Alessandro Rosa

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ORCiD

EDUCATION

PhD in Mathematics 2025 - Present
University of Bologna, Bologna, Italy, XLI cycle

Master Degree in Mathematics 2022-2024
University of Bologna, Bologna, Italy, 24/07/2024
- *Thesis*: Rumin's Differential Forms and L^2-Hodge Decomposition in Sub-Riemannian Contact Manifolds
- *Supervisor*: Annalisa Baldi (annalisa.baldi2@unibo.it)
- *Final mark*: 110/110 with laude

Bachelor Degree in Mathematics 2019-2022
University of Bologna, Bologna, Italy, 30/09/2022
- *Thesis*: Il Teorema di Connettività per i Campi Vettoriali di Hörmander, e Applicazioni
- *Supervisor*: Andrea Bonfiglioli (andrea.bonfiglioli6@unibo.it)
- *Final mark*: 110/110 with laude

High School Diploma 2014-2019
IIS "Francesco Alberghetti" Liceo delle Scienze Applicate, Imola (BO), Italy
- *Final mark*: 100/100

EMPLOYMENT

Current employment
- *Researcher*, INFN - Florence section, Development of Flash Simulation techniques for radiation detectors and other physical systems using Generative Models and Physics-Informed Neural Networks (PINNs) - Project SPOKE 2 (PNRR as part of the ICSC Project - Italian Research Center on High Performance Computing, Big Data and Quantum Computing)
Supervisor: Lucio Anderlini (lucio.anderlini@fi.infn.it) 2025-Present

Previous positions
- *Teaching assistant*, Analisi Matematica II (Calculus II), Bachelor degree in Astronomy, University of Bologna (24h) (profs. L. Lanzani, A. Parmeggiani) . AY 24-25
- *Teaching assistant*, Analisi Matematica I (Calculus I), Bachelor degree in Astronomy, University of Bologna (24h) (prof. M. C. Tesi). AY 24-25
- *Teaching assistant*, Analisi Matematica IB (Calculus I), Bachelor degree in Mathematics, University of Bologna (30h) (profs. A. Baldi, A. Bonfiglioli). AY 23-24
- *Teaching assistant*, Analisi Matematica IA (Calculus I), Bachelor degree in Mathematics, University of Bologna (30h) (profs. A. Baldi, A. Bonfiglioli). AY 23-24
- *Teaching assistant*, Analisi Matematica I (Calculus I), Bachelor degree in Astronomy, University of Bologna (24h) (profs. L. Lanzani, A. Parmeggiani). AY 23-24
- *Teaching assistant*, Analisi Matematica (Calculus I and II), Bachelor degree in Computer Science & Information Science for Management, University of Bologna (108h) (profs. D. Morbidelli, M. Mughetti, M. Casali). AY 22-23

SCIENTIFIC INTERESTS

- Riemannian and Sub-Riemannian Geometry
- Differential forms in Carnot groups and contact manifolds (Rumin and de Rham complexes)
- Calculus of Variations, Harmonic Analysis and Functional Analysis
- Classical Numerical Analysis (FEM, spectral and variational techniques)
- Artificial Intelligence, Machine Learning, PINNs applied to simulations of complex physical systems

PUBLICATIONS

- L^p-Hodge Decomposition with Sobolev classes in Sub-Riemannian Contact Manifolds (2025) https://doi.org/10.1016/j.jmaa.2025.129739

EXPERIENCES

- *Participant*, "International Masterclass hands on Particle Physics", Department of Physics, University of Bologna. 25/02/2019
- *Alternanza scuola-lavoro* (high school work-based learning program), Pollution s.r.l., Budrio (BO). Activities: assembly, testing, and quality assessment of the products offered by the company for environmental pollution analysis. Summer 2018-2019
- *Volunteering*, Banco Alimentare Emilia-Romagna, Imola, Italy 2019
- *Participant*, CAD 3D PON project (SOLIDWORKS), Imola (BO), (30h). 04/2018
- *Participant*, Summer school "OLIFIS ER-Marche 2017", Bagnacavallo (RA), Italy. Activities: lessons and workshops in preparation to AIF Teams Physics Olympiad. 4-9/09/2017
- *Participant*, "OII Olimpiadi Italiane di Informatica", Imola (BO). 2016-2017
- *Participant*, "Olimpiadi della Matematica", Imola (BO). 2016-2017
- *Participant*, "OLIFIS Olimpiadi di Fisica", Imola (BO). 2016-2017

CONFERENCES/WORKSHOPS/COURSES ATTENDED

- *Three Days in Sub-Riemannian Geometry*, University of Bologna, Italy (link). 16-18/06/2025
- *Numerical resolution of Differential Equations for applications using Physics-Informed Neural Networks*, PhD Course in Smart Computing (prof. A. Bombini) (24 hours), University of Firenze, Italy. 01/25
- *Elements of Fractional Calculus*, PhD Course in Mathematics (profs. A. Giusti, I. Colombaro) (30 hours), University of Bologna, Italy. 12/24 - 01/25
- *Noncommutativity at the Interface of Topology, Geometry and Analysis (first JHU-UNIBO Conference)*, University of Bologna, Bologna, Italy (link). 24-28/06/2024
- *NonPUB24 - Nonlocal and nonlinear Partial Differential Equations at the University of Bologna*, University of Bologna, Bologna, Italy (link). 6-7/06/2024
- *Symposium in Harmonic & Complex Analysis, Microlocal & Geometrical Analysis and Applications*, University of Bologna, Bologna, Italy (link). 24-26/01/2024
- *Mathematical Relativity*, PhD Course in Mathematics (prof. A. Giusti) (18 hours), University of Bologna, Italy. 12/24 - 01/25
- *Nonlinear Meeting in Bologna*, University of Bologna, Bologna, Italy (link). 6-7/06/2022
- *Seminari di Analisi Matematica Bruno Pini* (periodic seminairs), University of Bologna, Bologna, Italy (link). 2021-Present

SKILLS

Computational

- Programming languages: Python, C++, Matlab
- Machine learning libraries: PyTorch
- CAD programs: SolidWorks, AutoCAD 2D (ECDL Specialized Level, May 2018)
- Others: LaTeX, HTML, Office

Languages

- Italian: Mother tongue
- English: B2

Imola, 01/08/2025

ABSTRACT OF ON GOING RESEARCH AT INFN

I am currently working at INFN as a researcher in a specialized team focused on developing fast simulation techniques for radiation detectors using innovative approaches. Specifically, I am applying and advancing new Machine Learning methodologies within data-driven and data-discovery frameworks, particularly Physics-Informed Neural Networks (PINNs), to solve partial differential equations (PDEs) arising from real-world physical problems.

My work integrates my background in theoretical mathematics - especially in PDEs, functional analysis, differential geometry and numerical analysis - with practical physical modeling. I employ these techniques to simulate innovative Resistive Silicon Detectors (RSDs) and 3D Diamond Detectors with graphitic electrodes, modeled via initial and boundary value problems derived from third-order quasi-static Maxwell equations in constrained geometries.

The aim is to enable high time-resolution particle detection for next-generation hadronic machines, such as the High-Luminosity Large Hadron Collider (HL-LHC) at CERN. From a computational standpoint, I use PyTorch and NVIDIA Modulus - frameworks tailored for PINNs - to train deep learning models efficiently. In terms of sensor design, we are also applying optimization strategies to improve electrode configurations and sensor geometries, with the goal of maximizing data resolution.

ABSTRACT OF MASTER THESIS AND RELATED RESULTS

The aim of this thesis is to prove a Hodge Decomposition Theorem for L^2 differential forms, defined in the setting of the Rumin complex, on sub-Riemannian contact manifolds. The first chapters focus on the construction of the Rumin complex in Carnot groups, which is homotopically equivalent to the de Rham complex, thus it preserves its cohomology, and in particular, on its formulation in the Heisenberg group. In many problems in Analysis and Differential Geometry, the Rumin complex was proved to suite better the anisotropic structure of Carnot groups compared to the usual de Rham complex. Several results concerning Sobolev-Poincaré-type inequalities for differential forms have been obtained using the Rumin complex to derive sharp estimates. Subsequently, we studied the Rumin complex on sub-Riemannian contact manifolds, which are locally contact-diffeomorphic to the Heisenberg group. More precisely, in contact manifolds with bounded geometry, we generalized a Sobolev-Gaffney-type inequality that was recently proved and we established a global hypoellipticity estimate for the Rumin Laplacian. Thanks to these results, using a variational approach similar to the one that Morrey employed for the decomposition on Riemannian manifolds, we proved not only the C^∞ Hodge Decomposition for the Rumin complex on compact contact manifolds without boundary but also the L^2 decomposition, obtaining regularity for weak solutions of the Poisson equation for differential forms.

Then, in the article *L^p-Hodge Decomposition with Sobolev classes in Sub-Riemannian Contact Manifolds*, this result was extended to the L^p case $(1 < p < \infty)$, through the use of Sobolev embeddings, Sobolev–Gaffney-type inequalities, and homotopy formulas related to the potentials of the Rumin's differential forms, in order to obtain L^p regularity for solutions of the Poisson equation associated to the Rumin's Laplacian. This work led to the characterization of the L^p cohomology groups on closed sub-Riemannian contact manifolds by studying Rumin's L^p-harmonic forms. As a further application of the Hodge decomposition theorem, we proved L^p-type Poincaré inequalities, which generalize the corresponding inequalities for functions with respect to the standard sub-Laplacian.

ABSTRACT OF BACHELOR THESIS

The aim of this thesis is to prove the Connectivity Theorem for a Hörmander system of vector fields, which provides a sufficient condition for the connectivity of an open set in $\mathbb{R}^N$ via piecewise integral curves of the vector fields, and to present some of its applications. In the first chapter, we introduced the prerequisites with particular emphasis on a lemma that relates the integral curves of the commutator of m vector fields to the composition of an appropriate number of flow maps of the vector fields forming the commutator itself. The second chapter is entirely dedicated to the proof of the Connectivity Theorem and to the analysis of the definition of subunit curves in an open set with respect to a family of vector fields X, known as X-subunit curves. In the third chapter, we provided an introduction to the Carnot-Carathéodory distance, also known as the X-control distance, and we proved the remarkable Chow-Rashewskii Theorem. Under the assumptions of the Connectivity Theorem, this theorem establishes an estimate between the Euclidean metric and the X-control distance through two inequalities, which further implies the equivalence between the topology induced by the X-control distance and the Euclidean topology. Finally, we investigated propagation sets via integral curves of the vector fields in X and via X-subunit curves. Using the definition of invariance of a set with respect to a vector field and applying the Nagumo-Bony Theorem, we proved that the closure of the set of points reachable from a fixed point P in a given open set, through piecewise integral curves of the vector fields in X and their opposites, is equal to the closure of the set of points reachable from P through a specific subset of piecewise C^1 X-subunit curves.