MECHANICAL ENGINEERING | PHYSICS | PRESERVATION OF THE ARCHITECTURAL HERITAGE | STRUCTURAL, SEISMIC AND GEOTECHNICAL ENGINEERING | URBAN PLANNING, DESIGN AND POLICY | AEROSPACE ENGINEERING | ARCHITECTURE, BUILT ENVIRONMENT AND CONSTRUCTION ENGINEERING | ARCHITECTURAL, URBAN AND INTERIOR DESIGN | BIOENGINEERING | DATA ANALYTICS AND DECISION SCIENCES | DESIGN | ELECTRICAL ENGINEERING | ENERGY AND NUCLEAR SCIENCE AND TECHNOLOGY | ENVIRONMENTAL AND INFRASTRUCTURE ENGINEERING | INDUSTRIAL CHEMISTRY AND CHEMICAL ENGINEERING | INFORMATION TECHNOLOGY | MANAGEMENT ENGINEERING | MATERIALS ENGINEERING | MATHEMATICAL MODELS AND METHODS IN ENGINEERING
DOCTORAL PROGRAM IN INFORMATION TECHNOLOGY

Introduction
The Ph.D. programme in Information Technology (Ph.D. IT) covers research topics in four scientific areas, associated to different facets of the field of Information and Communication Technology, namely Computer Science and Engineering, Electronics, Systems and Control, and Telecommunications. This broad variety of research topics perfectly captures the core mission of the corresponding sections of the Dipartimento di Elettronica, Informazione e Bioingegneria (DEIB). New research topics and cross-area research fields are also covered, such as machine learning, big data, intelligent data analysis, Industry 4.0, internet of things, bioinformatics, quantum computing, ecology, environmental modelling, operations research, and transportation systems. The Ph.D. IT programme is the largest at the Politecnico di Milano in terms of number of students. Every year, more than 90 new students join the programme, for an overall number of around 400.

Topics
Research at DEIB in the field of Information Technology is supported by 35 laboratories, and is organized in 4 main areas.

- Computer Science and Engineering (Vice-Chair: Prof. Francesco Amigoni):
  - Information systems, Database management, Information design for the web, Methods and applications for interactive multimedia, Embedded systems design and design methodologies, Dependable systems, Cybersecurity, 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-Chair: Prof. Angelo Geraci):
  - Circuits and systems, Single photon detectors and applications, Radiation detectors and low noise electronics, Electronic circuit design, Electron devices.
- Systems and Control (Vice-Chair: Prof. Simone Garatti):
  - Control theory and its applications, Robotics and industrial automation, Dynamics of complex systems, Planning and management of environmental systems, Operations research and discrete optimization.
- Telecommunications (Vice-Chair: Carlo Riva):
  - Networking, Applied electromagnetics, Optical communications, Quantum communications, Wireless and space communications, Remote sensing, Signal processing for multimedia and telecommunications.

Industrial collaborations
Due to its intrinsic technological nature, the Ph.D. IT programme features many industrial collaborations. More than 50% of the Ph.D. candidates are funded by companies or by international research projects involving industrial partners. Indeed, the Ph.D. School envisions the collaboration between university and companies as the ideal ground to convert invention and scientific research into technological innovation. Nevertheless, alongside applied research projects in collaboration with industrial partners, the programme is also able to preserve a strong characterization in fundamental research. To monitor the activities and development of the Ph.D. programme, the Faculty Board cooperates with an industrial Advisory Board, composed by members of public and private companies, working in management, production, and applied research. The two boards jointly meet once a year to identify and suggest new emerging research areas and to foster the visibility of the Ph.D. IT programme in the industrial world.

Educational aspects
The teaching organization and the course subjects reflect the scientific interests of DEIB faculties. The curricula include a wide choice of courses (about 20 per year), and more than 30 courses for basic soft and hard skills offered by the Ph.D. School of the Politecnico di Milano. Access to external courses and summer schools is also encouraged. The challenge is to promote interdisciplinary research while offering advanced help to students to make the best choices according to the regulatory scheme of the programme. Students must undergo a yearly evaluation of the progress in their research and course work.

Internationalization
Every year, several courses are delivered by visiting professors from prestigious foreign universities. Moreover, the Ph.D. IT programme encourages joint curricula with foreign institutions. The programme has several Double Degree and Joint Degree agreements with institutions from countries in all continents. Every year the programme receives more than 150 applications from foreign countries and about 15% of our selected Ph.D. candidates have applied from outside Italy.

Conclusions
The core mission of the Ph.D. IT programme is to offer an excellent doctoral level curriculum, through high-quality courses, a truly interdisciplinary advanced education, cutting-edge research, and international and industrial collaborations.
PHD BOARD OF PROFESSORS

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<td>IBM Italy</td>
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Prizes and awards

In 2023 the following awards have been obtained by Ph.D. candidates:

- wDimitris N. Chorafas Award - Fabio Bonassi, Matteo Castiglioni
- Prof. Florian Daniel PhD Thesis Award - Davide Di Vita
- Springer Award - Luca Barbieri, Matteo Castiglioni, Serenza Curzel, Andrea Galimberti, Mémèdhe Ibrahimii,
  Steven Kleber Caicedo Mejillones, Livia Iestling, Paola Piedimonte, Saverio Ricci, Fabio Bonassi, Lorenzo Jr.
  Sabug, Danilo Saccani
- KUKA Innovation Award - Nicolò Lucchi, Elias Montini, Isacco Zappa
- Marisa Bellisario Award - Arianna Adelaide Maurina
- IEEE International Symposium on Personal, Indoor and Mobile Radio Communications - Best Paper Award - Paolo Fiore
- 29th ACM International Conference on Computing Frontiers - Best Poster Award - Roberto Rocco
- 7th IEEE Conference on Control Technology and Applications - Outstanding Student Paper Award - Matteo
  Luigi De Pascali
- Fondazione Cogeme - Premio nazionale "Si può fare di più" - Laura Boca de Giuli
INNOVATIVE D.O.D. PRINTING FOR MICROMETRIC INDUCTORS MANUFACTURING

Giuseppe Barbalace - Supervisor: Prof. Dario Andrea Nicola Natali

In the framework of electronics component manufacturing, additive technologies (more popularly known as 3D printing techniques) are gaining a growing importance year by year. These techniques, thanks to their properties of implementation easiness, fabrication speed, amount of required material and limited energy consumption, are of great interest when compared to standard subtractive technologies. Printed electronic devices performances noticeably improved in recent years and, unlike standard ‘rigid’ electronics, they are characterized by compatibility with flexible applications and roll-to-roll processes. Among passive components manufacturing through additive techniques, the production of high quality micrometric integrated inductors can be of great interest in different contexts. Standard inductors could be created through electrochemical processes, but they imply a lot of wastes and high costs to reach conductor thickness of relevance to obtain high quality. Shifting to inkjet printing is of great interest for such purpose, because conductor thickness can be increased by simply depositing more layers. However, such technique requires conductive ink with high conductivity, micrometric and stable accuracy in deposition. This thesis investigates the utilization of an innovative printing methodology to obtain high quality factor micrometric silver inductors, according to specifications compliant with Galvanic Isolators applications in Very High Frequency range. Silver ink was deposited onto polyimide substrates with piezoelectric Drop-On-Demand (D.O.D) inkjet printing. The employed tool enabled to both customize deposition trajectories and to keep a micrometric deposition accuracy in hours of activity, required to print up to 30 layers. Printings became conductive after an annealing treatment, at temperatures noticeably lower than the standard electronic processes ones (below 250 °C). Obtained printed inductors occupy a noticeably smaller area, with tracks width and inter-track spacing below 100 μm which are unprecedented in the literature so far. Finally, a process to connect pads on a top metal layer with printed inductors on a bottom metal layer was successfully implemented, by allowing VHF-measurements to be performed. Implemented process enabled to grant a stable inductance value and to obtain a quality factor (ratio between reactance and resistance) above 1, even if it implied also a not-negligible resistance increase with frequencies with respect to the simulations. Optimization of this process can be of interest for microelectronics manufacturing and for the integration of printed components with standard circuits.

Fig. 1 - Best quality inductor of this work, obtained by printing 30 layers.

Fig. 2 - Solid line: values of inductance, quality factor and resistance measured in VHF range after VHF-pads process for a 27-layers inductor. Dashed line: simulations obtained by using the measured conductivity of an inductor with the same layout, created in the same printing session, that did not undergo to VHF-process. Simulations do not take into account lift-off residuals.
Conventional single-agent localization methods have been demonstrated to provide unsatisfactory performances for mission-critical control applications where strict requirements are imposed, such as ultra-high reliability, ultra-low latency, and ultra-accurate positioning, due to the limited sensing/computing capabilities of ego systems. In contrast, cooperative positioning approaches enable interconnected agents to share information across the network with huge benefits in terms of accuracy, reliability, and safety. Indeed, as depicted in Fig. 1, the sensing capabilities of several agents (i.e., vehicles) can be heavily augmented thanks to the exchange and combination of multiple local measurements. This doctoral dissertation, authored by Luca Barbieri and supervised by Prof. Monica Nicoli, focuses on the development of novel cooperative localization and learning strategies in the context of mission-critical control networks. The goal is to provide competitive solutions for obtaining precise positioning in harsh propagating environments as well as reliable environmental mapping in highly-dynamic scenarios.

In the first part of the thesis, the localization problem is initially tackled by proposing novel augmentation strategies allowing to improve the reliability of the sensing at each agent. In particular, we consider a wireless network where each connected agent is tasked to localize itself based on location measurements extracted from radio signals. To cope with complex propagating conditions originating from the environment in which the agents are deployed, the proposed augmentation strategy statistically describes the propagation characteristics of the environment and combines hybrid localization measurements so as to reduce the uncertainty of the agents’ position. Once the agents are able to localize themselves, the research is moved to the mapping of the surrounding environment. Specifically, the proposed perception system leverages distributed learning methods for reliable perception at the agents. Fully decentralized, consensus-driven Federated Learning (FL) strategies are developed where in-network processing functions among cooperating agents replace energy-hungry operations carried out at a centralized location to enhance the resilience of the overall training platform.

Several communication-efficient designs are proposed to optimize the accuracy, latency, or training time by selecting in an intelligent way the parameters that have to be exchanged over the network during the FL optimization process. Then, localization and environmental mapping functionalities are merged into a unified framework. Under this framework, agents are assumed to be equipped with imaging sensors, namely lidar devices, for collecting information on their surroundings. Data-driven methods are designed to let the agents efficiently process the lidar point clouds and localize passive static targets present in the environment. The cooperation is then exploited to coherently fuse the individual detections made by the agents and consequently improve the localization of the targets. Once the targets have been localized with high accuracy, they are exploited to further refine the agents’ position.

Finally, the research activities are concluded by proposing a trustworthy environmental perception system. The proposed framework integrates Bayesian inference tools into the aforementioned FL-based perception methods so as to reliably quantify uncertainty arising from limited data availability at the agents. Compared to the previously-proposed FL systems that target the learning of a single value for the ML model parameters, the goal of the proposed Bayesian FL approach is to learn the (shared) global posterior distribution across all cooperating agents. Employing such a scheme allows the agents to weigh their decisions according to the posterior and, thus, provide reliable predictions that can be employed under safety-critical conditions. The results achieved during the Ph.D. demonstrate that the proposed approaches can be applied to a wide range of challenging problems that require highly-accurate, low-latency, trustworthy outcomes which are fundamental requirements envisioned for future Industrial Internet of Things (IIoT) and Connected Automated Vehicle (CAV) services.
In the Big Data era, the variety and volume of multimedia assets have exploded. We constantly interact online by exchanging multimedia objects like images, audio clips, or videos. Moreover, scientific data such as satellite imagery (i.e., images of the ground taken by a moving platform, like an aircraft or satellite) and microscopic images (i.e., western blots) are now available from numerous portals. However, this proliferation of content has also opened up new avenues for manipulation and misuse.

The multimedia forensics (MMF) community studies techniques for ensuring the authenticity of these objects. MMF aims to detect non-invertible traces left by editing operations, known as forensic footprints (FFs), using classic signal processing techniques and more recent data-driven approaches such as neural networks (NNs). Despite these efforts, MMF’s state of the art (SOTA) presents some drawbacks when dealing with the current data scenario.

For instance, data-driven techniques lack interpretability, i.e., knowing what prompted a detector to make a specific decision, and confidence estimation, i.e., understanding whether the response of a detector is reliable. Moreover, researchers do not have guarantees about their adaptability to new data modalities or generalization capabilities over new manipulation techniques. The birth and rise of editing techniques based on deep learning, e.g., Generative Adversarial Networks (GANs) and similia, poses new challenges to MMF researchers. New methods surface continuously and introduce new FFs that are hard to detect with state-of-the-art tools.

MMF forensics must face these challenges simultaneously; therefore, this thesis aims to bridge the gap between data-driven techniques and the current forensic needs. In particular, our goal is the development of data-driven forensic techniques for unusual data modalities, i.e., videos, satellite imagery, and microscopic images, while contemporarily addressing the flaws mentioned above. Concerning video signals, we propose a pipeline for the spatiotemporal localization of splicing attacks. This pipeline exploits an ensemble of Convolutional Neural Networks (CNNs) for extracting codec-related information and spots splicing attacks as inconsistencies in the extracted traces. As such, despite leveraging data-driven tools, it is interpretable since it leverages the well-known forensic concept of codec attribution. We also analyze the task of detecting facial manipulations in the subjects of a video, i.e., deepfake video detection. Once again, we exploit ensembles of CNNs but develop a slight architectural variation to provide the analyst with an interpretable map indicating the elements the networks find more informative for their analysis.

We also analyze the generalization capability of our solution in cross-dataset scenarios. We participated with this technique in the Deep Fake Detection Challenge (DFDC) hosted on Kaggle, reaching the 41st position over 2116 contenders.

We then analyze the varicolored world of satellite images. Satellite images are a multi-modal data asset, including Electro-Optical (EO) images, i.e., images capturing the reflection of the solar radiation by the Earth’s surface, as well as active measures like Synthetic Aperture Radar (SAR) signals. We then develop a pipeline for the detection of satellite images, namely panchromatic, RGB, and SAR images.

We start our analysis by developing a CNN-based solution for attributing a CNN-based image to the satellite that generated it. We use uncertainty estimation techniques to assess the confidence of the CNN in processing the samples and use such measures to reject images of unknown origin. We then use CNNs to extract sensor-related features patch-wise and localize copy-paste attacks as incongruencies in the spatial distribution of this information. Even though both solutions exploit CNNs as feature extractors, they report interpretable forensic information.

Moving to satellite RGB images, we analyze how some of their properties affect the detection capabilities of state-of-the-art forensic tools. In particular, we study how histogram enhancement operations used for processing this kind of data can aid in extracting and simultaneously hide useful forensic traces for copy-paste localization. We then develop a pipeline for the detection of images super-resolved with CNNs. These techniques leave visible and well-known artifacts in the Fourier domain. A simple anomaly detection algorithm trained on native high-resolution images generalizes well on different superresolution methods, even in data scarcity and strong compression conditions.

Our work on SAR imagery instead focused on two different tasks. Given the sensible role these signals have in military and intelligence applications, we develop a CNN-based pipeline to anonymize amplitude SAR imagery, i.e., to remove sensitive content such as urban areas while keeping the samples credible enough not to raise suspects around their integrity. We then develop a pipeline for localizing splicing attacks on the same imagery. This solution combines high-frequency residuals and CNNs, producing an interpretable feature map that provides the analyst with insight into the editing history of the image. Our work on SAR images is the first documented in the forensic literature.

We conclude the thesis with an analysis of microscopic images, more specifically of western blots. Western blots are the result of measurements in the field of molecular biology. We study the possibility of generating synthetic images of western blots exploiting deep learning techniques like GANs. We then gauge the detection capabilities of data-driven forensic tools developed in the challenging scenario of not having access to these synthetic samples. Even if we do not optimize these instruments over these signals, we can recognize them efficiently even in in-the-wild settings, e.g., under JPEG compression. The results of this thesis show that we can analyze data modalities different from standard digital pictures using similar concepts to those already known by the MMF community and that incorporating them with data-driven tools can lead to effective yet interpretable responses. Given the rate at which multimedia data exchanges evolve and new data modalities emerge to the public, many research directions stem from this investigation. A deeper understanding of the lifecycle of these new multimedia objects will always be necessary, as well as the development of out-of-the-box techniques for obtaining interpretable and confident responses from forensic instruments. Finally, translating results and findings from different data modalities can be beneficial in developing and re-using techniques, leading towards the development of universal foundational forensic tools.
THE TWIN-IN-THE-LOOP APPROACH FOR VEHICLE DYNAMICS ESTIMATION AND CONTROL: METHODS AND APPLICATIONS

Federico Dettù - Supervisors: Prof. Simone Formentin

In vehicles, the ever increasing computing power in on-board Electronic Control units enables the use of demanding software components. Specifically, vehicle Digital Twins are full-fledged dynamic simulators, used for off-line design and testing: recent developments allow for the real-time execution of these models on on-board vehicle control units. What would be the impact of embedding such sophisticated models in on-line estimation and control algorithms? This is the question tackled in this thesis, in which we develop, analyse and validate a framework named Twin-in-the-Loop (TiL). On the control side, in typical design frameworks a certain controller (possibly a very sophisticated one) is finely tuned on increasingly complex vehicle models, up to a final implementation on the real vehicle, requiring a long and costly End-of-Line calibration: we change this framework by directly employing the controlled simulator on the real vehicle as an openloop feedforward contribution, while a simple compensator -e.g. a PID- is enforced to guarantee stability of the overall system. After validating and comparing the approach against a benchmark, we tackle some practical problems of it: specifically, we address the problem of tuning the TiL compensator directly from data, while guaranteeing some robustness in the process. A schematic representation of the TiL-C is given in Fig. 1. On the estimation side, recent research showed as TiL observers (employing a vehicle simulator as a plant replica) are able to outperform benchmark ones: a critical aspect when considering TiL estimators also lies in the calibration of the algorithm itself. In this work, we extend and experimentally validate the original formulation to the problem of estimating unknown parameters (such as the vehicle mass and moments of inertia). Then, we focus on the problem of calibrating the estimator closed-loop correction law. Due to the high number of parameters to be tuned, a reduction of the complexity is necessary in order to have a well posed optimization problem: this is made further complex by the fact that the Digital Twin is a black-box object, thus preventing the use of classical observer tuning approaches (e.g. the Kalman Filter theory). To solve the problem, we employ both supervised and unsupervised learning approaches; eventually, we show as the automatic complexity reduction is more performing than one carried out via physics-inspired considerations. A schematic representation of TiL-F is given in Fig. 2.

Fig. 1 - The Twin-in-the-Loop control scheme, as developed in this thesis. The above part represents the digital twin loop, the lower one the real vehicle loop.

Fig. 2 - The Twin-in-the-Loop estimator scheme. The above part represents the real vehicle and its measured variables, the lower one the digital twin acting as a system replica.
MULTIPHYSICS MODELING OF AUDIO SYSTEMS IN THE WAVE DIGITAL DOMAIN

Riccardo Giampiccolo - Supervisor: Prof. Augusto Sarti
Co-Supervisor: Prof. Alberto Bernardini

Audio systems, such as audio sensors and actuators, are pervasive devices that have taken over many different markets, ranging from the classical consumer electronics market up to that of biomedical devices. Many are the components and the transduction principles on which audio systems rely, as well as many are the physical domains - such as electrical, acoustic, mechanical, magnetic, etc. - involved in the digital/analog processing chains characterizing such complex systems. The physical domains do not only interact in a nonlinear fashion but are in turn affected by many different types of nonlinearities which are highly responsible for the peculiar characteristics of the audio gear. In order to outline, digitally replicate, and process the signals of such systems, multiphysics models account to account for such nonlinear behavior must be derived. In the literature, the physical modeling of audio systems has been addressed following both distributed and lumped approaches. In this thesis, we decide to employ Lumped-Element Models (LEM), although being generally characterized by less descriptive power than distributed models, since they show many different properties which can be highly valuable for our purpose. Our ultimate goal, in fact, is to derive real-time digital signal processing algorithms for enhancing the acoustic performance of audio systems leveraging the underlying physics. In particular, we are interested in the modeling of multiphysics systems that have as input or output signals an electrical quantity. It has been demonstrated that, in such cases, LEMs are a well-suited modeling methodology given that, for example, they can be easily interfaced with such kinds of systems and they can be digitally implemented in an efficient fashion. Moreover, it is possible to exploit the analogies between electrical and other physical domains in order to derive equivalent circuit representations of audio systems that allow us to analyze all the physical domains in a unified fashion. Among the methods for the implementation of LEMs, we take into account Wave Digital Filters (WDFs) since, over the past few years, they have demonstrated good properties for the digital realization of nonlinear audio circuits or, more in general, of physical systems described by means of electrical equivalents. Introduced by A. Fettweis in the late 70s, WDFs are a particular class of digital filters based on physical modeling principles. Circuit elements and topological interconnections are realized as input-output blocks characterized by scattering relations. Port voltages and currents are substituted by a linear combination of incident and reflected waves; in addition, a free parameter is introduced into the port description leading to several numerical advantages. Amongst others, the possibility of solving circuits with up to one nonlinear element (characterized by explicit mapping) in a fully explicit fashion can come in handy for the processing and emulation of multiphysics circuits. In general, WDFs preserve the stability properties of the reference circuit; moreover, they are modular, accurate, and efficient, proving to be suitable to be employed in digital audio signal processing algorithms for consumer electronics applications. In this thesis, we thus propose new Wave Digital (WD) modeling techniques able to efficiently describe the different physical domains of audio systems in a modular fashion. For example, we provide new models of audio transformers, piezoelectric loudspeakers, and guitar pickups. As far as audio transformers are concerned, we take into account the modeling of magnetic saturation by means of Canonical Piecewise-Linear functions, and the modeling of rate-dependent hysteresis by encompassing a particular Recurrent Neural Network trained on measurement data into a WD block. We then generalize the Scattering Iterative Method (SIM), i.e., a fixed-point iterative method able to solve WD structures characterized by an arbitrary number of nonlinear elements and one single topological junction, deriving a hierarchical version - which we called Hierarchical SIM (HSIM) - able to accommodate both multiple nonlinearities and junctions; in fact, this is typically the case in multiphysics systems. We then exploit the high number of embarrassingly parallelizable operations of HSIM for deriving parallel implementations able to speed up the circuit emulation and cope with the latest developments of Digital Signal Processors (DSPs) as far as multi-core Central Processing Units (CPUs) are concerned. We then show how it is possible to apply Newton-Raphson routines to nonlinear WD structures organized in the form of a connection tree for enhancing the convergence speed. Once both models and methods for multiphysics emulation of audio systems are introduced, we show how it is possible to use them for deriving virtualization algorithms. In fact, we introduce a new class of digital signal processing algorithms able to impose the behavior of target sensors/actuators using novel processing chains based on circuit inversion. Such algorithms can be exploited for the compensation/linearization of audio transducers, but especially for modifying their behavior making them sound like other transducers. We analyze from a theoretical standpoint such algorithms, providing ready-to-use schemes and block diagrams for deriving the circuitual inverse of physical models, as well as for applying the virtualization chains to all the possible input/output configurations. Finally, in applications in which virtualization algorithms might not be able to impose a target behavior due to very strict physical constraints of the audio transducers, we propose to exploit psychoacoustic effects. We address the case of low-frequency enhancement in small-size transducers, and we propose to use Virtual Bass Enhancement (VBE) systems, which exploit psychoacoustics to trick the human perception of sound. We first propose a circuit equivalent realization of a generic time-domain VBE system, enabling the design of new VBE algorithms in analog, digital, and hybrid analog/digital audio applications. Then, we introduce a novel VBE system that relies on deep learning techniques for music demixing. The method solves known problems of common techniques and overcomes the state-of-the-art method as far as bass enhancement is concerned. In conclusion, the models and methodologies introduced in this thesis pave the way toward increasingly efficient and accurate real-time digital signal processing algorithms for enhancing the acoustic performance of audio systems.
Reconfigurable intelligent surfaces (RIS) have been introduced to enhance the propagation environment by manipulating incoming electromagnetic waves. Comprised of a multitude of passive elements, RIS can modify the electromagnetic characteristics of the propagation environment based on their configuration. Some of the enhancements that RIS offers include increasing the signal-to-noise ratio at the receiver, expanding cell coverage, and improving communication security.

The configuration of phase shifts in RIS determines how incoming waves are scattered or reflected. Thus, designing these phase shifts effectively is essential to achieve the desired objectives and enhance the communication system. To effectively design these phase shifts, the knowledge of the channel characteristics is necessary. However, channel estimation becomes a challenging task in the presence of passive RIS. Passive RIS lacks active elements and, consequently, the processing capability to transmit/receive pilot symbols. Therefore, channel estimation must occur at the endpoints of the communication system, such as at the base station (BS) while users transmit pilot symbols. When a passive RIS is integrated into the communication system, the channel comprises both the cascaded BS-RIS-UE channel and the direct channel between the BS and the user. In passive RIS deployment scenarios, the cascaded channel experiences double path loss, including the loss between the user and the RIS, and between the RIS and the BS. To counteract such significant end-to-end path loss, the RIS can be equipped with a substantial number of elements to increase antenna gain when reflecting incoming waves. However, larger RIS aperture sizes result in larger, more complex, and demanding channel matrices, necessitating extensive pilot lengths for accurate estimation. Nonetheless, relying on long training periods is often impractical. Hence, there is a pressing need for efficient channel estimation methods. This thesis proposes multiple solutions to efficiently estimate the channel while utilizing fewer pilot symbols compared to conventional methods like Least Squares. Initially, it is demonstrated that there exists correlation among the RIS elements due to its planar structure and inter-element spacing. Due to the existing correlation, the RIS-related channel resides within a subspace with a dimensionality lower than the number of elements. Leveraging this insight, an iterative method is developed to generate bases for the channel space, optimizing the channel estimation phase. These bases are then utilized as RIS configurations during pilot transmission, allowing exploration of the subspace where the RIS-related channel is situated. A non-parametric estimation method called reduced-space least squares (RS-LS) is introduced, which outperforms least squares in terms of training overhead. By leveraging the geometric properties of the channel, particularly in millimeter-wave and THz bands, the pilot length can be further minimized. These bands exhibit channels with few multipaths, resulting in low rank and sparsity characteristics. Consequently, constructing the channel requires only a limited number of parameters. Rather than estimating the entire channel matrix, only a handful of parameters need to be estimated. Building upon this concept, a novel Maximum Likelihood Estimator (MLE) is introduced to estimate the channel using a reduced number of pilot symbols, capitalizing on the channel's sparsity characteristics. Moreover, the proposed MLE supports the estimation of both near-field and far-field channels by using the general array response expression, instead of relying on a far-field approximation. In addition, the proposed MLE scheme incorporates dynamic RIS configuration selection during the training phase, further reducing the pilot overhead. In this approach, the RIS phase shifts aren't randomly selected from the codebook; instead, they are chosen based on the channel state information obtained from previous pilot transmissions. The implementation of dynamic RIS phase shift selection begins from the third pilot transmission since the BS requires initial knowledge of the channel to select the RIS configuration for subsequent pilot transmissions. During the initial two pilot transmissions, when the BS lacks prior knowledge of the channel, the RIS phase shifts are randomly selected from the codebook. Given the substantial RIS aperture size, each phase shift configuration within the codebook corresponds to a sharply defined and narrow beam shape. Consequently, a random RIS configuration may not yield a sufficient SNR level to achieve an approximate and rough estimation of the channel. Hence, to improve the efficiency of the proposed MLE, two widebeam configurations for the RIS are introduced for use during the initial two pilot symbols. This ensures that the first two pilots deliver valuable insights into the user's location. The channel experienced by a mobile user changes over time, requiring periodic channel re-estimation and adjustment of RIS phase shifts accordingly. However, large-scale channel parameters, such as angles and distance, change gradually over time, suggesting that they can be tracked instead of being completely re-estimated. Thus, we propose a tracking scheme based on the MLE method, which effectively monitors a mobile user's movement and adapts the RIS configuration based on the user's changing position.
MODEL-DRIVEN DEVELOPMENT OF FORMALLY VERIFIED HUMAN-ROBOT INTERACTIONS

Livia Lestingi – Supervisor: Prof. Matteo Giovanni Rossi

Context and Motivations
Breakthrough technological advancements are shaping the future of the service sector. Highly sophisticated robotic systems under development today are bound to transform the job market once they become commercially available. Using robots in care can increase service quality; however, robots are not a substitute for humans but a tool to improve their actions.

This work attempts to answer the question of the feasibility of such a step by addressing the analysis from the software engineering standpoint. In particular, it sheds light on the development of collaborative service robot applications in healthcare. Nowadays, a robot may be adequately equipped to sense multiple aspects of its surroundings, efficiently detect obstacles, grasp and manipulate fragile objects, perform surgery, and make decisions in delicate situations. However, these skills usually constitute silos of software whose integration and reuse are challenging tasks. More generally, software engineering techniques for robotics are not mature yet to handle the complexity and changeability of service settings.

Service robots operate in unconstrained environments where humans, who they frequently interact with, constitute a significant source of uncertainty. Decisions made at an early design stage of the application determine up to 90% of the overall life-cycle costs, and numerous sources of uncertainty can hinder their validity. Therefore, it is of paramount importance to provide designers with frameworks to develop applications that are simultaneously reliable and flexible concerning the variability of the environment. Frameworks should also limit the gap between the developer’s knowledge and the prerequisites needed to access them, removing the barriers due to the developers’ lack of specialized skills.

Proposed Solution
Designing robotic applications to be deployed in delicate environments where robots will closely interact with humans is challenging, requiring a solid technical background in robotics and software design. This Ph.D. thesis proposes a model-driven framework to develop interactive service robot applications.

Target users are professional figures managing the logistics of service facilities where robotic applications will be deployed, such as clinical workflow analysts. The framework targets robotic applications set in known layouts, featuring a wheeled mobile robot and one (or multiple) humans requesting a service that requires interaction or coordination with the robot. While the geometry of the layout is known, humans are a source of uncertainty as they may make unpredictable choices and stray from the plan while interacting with the robot. Applications eligible for analysis come, though not exclusively, from the healthcare and assisted living settings, where people might be in pain or discomfort. Therefore, the development process encompasses features of human physiological (i.e., physical fatigue) and behavioral aspects, such as the unpredictability of the human decision-making process.

The framework exploits formal analysis to provide the robotic application designer with reliable insights into the outcome of robotic missions (each analyzed individually) constituting a scenario. Given the initial configuration of a scenario (e.g., positions of the agents, battery charge), the application designer receives an estimation of how likely the associated missions are to end in success (dually, in failure) and the physical effort each mission imposes on human subjects.

The framework’s workflow (shown in Figure 1) is structured into three macro-phases:

1) design-time analysis: the robotic application designer configures the scenario through a domain-specific language. Starting from the configuration, a formal scenario model is automatically generated together with a set of properties. Such properties are subject to verification to estimate quality measures of the scenario (e.g., the probability of success).

2) deployment: when the design-time results are deemed acceptable, the application designer deploys the scenario either in a physical environment or simulated environment; to enable the deployment, the formal model is converted into executable code communicating with the deployment environment through a middleware layer;

3) model adjustment: field data collected through deployment are fed to a learning technique to infer a refined model of human behavior and iterate the formal analysis. The application designer examines the refined quality metrics of the scenario and applies reconfiguration measures, if necessary.

Specifically, the thesis introduces a custom Domain-Specific Language (DSL) to specify the scenario under analysis in an accessible, user-friendly manner. The DSL is a lightweight textual notation expressing the features of the formal model that may vary between different scenarios. A formal modeling approach exploiting Stochastic Hybrid Automata is then applied to the entities involved in the scenario (i.e., the layout, the robots, and the humans), which incorporates a stochastic characterization of human physiological and behavioral aspects.

The workflow then envisages a deployment framework to run the scenario in a physical, simulated, or hybrid (partially physical and partially simulated) environment. A model-to-code mapping function converts the formally modeled entities into executable software components to ensure that the deployed system behaves correspondingly to the verified model.

Finally, the thesis introduces a novel active automata learning algorithm, called L*SHA, targeting Stochastic Hybrid Automata. The algorithm exploits signal processing and statistical techniques to infer a formal model from field data. The algorithm is domain-agnostic and has been tested against different case studies capturing different Cyber-Physical Systems, mainly to learn a refined model of human behavior as part of the development framework. Extensive experimental validation assessing the coverage, accuracy, and effectiveness of all the framework phases on illustrative realistic scenarios inspired to the healthcare setting.
Battery-less devices represent an excellent opportunity to enable a sustainable Internet of Things: ambient energy harvesting replaces batteries, leading to systems powered only with ambient energy that require zero maintenance and have a low environmental impact. Despite potentially supplying unlimited free energy, ambient energy is irregular, unpredictable, and usually insufficient to power battery-less devices continuously. Therefore, battery-less devices experience frequent and unpredictable energy failures that cause devices to shut down immediately. This leads to intermittent computation where devices compute only when sufficient energy is available, as shown in Fig. 1.

Challenges. The presence of energy failures introduces several connected challenges that prevent battery-less devices from being used as reliable sensors for the Internet of Things. Unlike mainstream platforms, battery-less devices consist of highly resource-constrained microcontroller units that run single non-concurrent programs and lack an operating system to manage the occurrence of energy failures. Therefore, when battery-less devices shut down due to energy failures, they lose their computational state and have to restart the computation all over again when energy is back. To ensure battery-less devices progress in their programs, they periodically need to save their program state onto a non-volatile memory location, which is persistent across energy failures, to restore it when energy is back. Although this ensures program forward progress across energy failures, the computation after energy failures may leave battery-less devices in a state unattainable in a continuous execution, causing unexpected behaviors that lead to results different from those of an equivalent continuous execution. Ensuring program forward progress across energy failures and avoiding unexpected behaviors introduce energy and computation overhead detrimental to battery-less devices’ performance, as ambient energy sources supply an unpredictable, limited, and scarce amount of energy. Therefore, efficient energy management becomes essential to extract the most possible work from harvested energy. Finally, although researchers actively tackle the various challenges posed by the instabilities of harvested energy, very few efforts are made in long-lasting real-world deployments of battery-less devices. Deployments of battery-less devices targeting real application scenarios are necessary to understand and demonstrate the potential of this technology, providing valuable experiences from which researchers can identify new possible pitfalls and further improve this technology. The PhD research tackles these challenges and provides several contributions to the state of the art.

Real use cases. We first work on the first multi-year deployment of battery-less devices that monitor the structural conditions of an archeological site. We devise three system design iterations, where we initially deploy battery-powered systems. Due to the high maintenance efforts of frequent battery replacements, we eventually switched to battery-less systems powered with kinetic and thermal energy. Our final design achieves zero-maintenance battery-less operations without compromising end-user requirements, as its sensed data provides comparable insights to battery-powered systems.

Intermittent programs consistency. We then target intermittence anomalies, consisting of unexpected behaviors caused by energy failures. We classify intermittence anomalies and identify new types of anomalies previously overlooked by existing literature, which may happen whenever devices interact with the environment. We devise a set of techniques to analyze their occurrence and design ScEpTiC, an open-source tool to test intermittent programs. Building on our work on intermittence anomalies, we devise intermittence awareness, a program design pattern that intentionally allows the occurrence of specific intermittence anomalies to gain new information regarding intermittent executions of programs. We show the potential of intermittence awareness by designing an intermittence-aware technique that reduces the energy overhead required to preserve the computation achieved inside loops. On average, our technique demonstrates a 35.2x lower energy consumption and a 48.4x faster workload completion time.

Energy efficiency. Next, we focus on improving the energy efficiency of mixed-volatile platforms, which feature a directly-addressable non-volatile memory location where developers can manually allocate portions of the program state. We design ALFRED, a virtual memory abstraction and compilation pipeline for mixed-volatile platforms that automatically identifies the most efficient mapping of the program state across volatile and non-volatile memory. Our experiments show that ALFRED reduces programs’ energy consumption by up to 170% and workload completion time by up to one order of magnitude.
ANALOG CIRCUIT DESIGN FOR IN-MEMORY LINEAR ALGEBRA ACCELERATORS

Piergiulio Mannocci – Supervisor: Prof. Daniele Ielmini

Ever since its introduction in 1945, computing systems have been built around von Neumann’s architecture, predicated on the physical separation of memory and computing units on grounds of flexibility and generality. At the same time, Moore’s law has dominated the scaling paradigm by predicting a yearly doubling in the number of transistors, consequently driving both academic and industrial efforts in the continuous miniaturization process. However, as data generation rates exceed the quintillion bytes per year and physical limits of complementary-metal-oxide-semiconductor (CMOS) technology mark the end of classical scaling, the increasingly data-driven workloads of modern-day applications exacerbate the energy and latency overheads associated with continuous data shuffling. In-memory computing (IMC) radically subverts the classical paradigm by performing computation in-situ within the memory elements by exploiting physical laws, unlocking theoretically unrivaled throughput and energy efficiency improvements. Among the wide spectrum of proposed IMC architectures, closed-loop in-memory computing (CL-IMC) with emerging memory devices has attracted interest for its capability to accelerate computationally heavy operations of increasing use in artificial intelligence and machine learning, such as matrix inversion and linear regression. In the wide spectrum of applications of IMC, this thesis work focused on the implementation of algebraic accelerators by exploiting both open-loop and closed-loop, feedback-based circuits built around crosspoint arrays of resistive memories. The work proceeded in a synergic fashion on three main standpoints, namely (i) the definition of a compact analytic model for matrix-based circuits, (ii) the expansion of the closed-loop IMC operational portfolio, and (iii) an experimental activity aiming at providing real-world demonstrations of proposed topologies and concepts.

As a fundamental cornerstone, a compact matrix-based representation of electrical characteristics of crosspoint arrays was established and extended to include typical nonidealities of densely-packed memory cells, such as the parasitic interconnection resistance. The compact model of the crosspoint array proved instrumental in the study of matrix-based feedback circuits, allowing the derivation of fundamental laws for the characterization of both static and dynamic behavior under a generalized circuit model. Particularly, for the static behavior, the impact of common nonidealities, including memory and input quantization, and the finite gain of operational amplifiers, were thoroughly studied, deriving practical upper and lower bounds on circuit accuracy. From the dynamic standpoint, closed-form relations describing the transient evolution and frequency characteristics of matrix-feedback circuits were provided as analytical solutions of the system of differential equations associated with a universal circuit prior and further extended to include nonlinear effects such as the saturation of operational amplifiers. A custom simulation framework based on the proposed analytical model was derived as an electronic design automation tool for fast assessment of both open-loop and closed-loop topologies, providing orders of magnitude improvements in terms of simulation turnaround with respect to conventional SPICE solvers.

From the operational portfolio standpoint, the work was aimed at both strengthening existing priors, including inverse-matrix-vector multiplication, linear regression, and leading eigenvector computation, and designing new circuits to explore a wider range of applications, exploiting both negative and positive feedback operation. Exhaustive modeling of the linear regression circuit allowed the optimization of speed and accuracy, while at the same time providing a stabilizing structure to overcome stability issues in more complex circuits. Moreover, by expanding the local feedback network to a matrix, the operational portfolio was extended to generalized regression or preconditioned linear system solution. The addition of a second local feedback network allowed the implementation of regularized regression priors, namely ridge and LASSO regression. The former was shown to be a central operation in baseband processing in next-generation communication systems under the massive MIMO framework, where IMC could provide substantial improvements in terms of energy and area efficiency while providing the same throughput of digital computing systems. Conversely, the LASSO regression circuit exposed the all-new possibility for CL-IMC circuits to dynamically change their operating characteristics by including nonlinear devices in the feedback network. A more complex structure, relying on both generalized and ridge regression, was shown to be capable of accelerating linear quadratic estimation problems in Kalman filters, a class of algebraic tools used in sensor fusion and estimation scenarios. From the positive feedback-based standpoint, an extension to the leading eigenvector circuit was devised by exploiting the stabilizing capability of the linear regression circuit. The proposed topology can act as both an eigendecomposition and singular value decomposition prior thanks to an iterative reprogramming procedure, and was shown to be capable of accelerating principal component analysis, a fundamental machine learning technique for classification and clustering applications.

Lastly, the experimental activity focused on two separate assessment of CL-IMC topologies exploiting CMOS-based memory devices, and on the characterization and analysis of hybrid-feedback systems exploiting emerging memory devices. From the CMOS-based demonstrators’ standpoint, a first 8 × 8 discrete circuit was designed as a test vehicle for simple tasks such as matrix-vector multiplication and inverse-matrix-vector multiplication. Experimental demonstrations revealed a complex trade-off between the equivalent amplification factor of a matrix circuit, optimal mapping procedure, and matrix condition number. A 84 × 64 integrated circuit allowed verification of more complex topologies by implementing linear and ridge regression topologies using a block-circuit approach. Experimental demonstrations of zero-forcing and regularized zero-forcing decoding under the massive MIMO framework were extensively conducted, closely matching the results of equivalent digital solvers working at the same memory and input precision. From the emerging memory-based demonstrators’ standpoint, a hybrid-feedback system for the acceleration of principal component analysis was devised and tested on ITIR RRAM arrays, demonstrating GPU-equivalent classification accuracy on the iris dataset. A dynamic-IMC-based reservoir computing system, exploiting MoS2 transistors for the reservoir layer and closed-loop computing for the training of the classification layer, was designed and experimentally verified by successfully demonstrating the classification of monochromatic images with 95.5% accuracy.

Owing to the overarching nature of IMC, encompassing device, computing core, up to the EDA toolchain, a strongly multidisciplinary approach is needed to co-optimize all components and fully unleash the IMC potential. To this aim, the obtained results strengthen the position of CL-IMC as a promising candidate for next-generation energy-efficient algebraic accelerators.
BIG DATA INTEGRATION: SUPPORTING VARIOUSLY-STRUCTURED DATA BY MEANS OF METADATA AND DATA LAKES

Davide Piantella – Supervisor: Prof. Letizia Tanca

Nowadays, we can access an amazing amount of easily available data to extract relevant knowledge useful for making the right decision. With all this data available, even regarding very specific contexts and domains, a decision might in principle range from which book we should read next week to which medication we have to prescribe for a patient. Note that many barriers hinder making sense of this vast amount of data, also because we often have many different data sources, with different quality levels. In addition, if we need to use data from more than one data source, evaluating their reliability and trustworthiness becomes very important, and is even more critical in the context of data integration, which consists of aligning various data sources to provide uniform access to their data even if they have different database schemata, different data formats, semantic and representation ambiguities, and data inconsistencies. In fact, when we have a lot of data and several data sources, sooner or later we will face conflicting information, that can be due to many different reasons, e.g., outdated values, noisy data, ambiguities in the representation of the same information or, more trivially, errors. While data integration has been thoroughly studied for almost 40 years, the same techniques cannot be directly applied to big data contexts due to the extreme size and format heterogeneity of datasets. One possible solution to enhance the data integration capabilities when dealing with unstructured data is to leverage metadata, i.e., information describing the different characteristics of the data itself. How to properly extract metadata from unstructured data and how to rely on them to enhance the integration process are open research questions that we face in this work. Another possible method to support the integration of unstructured data, such as natural language texts, is to extract the semantics expressed in them. In fact, when dealing with such data, the goal of data integration should be to understand if different sources claim information with the same semantics, even though they might use different words or languages. This can be achieved by using NLP techniques and deep-learning frameworks. The paradigm of data lakes is an emerging trend used to store the vast amount of data that we have available. One of their main features is their capability to ingest raw data without any preprocessing, allowing us to store and combine relational data, texts, images, logs, streaming data, and others, when needed. Even in this context, metadata are of paramount importance since they provide the data lake with valuable information about the datasets we feed, even before having to directly process the raw data, which is a very complex and expensive operation given the significant heterogeneity of formats and the high dimension of input data. We now introduce the contributions of our research.

Data fusion methods exploiting source metadata

The data fusion task, which is part of the data integration process, aims to discover the true value of a data item, thus resolving value conflicts among different data sources. We present STORM, a novel unsupervised algorithm for data fusion that leverages source authority as metadata to evaluate the trustworthiness of each given data source and, based on that, to find the true value(s) for a specific data item. We provide a new definition of source authority, considering authoritative sources as the ones that many other sources have copied; this is based on the reasonable assumption that when source administrators decide to copy from other sources, they will choose to copy from those that they perceive as the most trustworthy ones. Another key feature of STORM is its value reconciliation phase: before applying our truth discovery strategy, we leverage a novel token-based string-similarity metric to cluster together variant values represented by different strings referring to the same concept. We designed STORM to work in the most complex scenario of data fusion, called multi-truth, in which there can be more than one true value for a data item. An extensive experimental campaign on real-world and synthetic datasets shows that STORM outperforms the eight best-performing state-of-the-art competitors. The paper describing the STORM algorithm has been published in the VLDB Journal and presented at the 48th VLDB International Conference.

Clinical data lakes: a case study

We chose the healthcare domain as a case study, given its increasing availability of data and the urgent need to ingest, analyze, and integrate datasets with heterogeneous formats (e.g., discharge letters in textual form, medical images, vital signs monitoring, and laboratory results) provided by many data sources, often unstructured. Specifically, we identify a minimum clinical metadataset containing the minimum set of metadata that sources must attach to each dataset before it can be ingested in the data lake. For each dataset, metadata include useful information regarding patients, data source, format of the data, and the actual content itself. Further metadata, in addition to the minimum metadataset, can help the analysis of specific types of data, such as discharge letters written in natural language. Extracting domain-specific metadata from texts is challenging, especially if we consider languages different from English, since most of the state-of-the-art techniques are tailored for the English language. To solve this challenge, we propose a pipeline to extract medical concepts expressed in Italian natural language texts describing accidents during working activities. These metadata can help to resolve conflicts among different sources describing the same injuries and extract relevant knowledge from past accidents to highlight dangerous behaviors. An additional approach for extracting the semantics expressed in texts is the usage of word embeddings. We propose a new clinical word embeddings designed for the Italian language, specialized for the biomedical field. Experimental results on three datasets show that our approach using word embeddings achieves good results with respect to competitors, despite the considerably lower availability of training data. The papers describing our pipeline to extract medical concepts and our word embeddings model have been presented at SEBD, the major annual Italian research conference of the database community.

Despite being a crucial aspect, the performance analysis of a data lake in the healthcare domain is very difficult to assess, because of the lack of data-generating systems capable of synthesizing data of such a peculiar domain. To overcome this difficulty, we propose a new, fully customizable healthcare synthetic data generator, that supports the performance evaluation of a data lake system in the healthcare domain by producing synthetic data with the desired performance profile. The paper describing our generator has been presented at EPEW 2023.

Sentence embeddings for data fusion

More and more often, we find data sources that contain values in textual form, which, because of their length, are very difficult or impossible to integrate with the usual data integration process. To solve this problem, we propose FuSE: a new pipeline designed to integrate data sources containing dirty values and long natural language texts. Leveraging sentence embeddings, FuSE clusters the different values provided for the same data item that share the same semantics. With this preprocessing, any data-fusion algorithm can process natural-language texts of arbitrary length without modifying its methodology and without losing the semantics expressed in the values. An extensive experimental evaluation shows that FuSE consistently enhances the effectiveness of several data-fusion algorithms.
CdTe AND CdZnTe DETECTORS AND CMOS READOUT ELECTRONICS FOR HIGH ENERGY RESOLUTION X-RAY IMAGERS WITH HIGH PHOTON FLUX CAPABILITIES

Jacopo Quercia - Supervisor: Prof. Giuseppe Bertuccio
Co- Supervisor: Dr. Filippo Mele

Great research efforts have been and are currently made in the development of X-ray image sensors with photon counting and energy resolving capabilities due to their impact in a wide range of fields both in scientific research and industrial applications. Among them, an emerging X-ray imaging application is non-destructive real-time testing in factory production lines in the food, pharma and recycling industry, representing a core driver behind this research work. Taking advantage of the penetrating nature of hard X-ray in the 1-100 keV range, low density foreign bodies like plastic, bones and other organic materials can be detected efficiently inside packaged products moving quickly on a conveyor belt. This is reached by coupling an X-ray sensor with energy-resolving capabilities to artificial intelligence algorithms, that can analyze an image in real-time. Furthermore, the energy-resolving capabilities of the sensor enable the acquisition of hyper-spectral images, allowing real-time material analysis of the samples. For this application, Cadmium Telluride (CdTe) detectors, or more complex alloys of CdTe like Cadmium Zinc Telluride (CdZnTe or CZT), represent a suitable choice given the specific set of requirements needed in terms of stopping power, energy resolution and handling of high rates of incoming radiation. Semiconductor detectors based on CdTe are currently an established solution for direct proportional conversion of X-ray in the 1-100 keV range into an electric charge signal that can be read-out by an electronic processing chain. This is achieved thanks to the high atomic number of its constituent elements, guaranteeing high stopping power of incoming photons and their conversion into proportional electric charge through photoelectric absorption, allowing for precise energy resolved measurements. In addition to suitable X-ray absorption properties, CdTe and CdZnTe also show good electrical properties, making them promising candidates for high-energy resolution room temperature operation. However, in order to fully exploit the properties of CdTe and CdZnTe detectors for real-time industrial controls, the development of dedicated readout electronics is needed to produce the best trade-off between energy resolving capabilities and high-rate operations. High photon count rates represent in this context a key factor to enable the acquisition of high contrast images even when samples are exposed to short bursts of X-ray, given the inherent need to check packaged products quickly and in high volume within a factory environment. This trade-off stems mainly from higher electronic noise levels experienced at short processing times, in the deep sub-microsecond range. In recent years, however, our group has demonstrated state-of-the-art energy resolutions at short processing times, with a 617 eV FWHM width of the 59.5 keV line achieved at a peaking time of 50 ns and a pulse occupation time of 150 ns. This was done coupling an ultra-low noise research-grade Charge Sensitive Amplifier (CSA) named SIRIO to a Schottky type CdTe pixel detector, with a 800 μm pitch. Schottky type CdTe detectors can provide excellent energy resolution thanks to the implementation of rectifying contacts that can greatly lower the leakage current. However, this class of detectors have since then been found to be also limited by non-idealities in the detector response, such as the poorer transport properties and the higher fluorescence yield of high atomic number materials. This aspect stimulated the development of a custom simulation toolkit that could reliably predict the detector response simulating both photon energy deposition within the detector volume and signal induction at its electrodes, proposing novel approaches for the simulation of charge cloud broadening under carrier diffusion and electrostatic repulsion effects. Non-stationary gain effects present in pulsed-reset CSA operated in wide dynamic range scenarios were also studied, developing an analytical model that could quantitatively describe the non-stationary gain induced distortion in charge read-out. Part of the work was also devoted to a technology transfer collaboration with a leading company in real-time defects and contaminants detection, primarily tailored to the food industry, for the development of CMOS Application Specific Integrated Circuits (ASIC) that were ultimately embedded at the core of their inspection technology.
Data Ecosystems and Data Science for Scientific Data

Edoardo Ramalli - Supervisor: Prof. Barbara Pernici

The quantity of generated and shared data is larger than ever, and, as a result, many data-driven applications have been developed and used in many aspects of our lives. One of the primary applications is to use data to make predictive models. Since the application of predictive models is pervasive, and the amount of shared data is constantly increasing, the generation of a predictive model is shifting from a model-centric approach to a data-centric approach. One of the main challenges in this context is to collect, organize, and effectively extract value from large quantities of data when, for instance, their source, representation, and quality levels are heterogeneous, guaranteeing quality data and a sustainable data life cycle. Scientific predictive models (in short, predictive models, or models) are developed on scientific data representing real-world chemical-physical phenomena. Some examples regard meteorology, biology systems or chemical kinetics. The latter field, particularly combustion chemistry, is fundamental to the current energy transition agenda since it studies optimizing fuel efficiency and consumption and developing new sustainable and green fuels. To match the ambitious goal of a carbon-free planet, it is necessary to speed up and refine the development process of new scientific predictive models and improve their accuracy with ad-hoc data management, data science, and data-sharing techniques. It is, therefore, necessary to improve the development process of scientific predictive models to meet the goal of a sustainable process, more accurate predictions, and faster delivery of predictive models for the current energy transition. At the same time, the promising results of data science and big data management in countless fields can match these needs. However, applying such computer science disciplines into the scientific domains, even though particularly promising, is challenging and requires a transformation and adaptation of both sides. In summary, on the chemical kinetics side, the current and consolidated process needs to be rethought. Instead, on the computer science side, a plug-and-play solution using the already available data science and data management technologies is not possible. Therefore, this thesis aims to bridge this gap, explaining the challenges and proposing a solution. The challenges include but are not limited to the unique characteristics of the scientific data and domain requirements, such as experimental uncertainty, low data quality, and confidentiality, that make applying traditional methodologies to share and leverage the data challenging. This interdisciplinary research investigates, as a whole, the development process of a scientific predictive model and how it can be improved by adopting data ecosystem (DE) and data science technologies. This thesis focuses on the following requirements: 1) the design of a sustainable DE to support a quality process, 3) the identification of the predictive model development process, classification of scientific data, and their properties, 2) the design of an effective DE to support a quality process, 3) the definition of an effective model evaluation methodology, 4) the use of appropriate data science techniques to guide the improvement and development of scientific predictive models. These requirements and challenges are valid across multiple scientific domains, but the interdisciplinary nature of this thesis requires the design and the implementation of a sharing platform in which the data consumer and producer are distinct entities, whereas, in scientific domains, a user is typically both simultaneously. Moreover, there needs to be more attention on how to make such projects long-term initiatives, thus lacking a sustainability plan from an information system perspective. The proposed solution addresses these challenges with the design and implementation of a DE. The literature has examples of centralized, federated, or distributed DE. All of them have advantages and disadvantages. This work, to conciliate the design principles of DE and to address the previous challenges and domain requirements, proposes a new hybrid DE configuration: central data management with federated computational resources. This hybrid architecture is a trade-off between the centrality of an organizational DE that has control over the data but simultaneously encourages and promotes data sharing and the scalability of the system. The development of a predictive model is a data-driven activity. Thus, the data has a direct and massive influence on the resulting products. Model validation in the context of a predictive model is highly dependent on the quality, quantity, and diversity of the data used for the validation. Therefore, this thesis also proposes a methodology to assess the diversity of a dataset, ensure certain data quality in the scientific environment, and predict the missing information. In particular, during model validation, the simulated data by the predictive model are compared with the experimental data available in the DE repository. However, experimental data are affected by uncertainty, and quite often, this information is missing, even if it is crucial to assess the model performance properly. Given these challenges, this thesis demonstrates the application of knowledge graph embedding to predict the missing uncertainty information. Finally, this thesis proposes a standardized, objective, and systematic model evaluation procedure to understand why, where, and how much the prediction of the model deviates from the experimental data, developing ad-hoc algorithms. The thesis also investigates the ethical impact of the different model development process stages and proposes the corresponding mitigations. Finally, it is presented a novel adaptive sampling algorithm that achieves at the same time good generalization and optimization capabilities, unlike other sampling algorithms, leveraging the generalization capabilities of neural networks and the geometric properties of the Delaunay triangulation. Applications of such algorithms vary from the design of experiments to selecting the most informative set of training data, thus reducing the amount of information and resources needed to develop a predictive model. Regarding improving a chemical kinetic model, it is investigating applying a promising chemical reaction neural network technology to develop a hydrogen model. In the training process, this neural ordinary differential equation combines the black-box approach of NNs with well-known physical-chemical laws. After investigating the capabilities of such technology, this work proposes incorporating element conservation in such architecture.
EXPLOITING HYPERPARAMETER OPTIMIZATION AND CONTROL FREQUENCY IN REINFORCEMENT LEARNING

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Reinforcement learning (RL) aims at learning a policy of actions in sequential decision-making problems by interacting with an environment to maximize some reward signal. Since the agents need to learn via trial and error in a way similar to how humans and animals learn, RL can be considered the closest approach to artificial intelligence. Despite the simplicity of the general framework, RL has achieved many significant successes in various challenging fields in recent years for a wide range of domains, from robotic control to financial trading. However, the learning process when complex models are adopted is not so straightforward: configuring and setting up RL environments and algorithms efficiently can be challenging since many factors can significantly impact their ability to learn. On one hand, the environment set up requires a thorough comprehension of the problem and a careful design of the fundamental components, such as the reward function. Furthermore, most RL algorithms deal with discrete-time environments where interactions happen at a fixed time scale. Therefore, if the true system evolves in continuous time, there is the need to configure the control frequency of the agent, which has a non-negligible effect on the learning capability of the algorithms. On the other hand, RL techniques make extensive use of hyper-parameters to let the user control their behavior. Usu...
GENERATIVE EMPATHETIC DATA-DRIVEN CONVERSATIONAL AGENTS FOR MENTAL HEALTHCARE

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Introduction
Building conversational agents is one of the oldest problems in Artificial Intelligence (AI). This problem pertains to Natural Language Processing (NLP), the area of AI that deals with human language-related applications. In the last decade, in NLP, there has been a rising interest towards empathetic computing to improve the perception of conversational agents as intelligent, opening the pathway towards empathetic conversational agents. These empathetic conversational agents are characterised by cognitive and emotional intelligence. This work focused on developing conversational agents capable of simulating empathy in mental healthcare-related scenarios, where empathy is a desideratum. We proposed solutions based on data-driven (deep learning) techniques to build all the dialogue agent’s text and speech processing modules.

Background
The introduction of deep learning-based techniques significantly impacted the NLP area. In particular, the recent results of large language models showed how sufficiently complex deep neural network models trained on large amounts of text data can solve many complex tasks. These tasks include those related to dialogue analysis and generation ones. Moreover, the same deep learning techniques and neural network architectures used for written language have also been successfully adopted in speech processing, improving speech recognition and expressive speech synthesis results. These modules are necessary to enable spoken interaction and consequently improve the pro-social attitude towards the agent, favouring the empathetic relationship in the dialogue. From a functional perspective, conversational agents have five main components (see Figure 1): Automatic Speech Recognition (ASR) to transcribe the spoken input; Natural Language Understanding (NLU) to process the input text; Dialogue Manager (DM) to keep track of the conversation status and plan responses; Natural Language Generation (NLG) to generate a written response; Text-to-Speech (TTS) to utter the generated response. In the context of empathetic conversational agents, there is a strong focus on high-level aspects (attributes) of the dialogue, like intent or emotional status, which affect different features of the interaction, from physical ones (e.g., prosody) to abstract ones (e.g., semantic). Empathetic agents should perceive these aspects in the user and respond accordingly. Some mental healthcare or counselling applications have been developed recently with attention to the empathetic aspects of user interaction (e.g., WoeBot or Wysa). These applications mainly rely on traditional expert-driven approaches and rule-based techniques. In our work, we focused on deep learning-based approaches to check the applicability of these techniques in the target mental healthcare domain.

Contributions
From a functional perspective, we extended the basic chatbot architecture to include the modules necessary for empathetic computing. We extended the usual chatbot architecture to include the following (see Figure 1): Audio, Text and Multi-Modal Feature Extraction (AFE, TFE, and MMFE) modules to extract all the features characterising the interaction; High-Level Input and Output (HLIn and HLOut) modules, to convert, respectively, features to high-level aspects and vice-versa; Empathetic Controller (EC) module to predict the appropriate high-level aspects of the response; Voice, Text and Global Conditioning (VC, TC, and GC) modules to enforce the EC requirements on the response in the text and speech output. From a technical perspective, we developed end-to-end deep language models implementing empathy-related and text-related functionalities. We explored different learning paradigms and training approaches. Initially, we considered reinforcement learning and latent variational approaches to target the empathetic aspects. Subsequently, we kept the variational structure and moved towards curriculum learning approaches, introducing meta healthcare-specific dialogues, besides the other open domain and empathetic dialogues, in our data set to refine the dialogue agent towards the desired properties iteratively. Following the latest trends and results, we dropped the variational structure. We adopted a plain text solution to have the agent explicitly predict the high-level aspects (as plain text), focusing initially on intent. Finally, we scaled up this plain text approach and trained a multitask model for (conditioned) generation and recognition, capable of assessing intent, emotion, empathy, and other high-level aspects. We developed this last model to be programmable through textual prompts and be used as the actual core of the conversational agent. Concerning the speech input/output, we adopted existing state-of-the-art solutions for ASR and TTS, selecting a TTS that allowed controlling the speaking style (expressivity) of the uttered text. We developed an ad-hoc module to predict the desired speaking style from the text of the generated response. We deployed an application encapsulating the agent on a messaging platform (Telegram). The application allows users to chat with the agent by exchanging text or audio messages and to provide feedback on the conversations to help improve the agent in the long term (see Figure 2 for the logical behaviour of the application).