the photons will not be absorbed in the first few microns but within the total volume, for a total dose on the order of 1GGy per year. Many projects are ongoing all around the world to develop such kind of detectors. Among these detectors, one of the more interesting is the CAMP chamber developed by the Max Planck Advanced Study Group within the Center for Free Electron Laser Science. This multipurpose chamber is equipped by a pn-CCD (1 - 4 Mpixel) and operates with a frame readout up to 200 Hz making this detector able to meet all the requirements of the existing FELs but the 4.5 MHz burst mode operation foreseen for the European XFEL. Another interesting example of detector for the 4th generation light sources is represented by the X-ray Active Matrix Pixel Sensor (XAMPS) used in several experiments at LCLS. It is a silicon pixel array detector where the single pixel is in principle a classical semiconductor diode

with an integrated junction field effect transistor switch to facilitate the readout of the matrix. The principle of operation of XAMPS is very similar to that of CMOS pixel sensors. The XAMPS have many advantages (e.g. fast readout speed, single photon resolution, high dynamic range and so on) making these kind of detectors able to fulfill all the requirements of the existing FELs but as in the case of the pn-CCD they are not suitable for the burst operation mode of the European XFEL. In the XFEL burst mode operation every 100 ms (10 Hz) a train of 3000 Xray pulses equally spaced in time by 220 ns (4.5 MHz frame rate) is delivered, followed by a 99.4 ms of "silence". To fulfill the high repetition rate requirements of the European XFEL, three different 2D detectors are under development by three different European consortia: AGIPD (Adaptive Gain Integrating Pixel Detector), LPD (Large Pixel Detector) and DSSC (DePFET Sensor with Signal Compression). The Adaptive Gain Integrating Pixel Detector (AGIPD) is developed by a consortium of DESY (coordinator), PSI, University of Hamburg and University of Bonn. The AGIPD consists of a classical hybrid pixel array, with readout ASICs bump-bonded to a silicon sensor.

The LPD-project is managed by the detector group of the Rutherford Appleton Laboratory and executed in conjunction with the University of Glasgow. The LPD project attempts to achieve the large dynamic range required, by employing 3 different gain settings in parallel, each followed by its own analogue pipe line. DSSC project is developed by a consortium consisting of the MPI Semiconductor Lab in Munich (coordinator), the Politecnico di Milano, DESY (Hamburg), and the Universities of Heidelberg, Siegen and Bergamo. The DePFET Sensor with Signal Compression (DSSC), uses a non-linear response of the active sensor pixels to cope with the large dynamic range, and a digital memory to store images inside the pixels. In my research activity, I studied and characterized the topologies of the Multi-Linear Silicon Drift Detectors (MLSDDs) and Depleted P-channel Field Effect Transistor (DePFET). In the MLSDD architecture the charge generated by the incident radiation drift, by means of the drift field, laterally confined in parallel drift channels towards the readout anodes. The amplitude of the signal give the information on the energy release in the detector by the incident radiation, the

interaction point along the drift coordinate is given by the drift time and the information on the lateral coordinate is given by the anodes' segmentation. In the DePFET architecture radiation-generated electrons drift towards their minimum (internal gate) obtained by a suitable doping of the region underneath the channel. The collected charge has a steering effect on the transistor current, thus, the variation of the drain current give the information on the energy of the incident radiation (the 2D information on the position is given by the pixels). Once the readout process is complete the charge is removed by applying a positive voltage to the clear gate and the clear contacts. After this clear phase the DePFET is ready for a new irradiation. In this work three detector prototypes based on MLSDD architecture and one based on the DePFET were studied in terms of experimental characterization in order to understand the underlying physical models and identify the suitable solutions for the X-ray FEL sources. Results of complete measurement campaign by means of a high dynamic range test suite is provided for different detectors. Algorithms for complex data analysis and detector modeling have been developed and are extensively

discussed. This research activity was conducted within the framework of the DSSC consortium.

INVESTIGATION OF THE EMERGING PHYSICAL MECHANISMS LIMITING THE RELIABILITY OF NANOSCALE FLASH MEMORIES

Carmine Miccoli - Supervisor: **Alessandro Spinelli**

Flash memory is today the leading solid-state non-volatile memory technology, allowing high integration density, low costs and good reliability. The continuous scaling has been the main driver of the success of this technology, pushing it, however, to its physical limits: the reduction of the array pitch is today limited by the increasing capacitive coupling among adjacent cells, the low number of electrons controlling cell state is raising issues related to the discrete nature of the charge flux from/to the floating gate, single electrons stored in the tunnel oxide result into more and more severe threshold voltage instabilities during read and data retention. Aim of this thesis is to study the emerging physical mechanisms limiting the reliability of ultra-scaled Flash memories, highlighting from a theoretical standpoint the fundamental limitations to the functionality of nanoscale memory arrays. All the work has been carried out with a scaling perspective, trying to assess the ultimate scaling limitations and to propose feasible solutions able to extend the success of the Flash technology to the future technology nodes. A particular attention, moreover, has been devoted to then analysis and assessment of qualifications schemes for ultra-scaled Flash arrays.

The research activity carried out during the Ph.D. program was focused on the reliability constraints of decananometer Flash memories and resulted in a deep understanding from a physical standpoint of the emerging failure mechanisms which affect Flash operation and set the ultimate limits to the technology scaling. Experimental activities and modeling efforts, including Monte Carlo modeling of programming algorithms, analytical modeling of electron injection/emission statistics, analysis of post-cycling threshold voltage instabilities and compact modeling of NAND string current, aimed at the characterization of a wide range of physical mechanisms, such as few electron phenomena, variability sources of cell parameters, tunnel oxide and inter-poly dielectrics degradation due to electron trapping/detrapping and interface state creation/annealing, electrostatic interference between adjacent cells, impact of short channel effects and mobility degradation on NAND string current. The careful analysis of these mechanisms and the assessment of their impact on Flash reliability allowed to determine the fundamental scaling limitations and to propose feasible solutions for the future technology nodes, consisting in cell and algorithm design and

optimization. Experimental and modeling activities, moreover, were devoted to the design of characterization techniques for ultra-scaled Flash technologies: accelerated testing schemes for the evaluation of distributed cycling effects and threshold voltage instabilities during data retention, in fact, emerged as a challenging and demanding task for Flash qualification and the impact of this research activity was recognized by both the semiconductor industry and the scientific community, since the main results achieved in this field were cited by JEDEC documents ("JEDEC JEP122C: Failure Mechanisms and Models for Semiconductor Devices", tech. rep., JEDEC Solid State Technology Association, October 2011) and awarded at the 2012 IEEE International Physics Reliability Symposium (C. Miccoli et al., "Assessment of Distributed-cycling Schemes on 45nm NOR Flash Memory Arrays", IRPS 2012, pp. 2A.1.1–2A.1.7 was awarded the 2012 IEEE IRPS Best Student Paper Award). In order to assess the constraints to post-cycling data retention, the attention was focused to cycling-induced damage creation and post-cycling threshold voltage instabilities, which were investigated under a wide range of experimental conditions. This analysis led to

the assessment and validation of a universal damage-recovery model, allowing the development of accelerated qualification schemes which accurately reproduce the real on-field usage of the memory device. Spurious effects which may emerge during the testing procedure itself, compromising the activation energy evaluation and the correct interpretation of distributed-cycling qualification schemes were also addressed, gaining a deep understanding of qualification schemes for nanoscale Flash devices. From a physical standpoint, damage creation and recovery dynamics and mechanisms were addressed via compact modeling of NAND string current. This approach allowed to evaluate the impact of electrostatics interference and short channel effect on NAND operation and to identify the major failure oxide degradation and recovery mechanisms, consisting in the charge trapping/detrapping in the oxide and in the interface state creation/annealing. The analysis of threshold voltage instabilities revealed that the latter mechanism comes into play when cell threshold voltage is monitored at high read current, due to carrier mobility degradation. Results show that threshold voltage instabilities are increased and their activation energy is lowered with respect to the usual 1.1eV value given by charge detrapping whenever the saturation value of the string current moves too close to read current, thus, providing useful hints for the design of the read scheme and the choice of the operating voltages of the memory array. Then, the investigation of few

electron phenomena highlighted that cell state is controlled by a low number of electrons, which progressively decreases with size scaling, and, thus, the granularity of the charge flux into the floating gate emerged as a source of program noise, setting the ultimate limit to programming accuracy. In this regards, a careful investigation of the impact of control gate and floating gate design on the electron injection statistics (EIS) of decananometer NAND Flash memories was carried out, discussing the EIS scaling trend and the evolution of the FG design in terms of geometry and dimensions. Moreover, a detailed investigation of the accuracy of programming algorithms was performed by means of Monte Carlo simulations for the electron injection process, showing that narrower programmed distribution can be obtained with an optimized double-verify ISPP algorithm, with respect to a standard single-verify ISPP scheme, with minimal burdens on algorithm complexity and programming speed. These results are of fundamental importance for future NAND Flash technologies, especially for multi-level memory devices. Then, the impact of few electron phenomena also on data retention was taken into account, investigating the statistical dispersion of data retention of nanoscale NAND Flash memories due to neutral threshold voltage spread and electron emission statistics (EES): both the phenomena results in a distribution widening during retention, but the modeling results reveal that cell-to-cell variability and not EES will represent the major issue for

data retention dispersion of fresh devices in future nanoscale technologies. Finally, single electron detrapping from tunnel oxide during post-cycling retention was experimentally demonstrated in the sub-30nm regime and a statistical model was developed, showing that post-cycling data retention variability is ruled by detrapping statistics in aggressively scaled Flash technologies. In conclusion, this research activity provided the physical understanding, the modeling tools and the characterization techniques required to investigate the reliability of the state-of-the-art Flash memory technologies; the most of the emerging mechanisms, moreover, will likely affect also the future generations of charge-based memory technologies, including planar and 3D Flash architectures, and, thus, this thesis provides the reference against novel memories should be tested, in order to assess the improvements with respect to the conventional Flash technology.

LOGIC-BASED VERIFICATION OF MULTI-DIAGRAM UML MODELS FOR TIMED SYSTEMS

Alfredo Motta - Supervisor: **Luciano Baresi**

The Unified Modeling Language (UML) has gone from a relatively basic descriptive tool (i.e., a tool that serves to document software systems) to a sophisticated prescriptive one, that is, a tool that can be used to specify, analyze and implement complex software systems. Despite some good results in this field some fundamental problems hamper the actual adoption of UML models for the analysis of the systems in a real production environment.

First, a unified and coherent semantics of UML must be developed. In the last ten years researchers have been trying to ascribe UML with many different semantics, but all these attempts have been partial. While there seems to be a general consensus on the semantics of some individual diagrams, the composite semantics of the different views is still an open problem. The wide spectrum of the notation and the heterogeneity and overlapping of the different modeling elements have played against its complete formalization; as a matter of fact most of the existing approaches only focus on a limited number of diagrams (oftentimes they only consider a single type) and neglect the interdependencies with the other views of the system. However multiple views mean

better quality since different UML diagrams emphasize different aspects of the system. Second, to spread the use of UML model verification at large scale the inherent complexity of formal methods in terms of usability must be decreased. For example, in the classical approach to formal analysis the user is required to manually construct the formal model of the system in the language that is accepted by the verification tool. The construction of such model typically requires good knowledge of both the application domain and of the verification technology. In turn this activity requires mastering techniques like abstraction and refinement, model checking, or theorem proving that require a dedicated background. To avoid the manual construction of the formal model different tools have been developed to transform the UML models to a variety of formal notations, but the vast majority of them neglect the difficulty of hiding the underlying formal notations and tools to the UML user. Without a dedicated expertise in this field the user is not able neither to enact the verification phase, or to understand the verification results. Oftentimes a formal verification expert is required, making the UML formal verification a niche activity. This thesis presents a significant

step towards solving these problems by means of an advanced verification framework made of the following elements:

- A significant and consistent subset of UML, called MADES UML, where timed-related properties can be modeled carefully. MADES UML supports different behavioral views connected by means of a shared set of events.
- A formal semantics based on metric temporal logic which offers the flexibility and scalability we need to formalize a wide and rich notation like MADES UML. The formal semantics is used to feed a bounded model/satisfiability checker to allow users to verify their systems, even from the initial phases of the design.
- An advanced prototype verification tool called "Corretto". Using "Corretto" UML engineers can exploit both a well-known modeling notation and advanced verification capabilities seamlessly. Properties are expressed using a high-level notation, and verification results produced by the underlying verification tool are linked back to the corresponding UML elements in the model.

ENERGY-SAVING PHOTONIC SWITCHING AND NETWORKING

Francesco Musumeci - Supervisor: **Achille Pattavina**

Traffic in telecommunication networks is estimated to substantially grow in the near future. As the Information and Communication Technology (ICT) sector already consumes a relevant portion of the global world electricity, one of the most challenging issues will be the reduction of its power requirement.

The core/transport section of telecommunication networks is the main target of this dissertation.

We will focus on multilayer architectures composed by an optical Wavelength Division Multiplexing (WDM) transport layer providing connectivity support to the classical electronic Internet Protocol (IP) layer. Such network structure is commonly identified as an IP-over-WDM network.

Several strategies can be adopted to reduce the energy consumption of transport networks. The adoption of optical switching technologies can enable substantial power savings, mainly due to the significant reduction in the number of used optoelectronic interfaces and the amount of electronic traffic processing, and thanks to the low-power consumed by photonic devices. In this thesis several aspects of energy-efficient networking are investigated. Specifically, we first evaluate the network

energy consumption performing a comprehensive comparison between different flavours of IP-over-WDM architectures. Such architectures mainly differ from the way they perform signal switching, i.e., either in the electronic (e.g., through IP routers or Digital Cross Connects) or in the optical (via opaque or transparent optical switching matrices) domain. Fault-tolerance is another aspect studied in this thesis, from the power consumption point of view. We highlight the impact of providing resiliency on the overall network power consumption, considering that protection resources can be set into low-power sleep mode and comparing different protection scenarios, namely, dedicated vs shared and link vs path protection strategies. Then, a recently proposed switching technique, the Time-Driven Switching (TDS) is also studied from the power consumption perspective. The TDS paradigm is a promising energy-efficient solution since it allows performing traffic grooming of "fractions" of wavelengths directly in the optical domain, thanks to the time-coordination of network elements, with no need for optoelectronic signal conversions, so that the consumption due to many

optoelectronic interfaces can be saved.

Finally, the potential energy savings of a management protocol for switching on and off optoelectronic interfaces in the network is analytically modelled using a probabilistic approach based on Markov chains, under the assumption that some devices are reserved for high-priority traffic and are set into low-power sleep-mode, whereas the other unused devices are fully powered off.

We demonstrate that relevant power savings, up to 60%, can be obtained in comparison to traditional IP-over-WDM network architectures where signal switching and regeneration operations are always accomplished in the electronic IP domain. Moreover, up to 15-20% of power savings are also obtained for protected IP-over-WDM networks by setting protection resources into sleep mode. Finally, we show that exploiting an intelligent strategy for managing the activation of optoelectronic devices enables high power savings, around 75-80% compared to the cases where all devices are fully powered-on, with low impact on the overall network performance (i.e., Quality of Service).

TOWARDS THE INTEGRATION OF NEURAL MECHANISMS AND COGNITION IN BIOLOGICALLY INSPIRED ROBOTS

Flavio Mutti - Supervisor: **Giuseppina Gini**

Reaching a target in the environment with an arm is one of the most relevant capabilities of mammals. The reaching task involves several computations that transform the perception of the target in a complete movement of the arm to reach it. First, the target must be perceived with at least an external sensory system, such as vision, and filtered in order to localize its position in the sensory frame of reference (FoR); second, the information coming from the sensory system(s) must be integrated with the proprioception information of the body, such as the position of the arm with respect to the body; third, the target position must be computed with respect to the arm FoR, performing a coordinate transformation between the sensory FoR and the arm FoR; fourth, the arm movement trajectory must be computed and executed. Typically, an intelligent behaviour is identified by an observer in a subject able to react to unexpected events, and to modify and manipulate the surrounding environment. It implies a strong correlation between the capability to perform actions by a smart subject and the high cognitive reasoning. Despite recent findings in neuroscience, the underlying mechanisms of

the human brain are far to be completely understood. How the brain processes information to solve the reaching task is one of the key feature that makes mammals on the top of the evolution chain. It is well known that the underlying neural circuitry is organized in several functional areas responsible to solve specific subtasks of the whole cortical information processing. It implies that an high level of synchronization among different areas is needed. Moreover, this functional organization follows the well known *divide et impera* paradigm. These anatomical and functional characteristics are interesting from a neuroscientific point of view since almost the whole brain is activated to solve a reaching task. Another interesting feature of the brain is that the underlying computational mechanisms of the different brain functional areas are widespread in mammals. Besides the scientific implication of this fact, from an engineering point of view it is interesting the capability of these computational mechanisms to self adapt to different bodies, exploiting their morphology. For these reasons, I conclude that the most interesting characterization of the basic

motion tasks as emerged from neuroscience are: first, the indication that the reaching task is the expression of a complex and intelligent behaviour; second, the high level of synchronization and organization of the different brain areas; third, the adaptability of the computational mechanisms to different body shapes. On the other hand, the robotics community addresses the reaching task since the early era of robotics. Despite many efforts to solve the problem of reaching task, a robust and generic solution is missing. However, it is commonly accepted that the capability to solve the reaching task is a very important characteristic of a robotic system, especially for humanoids. Interacting with the environment is the main goal of any robot, regardless the specific task performed. Moreover, a generic and robust solution is still missing, and several approaches are available, such as optimal feedback control, visual servoing, and adaptive control. However, these methods need to know some robot characteristics that could be not available such as kinematics, dynamics, and controller parameters. Of course, the robot interacts with the environment

pursuing a task that must be accomplished. Typically, the knowledge is intrinsically coded by the designer that programs the robot to perform specific trajectories, with several constraints, such as time execution, velocities, and accelerations. Moreover, in the industrial context, the robots perform repetitive tasks, that need high precision and few autonomous decisions. On the other hand, autonomous robots must solve high level problems without any explicit definition of them. They typically work in hostile, highly dynamic environments and they must take decisions with a partial knowledge of both the surrounding environment and the robot state. In this case, taking smart decisions is crucial for achieving the goals. An autonomous robot, working with these constraints, needs the capability to think autonomously and to take actions, pursuing its own goals. For this reason, a cognitive architecture seems the obvious answer to those problems that can be solved by robots and that need high autonomy in the decision-making phase. Classical approaches at the developing of cognitive architecture are based, among the others, on symbolic processing, rules, and statistical learning. Making a further step, some scenarios could need a robot that is not only able to take decision with respect to its past experience but that is also able to develop new goals and behaviours. This goal generation phase is grounded on some innate

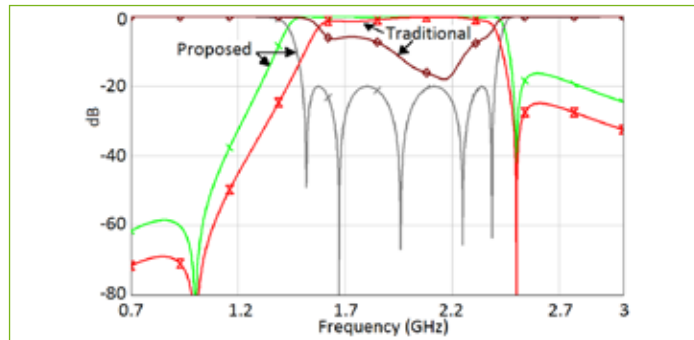
criteria that bootstrap the following behaviours. These new goals should represent an higher level of abstraction with respect to basic goals, towards an artificial consciousness. This processing is quite similar in humans. For example, let suppose that a primary need for a human is eating. Generally, the human will act to reach its objective. However, its own actions will be different if its surrounding environment is the jungle or the metropolis. In the first case, he will hunt animals or collect vegetables, whereas, in the second case, he will go to the market. But, definitely, in both cases he is pursuing its basic goal of eating. Both behaviours (or goals) of going to the market and hunting are higher level abstractions of the need of eating. These concepts are particularly relevant if the aim is the design of a complex cognitive architecture that is also able to adapt its own behaviour through the interaction with the environment. However, a cognitive agent can not interact with the environment without a computational framework able to process the incoming sensory information, to automatically estimate the environmental state, and to interact with the surrounding objects. In the same way, an architecture able to reach objects in space, given the perceived position through the sensory system, is useless without a plan that can be generated by a further level of processing, the cognition. The synergy among a cognitive architecture, the way in which

an agent perceive and interact, and the working environment, can drive towards a new generations of autonomous robots. This thesis pursues several objectives, at different level of complexity. First, I want to investigate several biologically inspired models of different cortical areas that are functionally grouped in the visual dorsal pathway. The comparison between each single model and its own state of art gives insight in the neuroscientific findings, related to computational mechanisms of the cortical areas. Second, a qualitative comparison among previously developed models permits to propose a common computational framework for those computations requiring a minimum level of cognition and that our brain is able to automatically compute. Third, a biologically inspired cognitive architecture is investigated. It is based on the interaction among the cortex and other areas of the brain (e.g. thalamus and amygdala) that typically are not well investigated. Fourth, the proposal of a roadmap for the developing of biologically inspired architecture is presented. These architectures must exploit the synergy between low-level computation and cognitive development. The analysis involves a comparison among different types of learning of both low level computational models and the cognitive architecture. A roadmap for the integration is proposed.

SYNTHESIS AND MODELING TECHNIQUES FOR MICROWAVE FILTERS AND MULTIPLEXERS

Matteo Oldoni - Supervisor: G. Macchiarella

This Ph.D. thesis covers subjects of interests for microwave engineers and researchers dealing with several problems often encountered in the design and realization of microwave filters and multiplexers. Though it is not meant to be a comprehensive handbook of practical solutions, it covers both theoretical aspects of modeling these devices and practical algorithms to follow in order to develop synthesis and semi-automated tuning software and techniques for real applications. The studied subjects can be logically grouped into two main areas: synthesis of 2-port filters and modeling of diplexers. Synthesis of microwave filters: the typical workflow to design a microwave filter starts from a given set of specifications, involving usually a passband (frequency range allowed through the filter) and a stopband (frequency range strongly attenuated). A rational response fulfilling them can be derived with standard methods (Butterworth, Chebyshev...) and it must then be "synthesized" by a physical network to implement the desired response. One of the techniques to achieve this is based on section extraction, a method introduced nearly a century ago, but still used in modern designs: it is relatively simple and allows to a-priori constrain the topology of the



1. Transmission and reflection response of a bandpass network designed with the proposed technique

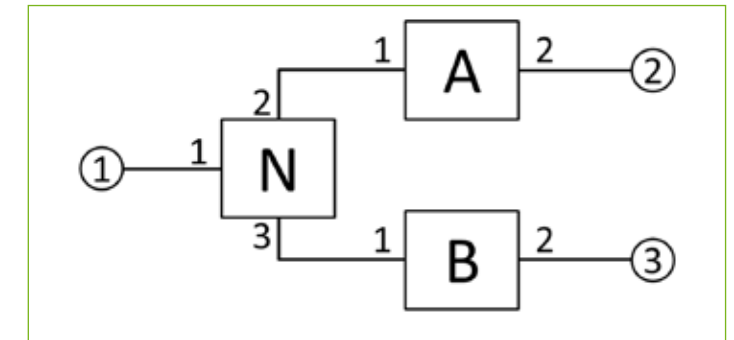
filter as a cascade of simple components. Basically, from the desired response at one of the ports, the designer identifies analytically which component is "seen", computes the remainder of the network and iterates these steps until all the components have been removed. One of the drawbacks of this method is that, when traditionally applied to a lowpass normalized prototype, it requires constant reactances (usually introduced by hung-resonators, which implement finite transmission zeros) and the physical circuit must thus be designed to approximate such ideal components. To overcome this approximation, this thesis introduces "reactive" nodes, which can be exploited by developing the synthesis directly in the bandpass domain. This is also extended to include

frequency-variant inverters, whose standard approximation is another important source of errors in the physical circuit (see Fig. 1). A further refinement of the section-extraction technique is proposed in this thesis: an analytic derivation of extraction conditions directly obtained on the scattering parameters. It allows moreover to evaluate the relevant information on the rest of the network at each step without critical polynomial computations. Another study describes a simple yet effective circuitual transformation to convert a triplet into the corresponding extracted-pole structure, often of easier practical implementation. This thesis also describes an original technique to solve the Feldtkeller equation, foundation for most design techniques, in

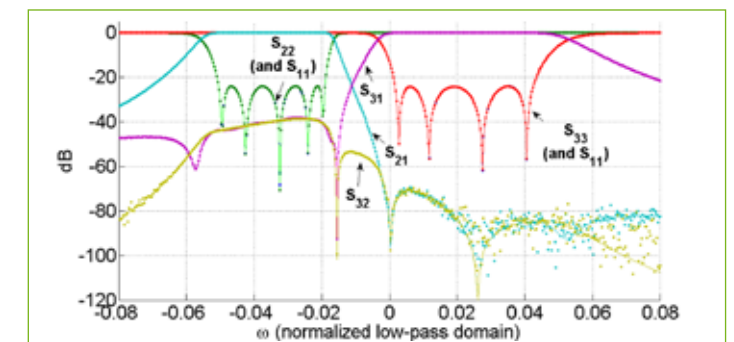
order to compute the poles of a lossless network in a more accurate way. It is based on a concept derived from the field of Digital Signal Processing, the Cepstral analysis, and is shown to reach higher polynomial orders than traditional methods. Modeling of microwave diplexers: this area covers two de-embedding techniques whose applications include diagnosis and tuning of microwave diplexers respectively, which lack of analytical modeling procedures. They are derived by exploiting the algebraic structure of the underlying identification problem and are tested through several examples. Microwave diplexers are components which, in their simplest form, involve two filters connected through a junction (Fig. 2). They are typically used to separate received channel bands and to combine transmitted and received signals. The practical problem of diagnosing such devices arises when a prototype is manufactured: its response must be verified to identify the main sources of error so that they can be addressed by the successive design iterations. The first technique proposed in the thesis is devoted to this issue and is based on a dual-state junction. It requires switching the state of the junction at every measurement in order to provide two sets of measurements. This in turn allows identifying the equivalent measurements of the filters without disconnecting them from the junction (usually unfeasible) so that their model can be compared with the target design. This is a slow technique but allows operating

on a prototype device, which in general could exhibit a response very different from the desired one. The second proposed technique provides a way to improve the tuning phase of large-scale fabricated devices. Tuning traditionally involves

thesis is based on a rational approximation scheme applied to a particular set of equations derived analytically from the diplexer. This method returns a fitted polynomial model of the two filters which can be used to identify the tuning elements to act upon. This method is



2. Simple model of diplexer



3. Measured (dots) and fitted (solid) responses of a microwave diplexer

a trial-and-error process to correct the mismatches with respect to the target response due to fabrication tolerances by acting on ad-hoc tuning elements (usually screws on the lid). The lack of analytical methods requires such steps to be carried out by highly-skilled operators whereas the technique proposed in this

suited for real-time tuning of devices in mass-production.

HIGH SENSITIVITY SINGLE PHOTON AVALANCHE DIODES FOR TIMING APPLICATIONS

Francesco Panzeri - Supervisor: **Ivan Rech**

Nowadays many scientific applications, which require the detection of very faint and fast decaying optical signals, rely on measurement systems with single photon sensitivity. Fluorescence Lifetime Imaging Microscopy (FLIM), diffuse optical tomography and Forster Resonance Energy Transfer (FRET) are just few examples. Today Single Photon Avalanche Diodes (SPAD) are the best choice when it comes to single photon detection. In the last decade they were able to overcome Photomultiplier Tubes (PMT) thanks to the advantages of solid state devices (compact size, lower voltage operation, insensitivity to magnetic fields) and in terms of photon detection efficiency. Single channel single photon modules featuring SPAD devices are already a well proven commercial product. This generation of SPADs shows great performances in terms of timing resolution (35ps), dark counting rate (10cps for a cooled 50um diameter detector) and afterpulsing (1%).

But science still wants more and a strong need for detectors with both high sensitivity and high temporal resolution and for multidimensional system showed up. On one hand, up to now, only detectors with high temporal resolution but limited

sensitivity in a one part of the spectral range or detectors with high sensitivity over the whole visible spectrum but poor temporal resolution can be found: a device capable of combining both high photon detection efficiency and high temporal resolution does not exist. On the other hand, large SPAD arrays were demonstrated only using a standard CMOS technology, which led to a severe worsening of the overall device performance.

As a matter of fact, two different approaches for SPAD fabrication stand out: the first one is based on custom technology and the second one is based on standard high voltage CMOS technology. CMOS SPADs are fabricated by reusing the technological steps of a standard CMOS technology. The big advantage of this approach is the possibility to exploit state-of-the-art CMOS electronics to design large arrays of smart pixels. However a major drawback concerning the SPAD performances turns out to be hard to overcome: the use of a standard CMOS process makes it impossible for the designer to develop devices with both a high photon detection efficiency and a low dark counting rate. On the other hand, a custom technology process, i.e. a technology process suitably tunable by the designer, allows

the development of high performance SPADs but makes electronic circuit integration, and thus array fabrication, more difficult. However, since the detector performances, especially in terms of sensitivity, matter the most in almost every application, the choice of a custom technology for SPAD fabrication is mandatory.

Aim of this work is the design of a new SPAD device able to combine both high photon detection efficiency and high timing resolution, while preserving other features, such as a low dark count rate, a low afterpulsing probability and a large active area. The target performances are a 40% photon detection efficiency at a 800nm wavelength and a resolution under the 100ps barrier. The second goal is the development of solutions aimed at the fabrication of large custom SPAD arrays, including the new designed detector, able to preserve the high performances of a single discrete detector.

Before my PhD studies, existing SPAD devices were not able to simultaneously satisfy all the applications requirements in terms of photon detection efficiency and temporal resolution. In particular, a device capable of combining both high

photon detection efficiency and resolution did not exist. In order to design a new SPAD detector, able to combine both high sensitivity and high timing resolution, suitable simulations tools were developed and an intensive study on novel device structures, capable of overcoming the limitations of the existing ones, was carried out. This led to the development of a new red enhanced SPAD, that has been consequently fabricated at the IMM-CNR foundry in Bologna (Italy). The new detector has been fully characterized and it proved to be a significant improvement with respect to existing technologies. In particular, a 40% photon detection efficiency combined with a 90ps resolution was measured at an 800nm wavelength.

The second phase of this work concerned the development of large custom SPAD arrays for photon timing applications, i.e. arrays featuring either the existing thin SPADs or the new red enhanced SPAD. To this aim, on one hand we exploited work carried out at Politecnico di Milano that allows the integration of the timing front-end next to the SPAD detector, providing the same temporal resolution of a single channel in a multiple channel system. On the other hand, we developed a new family of active

quenching circuits, with low power consumption and low area occupation, thus suitable for operating a large SPAD array.

Thanks to this work, a complete single red enhanced SPAD module was developed and has been successfully employed in one of the scientific applications demanding for it, i.e. single molecule Forster resonance energy transfer on DNA molecules. Moreover, all the tools (i.e. the detectors, both thin SPAD and red enhanced SPAD, the timing front-end and the active quenching) for the design of a large high performance SPAD array for timing applications are now available. A 32x1 thin SPAD array has been consequently demonstrated while a red enhanced SPAD 32x1 array is under production.

TRAFFIC MONITORING IN ITS: WIRELESS ARCHITECTURES AND ALGORITHMS FOR TRAFFIC STATE ESTIMATION

Alessandra Pascale - Supervisor: **M. Nicoli**

The PhD thesis faces one of the most relevant problem of our society: traffic congestion. The research has been developed in the framework of intelligent transportation systems (ITS). The goal of ITS is to solve issues related to traffic exploiting the potentiality of information and communication technologies (ICT) applied to transport engineering. In particular the thesis focuses on traffic control systems as essential for the achievement of a sustainable and safe mobility. Monitoring systems for traffic control collect a great amount of data that must be efficiently processed to support operations of traffic management. Data are usually provided at sparse and not regular locations on the road, but the development of control strategies requires a pervasive knowledge of the entire traffic field at the present time and the ability to generate reliable prediction of its evolution. The dissertation focuses on this problem and identifies two different solutions. The first one consists in the proposal of new technologies for traffic monitoring based on wireless sensor networks (WSN). Compared to conventional infrastructure-based monitoring systems, this technology facilitates a denser deployment of sensors along

the road, resulting in a higher spatial resolution in sampling traffic parameters. A study is conducted also on data coming from vehicles equipped with GPS to analyze the daily speed patterns for the construction of an efficient, reliable and accurate historical database. The second solution is the development of statistical estimation techniques to compensate the limits of existing monitoring systems and provide pervasive and accurate knowledge of traffic evolution to traffic control systems. In particular, a non-parametric prediction method based on adaptive Bayesian network (ABN) able to adapt to the traffic conditions (flowing or congested) is presented. The thesis focuses its attention also on a parametric approach. The cell transmission model (CTM) is improved to take into account the random behavior usually observed in real traffic; a particle filter (PF) for traffic estimation built on this model is proposed. Parametric approaches are analyzed to be applied on both small-scale and large-scale networks. Large scale traffic reconstruction and estimation is recognized as a relevant research field as it requires a large computational cost often not compatible with real-time requirements of traffic control systems. We propose

to divide the traffic network in smaller subnetworks that make their own estimation using local measurements; these results are then updated making these subnetworks cooperating to share traffic information. This new solution is able to guarantee high accuracy and at the same time low computational cost. These requirements are fundamental in case of real-time operating of the control systems. The methods presented in the thesis have been calibrated and validated on real data provided by the PeMs project and WAY srl, demonstrating the validity of the proposed approaches.

CONTEXT-AWARE DATA PERSONALIZATION: ISSUES AND SOLUTIONS

Emanuele Rabosio - Supervisor: **Elisa Quintarelli**

The term *information overload* refers to the difficulty to understand and make decisions when too much information is available; in the era of Big Data this problem is becoming dramatic, since users may be literally overwhelmed by the cataract of data accessible in the most varied forms. With *context-aware data tailoring*, given a target application, in each specific context the system allows the user to access only the view (over a global data schema) which is relevant for that application in that context; this normally produces a great reduction of the mass of available data, along with a specialization of this data to the current personal interests of the user.

This doctoral research begins by considering an existing context model named Context Dimension Model (CDM), able to represent all the available contexts in a given scenario – constituting the *context schema* – through a tree-shaped structure. Starting from the CDM, some context-related issues particularly relevant for data tailoring are studied.

First, an RDF representation of context schemas is proposed, providing suitable RDFS classes and properties. A complete and independent set of RDF

integrity constraints is used to guarantee the compliance of the representation with the CDM definition. To this aim, some categories of constraints already defined in the literature are employed together with novel ones; SPARQL queries to check the satisfaction of the new kinds of constraints are proposed, and some theoretical properties are investigated.

Second, context schema evolution is considered. The useful perspectives to be used in context-aware data reduction depend on the application requirements, which are intrinsically dynamic and thus can evolve. In this scenario it is natural that some context-aware applications be not up-to-date, since they still use obsolete context schemas. This issue is tackled defining a set of evolution operators that the designer must employ to perform the updates; each operator is also associated with the changes that have to be applied to the contexts defined according to the old schema in order to make them compliant with the new one. Moreover, we study the implications of the schema evolution on the association between contexts and data, and provide techniques to optimize sequences of operators. A prototype tool implementing the

proposed operators confirms the effectiveness of our strategy.

Finally, we leave context modeling issues to deal with the interaction between context and user preferences. In fact, in order to determine the most suitable data portion for a certain user in a certain context, the contextual information may be coupled with the user personal preferences. Since the contexts are obtained by combining the values of the various dimensions, and the number of possible configurations may rapidly grow to several hundreds also for small context schemas, requiring users to manually specify long lists of preferences for each possible context means really expecting too much from their spirit of collaboration. In this research, we propose a methodology where contextual preferences on tuples and attributes of a relational database are learned from the previous user's querying activity, gathering knowledge in terms of association rules. Experimental results highlight both the effectiveness of the approach and the utility of enriching user preferences with contextual information.

CONTEXT-AWARE DATA MANAGEMENT: A FULL-FLEDGED SYSTEM BASED ON ANSWER SET PROGRAMMING

Angelo Rauseo - Supervisor: **Letizia Tanca**

In a world made of global interconnections and networking systems, the variety and abundance of available data generates the need for effective and efficient gathering, synthesizing, and querying process, removing information noise. This thesis realizes a system where context awareness is integrated with - yet orthogonal to - data management, where the knowledge of the context in which the data are used drives the process of focusing on currently useful information (represented by means of views), keeping information-noise at bay. This activity is called context-aware data tailoring. The approach proposed in this thesis supports context-aware data tailoring by adopting a powerful context modeling tool known as Context Dimension Tree (CDT), used to define contexts and support the design of accompanying context-dependent views used to assemble contextualized data. The context is evaluated and validated by means of logic in Answer Set Programming (ASP); the discovered combinations of values constituting the current context are varied and mapped to their corresponding interesting data by the associated views in a uniform process, never leaving the ASP environment.

Inconsistencies have also been taken into account. In fact, sometimes the context information evaluated by the system is compatible with distinct (possibly mutually inconsistent) contexts: in this case, the system has to be ready to provide the user, or the application, with different views, each compatible with one of these contexts and refer the associated contexts for consistency checking. Special cases, in which particular behaviors must be substituted to the standard composition process applying to the context views, are also supported by means of overriding facilities designed to enable a very fine grained control over the contextualization process. In particular, the proposed approach uses ASP techniques to (i) validate the perceived context against feasible contexts extracted from a CDT provided along with application scenario, (ii) convey to the user the context-dependent views associated to the (possibly multiple) current contexts, (iii) use the views to retain from the underlying dataset only the relevant data for each such context, returning only interesting data and removing noise, (iv) finely control the contexts by means of integrated support for contextual preferences and overriding

mechanisms for the views; all this retaining the orthogonality of context modeling to the data while adopting the same framework as for views and data representation. A prototype is introduced along with experiments and experimental results, considering the actual efficacy wrt. design support, validation and consistency of obtained answers through the tailoring process described in the approach proposed. A real-world application scenario, in which the approach is being actively adopted, is also discussed.

SCALABLE AND ENERGY-EFFICIENT NEXT-GENERATION PHOTONIC NETWORKS

Giuseppe Rizzelli - Supervisor: **Achille Pattavina**

We are currently facing two major challenges for the development of future photonic networks: scalability and energy efficiency. The process of evaluating the impact on the network of the expected increase of traffic demand is called scalability analysis. It is one of the most important tasks for a network designer, along with energy consumption reduction which has become a mandatory target for next generation communication networks. Ultra-high definition video, 3D Internet, 3D multimedia, multimedia-supported social networks are some of the new broadband services responsible for the current growth of traffic demand. Over the past 10 years we have witnessed a traffic rate increase of about 60% per year. Therefore, optical transport of per-channel bit rates beyond 100 Gb/s is under active research since aggregated traffic per node will soon saturate fiber capacity. As a matter of fact, 100 Gb/s technologies have been already standardized in 2010 for both Ethernet and Optical Transport Network (OTN), and 400 Gb/s and 1 Tb/s interfaces are becoming mature candidate as transmission systems for Next-Generation Photonic Networks (NGPNs). During the last decade, not only transmission systems but also network architectures

have faced tremendous changes. Although current optical networks are static, Wavelength Switched Optical Networks (WSONs) represent the next step towards fully flexible and dynamic networking to cope with the increasing demands of emerging dynamic applications. In order to "operationalize" dynamicity in optical networking a suite of control plane protocols and a reconfigurable optical layer are needed. As for the former, Generalized Multiprotocol Label Switching (GMPLS) seems to satisfy all the requirements. As for the latter, Reconfigurable Optical Add/Drop Multiplexers (ROADMs) enables the high level of automation and efficiency requested by WSONs. For current and future ROADMs, the Wavelength Selective Switches (WSS) represent the core switching elements. The port size of WSS is a critical parameter for WSS-based ROADMs as it limits the maximum traffic that optical nodes can manage, and in turn it affects the scalability of the network. The deployment of a WSON represents a huge investment for telecom operators. Thus, the network design phase has to be carefully addressed in order to prevent cost and energy waste. In the first part of this research work I have developed a novel software tool for the design of

WSONs. Particularly, with respect to existing works, an ad hoc scalability analysis algorithm has been designed. It encompasses a more realistic physical impairments estimator for coherent systems and addresses all the features of WSS-based ROADMs. Moreover, it allows us performing a cost and energy consumption analysis in order to trace for the first time the future evolutionary path in terms of network upgrades of a real WSON based on real traffic profiles and growth-rate projections. This study has been carried out in collaboration with Telecom Italia Labs.

We have found that a) the network scalability and the roadmap for network upgrades depend on the type of traffic evolution, b) the benefits in terms of cost/energy efficiency of hybrid EDFA/Raman amplification (HRA) come above a certain transmission data-rate value, c) the G.652 fiber type does not effectively affect network scalability but it reduces costs and power consumption with respect to G.655. Finally we have estimated the WSS port-count requirement in a real WSON with realistic traffic value. We have found that it increases linearly with traffic but we can achieve about 50% of WSS port savings by employing HRA scheme in all simulated scenarios.

Larger traffic implies higher number of equipments with high transmission speeds and switch capacities being deployed. This contributes to the increasing energy consumption of the Information and Communication Technology (ICT) field which currently represents about 8% of the total electricity consumption all over the world. At the 2007 Nature Photonics Technology conference in Tokyo it was emphasized that "by 2020, Telecoms would move from switching Terabits to Petabits, but based on today's technology a 100 Pbit/s IP router would consume 10 Megawatts and require a nuclear power station to supply it with electricity". Optical networks have been migrating from Opaque (Optical-Electrical-Optical (O-E-O) conversions at every transit node) to Translucent which employs O-E-O devices only where strictly needed, in order to minimize the power-greedy O-E-O operations. However, in order to maximize energy efficiency, also the higher network layers must be involved in the design process. Multi-Layer design for translucent networks has been proposed as an effective strategy to reduce the network cost and IP-over-WDM has been identified as a promising two-layer architecture to increase energy savings. The second part of this thesis focuses on the energy consumption of translucent IP-over-WDM backbone networks. With respect to existing works, I have proposed a novel power consumption model which also addresses the housing constraints of both IP and WDM layers (i.e., rack/shelf model) and, for the first time,

I have evaluated the energy savings brought by different Traffic-Aware Multi-Layer design strategies (i.e., resource utilization adaptation with daily traffic variations) for translucent networks via a Mixed Integer Linear Programming (MILP) formulation. Telecom operators seek for novel network design strategies which represent a good compromise between energy and cost. In fact, energy efficiency does not always mean cost efficiency. I have shown that high energy savings can be achieved by performing symbol-rate adaptation combined with sleep-mode management of network devices (i.e., switching resources on-off). However, this approach results in higher costs in terms of optoelectronic (OE) interfaces. Therefore, I have proposed a new strategy to achieve the best trade-off between energy and cost.

The impact of optical transmission reach on the power consumption of IP-over-WDM networks has been also investigated. Since a longer optical reach does not come for free, (i.e., it implies more complex circuitry, Digital Signal Processing (DSP) and Forward Error Correction (FEC) modules to compensate for impairments and transmission errors, Raman amplification instead of EDFA, higher fiber quality, etc.), the common belief of "the higher the reach, the lower the cost" may not be true in any case. I have proposed a reach-related power consumption model based on 100G DSP's complexity showing that in order to prevent from cost and energy waste, a network designer must accurately choose whether

extended-reach technologies are preferable to short-reach ones. This second part of my study has been carried out in collaboration with Alcatel-Lucent Bell Labs France. Vendors and network operators cannot fail to consider the new challenges fostered by the never ceasing thrust towards energy and cost effective networks. The developed simulation and optimization tools and the promising results obtained throughout this research study represent the starting point for further investigation aimed at providing a wider range of networking solutions tailored on the basis of clients' needs, while ensuring high level of customer satisfaction, from the cost, power consumption and traffic variation accommodation point of views.

A DECLARATIVE APPROACH TO SELF-ADAPTIVE SERVICE ORCHESTRATIONS

Leandro Sales Holanda Pinto - Supervisor: **Gianpaolo Cugola**

Most modern software systems have a decentralized, modular, distributed, and dynamic structure. They are often composed of heterogeneous components and operate on several different infrastructures. They are increasingly built by composing services; that is, components owned (designed, deployed, maintained, and run) by remote and independent stakeholders. The quality of service perceived by the clients of such a composite application depends directly on the individual services that are integrated in it, but also on the way they are composed. At the same time, the world in which such applications are situated (in particular, the remote services upon which they can rely) change continuously. These requirements ask for an ability of applications to self-adapt to dynamic changes, especially when they need to run for a long time without interruption. This, in turn, has an impact on the way service compositions are implemented using ad-hoc process languages defined to support compositions.

Indeed, the principles behind Service Oriented Computing (SOC) has brought a simplification in the way distributed applications are developed. We claim, however, that the fully potential of SOC

is still to be reached and it is our belief that this is caused by the same tools used to build such service compositions. Indeed, mainstream approaches failed to support dynamic, self-managed compositions, characteristics they must have due to the changeable world they are embedded in, where it is essential to be able to adapt to changes that may happen at run-time. Unfortunately, mainstream SOC languages make it quite hard to develop such kind of self-adapting compositions. It is specially hard because they too closely resemble traditional languages, with their imperative style of programming: it requires service architects to take care of an intricate control flow, in which one tries to capture all possible ways things can go wrong and react properly to exceptional conditions. A great effort is required to program the application to continue to meet its requirements in the presence of anticipated or unanticipated changes.

In this thesis we present DSOL - Declarative Service Orchestration Language, a novel approach in which we abandon the imperative style adopted by currently available languages in favor of a strongly declarative alternative. DSOL allows an orchestration to be modeled by

giving a high-level description of the elementary activities, a loosely coupled implementation layer and the overall Goal to be met by the orchestration.

DSOL models are then executed by an ad-hoc service orchestration engine, which leverages automatic planning techniques to elaborate, at run-time, the best sequence of activities to achieve the goal. Whenever a change happens in the external environment, which prevents execution to be completed, DSOL engine behaves in a self-healing manner. Through dynamic re-planning and advanced re-binding mechanisms, it finds an alternative path toward the goal and continues executing it, until the goal of the orchestration is reached.

DSOL provides several advantages w.r.t. traditional approaches, ranging from a better support for the implementation of self-adaptive orchestrations to a more decoupled architecture in which they may smoothly evolve to cope with exceptional situations or to requirement changes. DSOL models also promotes a more readable and maintainable code through a clear separation of concerns, in which the orchestration logic is isolated from the logic to used to handle

and adapt to exceptional situations.

EXPLORATORY COMPUTING: DESIGNING DISCOVERY-DRIVEN USER EXPERIENCES

Luigi Spagnolo - Supervisor: Paolo Paolini

Large information spaces – i.e. websites involving hundreds or thousand of pages, corpora of contents such as digital libraries and archives, semantic knowledge bases, etc. – represent a strong challenge for the design of user experiences aimed at information seeking and sense making. Recent research proposes to integrate and complement the traditional approaches to information seeking – i.e. *hypertext navigation* and *search* – with more advanced and powerful *exploratory patterns*. In particular *faceted navigation*, nowadays largely adopted also by practitioners (e.g. in e-commerce websites), is a technique for providing users with guided search when they have an ill-defined goal (e.g. just “finding something interesting”) or need to acquire knowledge about the specific domain in order to accomplish the retrieval task. In addition, faceted exploration is potentially able to support a much broader range of complex knowledge needs and learning tasks. Exploratory interaction techniques can be employed to support business intelligence and online analytical processing (OLAP) applications through a form of visual, user-driven feature mining on the different dimensions of a dataset. With a similar approach, exploratory

experiences can be also useful for disseminating knowledge about a specific domain such as cultural heritage and education. Despite these potentials have at least in part already emerged, a whole picture of such a novel *exploratory computing* approach was however still missing, since previous research has mainly focused mainly on specific, empirical examples. For such a reason, I proposed a comprehensive framework of design and implementation strategies, named *Felis* – i.e. *Faceted Explorations for Large Information Spaces*. According to this general paradigm, exploration takes place over structured information spaces, described according to a more or less complex semantics, involving multiple *faceting properties*. These facets are intended as high-level, conceptual dimensions which are relevant from the potential users’ perspective, rather than system-oriented properties (e.g. locations at level of region or countries, rather than geo-codes). In such a context, the query (formulated by advanced user navigation) has the key role of defining the scope of the exploration within the whole space, i.e. the features that the “observed” information items should or should not possess. An exploratory application does not simply outputs the set of result

matching the query, but also provides users with *feedback information* about the properties shared by those selected items. The shared features are in their turn also used to iteratively refine the query, restricting (zoom-in) or enlarging (zoom-out) the scope of the exploration. Finally, different visualization strategies can be adopted to show the distribution of the observed properties, possibly at several levels of granularity, and highlight possible interesting patterns.

Felis four pillars. More in detail Felis is based on the four pillars listed below.

(a) *Semantic Knowledge representation and query formulation*. Classification concepts (for describing resources) and queries are represented in FelisQL, a language specifically conceived for supporting exploratory applications, which is in its turn an extension of the LISQL, developed by the LIS team at IRISA – University of Rennes. FelisQL is fully translatable into RDF and SPARQL, while being closer to natural language. The model should be also understandable by *domain experts* and *power users* of the applications, to support agile design and prototyping also when lacking strong programming expertise. FelisQL allows designers to

adopt a flexible semantics, also at different levels of granularity or detail for the same properties, also handling data coming from heterogeneous sources (e.g. folksonomies, controlled vocabularies, metadata extracted from text, etc.). Among its features, the language also

and peculiarity measures are visualized. (c) *Interface elements and patterns* for advanced (also semantic) querying. Such elements allow to compose arbitrarily complex combinations of sub-expressions, e.g. adding a new filter in conjunction or an

partitioning and aggregating them according to one or more dimensions (as in thematic maps and mosaic plots). In fig. 2 an example of multivariate canvas is shown together with a set of facet widgets for handling the specific item properties. **Case studies.** Experimental



1. Colored weighted terms and bar charts representing frequency and peculiarity of civilizations or periods relevant for venues of archaeological interest in Northern Italy. “Germanic peoples” is highlighted (with a green background) as having a significant positive peculiarity (it is very typical of Northern Italy), while “Ancient Greece” and “Italian Peoples” are shown as less peculiar for this area (with a red background)

includes a formalization of the set of syntactic transformations that allow to move from a stage to another of the exploration, by modifying the query. (b) *Relevance metrics* (based on association mining measures) for determining the degree of concepts of item features (e.g. the authors names, they affiliation, etc.) with respect to the specific context of the exploration, expressed by a query (e.g. one may want to understand how frequent are collaborations with authors affiliated to foreign research institute within a specific research area). Fig. 1 shows an example of how frequency



2. Example of pixel-grid visualization from PoliCulturaPortal, a portal allowing users to explore interactive narratives produced by Italian schools within a national context held by Politecnico di Milano. Each item is represented as a tassell of different shape and colour: the shape represents a fixed dimension (school level in the specific case) the colours may be used to highlight a number of other selectable dimensions

alternative one in disjunction, excluding the items with a certain feature, etc. (d) *Visualization strategies* for displaying both the facets and the set of results matching the query. In particular, we distinguish between *facet widgets*, allowing users to refine the query by inserting new restrictions and providing feedback about the specific properties of the current set of results (through mono-dimensional visualizations such as tag clouds and bar charts), and *canvases*, aimed at displaying the current set of results (at the main focus of the query) possibly highlighting,

evidence comes from real case studies: a prototype for the Directorate- General for Antiquities depending from the Ministry of Culture of Italy, as well as portals for Politecnico di Milano educational initiatives, for which several statistics have been collected and interactively visualized using JavaScript frameworks, Google Charts and Google Maps.

IMPROVING SYNCHRONIZATION AND DATA ACCESS IN PARALLEL PROGRAMMING MODELS

Ettore Speziale - Supervisor: **Stefano Crespi Reghizzi**

Today, parallel architectures are the main vector for exploiting available die area. The shift from architectures tuned for sequential programming models to ones optimized for parallel processing follows from the inability of further enhance sequential performance due to power and memory walls. On the other hand, efficient exploitation of parallel computing units looks a hard task. Indeed, to get performance improvements it is necessary to carefully tune applications, as proven by years of High Performance Computing using MPI.

To lower the burden of parallel programming, parallel programming models expose a simplified view of the hardware, by relying on abstract parallel constructs, such as parallel loops or tasks. Mapping of those constructs on parallel processing units is achieved by a mix of optimizing compilers and run-time techniques. However, due to the availability of an huge number of very different parallel architectures, hiding low-level details often prevents performance to be comparable with the one of hand-tuned code.

This dissertation aims at analyzing inefficiencies related to the usage of parallel computing units, and to optimize them from the runtime

perspective. In particular, we analyze the optimization of reduction computations when performed together with barrier synchronizations. Moreover, we show how runtime techniques can exploit affinity between data and computations to limit as much as possible the performance penalty hidden in NUMA architectures, both in the OpenMP and MapReduce settings. We then observe how a lightweight JIT compilation approach could enable better exploitation of parallel architectures, and lastly we analyze the resilience to faults induction of synchronization primitives, a basic building block of all parallel programs.

MACHINE LEARNING OF COMPILER HEURISTICS FOR PARALLEL ARCHITECTURES

Michele Tartara - Supervisor: **Stefano Crespi Reghizzi**

The complexity of modern computer architectures is constantly increasing every time a new one is released. Because of this, compiler writers cannot know in advance the exact effect of applying a given code transformation, since too many characteristics (size of the cache memories, pipeline length, degree of parallelism, etc.) actually influence the result. This is especially true when multiple interacting optimizations are considered.

Building an exact model of such architectures that can be used by compiler to decide what optimizations to apply to a program, in which order to apply them, or what values to assign to numerical parameters required by the compilation process is computationally infeasible. Therefore, all compilers use heuristics to make such decisions, based on program-dependent values available at compile-time, called features. Possible features are the average number of instructions in a basic block, the nesting level of a loop, the average number of successors for each instruction, etc. In order to fully exploit new architectures, compilers have to be updated as well, to allow the programmers to have full access to all the computational power they provide.

Unfortunately, while Moore's

law predicts that the number of transistors in processors doubles roughly every two years, Proebsting's Law tells us that the optimization level provided by compilers can be expected to double every eighteen years. Such numbers give us a clear insight about how difficult it is for compilers to keep the pace with the innovations introduced by the hardware.

Deep knowledge of the functioning of the architecture is required, including being aware of how the memory hierarchy can provide data in an optimal fashion, and how the functional units can be used together with the register to provide the correct operands at the correct time, preventing avoidable lag. Also, many parameters such as software pipelining strategies, instruction scheduling, blocking factors and loop unrolling depths have to be decided. Moreover, to obtain the best results on all architectures, the process of defining the heuristics should be repeated for every time a new version of the compiler is released, or a new target architecture becomes available, since different platforms require different optimizations and therefore different heuristics. It might take several releases of the compiler to exploit all the features of a new architecture, and, given the current rate

of evolution of the hardware, by the time the compiler is ready, a new architecture is likely to be available. The main problem is that most compiler optimizations can provide either speedups or slowdowns depending on the code they are applied to and depending on which other transformations are applied before and after the one being considered.

Deciding whether and when to apply an optimization algorithm is a daunting task, and the complexity of the architectures makes the usage of exact models to predict the outcome unfeasible, so compilers rely on heuristics to make such decisions.

The process of writing heuristics is, traditionally, mostly based on the personal experience of the compiler writer and involves a time-consuming trial and error process. Much work has been done recently to try and substitute the compiler writer with automated algorithms for performing this task. Iterative compilation and machine learning approaches have been studied, each with its own merits and shortcomings. This thesis work is rooted in this research area. First of all, it presents long-term learning, a new learning algorithm that aims at automatically determining efficient compilation heuristics.

Long-term learning tries to overcome the main issue of most iterative compilation and machine learning approaches (the long compilation times and the need for a time-consuming initial training phase) while still providing their advantages. Similar challenges have been faced already by recent works in the area, but, unique to long-term learning is the ability to solve them while generating human-readable heuristics (in the form of mathematical formulas) and while taking into consideration the fact that the single code transformation algorithms are not independent, therefore their heuristics need to be evolved in such a way to interact well with one another. In order to further speedup the execution of the long-term learning algorithm, this thesis presents a method to parallelize it across multiple machines or to execute it in parallel on a single machine by splitting up its resources, using an approach based upon MapReduce. This approach is not limited to long-term learning, but it is general and it can be applied to most iterative compilation algorithms. Finally, two proposals are presented as future work. First, a new lightweight compilation method for highly dynamic parallel programs, allowing one to divide the compilation process between compiletime

and runtime, keeping as much as possible of the heavyweight computations at compile-time, and applying at runtime only those transformations that could benefit from information not available at compile-time, using a technique derived from long-term learning to choose which optimizations to postpone at runtime. Second, starting from an analysis of the sensitivity to hardware faults of synchronization primitives, namely locks and transactional memories, a use of long-term learning as the basis for a novel approach to fault recovery is presented.

ELECTRONIC INSTRUMENTATION FOR ELECTROCHEMICAL CELL MONITORING IN LAB-ON-CHIP DEVICES

Marco Vergani - Supervisor: **Giorgio Ferrari**

Study of neural stem cells differentiation is one of the most appealing challenges in modern biology. For this purpose, researchers need new technologies for quantitative cellular monitoring, which may be developed combining different design methodologies with a multi-disciplinary approach. The European project EXCELL has been conceived in this framework, with the aim of developing a platform for simultaneous electrochemical and optical cell monitoring inside a microfluidic culture system.

The work presented in this thesis is focused on design and implementation of electronic instrumentation and its integration inside the EXCELL microfluidic platform. At this aim, two different multichannel instruments have been realized. First one is optimized for monitoring cell population growth and differentiation on interdigitated electrodes with an area of $6 \cdot 10^4 \mu\text{m}^2$ by measuring impedance in the 10mHz - 100kHz frequency range. For maximum versatility, the instrument can also perform time domain measurements with 5pA_{rms} input noise (100ms time averaging). The compact 24-channels prototype is fully integrated with a microfluidic platform to allow automatic

monitoring of cell cultures. The second instrument has been designed with the different aim of performing electrochemical imaging of exocytotic events on single or small groups of cells. It operates in parallel on 54 small electrodes (diameter of $5\mu\text{m}$) with 3pA_{rms} input noise, a time resolution of $54\mu\text{s}$ and 5kHz analog bandwidth.

A final part of the work contained in this thesis was devoted to explore a post-CMOS fabrication technique to deposit gold biocompatible electrodes on integrated circuits, thus integrating sensors and front-end circuits on the same substrate and overcoming the limitation set by connection between electrodes and electronics.

DESCRIPTION LOGICS AND SEMANTIC QUERY LANGUAGES IN ROBOTIC APPLICATIONS

Nicola Vitucci - Supervisor: Giuseppina Gini

Research in robotics has moved throughout several phases in its history: the sense-think-act paradigm, where inputs from the sensors are used to generate a plan which is then transformed into action, has been challenged by a behaviourist approach, where the control system responds dynamically to the changes in the environment by means of separate activities arranged in layers. The main difference between these two points of view is in the use of representations: while in the latter “the world is its best model”, the former, being rooted in artificial intelligence, needs symbols, concepts and reasoning abilities for building rich world models.

The interest in the behaviourist approach has been revived by recent theories on the importance of embodiment and neuropsychological development in robotics, so that sensing and acting are considered as tightly coupled and the focus is shifted on the robot body and its perception, introspection and proprioception; the study of this perspective is supported by the availability of research platforms such as the iCub, which provide researchers some common grounds for developing and testing such theories. On the other hand, approaches based on cognitive modelling focus

more on the different aspects of human intelligence such as the use of language, learning skills, generalization abilities and interaction with people; for this reason, the disciplines involved in research on cognitive robotics are many and diverse.

We are now in a phase where AI-based approaches are being reintegrated, albeit with different claims than in the past: rather than relying on purely symbolic approaches as the only models for intelligence, the current perspective is now to adopt symbols as a support for integration of different representations and as a way to code (and make readily available to robots) what is called high-level knowledge, which is the basis of human communication and interaction. In order to serve to this purpose a symbolic system has to interact with different sources of data, from the low level (such as data coming from sensors) to the high level (such as linguistic representations, plans, categories and so on); therefore, a symbolic representation should be able to integrate such different channels of information and possibly act as an interface among them.

Description logics define a logic-based framework for knowledge representation and reasoning

which has received much attention in the last decade, the reason being their decidability property which makes them more attractive with respect to traditional AI approaches (i.e. theorem proving based on first order logic). As description logics provide a unified formal approach to semantics, they have been used in many fields related to robotics for different kinds of applications along semantic query languages, which constitute the semantic counterpart of query languages for databases. In this thesis we discuss the issues related to the use of description logics and semantic query languages in the robotic domain, analyzing use cases from different yet related fields along with possible issues and examples of solutions. We focus in particular on the following aspects:

- Representation: as the knowledge base design is the first step to build a logic-based framework, what do classes, instances and relations represent in the specific domain and how to structure them accordingly?
- Reasoning tasks: as semantic languages are commonly used because of the reasoning facilities they offer, what kind of reasoning tasks are expected to be performed within the specific domain?

- Expressivity: as there exists different reasoning engines and semantic storage solutions which are optimized on specific logics, is there a minimum expressivity needed for the representation and reasoning tasks to use?
- Knowledge base management: based on the expressivity of logic, the reasoning tasks and the expected volume of data, what is the best solution for storing the knowledge base and how new data is added?
- Queries: what is the expected type of query to execute on the knowledge base and what are the languages to be used?
- Extensions: are any extensions to the standard description logics needed for the specific application?

By focusing on such knowledge representation issues we aim to have a better understanding of what does semantics mean in robotics and of the “level of semanticity” we can expect to be useful within robotic tasks; additionally, we analyze how different levels of information can be integrated by means of semantics. More specifically, the fields we explore are the following:

- Object representation, where the main problem is on whether a representation of an object based on part

decomposition can be effectively used and how it should be designed using a logic-based approach to make it usable and scalable;

- Grasping, where the main problem is on how to decide the possible grasps to be performed on an object, given a geometric representation of both the shape of a hand and the shape of the object itself in terms of a fuzzy extension of description logics;
- Cognitive architectures, where the main problem is on how to build an embodied ontology to integrate different representations (from low- to high-level) for concepts, using language as a guiding criterion to structure the knowledge.

Our aim is therefore to discuss strengths and weaknesses of a logic-based representation on different levels: in the thesis it is shown what is the amount of information provided respectively by humans (e.g. in defining names for concepts, grouping criteria for parts and so on) and by raw data. The long-term goal of this research is to obtain a suitable conceptual model for integrating all the available sources of information, thus semantics is here used as a means for achieving interoperability and for making the acquisition of new

information more structured and autonomous.

Language has a great deal of importance for “grounding” knowledge: grounding perceptions directly to symbols via a “translation” does not provide a sufficient account of the neural and cognitive processes underlying the low-level representation of entities, while language provides some organizational principles to guide the acquisition, organization and comparison of symbols. Knowledge representation formalisms such as DLs are based on language because they are used for providing common vocabularies in order to describe specific domains; thus, the integration of human-understandable concepts makes resources for robots accessible by humans; in fact, as a byproduct of our analysis of low-level information, we built several resources which can be useful for humans as well.

CONTENT-BASED MACRO-DESCRIPTORS FOR MUSIC CLASSIFICATION AND MULTIMEDIA INFORMATION RETRIEVAL

Massimiliano Zanoni - Supervisor: Augusto Sarti

As a privileged form of communication, music always has an important role in human life. The advent of the digital era carried an important evolution in music listening experience. Before the advent of the Web, users mainly approached music search and organization through mediators. Music shops, magazines, geographic distances are some examples. These mediators provided a perspective on musical content, by selecting and organizing them in a hierarchy of importance. Today, in comparison with some years ago, the musical content is no longer associated to a specific physical place and almost every content is just a click away. In the new scenario mediators risk to disappear and the perspectives flatten. For this reason, classical paradigms to organize, retrieve, browse and interact with musical content are no longer effective. New applications and paradigms are needed and scientific communities and industries are working to build novel mediators. In general, content navigation is still performed using traditional modalities, by exploiting meta-information and descriptors that are manually generated, with inevitable errors. In addition, tags are often unable to adequately capture a useful description of a musical excerpt because

of the tendency of music to carve new niches in-between consolidated styles, but also because of the tendency to visit different styles within a single musical piece. (e.g. mood and genre). Content-driven description and classification is, therefore, urgently needed. Unfortunately content-based analysis is generally based on low-level features that are naturally semantically poor, while creating the need for more compact semantic descriptions whose level of abstraction is more familiar to the user and it would allow to build human centered and personalized applications. In order to build effective solutions, from one side it is important to investigate how users understand contents, and how they would like to access them. On the other side, it is important to investigate how to model content and how to capture and represent their semantics. This is the well-known issue of the "gap between low-level and high-level features". The goal of this thesis is to overcome the limitations of current approaches by exploring a limited number of novel content-based time-varying and highly descriptive high-level features that are derived from a large number of low-level and mid-level ones.

Typical approaches to the definition of high-level features tend to distinguish between emotion-related (ED) and non emotion-related descriptors (NED). ED refer to the mood perceived in a song such as *happy, sad, furious* and so on. NED are those that cannot be directly connected to emotional states, for example, *musical genre* (rock, jazz), *timbral descriptors* (soft, hard), *rhythmic descriptors* (slow, dynamic) or other generic descriptors used in common languages (dull, memorable, easy). Two are the approaches to semantic description conceptualization adopted by both ED and NED: categorical and dimensional. Categorical approach is based on the assumption that musical experience can be represented by a limited number of innate and universal descriptors (categories). Even though the idea of grouping music into categories is intuitive it can lack in expressiveness. Dimensional approach, adopted in the thesis, overcome the problem through a definition of descriptors on a continuous domain.

Concerning non emotion-related descriptors, the generative models adopted for HLF modeling rely on example-based techniques. Each descriptor is built over a

highly representative training set of excerpts. In order to guarantee a sufficient resolution to capture the evolution over time, excerpts are chosen to be short, but long enough to guarantee the desired exclusive semantic homogeneity. One of the main issues of the approach is the difficulty of choosing the correct set of high-level features, and generating the related datasets accordingly. In this approach we investigate the possibility of identifying the macro-features and the related training datasets in an automated fashion. Each descriptor is described by a large set of LLF and defined as the log-likelihood of a Gaussian Mixture Model (GMM). Knowing that the excerpts that share a semantic description tend to be close in a well-defined low-level feature space, clustering techniques are applied in order to semantically group the excerpts. A feature selection algorithm is applied in order to select the best feature set that optimize the associated high-level features in terms of discriminant power and informative impact. Then, taking advantage of a predefined set of bipolar concepts borrowed by musicological research, we compare the GMM approach to regression functions.

Using the dimensional approach it is potentially possible to assign an emotional state for each instant of time and with a high semantic rate allowed by the annotation on a continuous space. Although this has many advantages, in some MIR applications it is difficult to appreciate such a

high accuracy. For this reason, in many applications it can be more suitable to reduce both temporal annotation rate (segmentation) and semantic annotation rate (categorization). Reduction of semantic annotation rate, also called categorization, aims at mapping English affective words on the AV or AVD spaces. In this thesis we consider the dataset (ANEW) of affective English terms. We used the mapped dataset in order to semantically group terms by applying clustering techniques with different distance functions.

Music segmentation is a popular topic in MIR area. It concerns to segment music pieces according to musical structures (verse, chorus, etc.) or in order to extract segments that exhibits a certain degree of homogeneity. One goal pursued in this thesis is the segmentation of music pieces according to the variations of emotional state in the AV space. A novel segmentation method is introduced. In order to capture emotion variations over time, analysis is performed using short musical excerpts. Each second of a song is tagged using the two coordinates in the AV space and a representative set of LLF are extracted. Arousal and Valence are then independently modeled through regression analysis. Regression functions are used for modeling the existing relationship between LLF and the AV dimensions. Mood segmentation is performed by applying of widely used pattern analysis techniques on the Arousal and

Valence functions over the time. As an example of a music recommendation system, an early implementation of a dynamic multimedia playlist generator is also proposed. Typical playlist generation systems use metrics that generally only account for similarity with the query song and used descriptors are to be intend valid for the whole excerpt. The system proposed in the thesis introduces some metric that is not only based on similarity with the query, but account for some user's preferences. Such preferences can be intentional control signals other types of stimuli coming from environmental events. These stimuli are properly mapped on a space composed of semantic and non-semantic features. In order to make the system reactive to fast stimuli, the proposed system considers each excerpt as a sequential collection of homogeneous musical fine grains. Each grain is analyzed independently. This formalization permits the system to be reactive and each time a new stimulus comes, a new ranked playlist of fine grain that best fit all the preferences can be generated.

The use of a limited set of semantic macro-descriptor proved to be suitable also for musical genre classification. Additional advantages in using a limited number of high-level features, is the ability to visualize musical descriptors in a natural and, possibly, non-invasive fashion (e.g. color shades).