Connecting to Humans: Biosignal Processing and PULP

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PULP Platform

Open Source Hardware, the way it should be!

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pulp-platform.org

youtube.com/pulp_platform

Outline

- Introduction and Motivation
- INAIL System / Cerebro Board
- Biowolf
- BioGAP
- UltraSound
- Moving to the next frontier…

Introduction and Motivation

What we want to do:

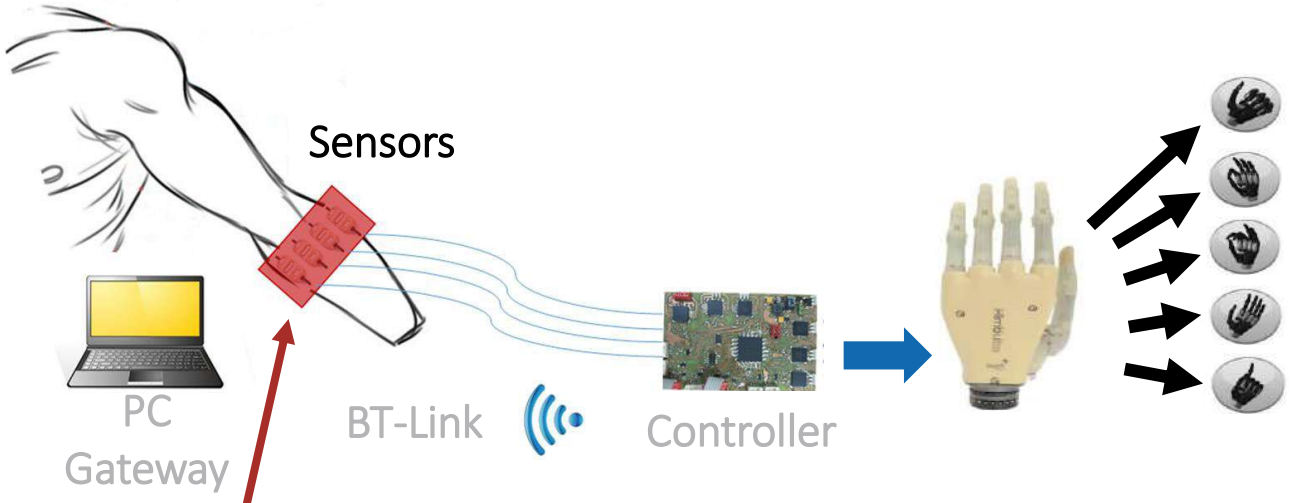
- At application level, we target to push the envelope of the edge computing for wearable systems

Which direction we follow:

- System design
- Sensors interfaces
- Algorithms

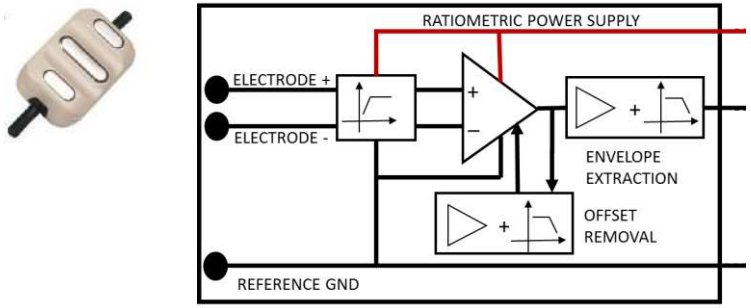
The first project: INAIL hand controller

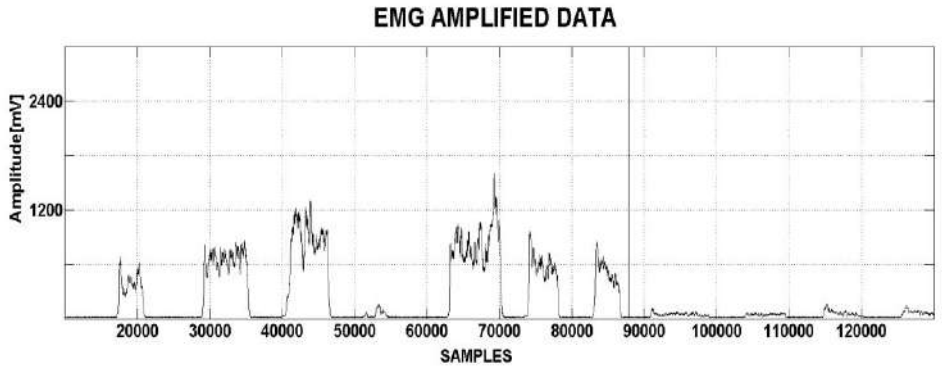
Design of an end-to-end controller for poliarticulated artificial hand.



Specs:

- Bandwidth 90-450Hz
- Internal Notch Filter 50Hz
- 0-3.3V single ended output span





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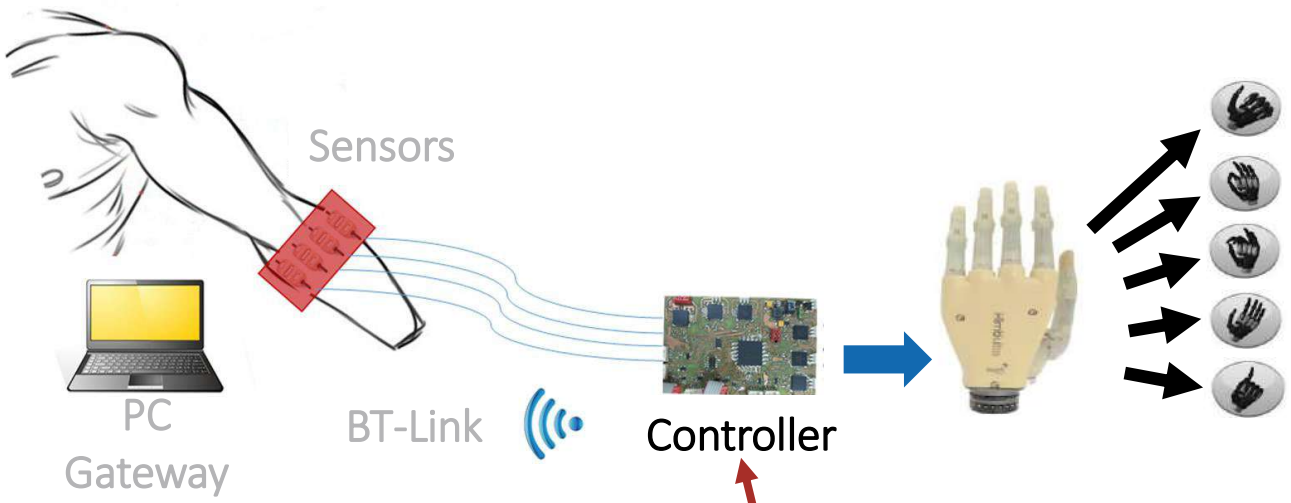
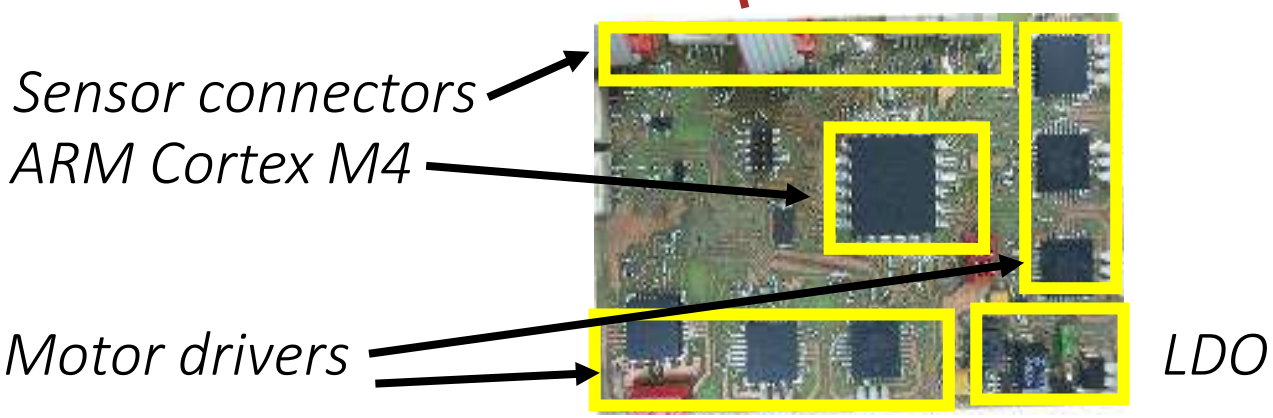
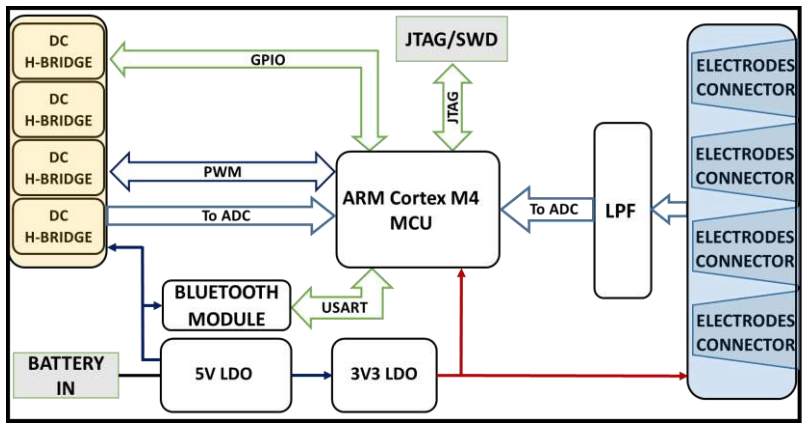


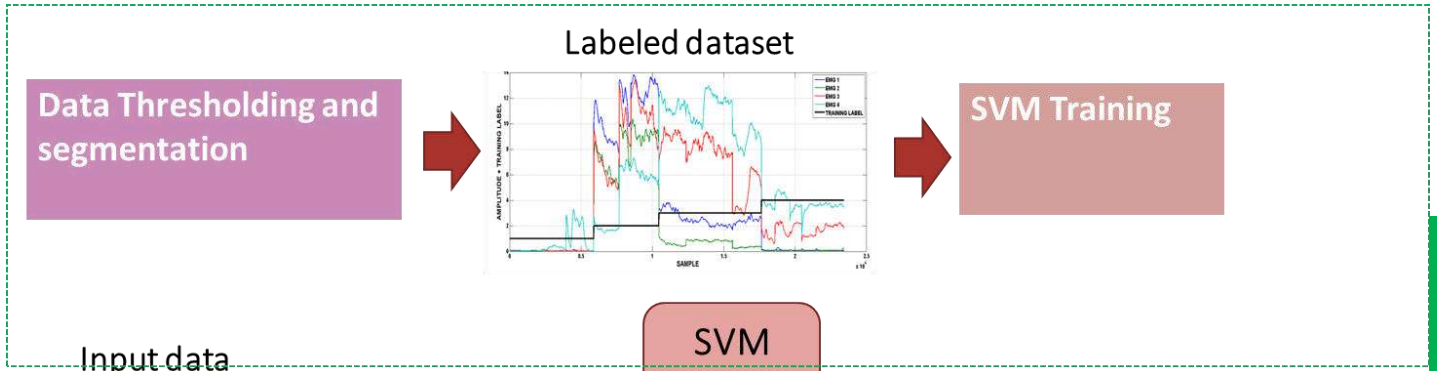
Specs:

- ARM-Cortex M4
- 100Mhz clock
- internal ADC

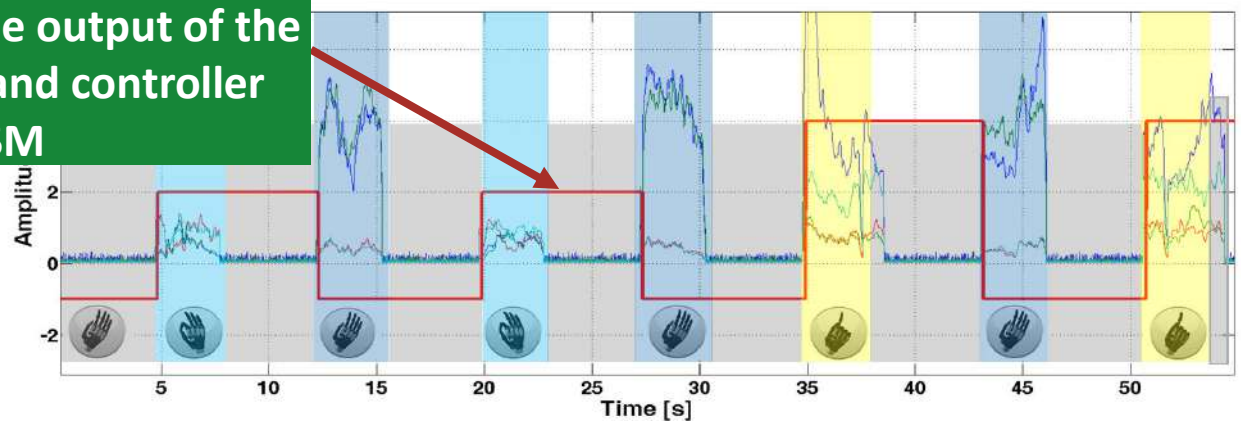




The first project: INAIL hand controller



Red bold line is the output of the hand controller FSM



- What we have achieved
  - Real time closed-loop control
  - Embedded SVM execution

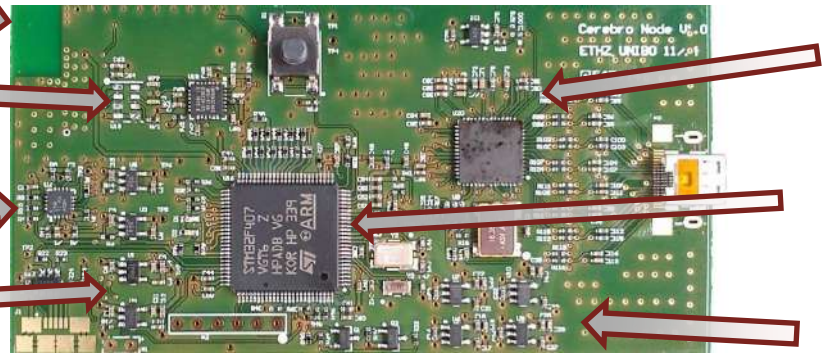
- What we can improve
  - Sensor inteface
  - Scalability

Moving towards Cerebro board

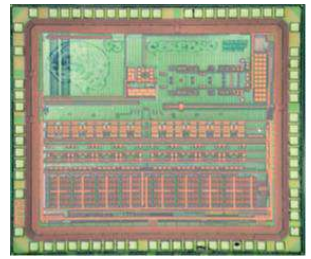
- Use low-cost passive sensors instead of conventional EMG
  - Scalable
  - Usable also for consumer HMIs
- Move part of the signal processing on the digital domain
  - More versatile

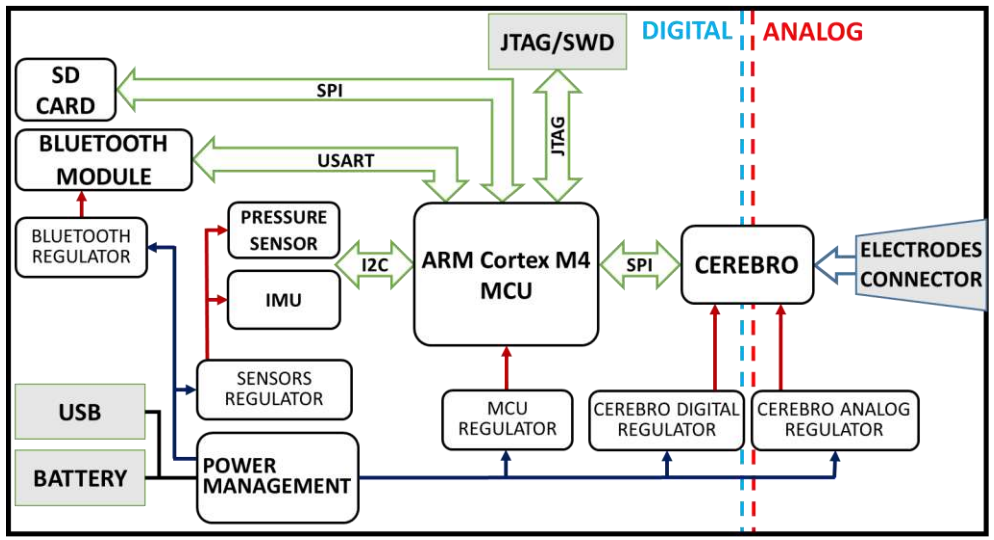
Cerebro ADC (2014)

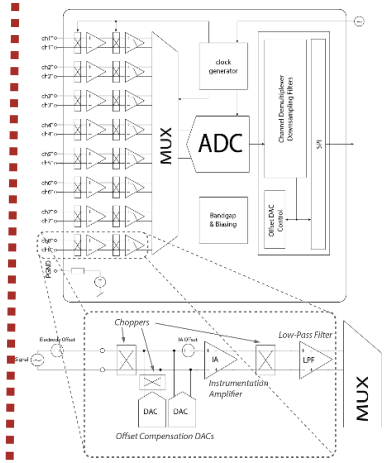
- BT antenna
- IMU
- POWER MANAGER IC
- DIGITAL REGULATORS



- Cerebro AFE
- ARM CORTEX M4
- ANALOG REGULATORS

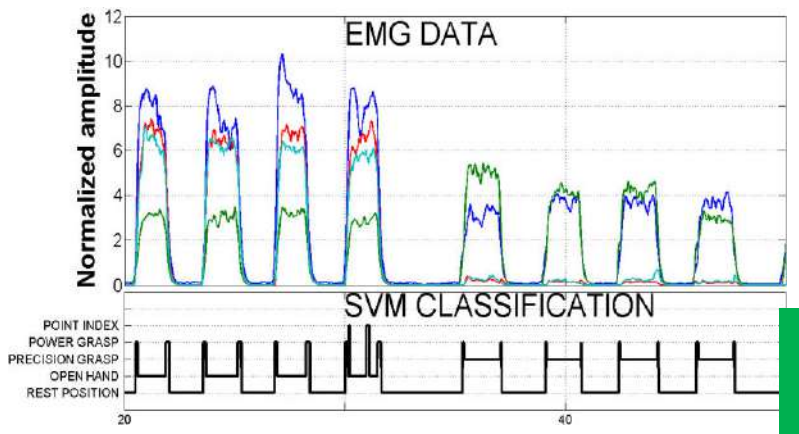


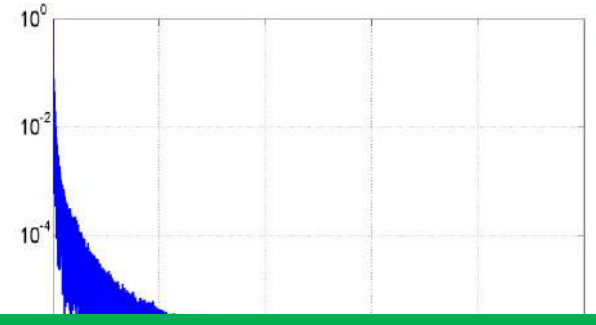




CEREBRO AFE	
Technology	130nm
#Channels	8
Sampling rate	8kS/s
CMRR	101dB
Input Impedance	235MOhm
RMS IR noise	0.82uV

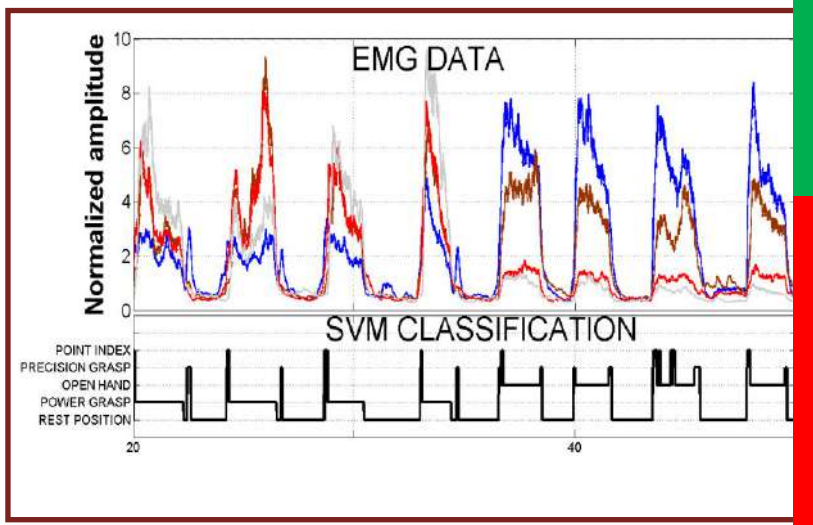
Passive low-cost electrodes





	RST	POG	OPH	PCG	PIX
RST	78817	0	868	3368	0
POG	1342	10570	0	2449	2327
OPH	0	0	15775	66	0
PCG	0	2	59	117653	0
PIX	0	905	0	3043	11565

→Accuracy



PCG	PIX
73	0
718	729
2816	886
13902	74
1648	17016

acy

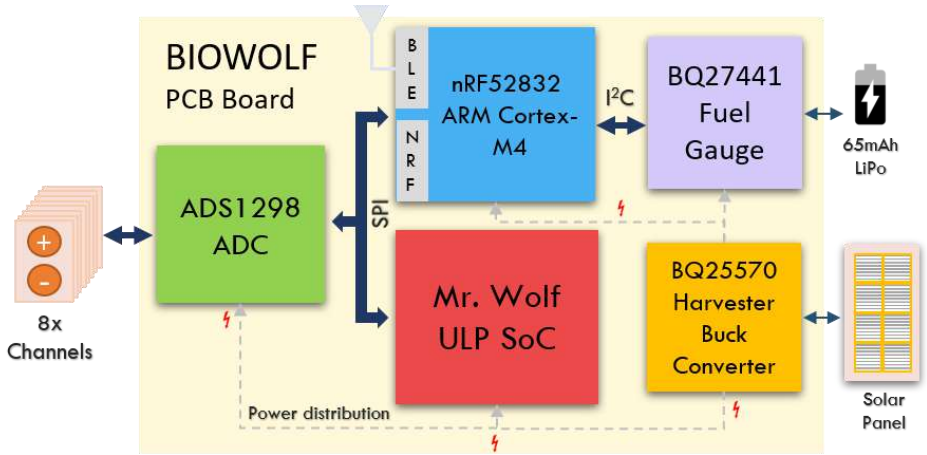
- What we have achieved
  - Real time digital signal conditioning for biopotentials
- What we can improve
  - Computational capability
  - Energy efficiency

Adding horsepower to the digital processing

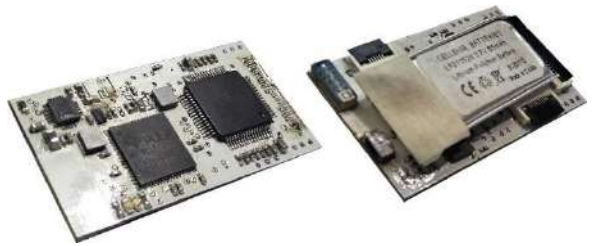
- Use a PULP chip to enable ML/DL algorithms
  - Design a form factor board for HMI with mrWolf
- Test the system on more biosignals
  - EMG,EEG,ECG

Embrace the (mr.)Wolf Within: Biowolf (2018)

Block Diagram



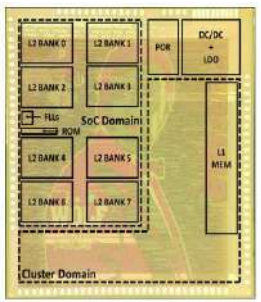
PCB implementation



Main Components

ADS1298

- Up to 8 ExG channels
- 24-bit of resolution
- 0.5 to 32 – Ksps.
- PGA up to 12x.
- Dry/Gel electrodes compatible.



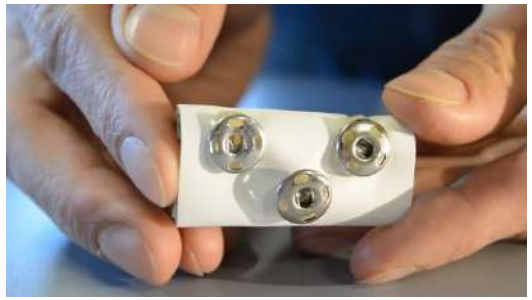
MR. WOLF

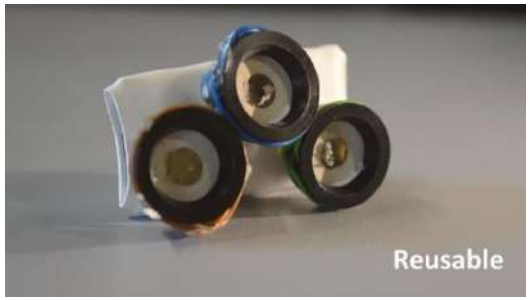
- 8 RISC-V cluster processors.
- Bit manipulation instructions.
- Voltage range (0.8V-1.1V).
- 40nm LP CMOS.
- 64kB/512 L1/L2 memory.

nRF52832

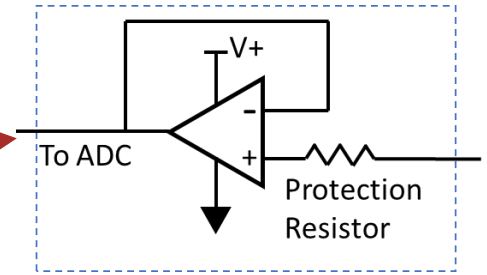
- ARM Cortex-M4.
- 64 MHz.
- Bluetooth 5 capable.
- NFC-A.
- 512/64 KB Flash/RAM.

Embrace the (mr.)Wolf Within: Biowolf





The system works with active/passive sensors



Testing the Wolf

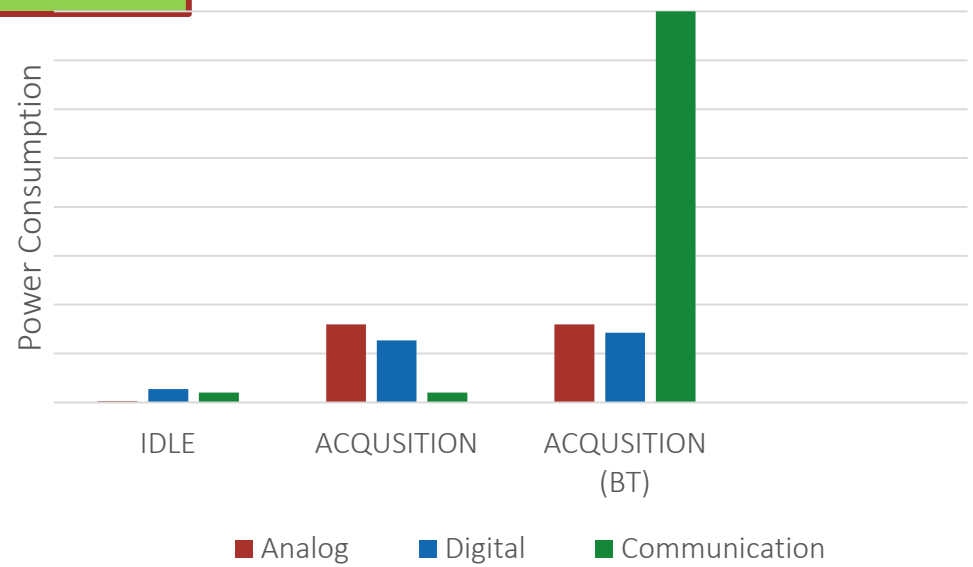
- System tested to validate electrical performance
  - Sampling rate 500 SPS.
  - Bandwidth 131Hz

Input-referred noise (0.5 100 Hz)
- PGA gain = 1 → 1.8uVrms
- PGA gain = 12 → 0.48uVrms

CMRR
- Electrode vs Reference → 92dB
- Digital re-referencing → 106dB

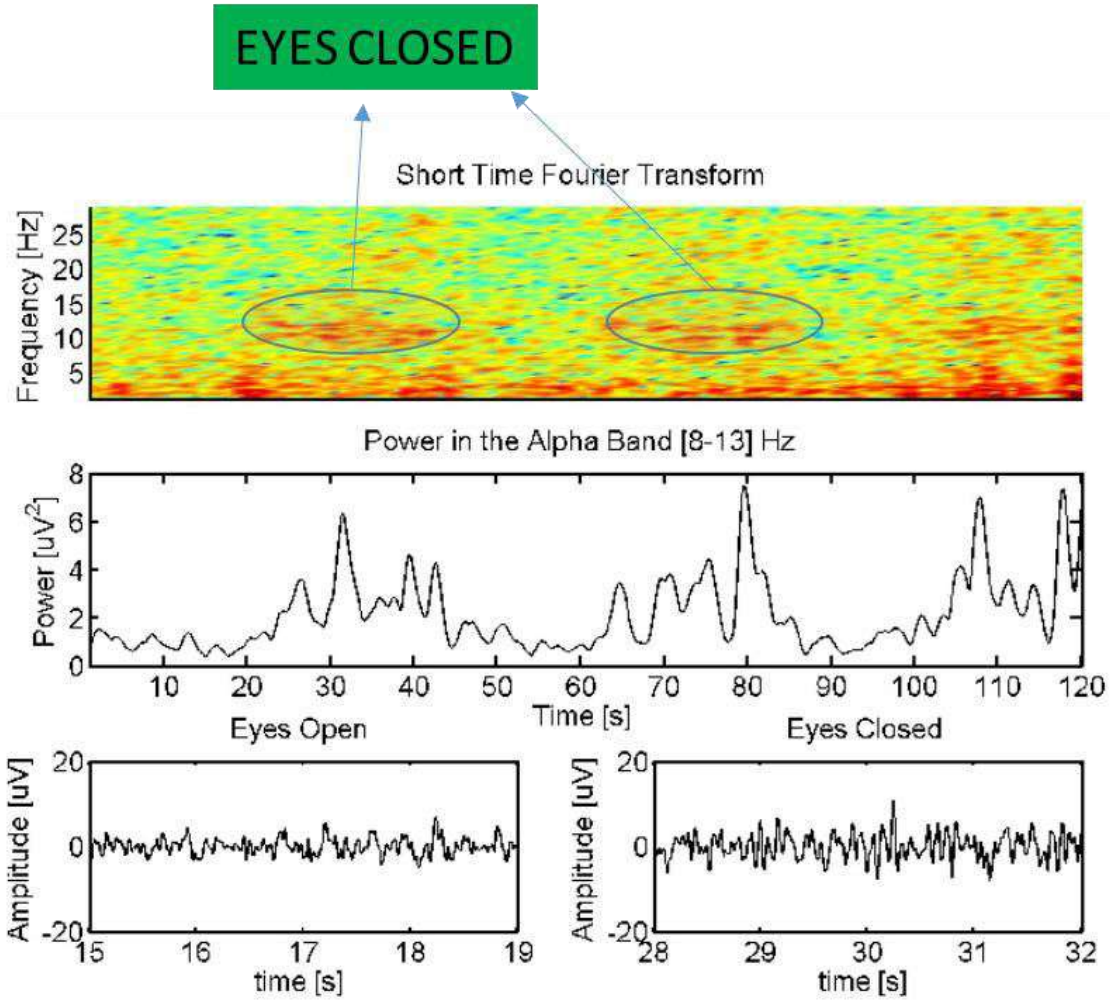
CHANNEL ISOLATION
- 95dB

IFCN compliant



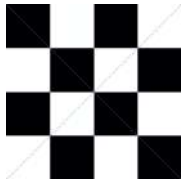
Testing the Wolf

- Alpha waves
  - Spontaneous brain response
  - Bandwidth 9-12Hz
  - Ideal for fast testing of BMIs
  - Used in neurofeedback apps
- Test
  - 20s opened/closed eyes
- Result
  - Increase of 3x Power in α-rythms

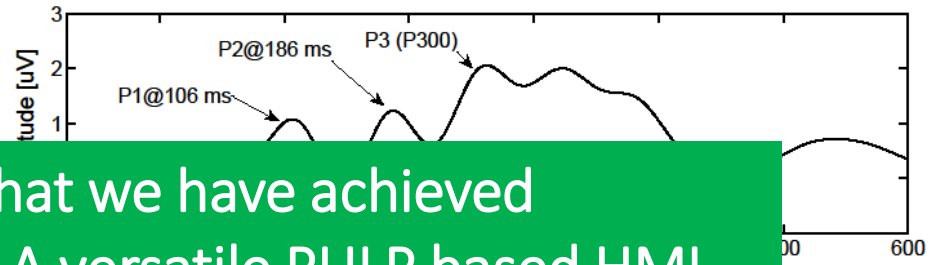


Testing the Wolf

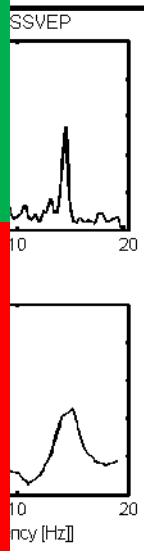
- **Test ERP**
  - time domain averaging of **100** repeated stimuli
- Result
  - P1,N1,P2,N2,P3 detectable (5x wrt noise le



Visual stimulus at 1 Hz
For ERP and SSVEP



- **Test SSVEP**
  - Frequency domain analysis (PSD) on 5s and 90s windows
- Result
  - SNR 16dB (main peak / avg power 10-30Hz
  - SNR 5dB (short 5.1s window)



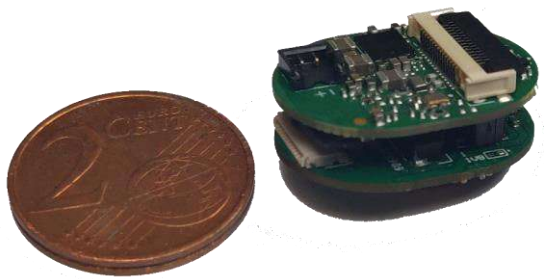
- What we have achieved
  - A versatile PULP based HMI for biopotentials
- What we can improve
  - Computational capability
  - Energy efficiency
  - Modularity

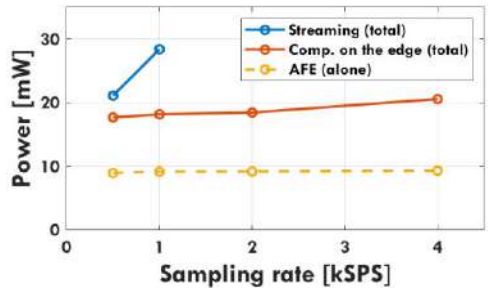
BioGAP: a GAP-based Gateway to Advanced Processing

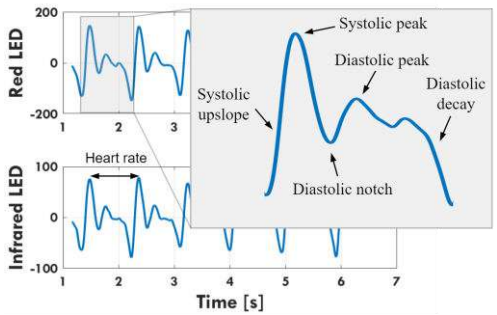
- Design modular sensor gateway based on GAP9
  - More signals (EEG,EOG,PPG,ECG,EMG, microphones, IMU…)
  - Can connect to other complex systems (eg US)…see next slides
  - Integrated form factor
- Novel sensors
  - Going towards dry, low cost, comfortable sensors

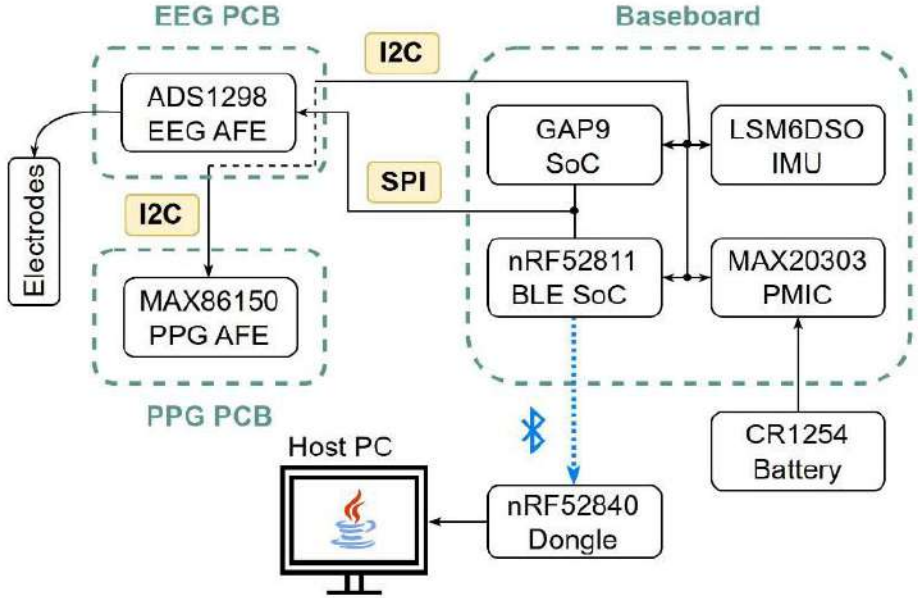
BioGAP: the ultimate wearable computing platform (2023)

- PULP-based computing platform: **GAP9**
  - TOPS capabilities, 10 RISC-V cores, 128 kB L1 memory, 1.5 MB RAM, 370 MHz operation (state-of-the-art performance for tinyML)
- Nordic nRF52 for BLE connectivity
- Can be flexibly connected to a **large variety of sensor interfaces**, for example:
  - ADS1298 ADC for measurement of biopotentials: **EEG, EMG, EOG**
  - MAX86150 PPG sensor: **HR, Pulse Oximeter**









A big step forward in our sensors

- We want to
  - minimize contact impedance,
  - reduce noise
  - maximize versatility

- Dry
- Active
- 500€

- Wet (GEL)
- passive
- 2-3€

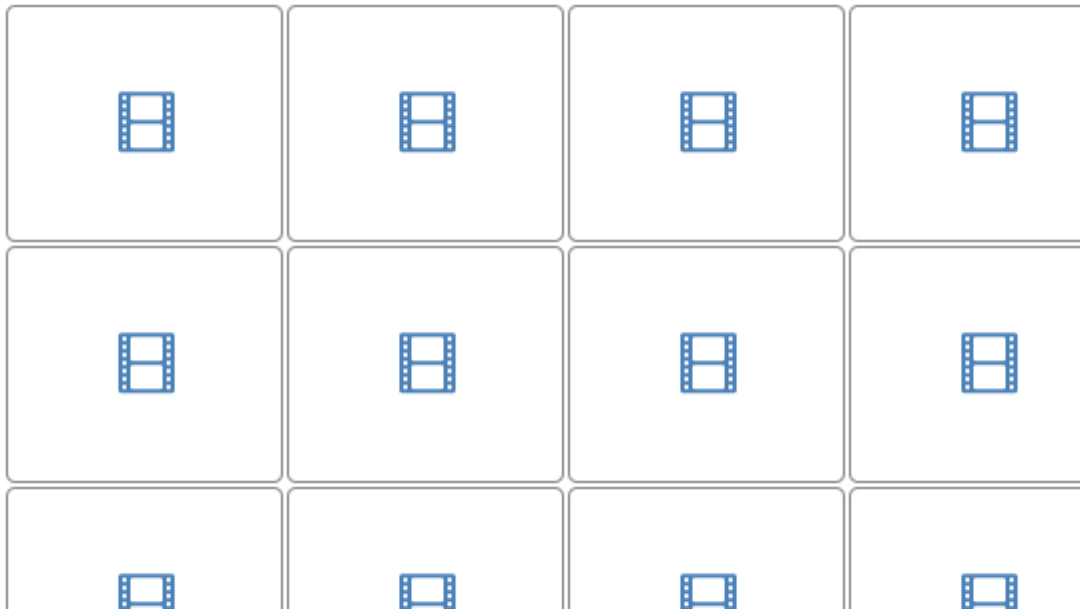
- Dry
- Passive/active
- 100€

DATWYLER

- Dry (25-300kOhm)
- Passive/active
- 10€

Headband for EEG monitoring

- BioGAP compatible Brain-computer interface
  - Drone control
  - Motor movement / motor imagery
  - Steady-state visual evoked potentials
- Clinical applications
  - Epilepsy monitoring
  - Clinical trials



BioGAP in a Headband Formfactor

Flexible pin-electrodes (SoftPulse, Dätwyler) for temporal and occipital regions

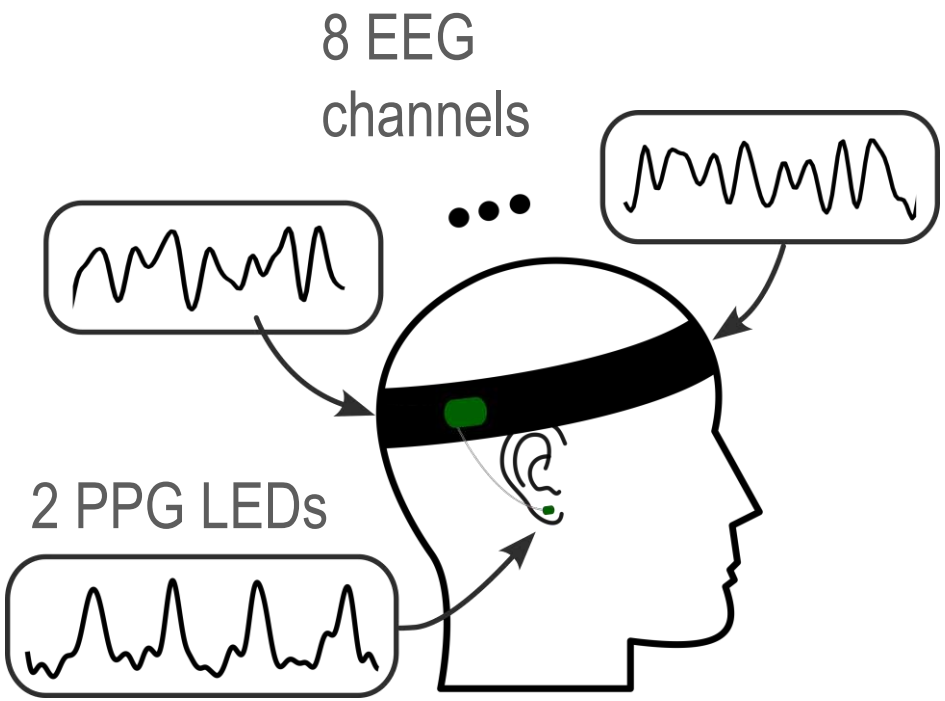
BioGAP

Flat electrode (SoftPulse, Dätwyler) for improved wearing comfort at frontal lobe

Dry electrodes enable **long-term EEG measurements**

Used for **drowsiness detection in** automotive application

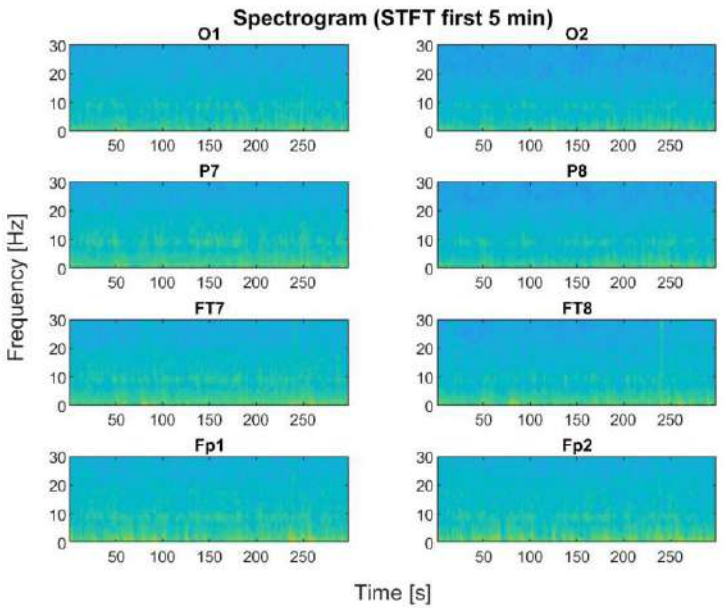
EEG based Drowsiness Detection – first study completed

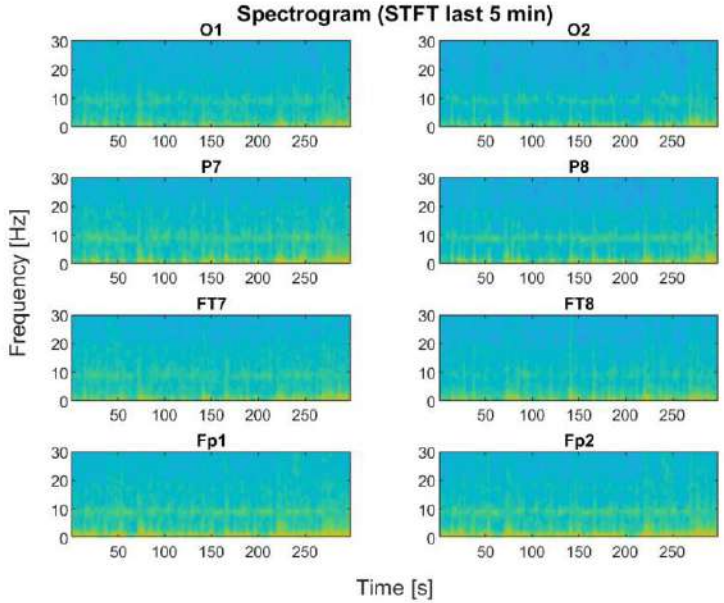


Driving simulator at the University of Modena
(7 distinct subjects)

Driving simulator at Maserati
(7 distinct subjects)

Data sneek peek from the Maserati measurements

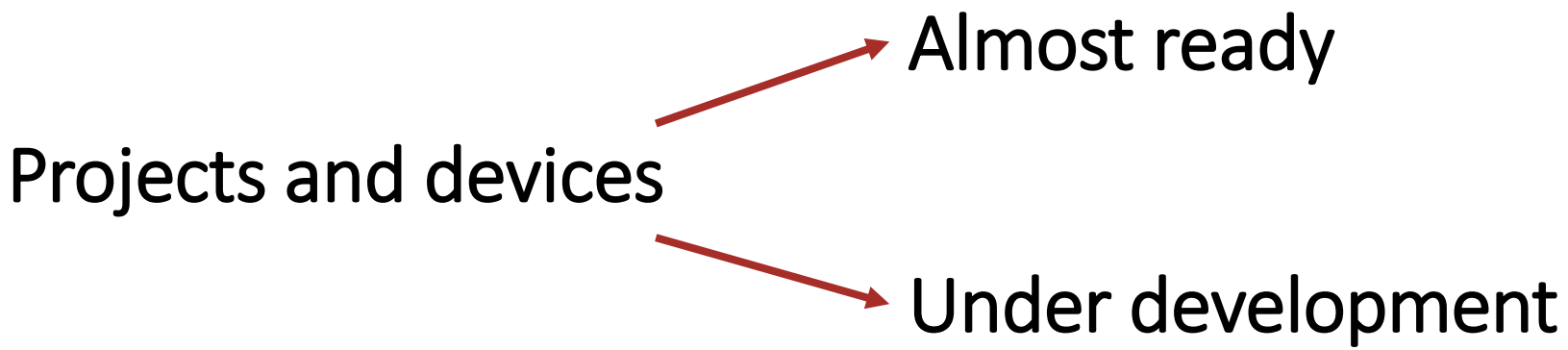




Alert → Drowsy

Increased power in alpha band (8-10 Hz)
Increased power in delta band (1-4 Hz)

Coming soon



We have several international ongoing project where we use our BIOPULP Devices

- Intelliman
- PEDESITE
- Listen to light
- Urban twins

EEG Glasses

Non-stigmatizing EEG monitoring

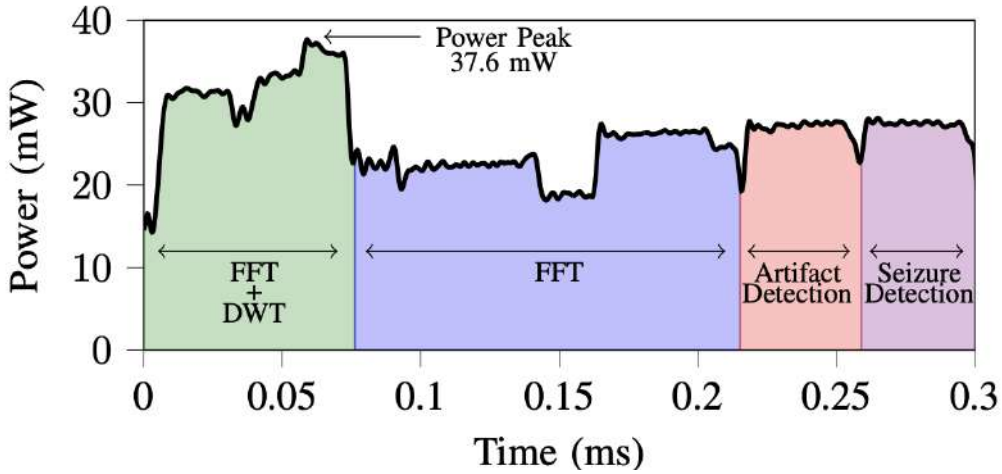
Temporal region

GAP9 + ADS1298

BioGAP + Sensors both ready
Integration into glasses **WIP**

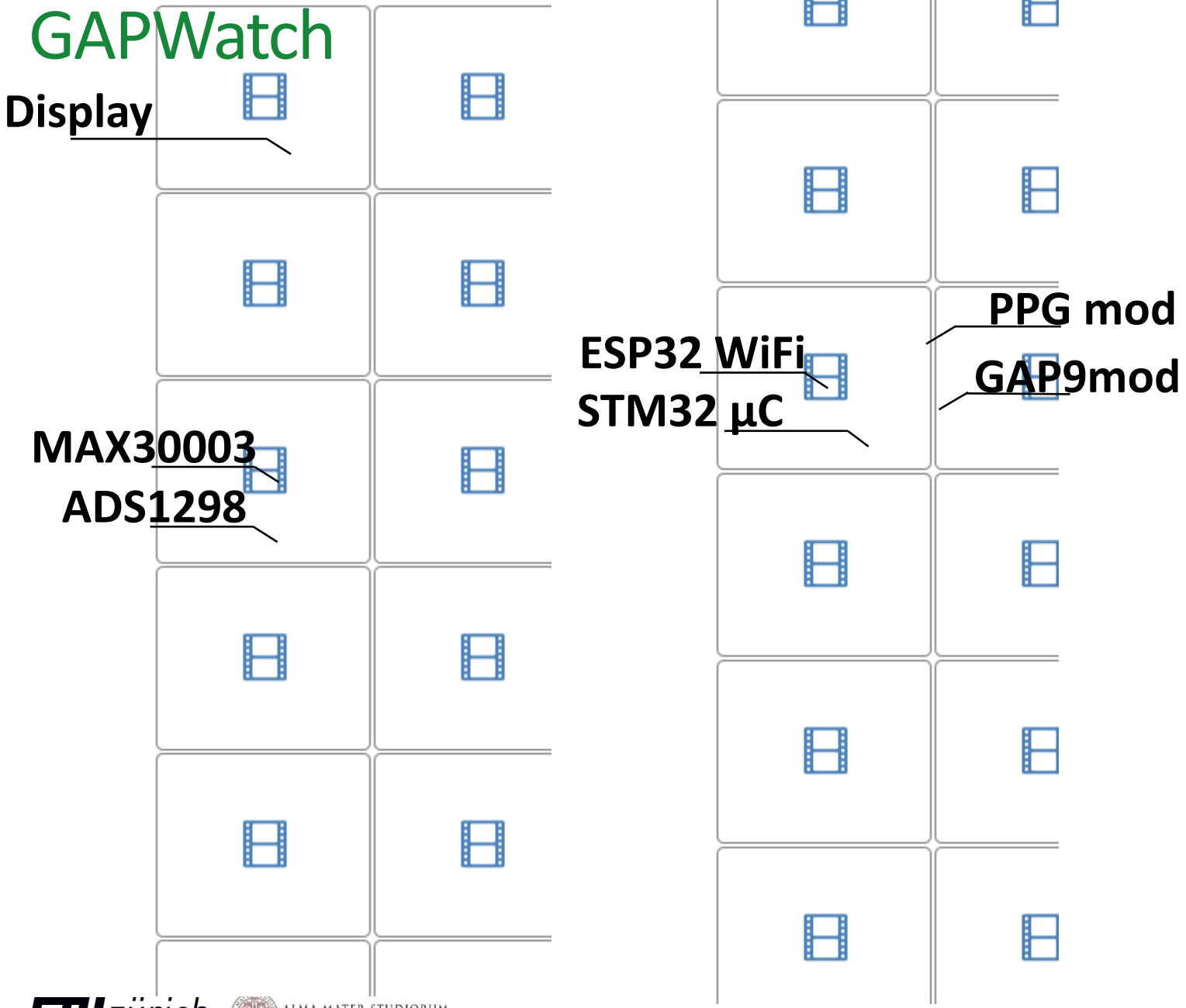
EEG Artifact + Seizure Detection

- XGBoost + Gradient Boosted Trees
  EEG Artifact Detection and Seizure Detection done in under 0.3 ms at a low cost of **7.93 µJ per inference**



Seizure detection also implemented with **CNN** models and **Transformer** model quantized to 8 bits

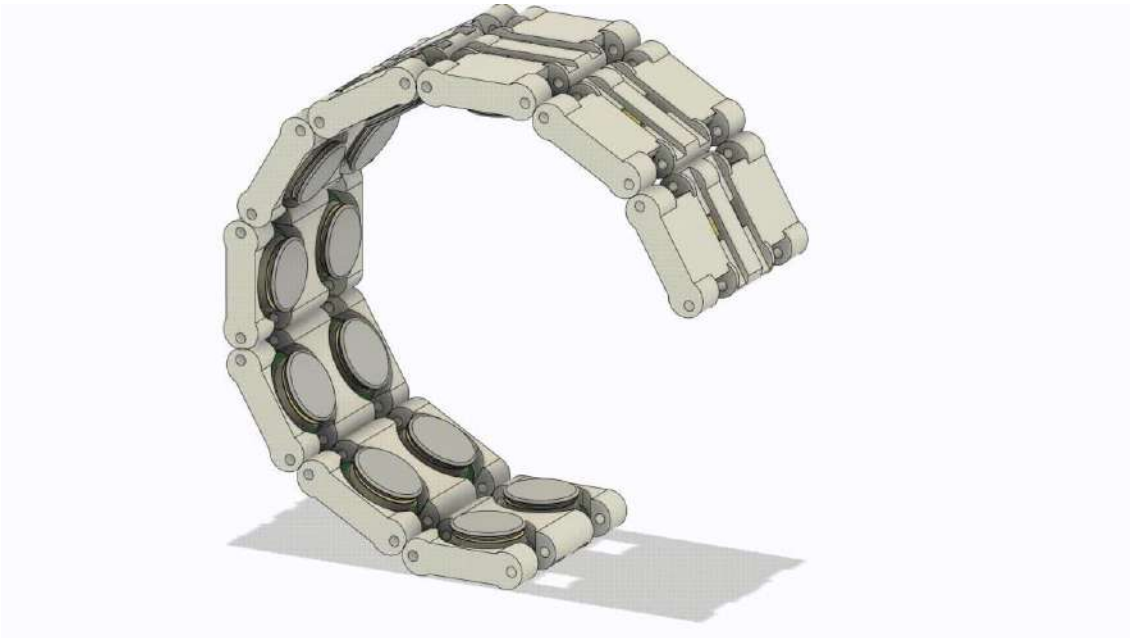
GAPWatch



Main features:

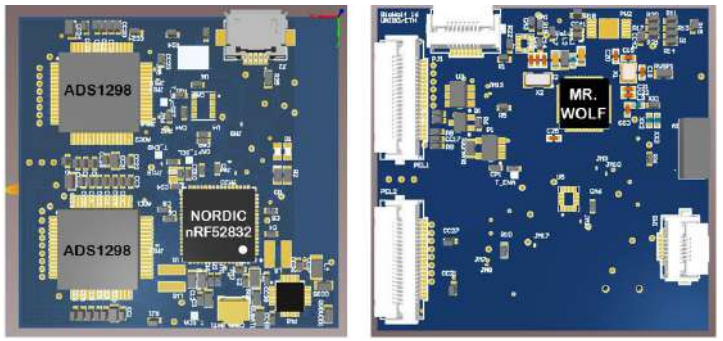
- **GAP9**
- **PPG** dual channel (MAX86140)
- 3D **ACC** (LSM6DSX)
- 16 channels **EMG** (two ADS1298)
- **ECG** single lead (MAX3003)
- Exposed spi/i2c interface to connect external sensors boards
- **WiFi** (ESP32)
- **µC** (STM32U585)
- GC9A01A **display** with touch interface (GC9A01A + CST816S)

EMG-Medium Density armband

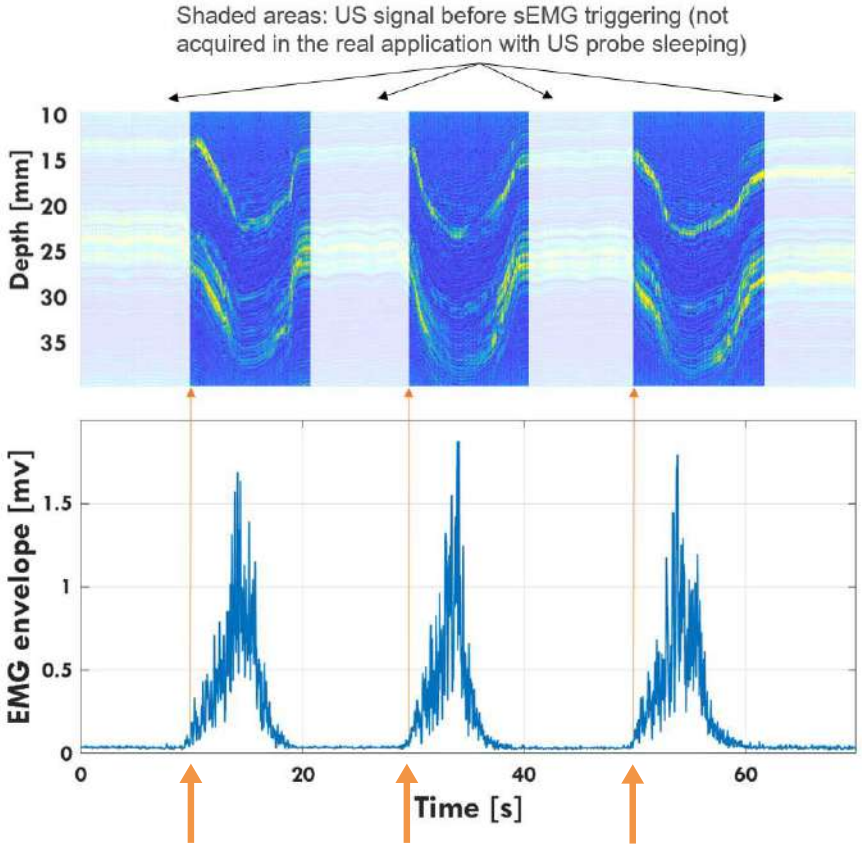


Main features:

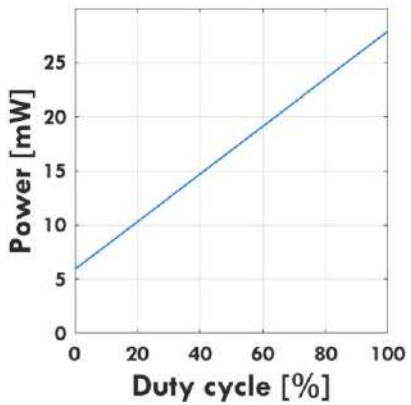
- **mrWolf (we will update to GAP9)**
- 16 channels **EMG** (two ADS1298)
- **µC** (nRF52832)



First results combining BioGAP (EMG) and WULPUS (US)



Biceps contraction detected by BioGAP → start WULPUS



WULPUS starts **faster than** the **electro muscular delay**

Why Wearable Ultrasound?

Why Ultrasound?

- Safe and noninvasive
- Senses deep tissue
- Relatively low-cost

Existing Systems:

- Bulky and obtrusive
- Power hungry
- Limited to imaging, closed.

Conventional US

https://www.mindraynorthamerica.com/specialties/radiology-ultrasound-machines/

Portable US

https://www.usono.com/probefix/

Wearable US

?

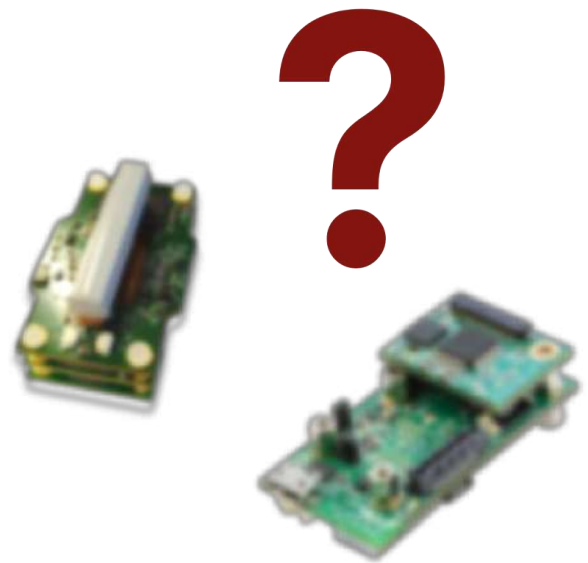
Wearable Ultrasound: System Design Challenges

Physical Requirements

- High sampling frequencies (4 – 30 MHz)
- High-voltage excitation (±15-100 V)
- High tissue attenuation (0.75 dB/cm/MHz)
- High peak data rates (~ 1 Gbps)
- Multichannel design (≥ 8)

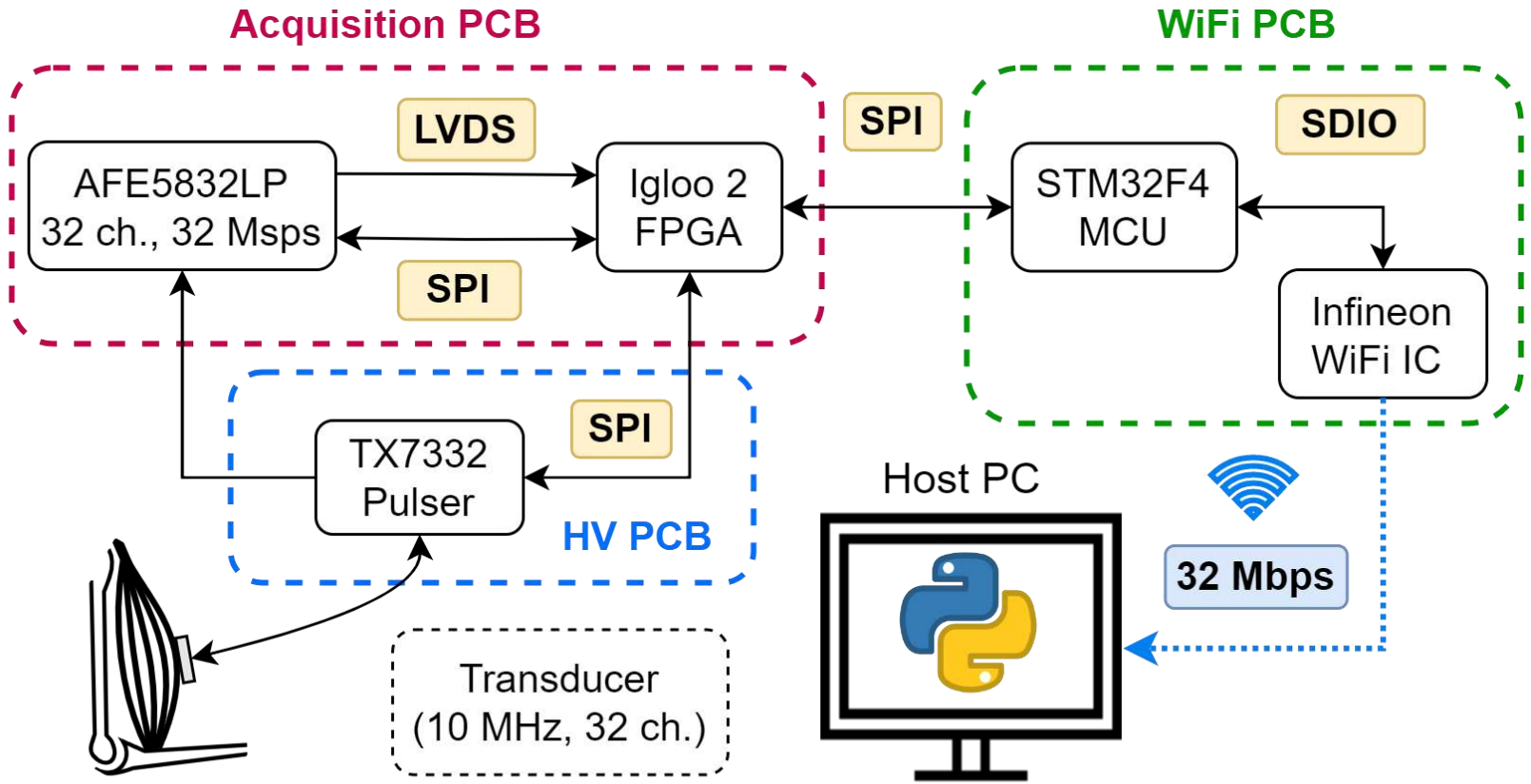
Wearability requirements

- Wireless link
- Compactness
- Low Power



US Dot: 32-ch. High-end Low Power Wearable Probe

Ultrasound Dot



55 x 30 mm footprint

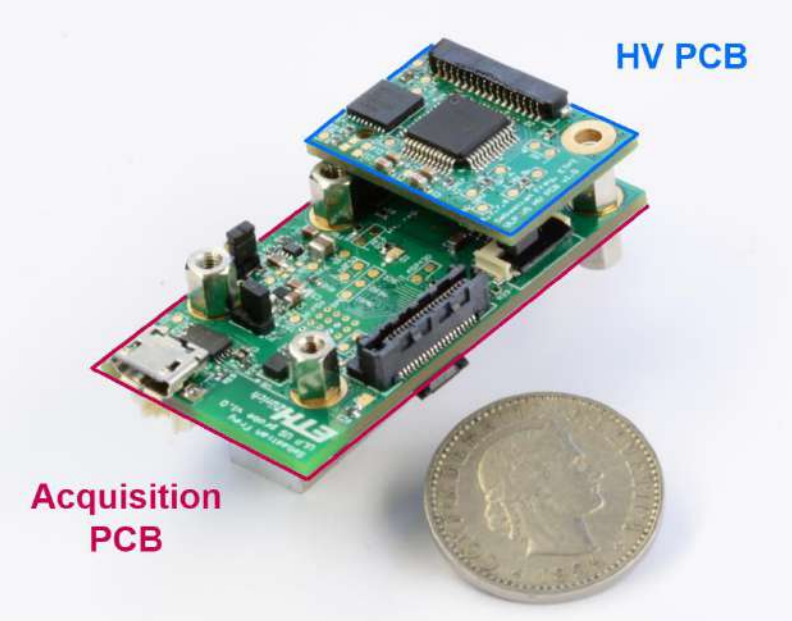
WiFi link **(32 Mbps)**

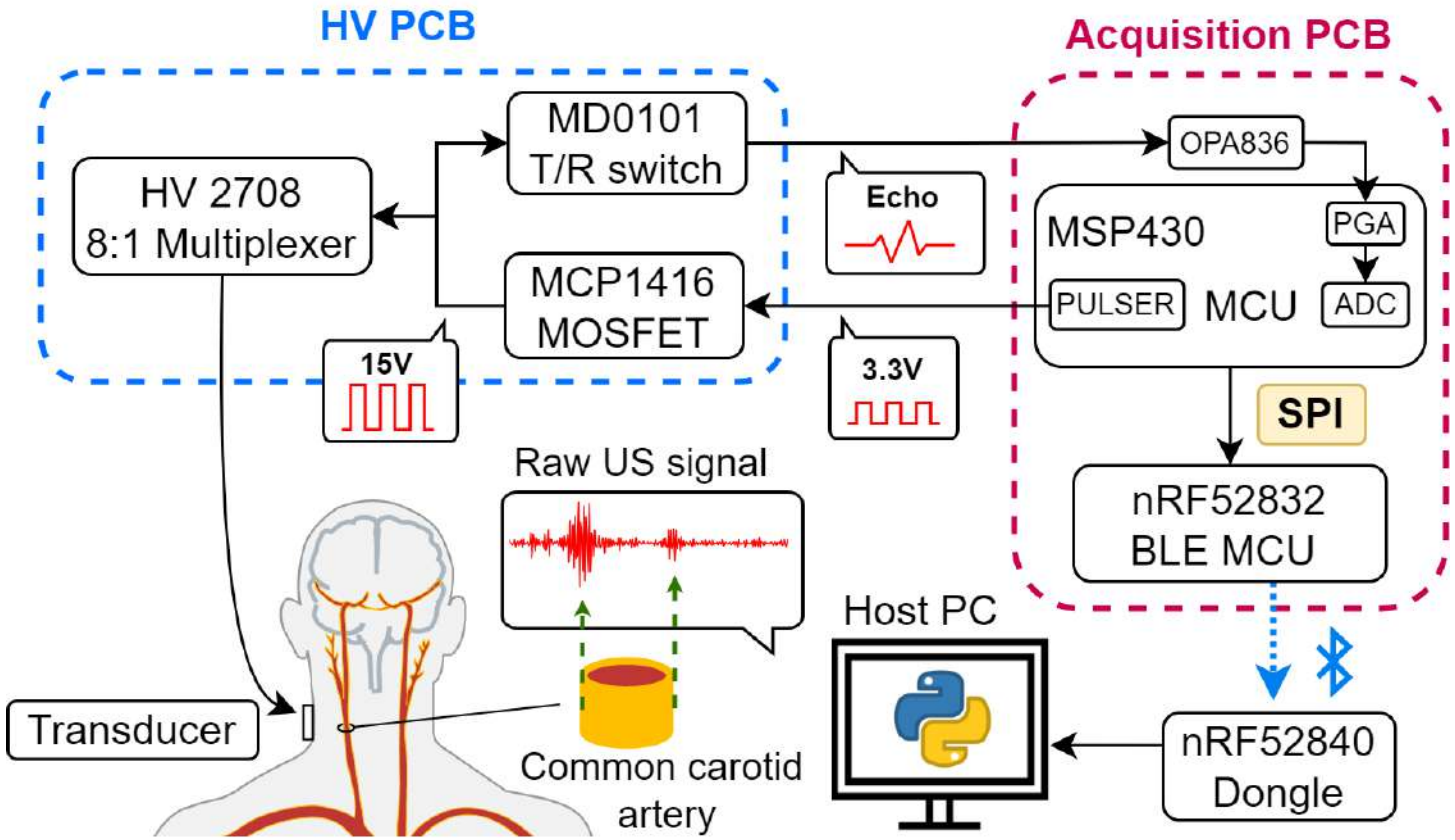
32 channels **(32 Msps)**

Low Power **(970 mW)**

WULPUS: 8-ch. Ultra Low Power Wearable Probe

WULPUS





46 x 25 mm footprint

BLE link **(300 Kbps)**

8 channels **(8 Msps)**

Ultra Low Power **(22 mW)**

Summary: US Dot and WULPUS

Ultrasound Dot

High-frequency, High-channel, Noise-sensitive applications

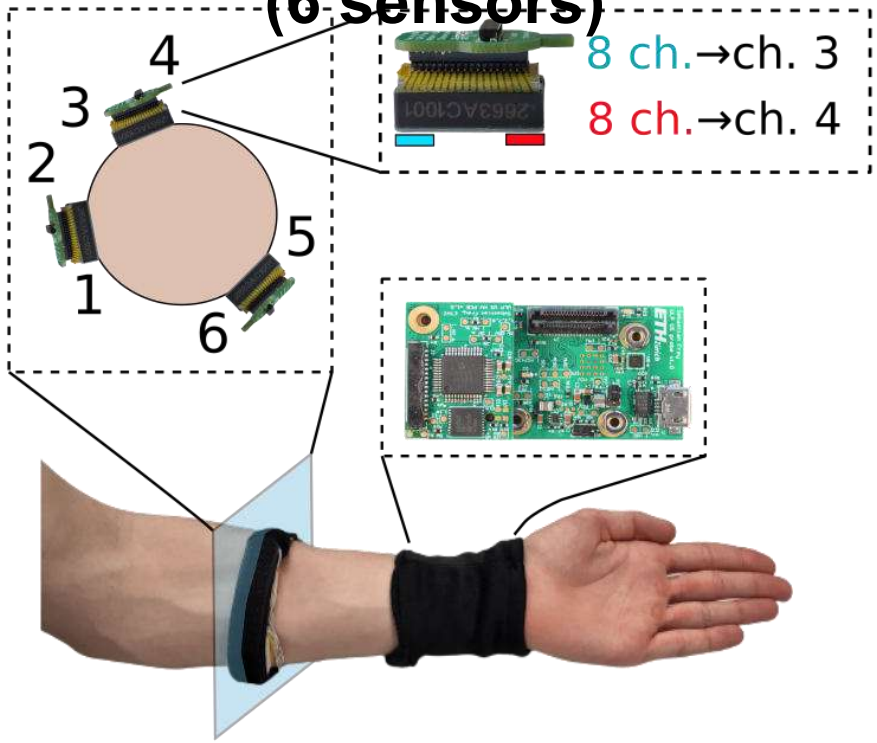
WULPUS

Low-channel, ULP applications, **Multiday** sensing

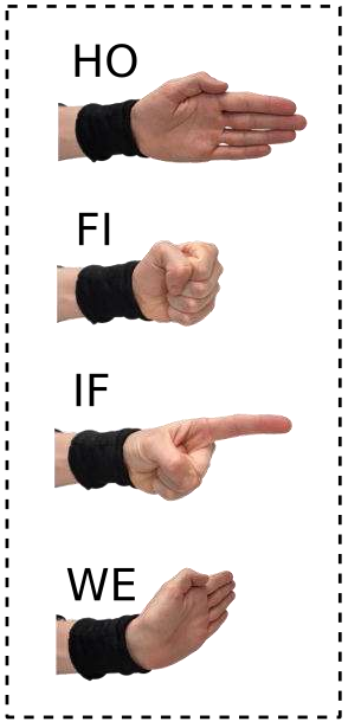
N channels	32 (individual)	8 (time-multiplexed)
ADC	**33 Msps** max (10 or 12 bit)	**8 Msps** (12 bit)
Gain	**21 dB** LNA + **27 dB** PGA + TGC	**30.8 dB** PGA + **10 dB** OpAmp
Wireless link	**WiFi** 4 (32 Mbps)	**BLE** (320 kbps)
Footprint	55 x 30 mm	46 x 25 mm

WULPUS: Hand Gesture Recognition

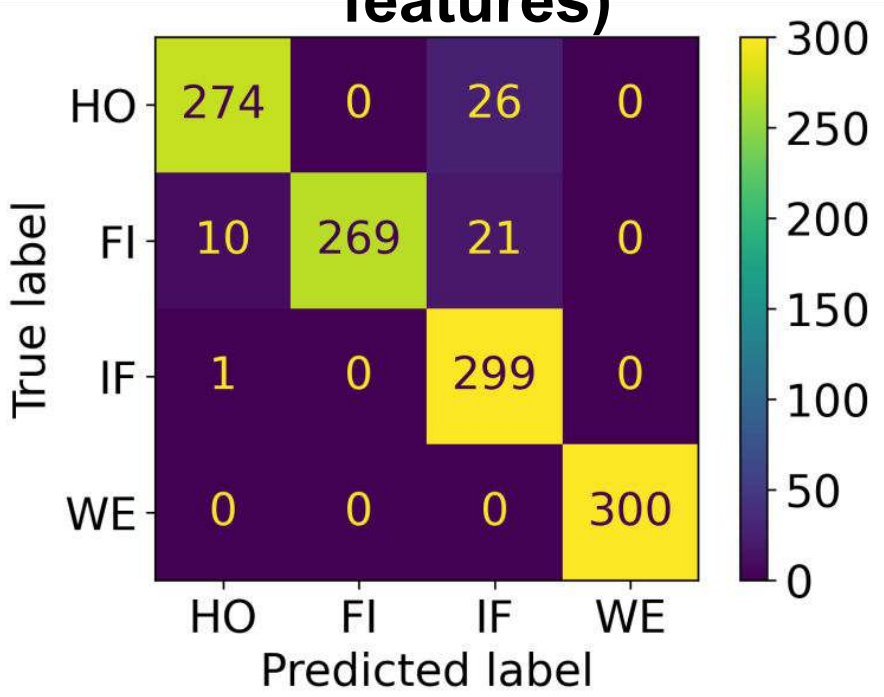
Ultrasound armband (6 sensors)



Gestures

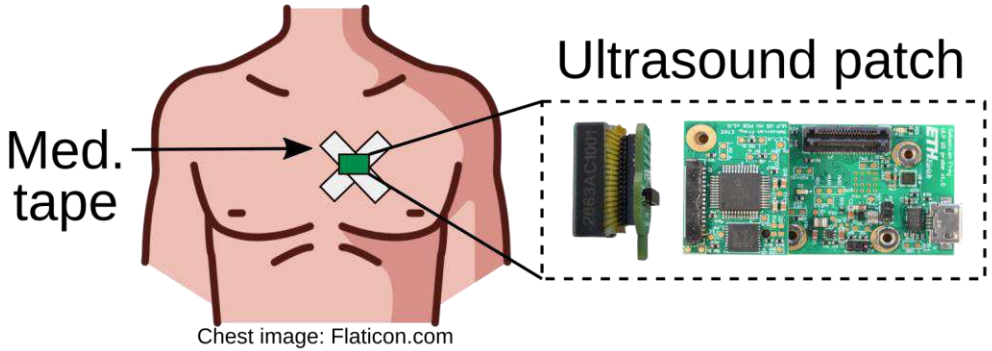


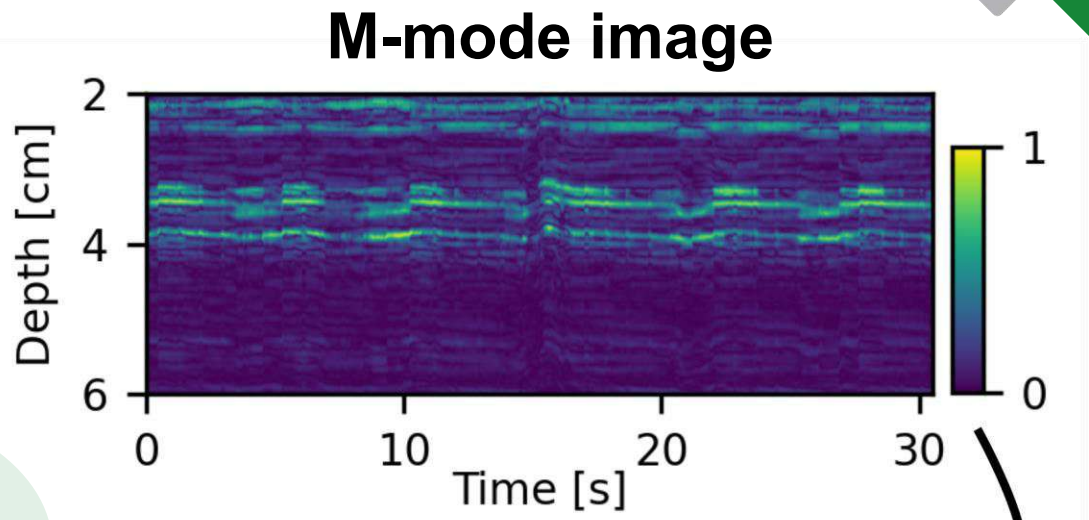
Confusion matrix (XGBoost + stat. features)



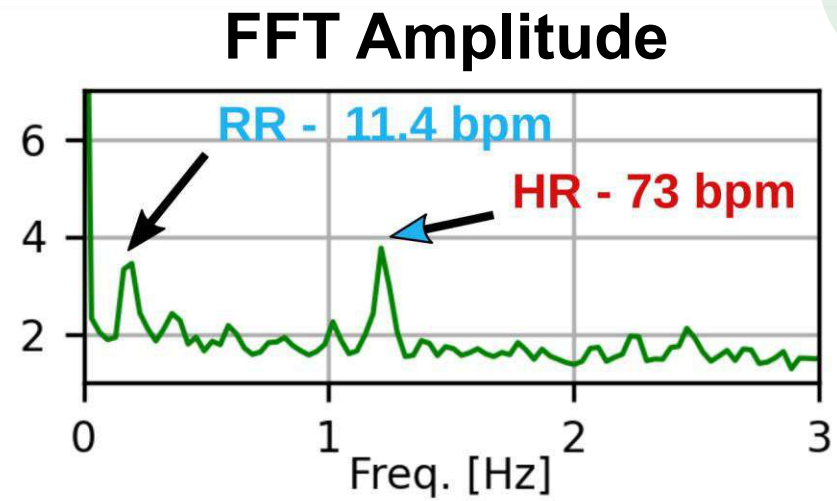
High classification accuracy (96 %)

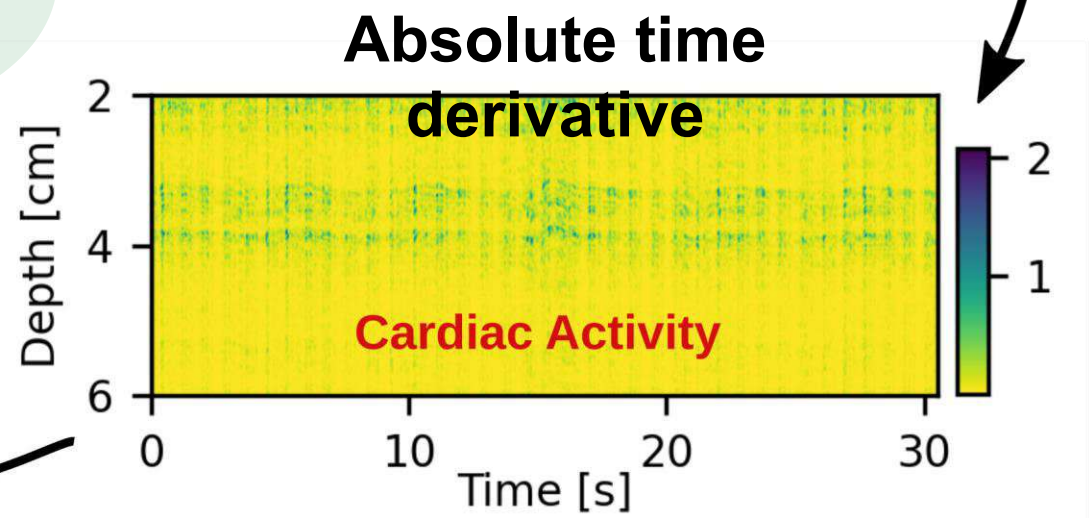
WULPUS: Cardiorespiratory Monitoring





Low error
3,4 % (RR)
2,4 % (HR)





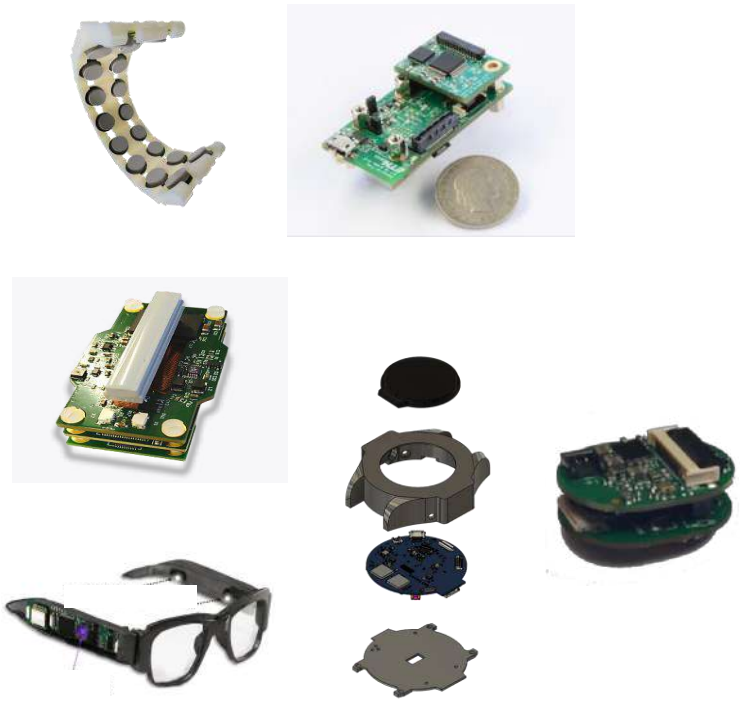
Conclusion

- We have a vivid and evolving full-stack ecosystem from sensors and silicon to applications and algorithms

Sensors

Processing

Devices

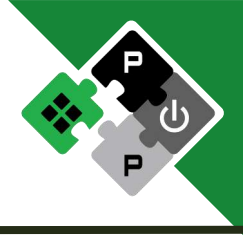


Applications

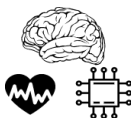
HMIs
- Healtcare
- Consumer

Signals
- ExG
- Audio
- PPG
- IMU

Wearables
- Earbud
- Wristband/Watches
- Eyeglasses



Thank you for your attention!



RISC-V Cores

RI5CY	Ibex	Snitch	Ariane
32b	32b	32b	64b

Peripherals

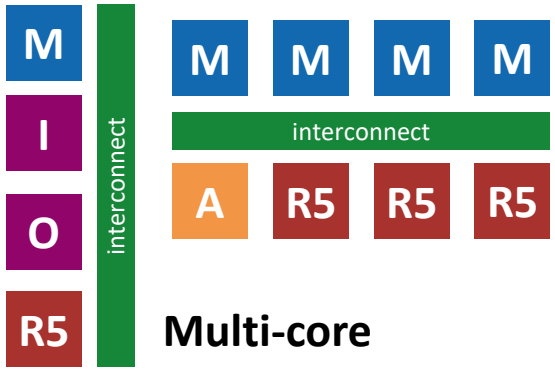
JTAG	SPI
UART	I2S
DMA	GPIO

Interconnect

- Logarithmic interconnect
- APB – Peripheral Bus
- AXI4 – Interconnect

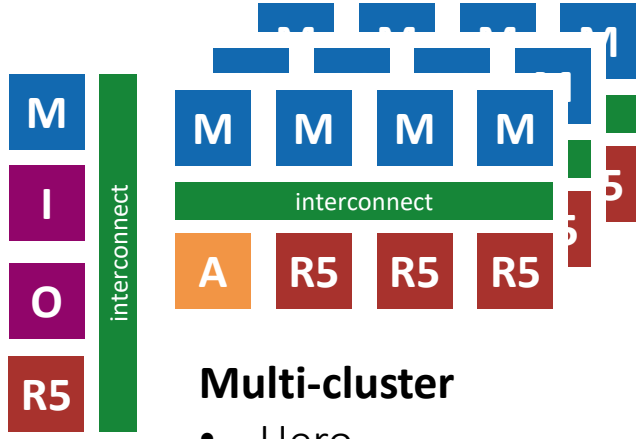
Single Core

- PULPino
- PULPissimo



Multi-core

- Fulmine
- Mr. Wolf



Multi-cluster

- Hero
- Open Piton

IOT → HPC

Accelerators

HWCE (convolution)	Neurostream (ML)	HWCrypt (crypto)	PULPO (1st order opt)