Maria Gragnaniello

Energy-Efficient Electronic Systems for Edge-AI-Based Healthcare Monitoring

Tutor: Prof. Michele Riccio

Cycle: XXXIX

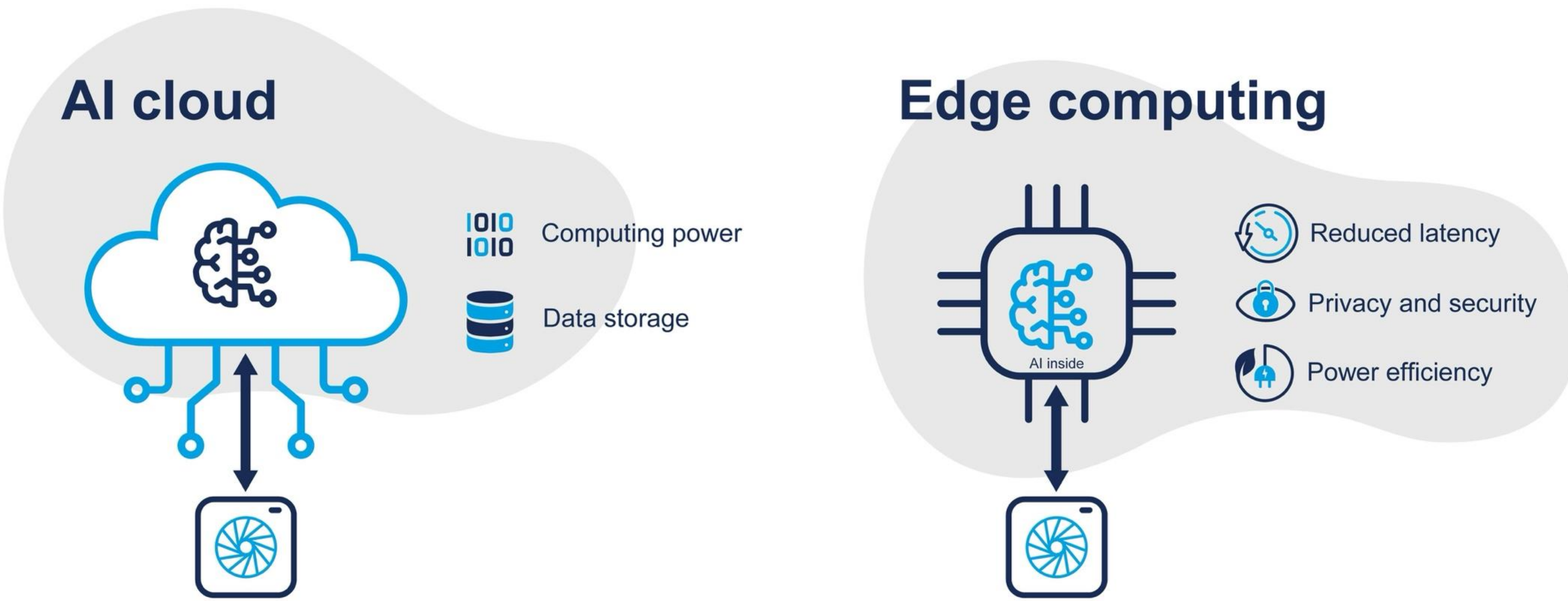
Year: Second

My background

- **BsC** and **MsC** Biomedical Engineering – 23th March 2023
- Tutor: Prof. Michele Riccio
- **OptoPowerLab** – DIETI
- PhD started 02/11/2023 – end date: 31/10/2026
- Scholarship funded by **PNRR** (DM **118/2023**)

Research field of interest

Edge AI redefines the boundary between sensing and intelligence. By embedding deep learning into wearable electronics, data are no longer sent to the cloud but interpreted locally, enabling faster, smarter, and more sustainable healthcare technologies.



The Traditional Cloud AI Paradigm

Most current wearable systems operate on a traditional **Cloud AI** paradigm.

Wearable Device Collects Data

Sensors on the wearable device gather various forms of data.

Transmits to Remote Cloud Servers

The collected data is then sent wirelessly to distant cloud-based data centers.

AI Processing in Data Centers

AI models and algorithms running on high-performance servers in the cloud analyze the raw data to extract insights, detect patterns, and make predictions.

Results Sent Back to Device

The processed information is then transmitted back to the wearable device for the user.

While powerful, **it introduces several critical limitations when applied to wearable devices**, hindering their effectiveness and user experience.

- **Latency Issues**
- **Privacy Concerns**
- **Connectivity Dependence**
- **Energy Drain**
- **Data Security Risks**
- **Carbon Footprint**

Edge Vs Cloud AI and Resource Challenges

Feature	Edge AI	Cloud AI
Latency	1-20 milliseconds (real-time)	100-500+ milliseconds (network-dependent)
Privacy	Data never leaves device;	Requires robust encryption and compliance protocols
Bandwidth	Minimal (metadata only, ~KB/day)	Substantial (raw data streams, ~GB/day)
Footprint	Low power consumption (from few mW to W per device)	High energy usage (data centers consume 1-3% of global electricity)

Modern AI requires unprecedented computational resources, creating bottlenecks for widespread deployment.

Memory Bottlenecks

Large models require 8-32GB RAM, exceeding mbedded device capabilities.

Processing Constraints

Inference operations demand 5-20 TOPS, straining mobile processors.

Thermal Management

AI acceleration generates even more heat in confined spaces without active cooling.

These constraints drive the need for specialized hardware and algorithmic optimization techniques to enable AI capabilities on resource-limited hardware.

A Multidisciplinary Approach

The research activity combines expertise from different disciplines to design intelligent wearable systems for health monitoring.

Biomedical

- **Analyzing physiological and biomechanical signals for continuous health monitoring.**

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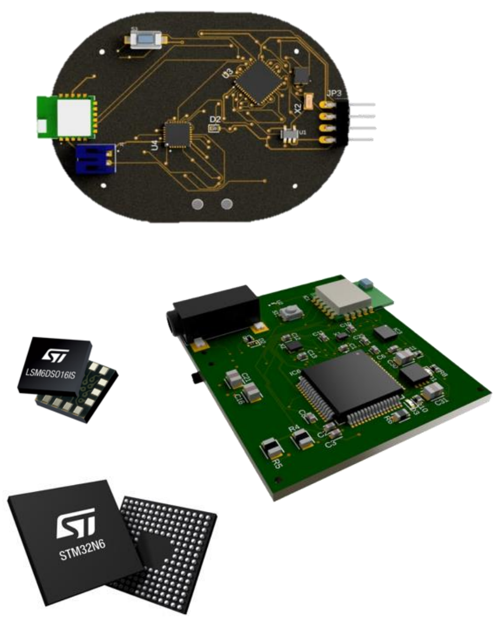
Electronics

- **Analog/Digital Front-End Design**
- **AI Hardware Dedicated**



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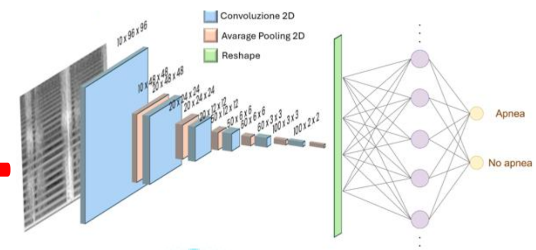
Computer Science

- **Model Development**
- **Model Optimization**
- **Edge Deployment**



MATLAB

ST Edge AI Suite

EDGE IMPULSE
a Qualcomm company

Results (1/3)

➢ **Consolidation of Edge AI Methodologies**

- Co-design of hardware, firmware, and AI algorithms for embedded biomedical systems
- Optimization of CNNs for real-time, low-power inference on MCUs

➢ **Development of an Automatic System for Sleep Apnea Detection**

- Design of a portable, low-invasiveness tracheal signal monitoring device
- Firmware for on-board acquisition and spectrogram-based CNN inference

✓ Achieved local apnea detection without cloud dependency, minimizing latency and power consumption

➢ **Comparison Between Cloud-based and Edge AI Approaches for Cardiac Monitoring**

- Experimental validation of embedded neural network vs. Lorentz statistical analysis

✓ Demonstrated higher accuracy, faster response, and lower energy consumption of Edge AI

➢ **Application of Deep Edge AI to Robotic Control**

- Implementation of embedded neural inference directly on sensor nodes

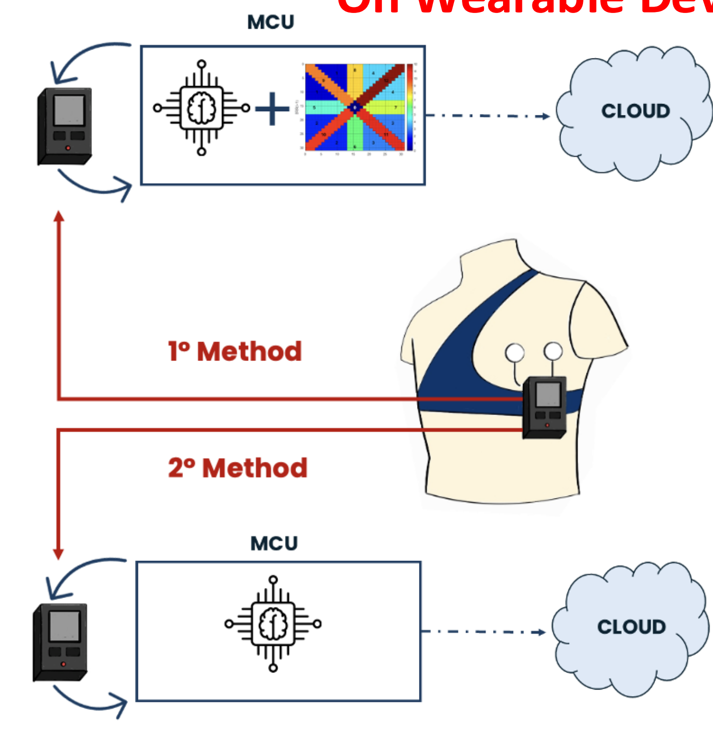
✓ Enabled reactive and natural control of wearable robotic devices (Sixth Robotic Finger)

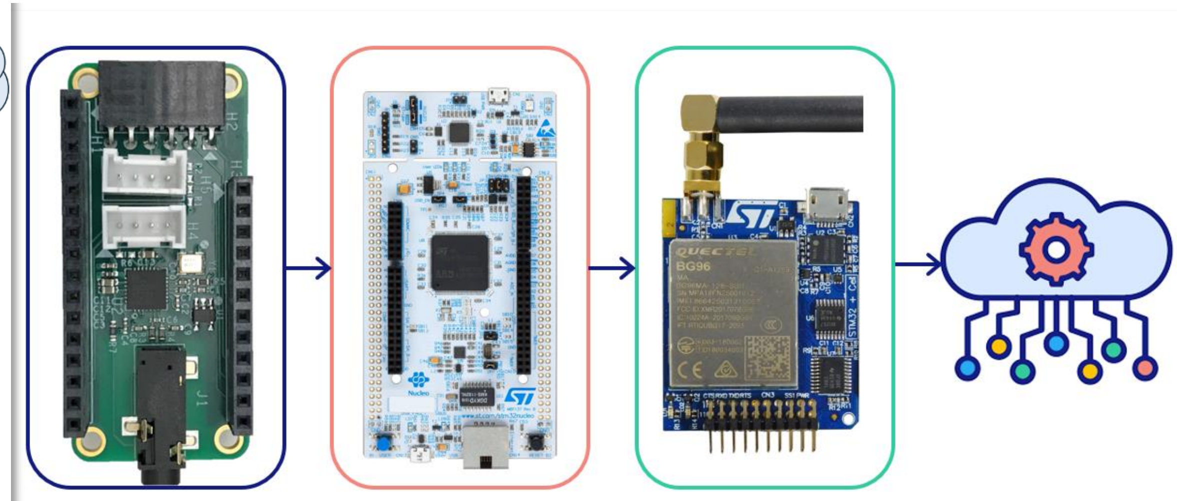
➢ **Optical Sensing for Non-invasive Physiological Monitoring**

- Study and validation of FBG-based pulse waves
- Correlation analysis with PPG signals for heart rate estimation

Results (2/3)

An Edge-AI Approach For Low-power, Real-time Atrial Fibrillation Detection On Wearable Devices Based On Heartbeat Intervals [J3]





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Results

1º Method (AI + Lorenz)

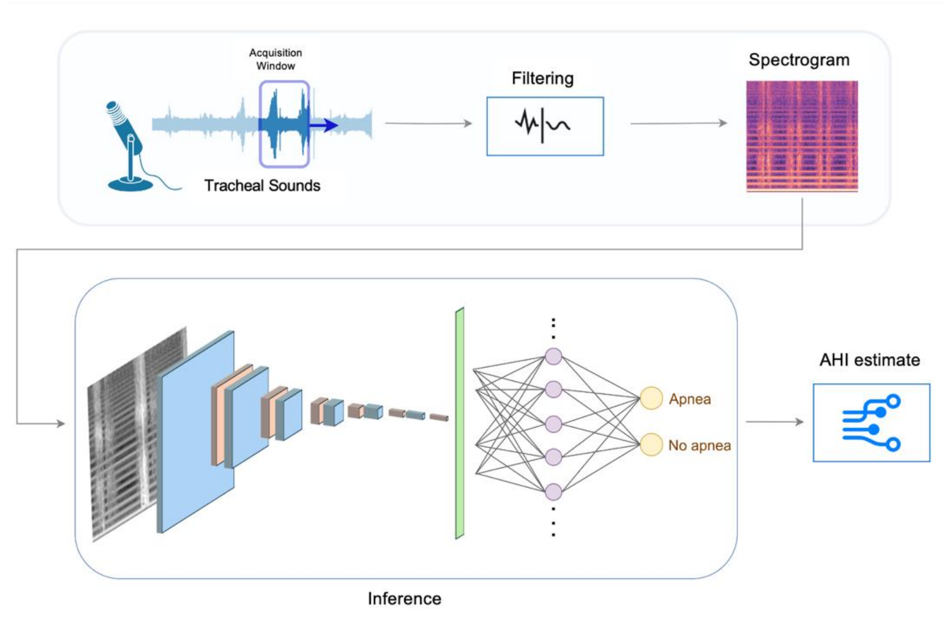
- Accuracy: AI (99.1%) + Lorenz (87.8%)
- Greater diagnostic robustness
- Total absorption: 0.92 mA
- Memory required: 514 kB Flash, 75 kB RAM

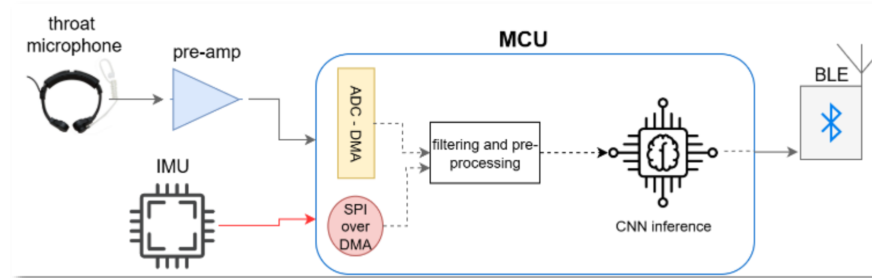
2º Method (AI)

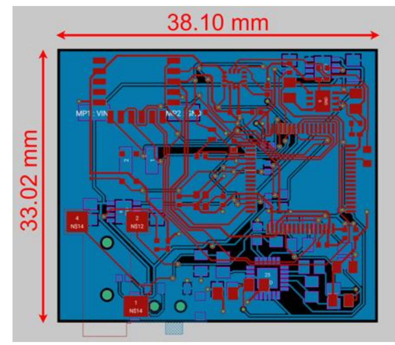
- Accuracy: 91%
- Greater efficiency and lightness
- Total absorption: 0.118 mA
- Memory required: 275 kB Flash, 50 kB RAM

Results (3/3)

A Power Efficient Wearable Solution for Sleep Apnea Diagnosis Based on Tracheal Sounds and on-Device AI [C4]

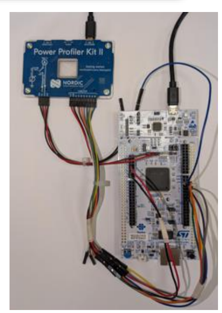






*Pictures are in scale

Float32	Accuracy	**86.95%**
	RAM	1.1 MB
	Flash	616 KB
Int8	Accuracy	**87.06%**
	RAM	285 KB
	Flash	197 KB



Average Current	Time	Function
136.11 mA	260 µs	Aquisition
100.42 mA	6.83 ms	Interpolation
130.11 mA	221.1 ms	Inference

*Test on demo-board

Third PhD Year – Research Plan

➢ **Main Research Objective**

Design and realization of a **multisensor wearable platform for multiparameter health monitoring**, integrating and consolidating all the methodologies and results achieved during the previous years. The objective is to implement a **fully autonomous Edge AI system** capable of executing the entire biosignal processing chain, from acquisition to inference, directly on the device.

➢ **Core Research Activities**

- Integration of **innovative sensing technologies**, including Fiber Bragg Grating (FBG) sensors or IMUs with embedded ISPU.
- Development of **optimized neural architectures** (1D/2D CNNs) combined with domain-specific preprocessing, adapted for embedded execution under strict memory and power constraints.
- Definition of **Figures of Merit** for the optimal design and dimensioning of low-power microcontroller-based systems, linking algorithmic complexity to power-performance trade-offs.
- Investigation of **distributed intelligence**, deploying lightweight models across sensing and processing layers to enable parallel, hierarchical inference.

Research products

Published

[J1]	**Gragnaniello**, M.; Marrazzo, V.R.; Borghese, A.; Maresca, L.; Breglio, G.; Riccio, M. Edge-AI Enabled Wearable Device for Non-Invasive Type 1 Diabetes Detection Using ECG Signals. Bioengineering 2025, 12, 4. https://doi.org/10.3390/bioengineering12010004
[C1]	M. **Gragnaniello**, T. L. Baldi, E. Landi, G. Salvietti, G. Breglio and M. Riccio, "Deep Edge-AI for Prosthetic Control: Feasibility of ISPU-Based Solutions for a Robotic Extra Limb," 2025 IEEE Medical Measurements & Applications (MeMeA), Chania, Greece, 2025, pp. 1-5, doi: 10.1109/MeMeA65319.2025.11068047.
[C2]	M. **Gragnaniello** et al., "A Feasibility Assessment on the Use of FBG Sensors for Pulse Wave Detection," 2025 IEEE Medical Measurements & Applications (MeMeA), Chania, Greece, 2025, pp. 1-5, doi: 10.1109/MeMeA65319.2025.11068062.

Accepted

[C3]	M. Cuomo, M. **Gragnaniello**, E. De Vita, V. Romano Marrazzo, G. Breglio, A. Iadicicco, M. Riccio, and S. Campopiano, "Pulse Wave Analysis Based on Fiber Bragg Gratings," presented at the 2025 INTERNATIONAL WORKSHOP on Biomedical Applications, Technologies and Sensors (BATS), 2025.
[C4]	M. **Gragnaniello**, F. Mariani, A. Borghese, V. Romano Marrazzo, G. Breglio, A. Irace, and M. Riccio, "A Power Efficient Wearable Solution for Sleep Apnea Diagnosis Based on Tracheal Sounds and on-Device AI," presented at the 2025 INTERNATIONAL WORKSHOP on Biomedical Applications, Technologies and Sensors (BATS), 2025.
[C5]	M. **Gragnaniello**, E. Andreozzi, D. Esposito, J. Centracchio, G. Breglio, A. Irace, and M. Riccio, "A Force Sensor-Based Approach for Continuous Blood Pressure Monitoring on Wearable Devices," presented at the 2025 INTERNATIONAL WORKSHOP on Biomedical Applications, Technologies and Sensors (BATS), 2025.

Submitted

[J2]	M. Cuomo, M. **Gragnaniello**, E. De Vita, V. Romano Marrazzo, G. Breglio, A. Iadicicco, M. Riccio, and S. Campopiano, "Pulse Wave Detection Using Fiber Optic Sensors: Comparison with Multiwavelength Photoplethysmography Devices," *IEEE Transactions on Instrumentation & Measurement*, 2025.
[J3]	E. Cinotti, M. **Gragnaniello**, S. Parlato, J. Centracchio, E. Andreozzi, P. Bifulco, M. Riccio, and D. Esposito, “An Edge-AI approach for low-power, real-time atrial fibrillation detection on wearable devices based on heartbeat intervals,” *Sensors, 2025*.

Summary of activities

	Courses	Seminars	Research	Tutorship	Total
Bimonth 1	**0**	**3.4**	**6**	**0**	**9.4**
Bimonth 2	**0**	**0**	**9**	**1.2**	**10.2**
Bimonth 3	**7**	**0.8**	**3**	**0.2**	**11**
Bimonth 4	**6**	**1.6**	**4**	**0**	**11.6**
Bimonth 5	**0**	**0**	**10**	**0**	**10**
Bimonth 6	**0**	**0**	**13**	**0.2**	**13.2**
Total	**13**	**5.8**	**45**	**1.6**	**65.4**
Expected	**30 - 70**	**10 - 30**	**80 - 140**	**0 – 4.8**	

Ad-hoc courses and School

- IoT and Embedded Electronic Systems for Industrial and Mechanical Applications: From Sensing and Monitoring to Remote Control.
- Fiber optic sensing and optoelectronic circuits: design and application.
- Supervised Autonomy: How to Shape Human – Robot Interaction.
- FIT4MEDROB INTERNATIONAL SEASONAL SCHOOL – Robotics and allied technologies for rehabilitation.

Conferences

- IEEE International Symposium on Medical Measurements and Applications (MeMeA 2025) Place & Dates: Chania, Greece, 28th–30th May 2025.
- 56th Annual Meeting of the Italian Electronics Society (SIE 2025)
  Place & Dates: Naples, Italy, 25th–27th June 2025.

Thank you for your attention!