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June 26 - 28, 2023

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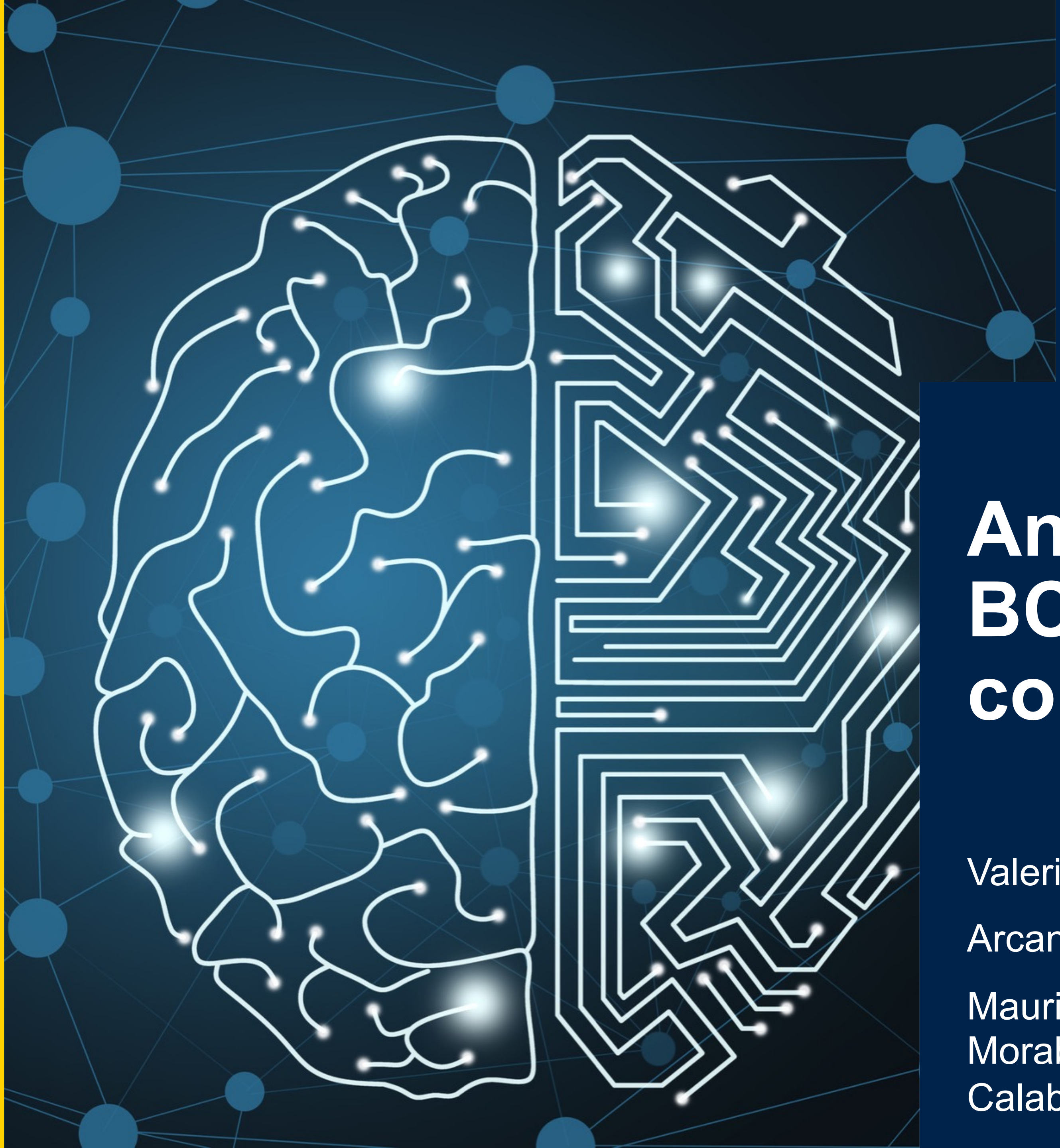

An embedded EOG-based BCI system for robotic control

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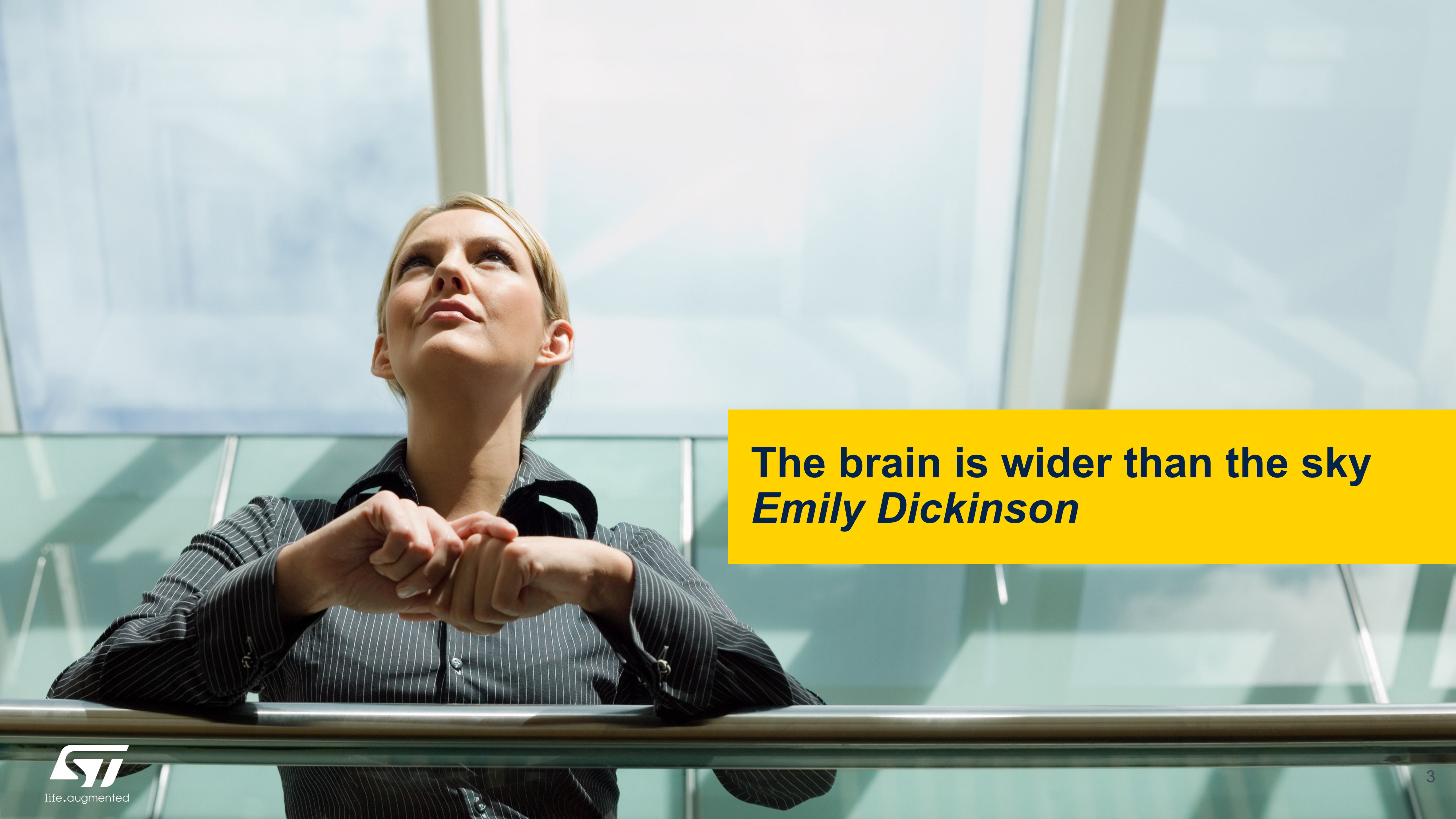
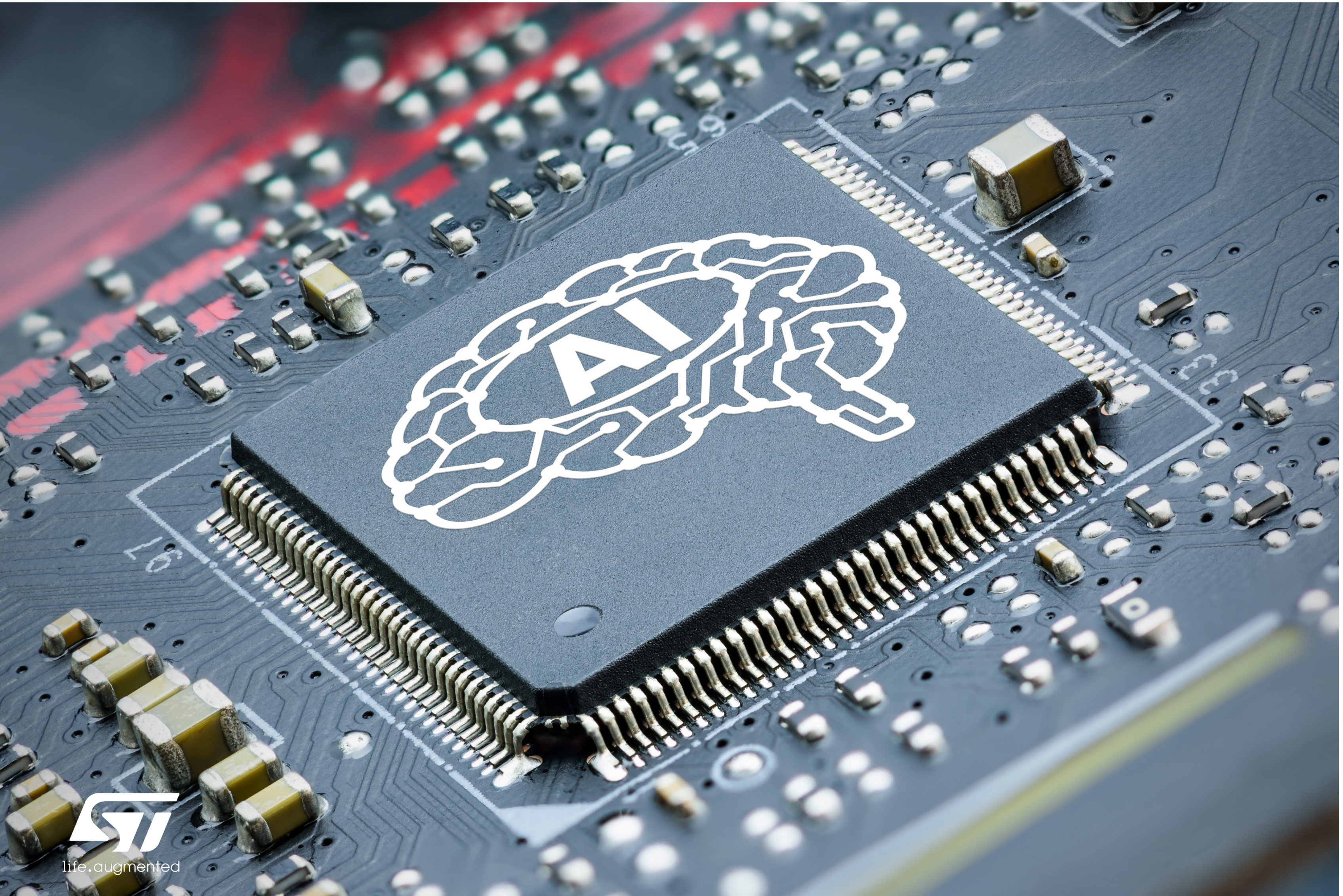


The brain is wider than the sky
Emily Dickinson

The future of machine learning is tiny



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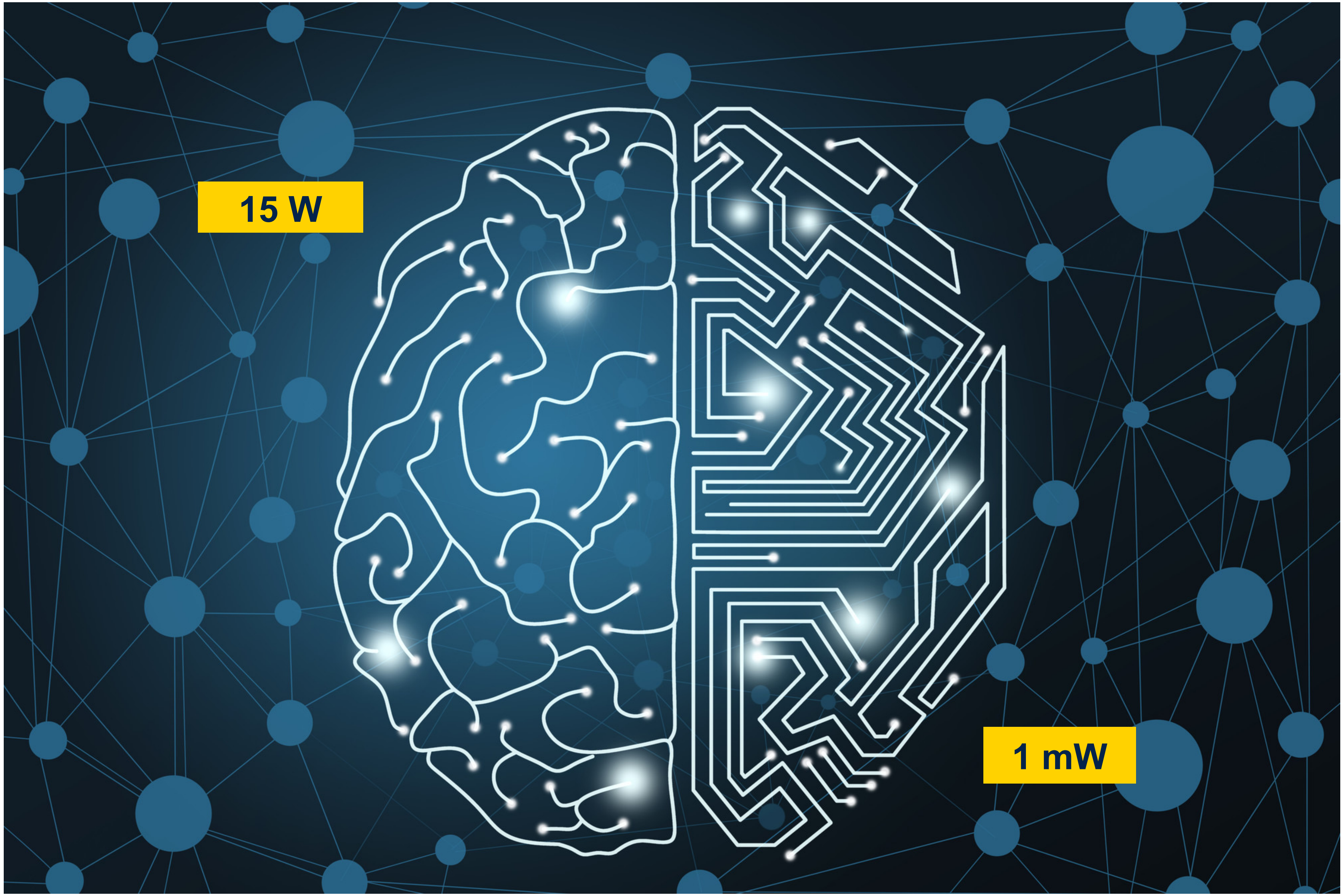
Power Consumption



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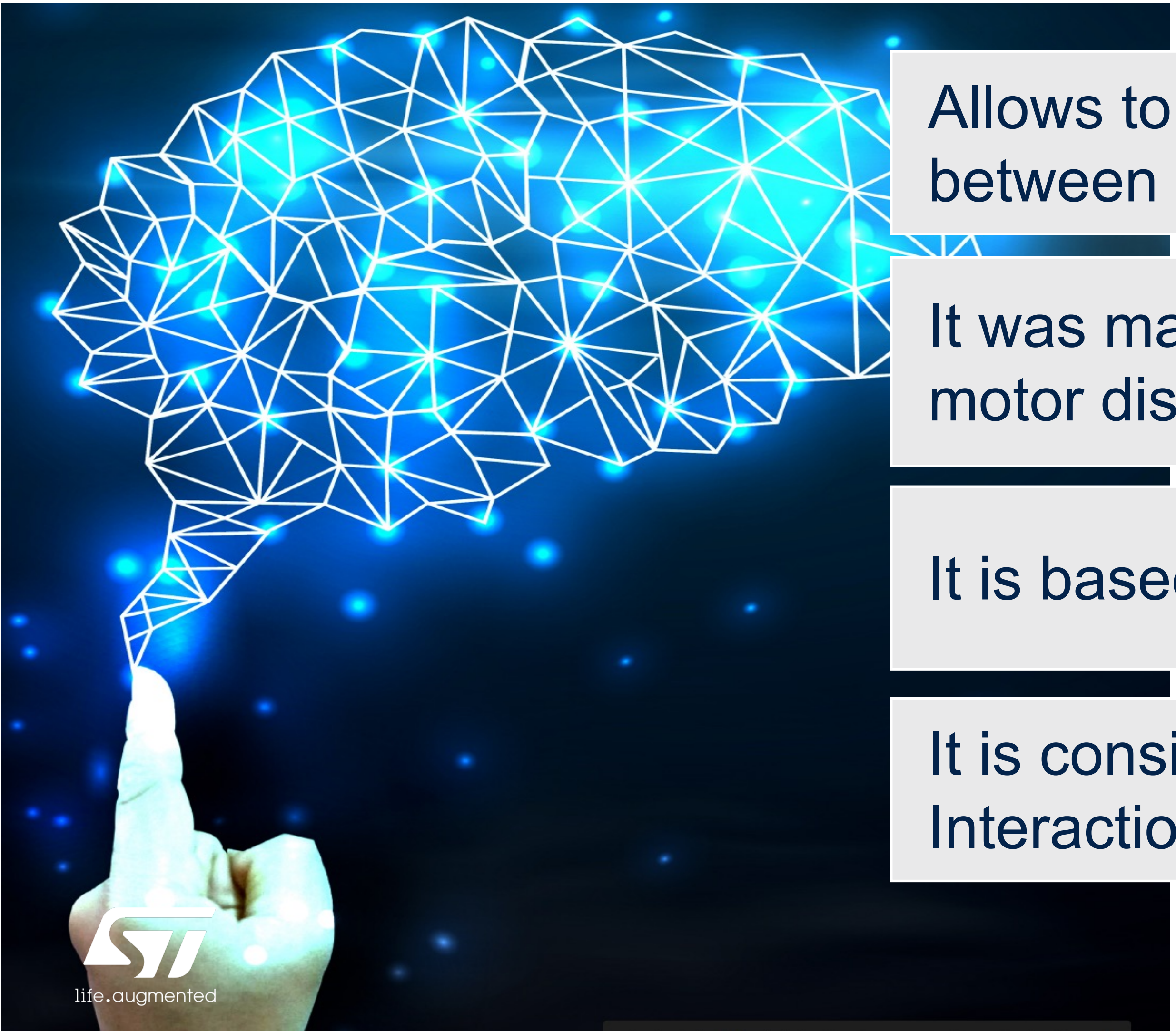
Brain Computer Interface (BCI)



Allows to establish a direct communication link between the human brain and an external device

It was mainly conceived to assist people with severe motor disabilities

It is based on grabbing and decoding brain waves

It is considered a new frontier of Human Machine Interaction (HMI)

State of the art

Li et al. [1] proposed a single blink EOG-based switch for the “start/stop” control of a wheelchair

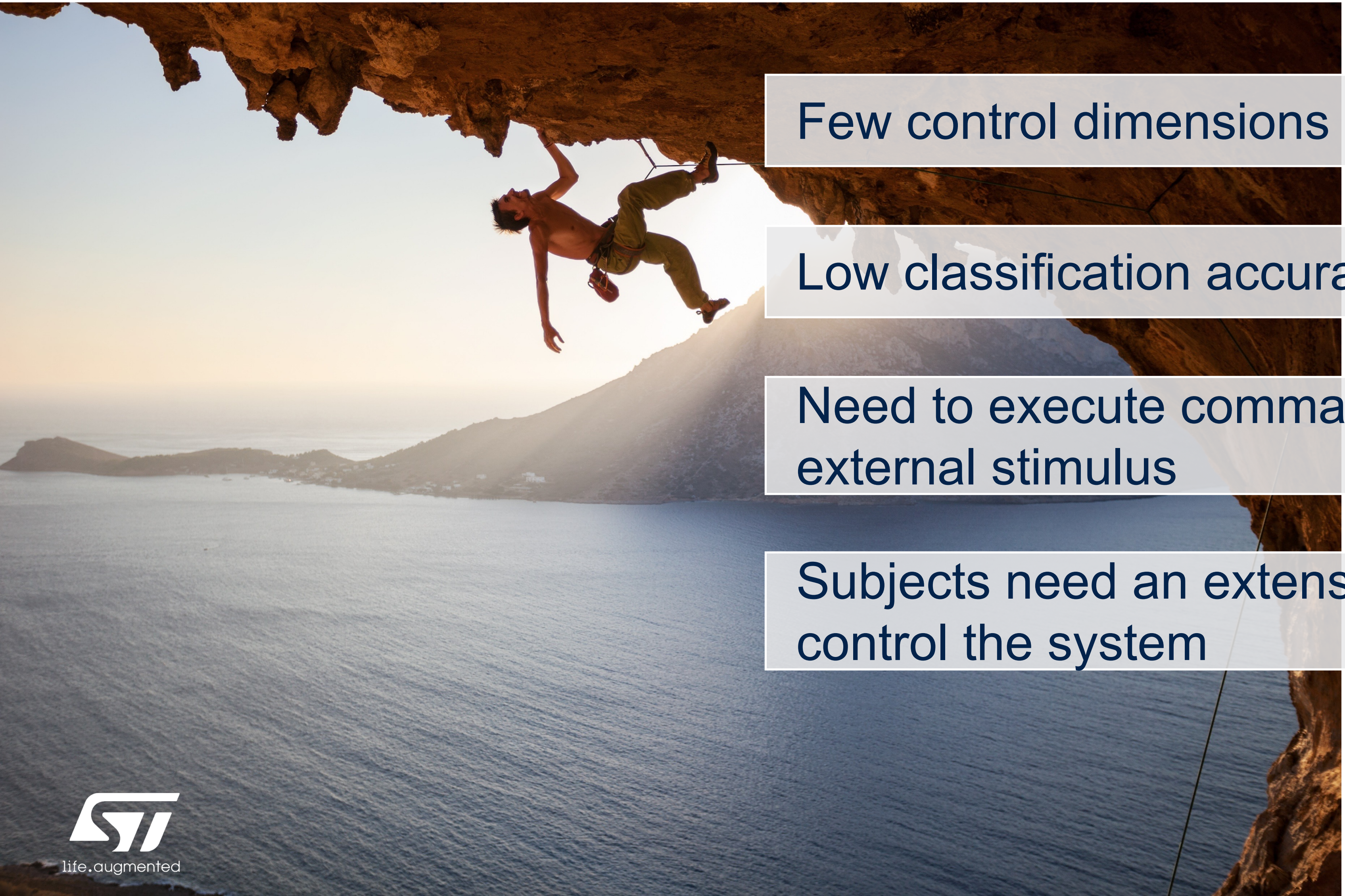
Djeha et al. [2] investigated a combination of EEG and EOG eye movements to allow the control of a wheelchair in a virtual environment. NN where used, with 93% accuracy

O’Brien et al. [3] took a multimodal approach using EOG and EMG data from the eyes to move Forward, Left, Right and Stop a wheelchair. Multiple Classification Ripple Down Rules model used, with 97.7% accuracy

Sharma et al. [4] detected eye closing/opening from EOG to build an interface for robotic arm control for a pick and place task with the average detection accuracy was 96.9%

[1] Y. Li, S. He, Q. Huang, Z. Gu, and Zhu Liang Yu. A eog-based switch and its application for “start/stop” control of a wheelchair. Neurocomputing, 275:1350–1357, 2018.
[2] M. Djeha, F. Sbargoud, M. Guiatni, K. Fellah, and N.Ababou. A combined eeg and eog signals based wheelchair control in virtual environment. In 2017 5th International Conference on Electrical Engineering-Boumerdes (ICEE-B), pages 1–6. IEEE, 2017.
[3] S. O’Brien and G. Alici. Control of an electric wheelchair using multimodal biosignals and machine learning. In 2021 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM), pages 994–999. IEEE, 2021.
[4] K. Sharma, N. Jain, and P. K Pal. Detection of eye closing/opening from eog and its application in robotic arm control. Biocybernetics and Biomedical Engineering, 40(1):173–186, 2020.

Challenges of BCI systems



- Few control dimensions
- Low classification accuracy
- Need to execute commands synchronously with an external stimulus
- Subjects need an extensive training to be able to control the system

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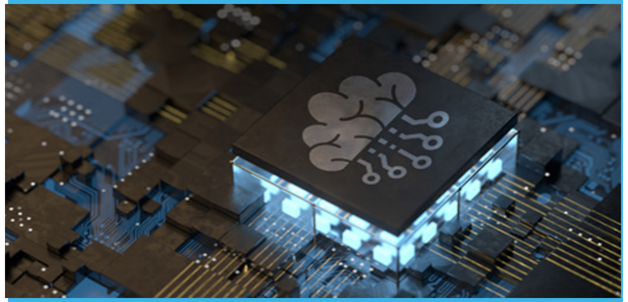
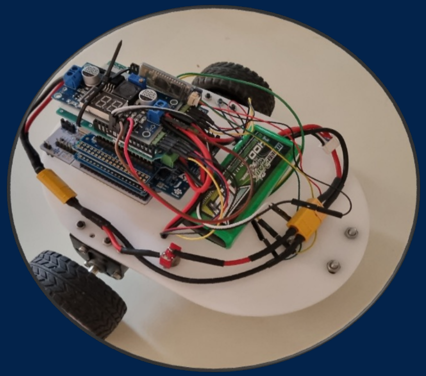
This work: brain computer interface for robotic control

READ SIGNALS FROM THE BRAIN



SIGNAL PROCESSING AND MACHINE LEARNING



SEND COMMANDS TO A ROBOT

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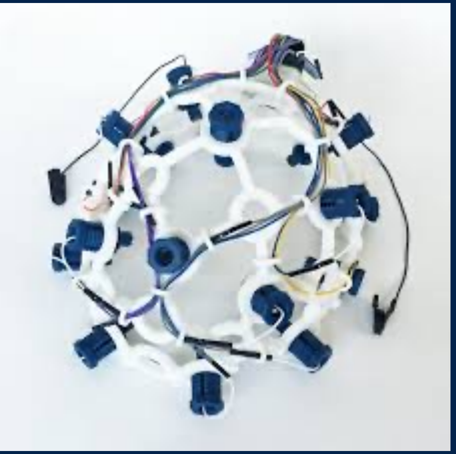
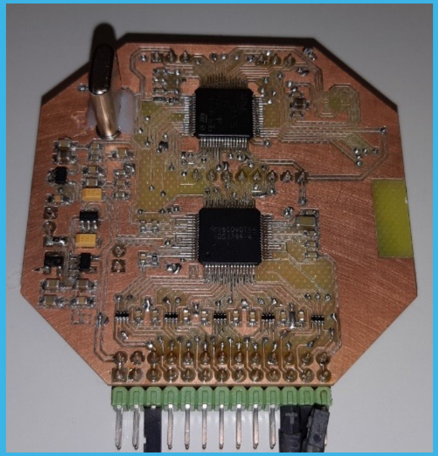
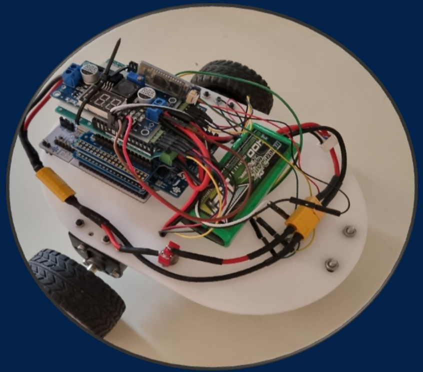
The hardware



HELMET FROM THE OPEN BCI PROJECT



CUSTOM BOARD WITH AN STM32 MICROCONTROLLER



WILL-E: 3 WHEELED ROBOTIC PLATFORM

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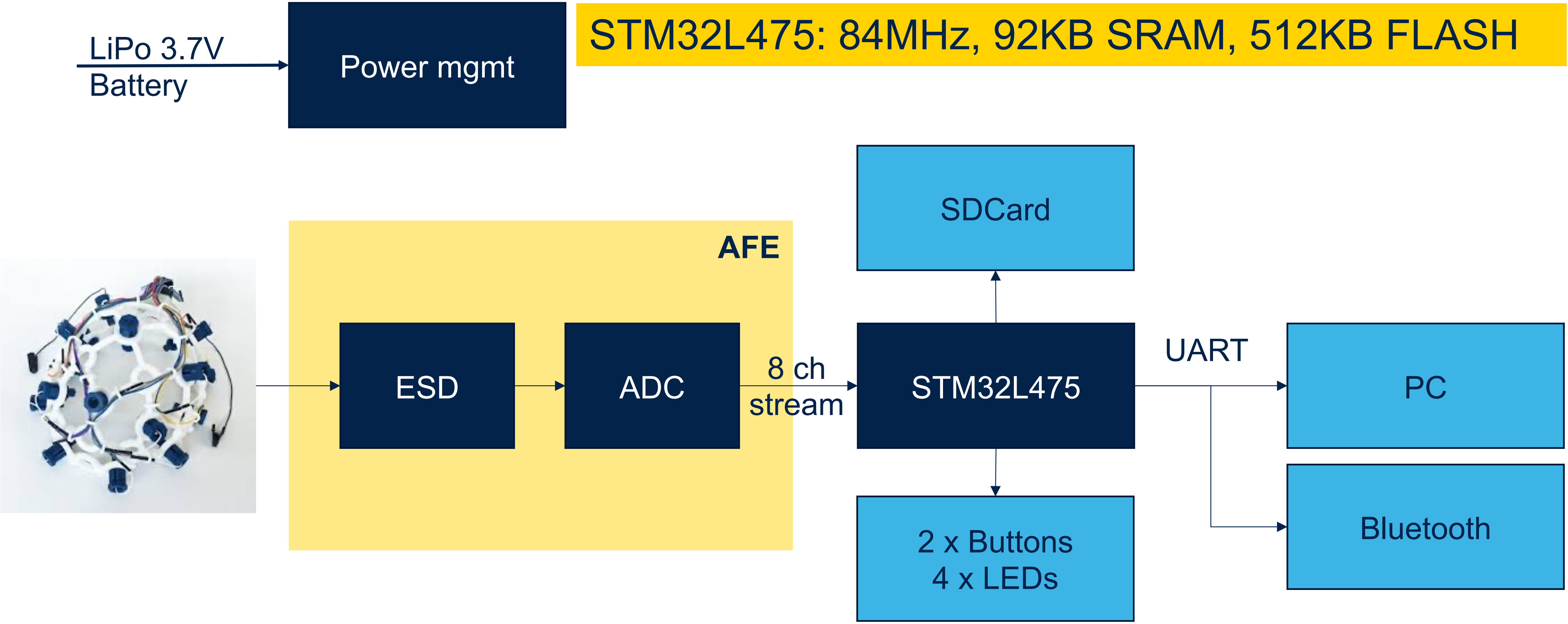
https://openbci.com/

Custom board with STM32 microcontroller



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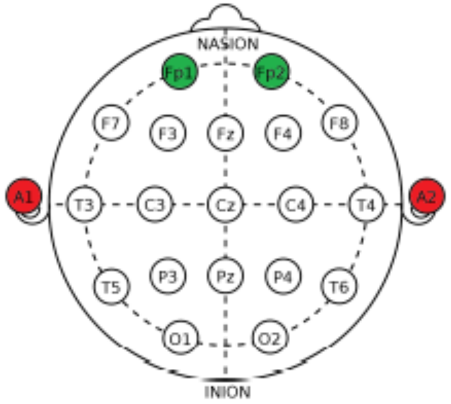
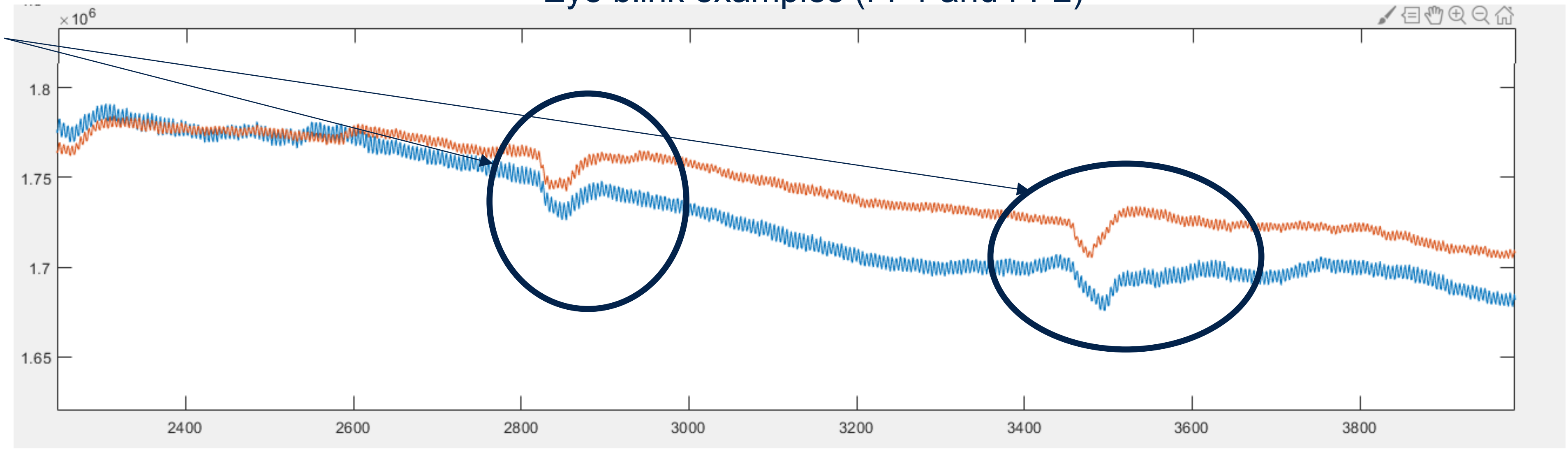
Machine learning on Electro-Oculography (EOG) signals



Goal: recognize voluntary/involuntary blinks and right/left winks from fronto polar sensors (Fp1 and Fp2)

Eye blink examples (FP1 and FP2)

Eye blinks



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Data collection

8 healthy adults without neurological disorders and without previous experience with BCI

Visual cue was presented on the screen indicating:
- LW (left wink)
- RW (right wink)
- VB (voluntary blink)

Note: IB (Involuntary blink) was spontaneous

Balanced dataset with 2600 samples has been collected and labelled

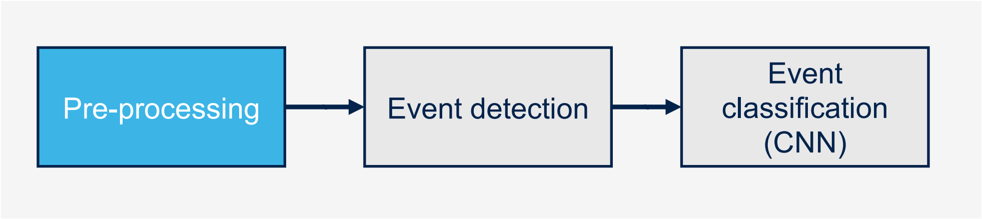
Firmware pipeline

EOG sensors

ADC → Pre-processing → Event detection → Event classification (CNN)

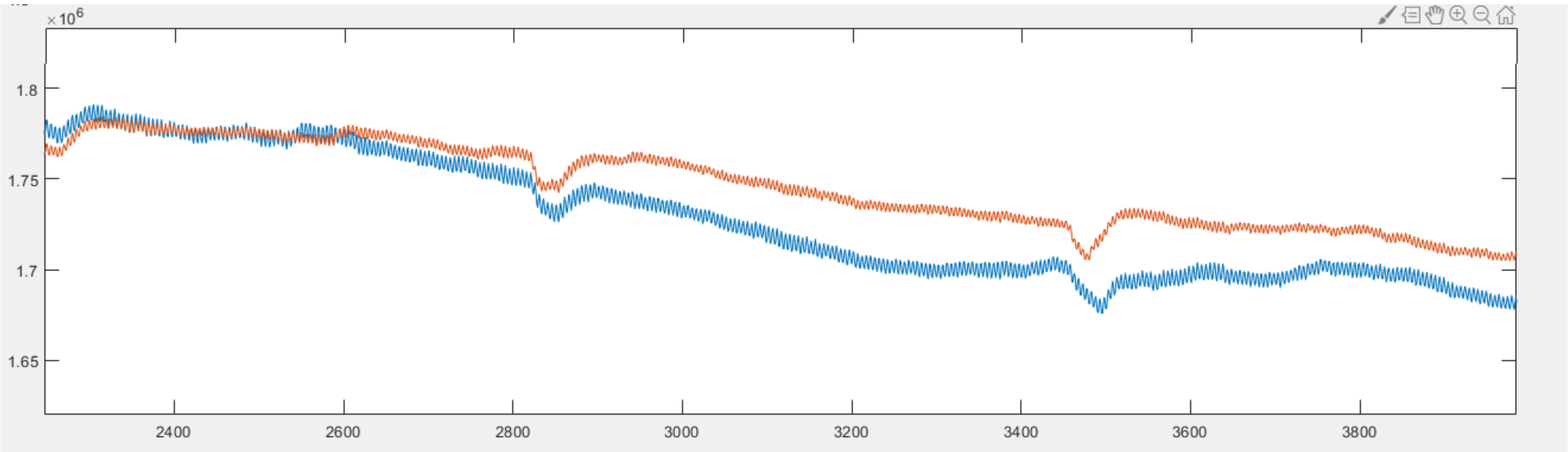
→ Blinks (Voluntary, Involuntary)

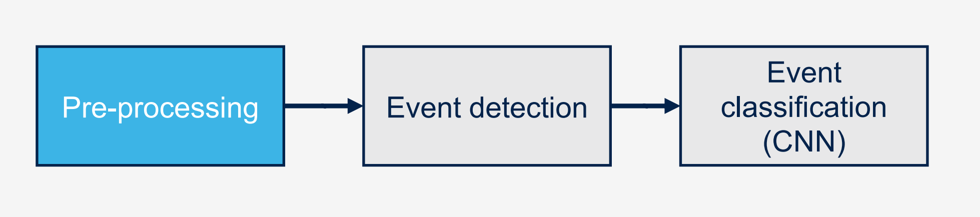
→ Winks (Left, Right)



Pre-processing

Aims at:
- Eliminating the DC component
- Reducing noise (50Hz/60Hz)

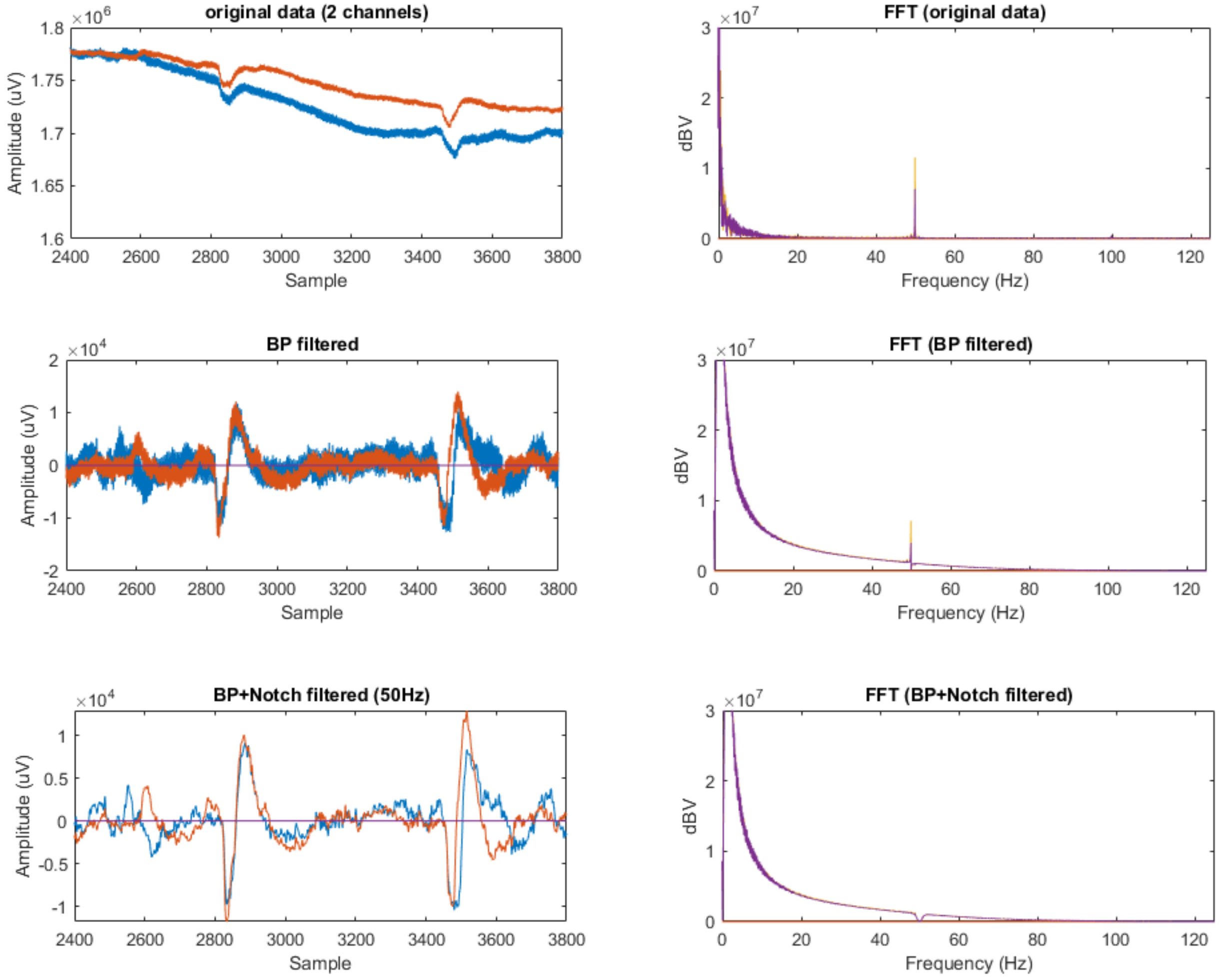


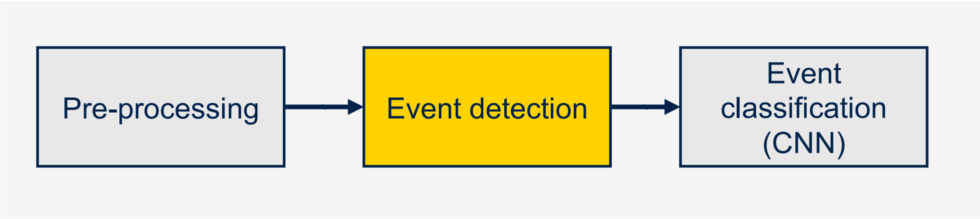


Pre-processing example

Real-time IIR band-pass filter
Cut-off frequencies:
f1= 0.1Hz
f2=50 Hz

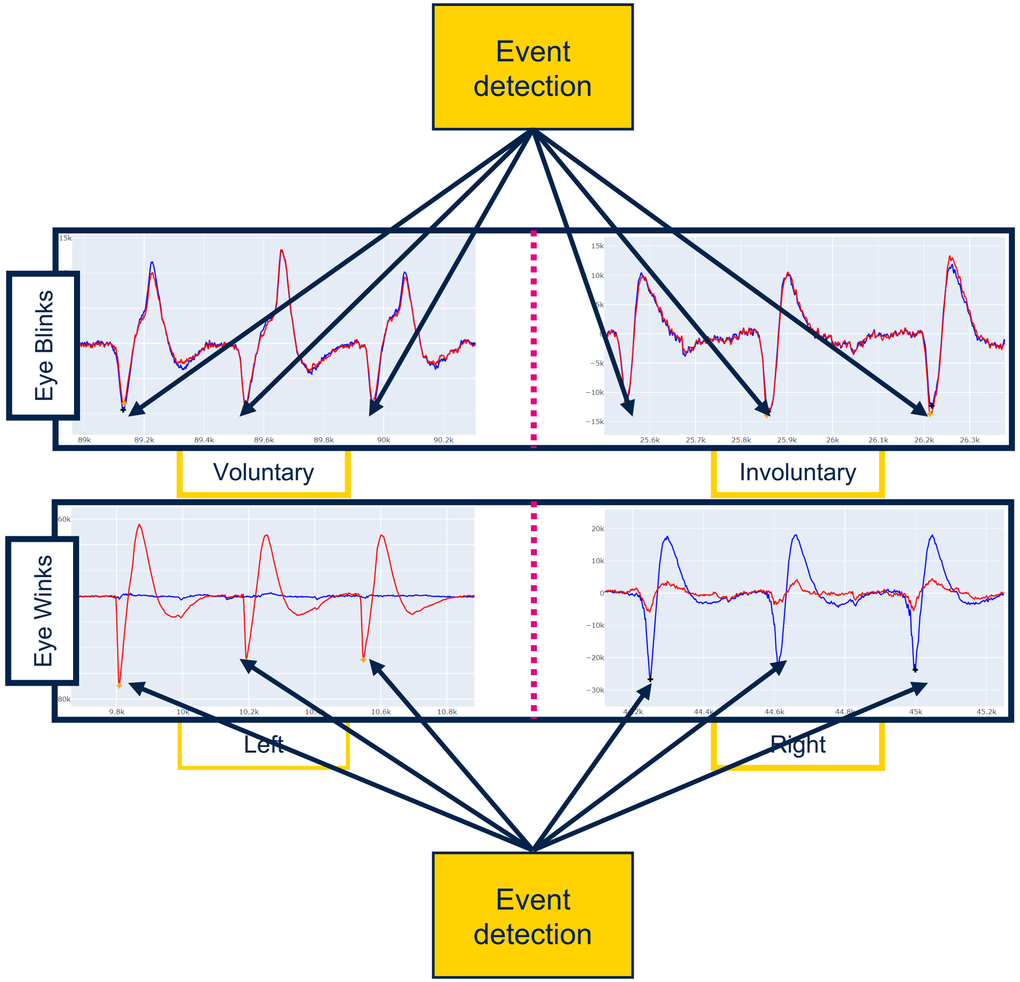
Real time IIR notch filter
f=50Hz





Event detection

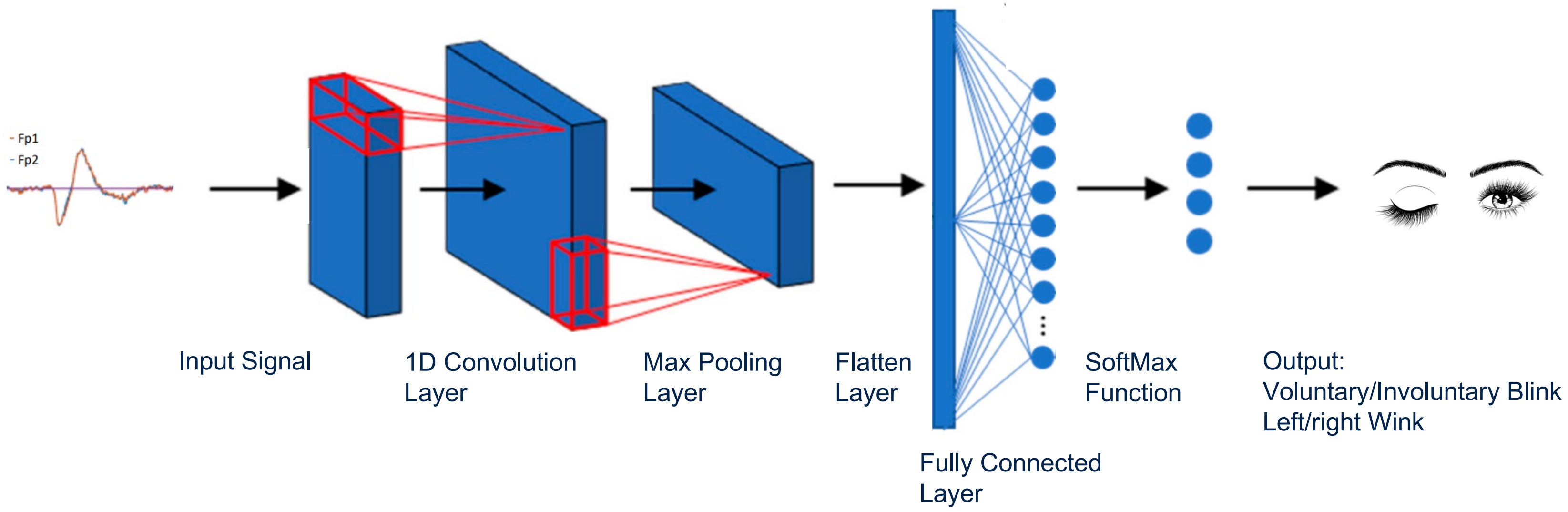
- Aims to detect negative peaks
- Algorithm is based on z-score
- It triggers the collection of 200 samples



Ref.: JPG van Brakel. Robust peak detection algorithm (using z-scores). Stack Overflow: New York, NY, USA, 2014

Pre-processing → Event detection → **Event classification (CNN)**

Event classification (CNN)




```
Model: "sequential"
_________________________________________________________________
Layer (type)                 Output Shape              Param #
=================================================================
conv1d (Conv1D)              (None, 191, 60)           1260
_________________________________________________________________
max_pooling1d (MaxPooling1D) (None, 9, 60)             0
_________________________________________________________________
flatten (Flatten)            (None, 540)               0
_________________________________________________________________
dense (Dense)                (None, 20)                10820
_________________________________________________________________
dense_1 (Dense)              (None, 4)                 84
=================================================================
Total params: 12,164
Trainable params: 12,164
Non-trainable params: 0
```

From keras to C

STM32 Cube.AI

Memory usage on MCU

Complexity: 262504 MACC
Used Flash: 65.64 KiB (65.64 KiB over 1024.00 KiB Internal)
Used Ram: 10.48 KiB (10.48 KiB over 128.00 KiB Internal)
Achieved compression: -
Analysis status: done

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Results

Accuracy: 99%

Footprint on STM32L475 MCU:
- Flash: 66 KB
- RAM: 11 KB

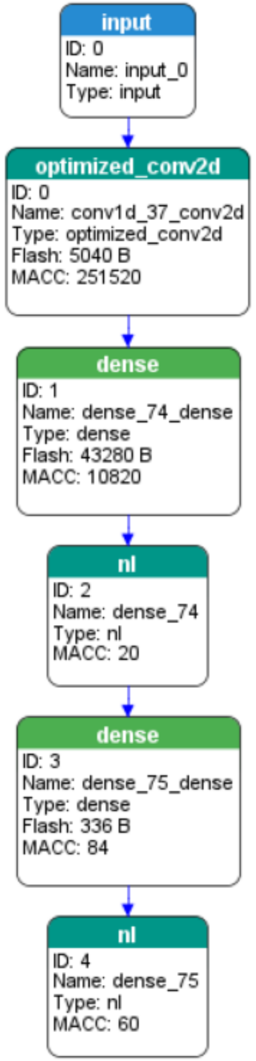
Complexity
- 270K MACC

$$\frac{\#\, training\ samples}{\#\, parameters} = \frac{2000}{12000} \cong 17\%$$

Confusion matrix:

	VB	IB	LW	RW
VB	98.6%	1%	0.3%	0.1%
IB	0.7%	99,3%	0	0
LW	0	0.2%	99.8%	0
RW	0.3%	0	0	99.7%

VB: Voluntary (or forced) Blinks
IB: Involuntary Blinks
LW: Left Winks
RW: Right Winks



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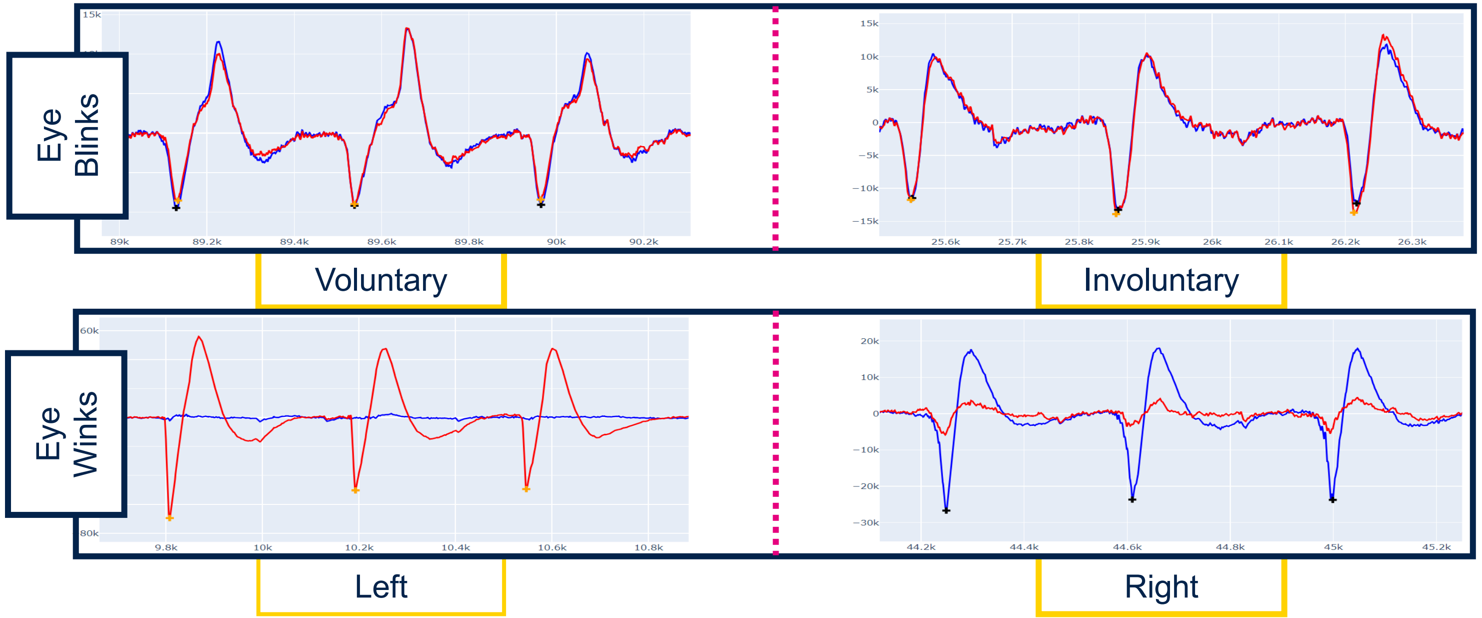
Execution on STM32L475 MCU

Inference time: 0.02 s
Acquisition time: 200/250 = 0.8 s (fs = 250 hz)
Total time: 0.82 s

Power consumption: 0.67 mW

GO AHEAD 20cm

NOTHING TO DO



TURN LEFT 45°

TURN RIGHT 45°

Commands sent to the Robot
VB: Go ahead 20 cm
IB: Nothing to do
LW: Turn 45° left
RW: Turn 45° right

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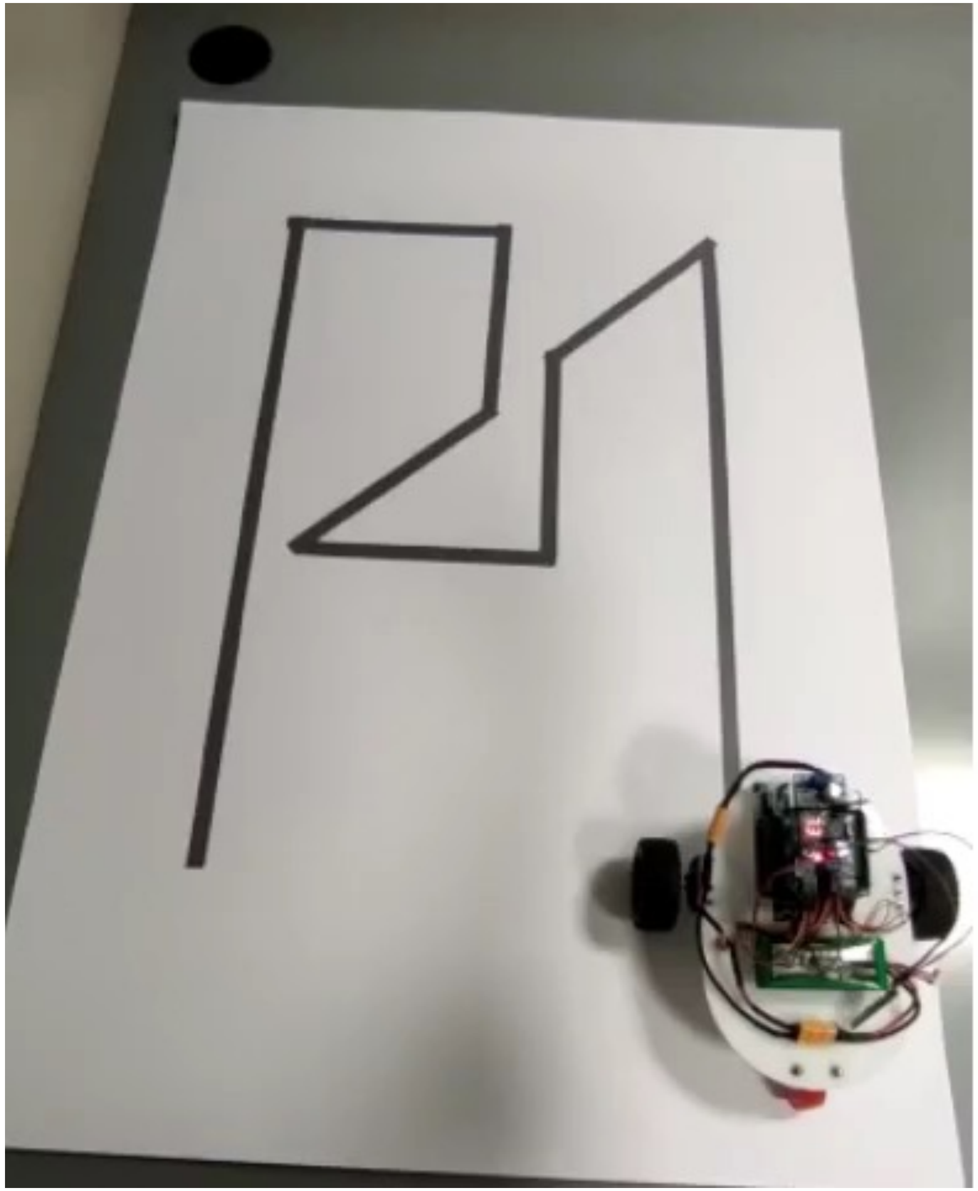
Complete algorithm running on the microcontroller



Conclusions

- First BCI system running on a tiny embedded device
- The CNN achieves 99% of accuracy
- It works in real time (0.02 s)

Future works

- Increase robustness to noise artifacts and body movements
- Personalization
- Gaze tracking from EOG signals

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Questions?

[1] Bruna A, Tomaselli V, Chepyk O, Mammone N, Morabito F C , Ruggeri G, Campolo M,"An Embedded EOG-based Brain Computer Interface System for Robotic Control", International Conference on smart and sustainable technologies (SpliTech), Split 20-23 June, 2023

[2] Chepyk O, Bruna A, Tomaselli V, Mammone N, Campolo M, Ruggeri G, Ieracitano C, Morabito F C, "An Embedded Deep Neural Model for EOG-controlled Brain Computer Interfaces", WIRN 2023, 7-9 June 2023, Vietri sul mare (Italy)

[3] Lo Giudice M, Mammone N, Ieracitano C, Campolo M, Bruna A R, Tomaselli V, Morabito F C, "Visual Explanations of Deep Convolutional Neural Network for eye blinks detection in EEG-based BCI applications", IEEE World Congress On Computational Intelligence, 18-23 July 2022, Padua (Italy)

[4] Ieracitano C, Mammone N, Lo Giudice M, Tomaselli V, Bruna A R, Morabito F C, "EEG recordings and Eye Tracking for Brain-Computer Interfaces and Robotics", Automatica 2021, Catania 8-9 September 2021

[5] Lo Giudice M, Varone G, Ieracitano C, Mammone N, Bruna A R, Tomaselli V, Morabito F C, "1D Convolutional Neural Network approach to classify voluntary eye blinks in EEG signals for BCI applications", IEEE World Congress On Computational Intelligence, 2020

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