Embedded Systems

Lecture 11
Digital Signal Processing - Project

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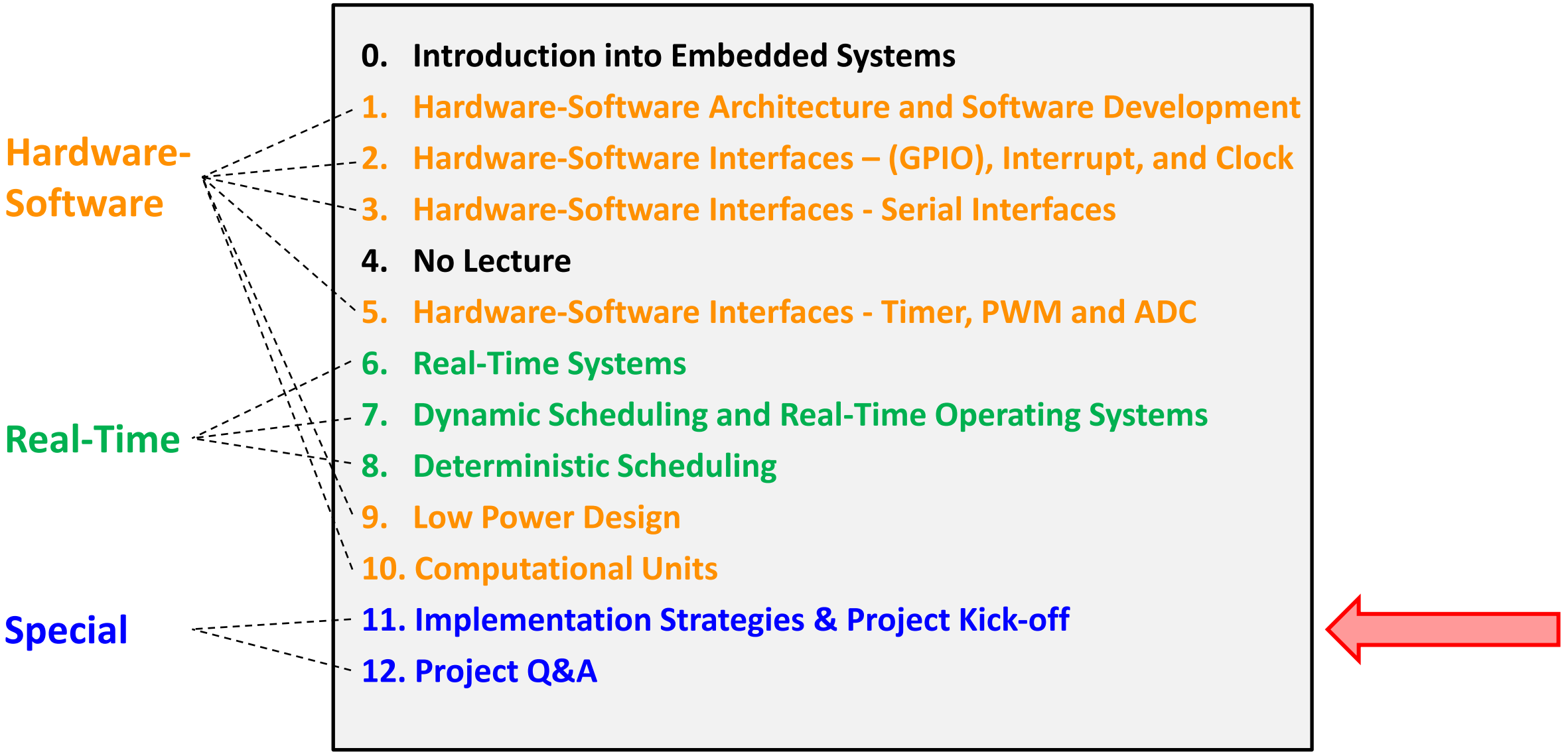
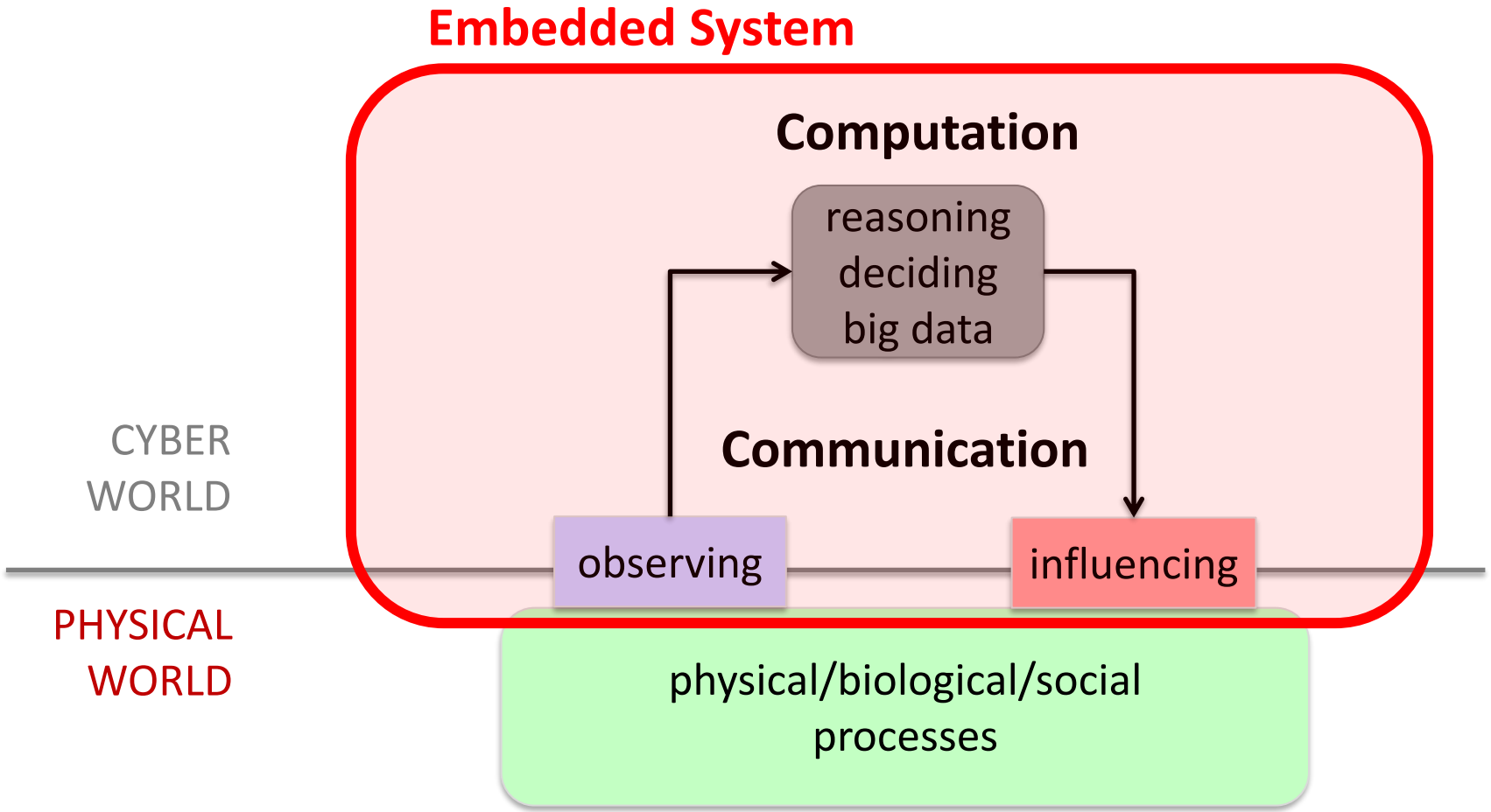
D-ITET Center for Project-Based Learning

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Where We are


Hardware-Software
Real-Time
Special
0. Introduction into Embedded Systems
1. Hardware-Software Architecture and Software Development
2. Hardware-Software Interfaces – (GPIO), Interrupt, and Clock
3. Hardware-Software Interfaces - Serial Interfaces
4. No Lecture
5. Hardware-Software Interfaces - Timer, PWM and ADC
6. Real-Time Systems
7. Dynamic Scheduling and Real-Time Operating Systems
8. Deterministic Scheduling
9. Low Power Design
10. Computational Units
11. Implementation Strategies & Project Kick-off
12. Project Q&A

Embedded Systems



Use feedback to influence the dynamics of the physical world by taking smart decisions in the cyber world

Components and Requirements by Example

- Hardware – Software System Architecture -

High-Level Software View

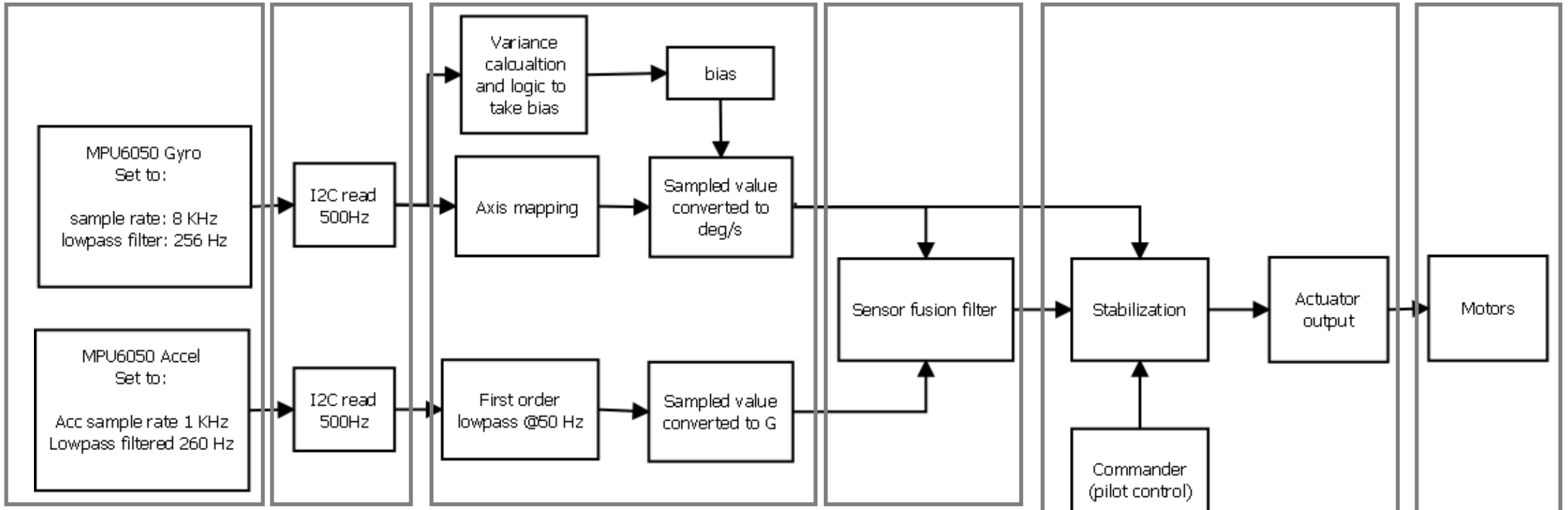
The *software architecture* supports

- *real-time tasks* for motor control (gathering sensor values and pilot commands, sensor fusion, automatic control, driving motors using PWM (pulse width modulation, …) but also

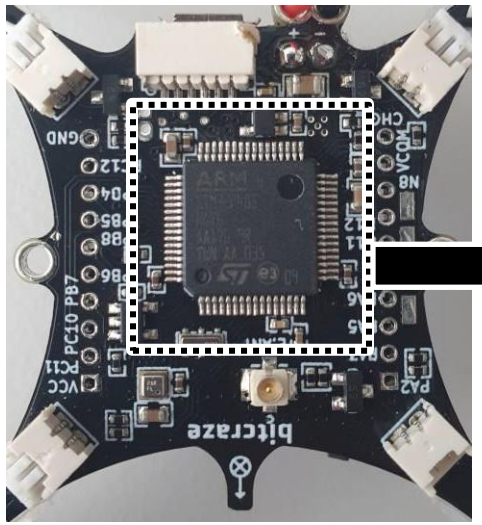
- *non-real-time tasks* (maintenance and test, handling external events, pilot commands, …).

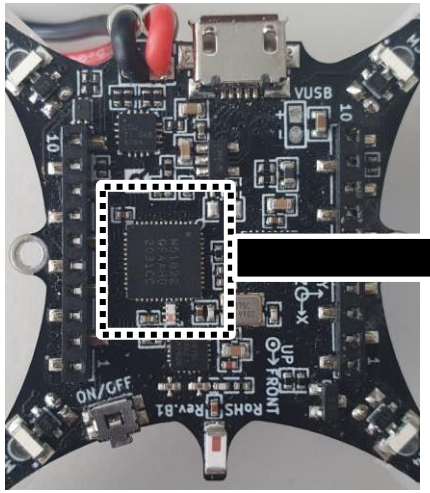
High-Level Software View

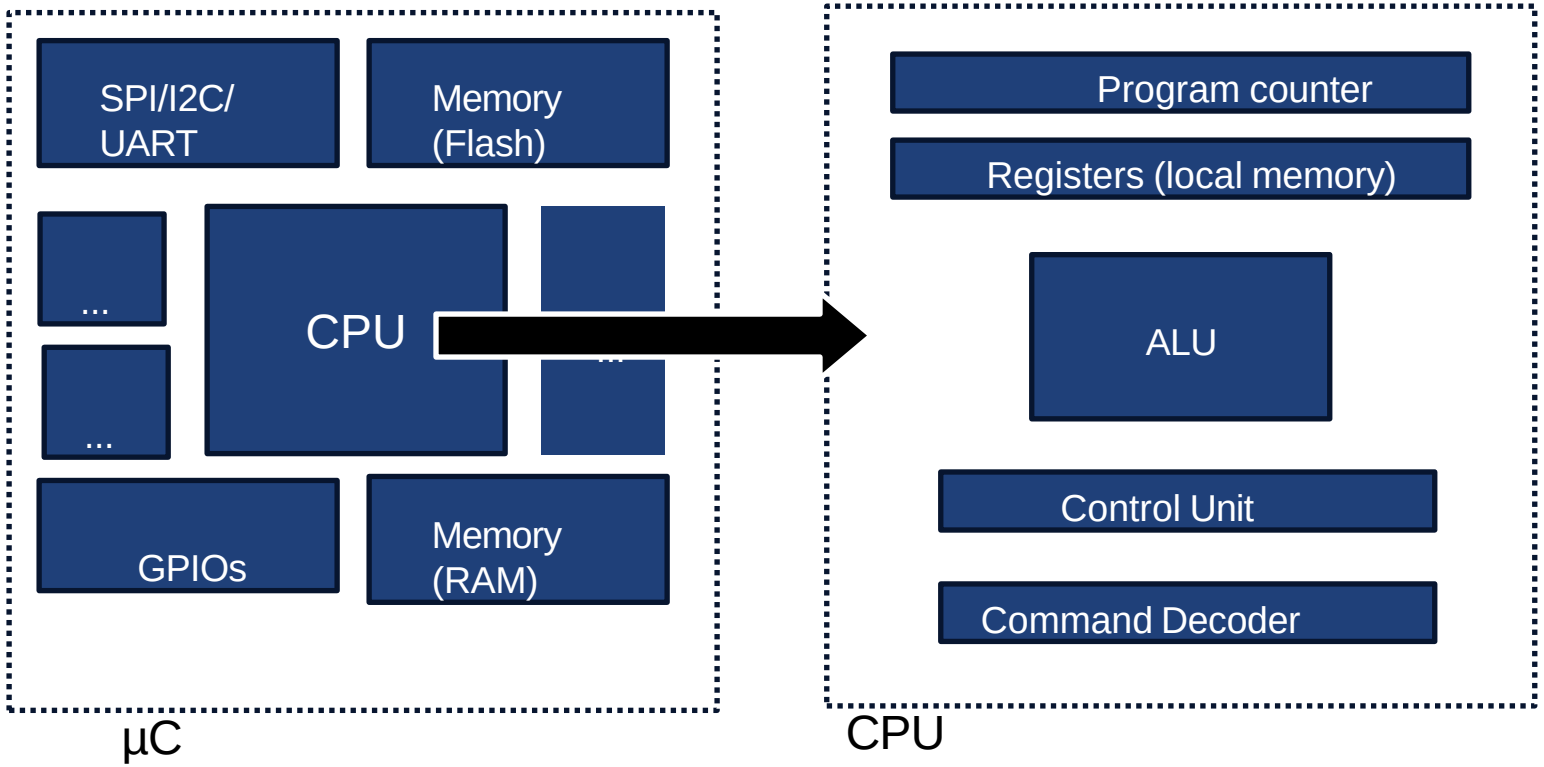
Block diagram of the stabilization system:



Where is the Software Processed?

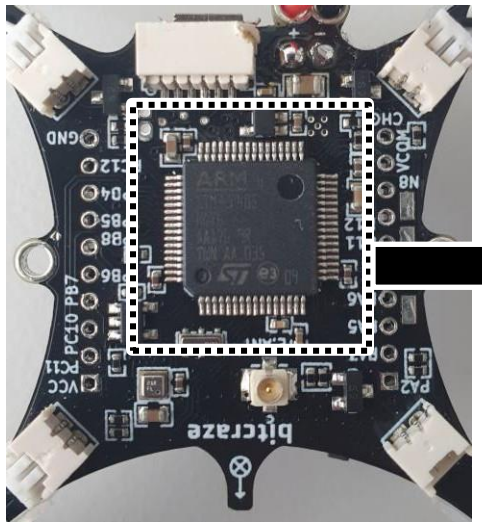


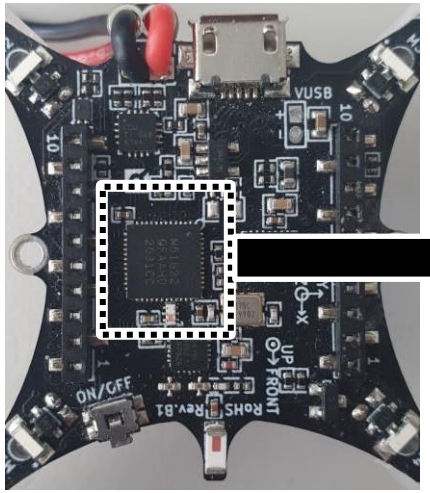




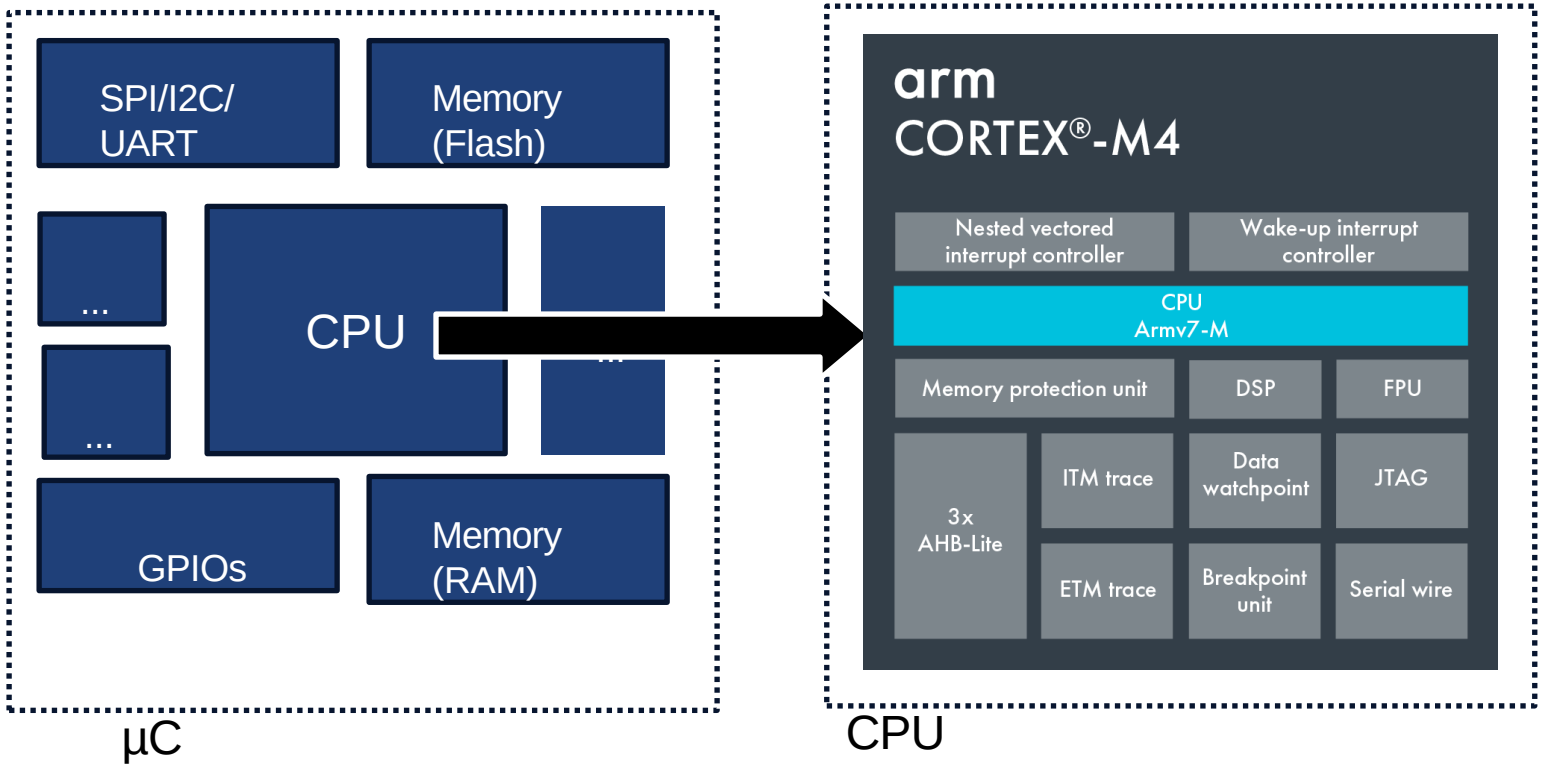
Embedded systems with drones

Where is the Software Processed?

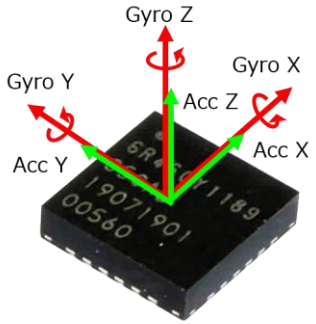




Embedded systems w ith drones

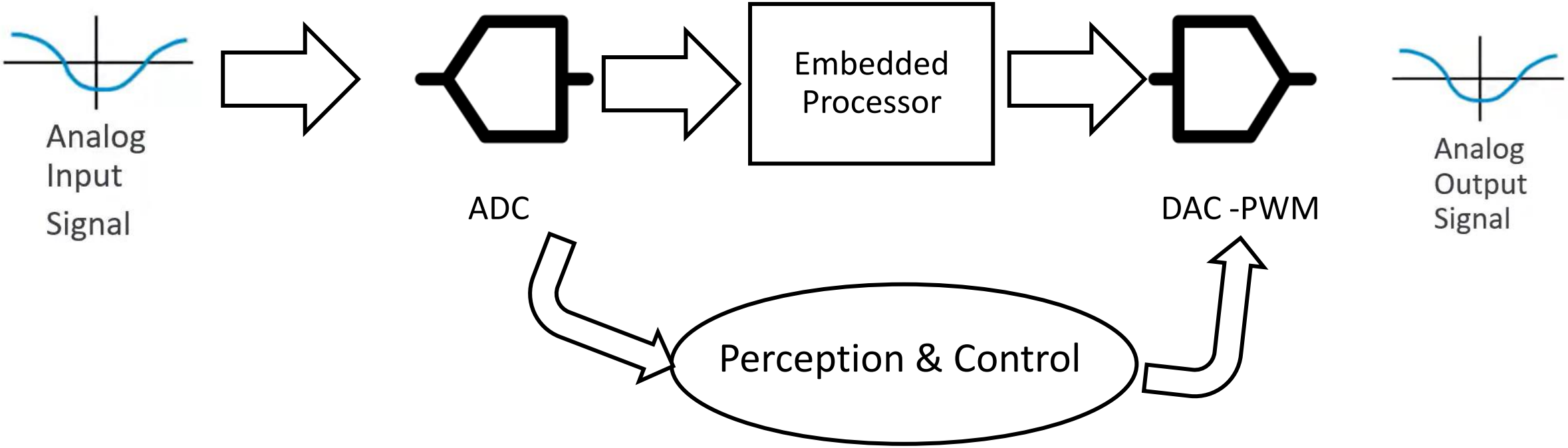


Digital Signal Processing



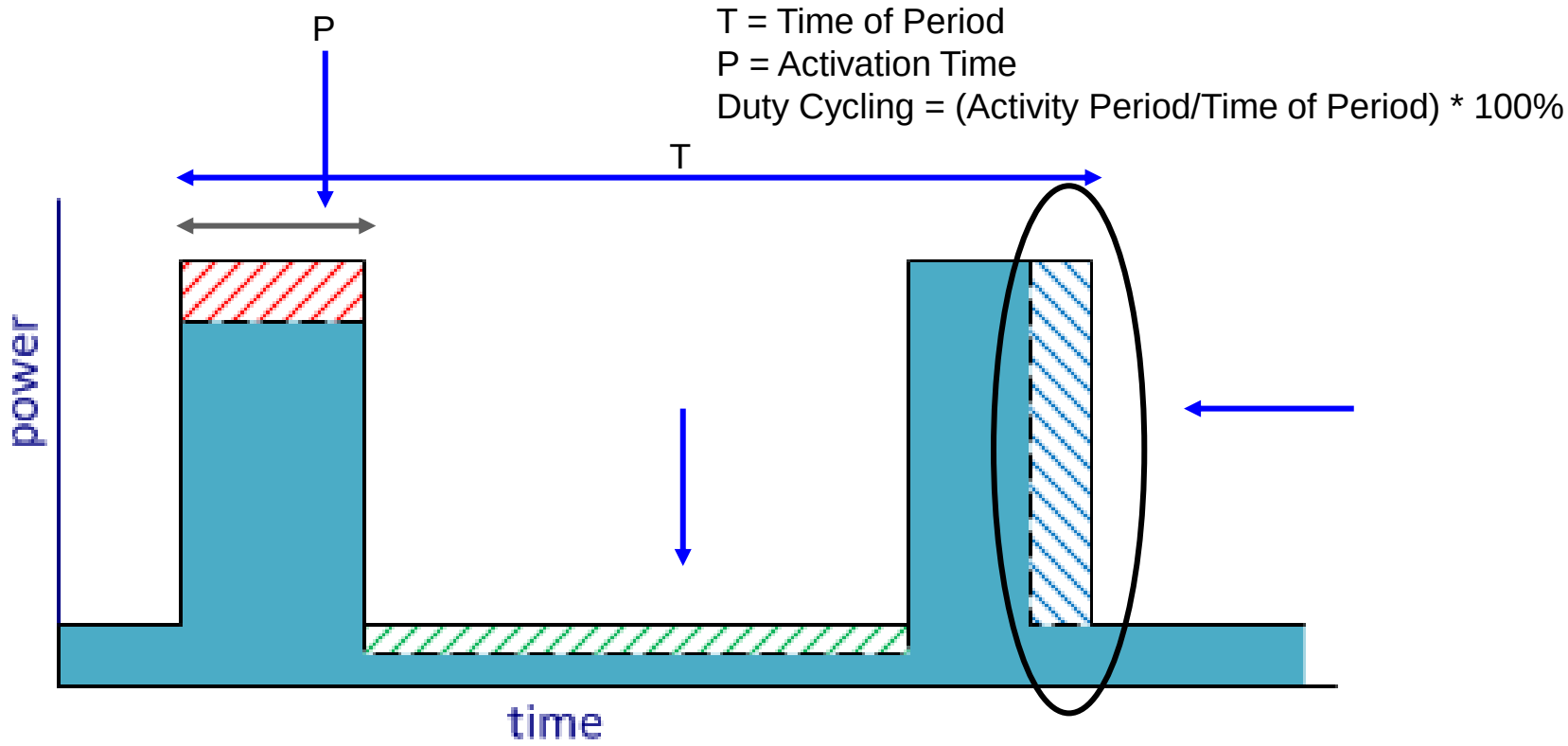
ARM Cortex-M4

with DSP Instruction



Performance is Energy – But also Latency!

- The relation and balance between the performance and execution time needs to be carefully analyzed to find a best compromise which leads to lowest energy consumption.

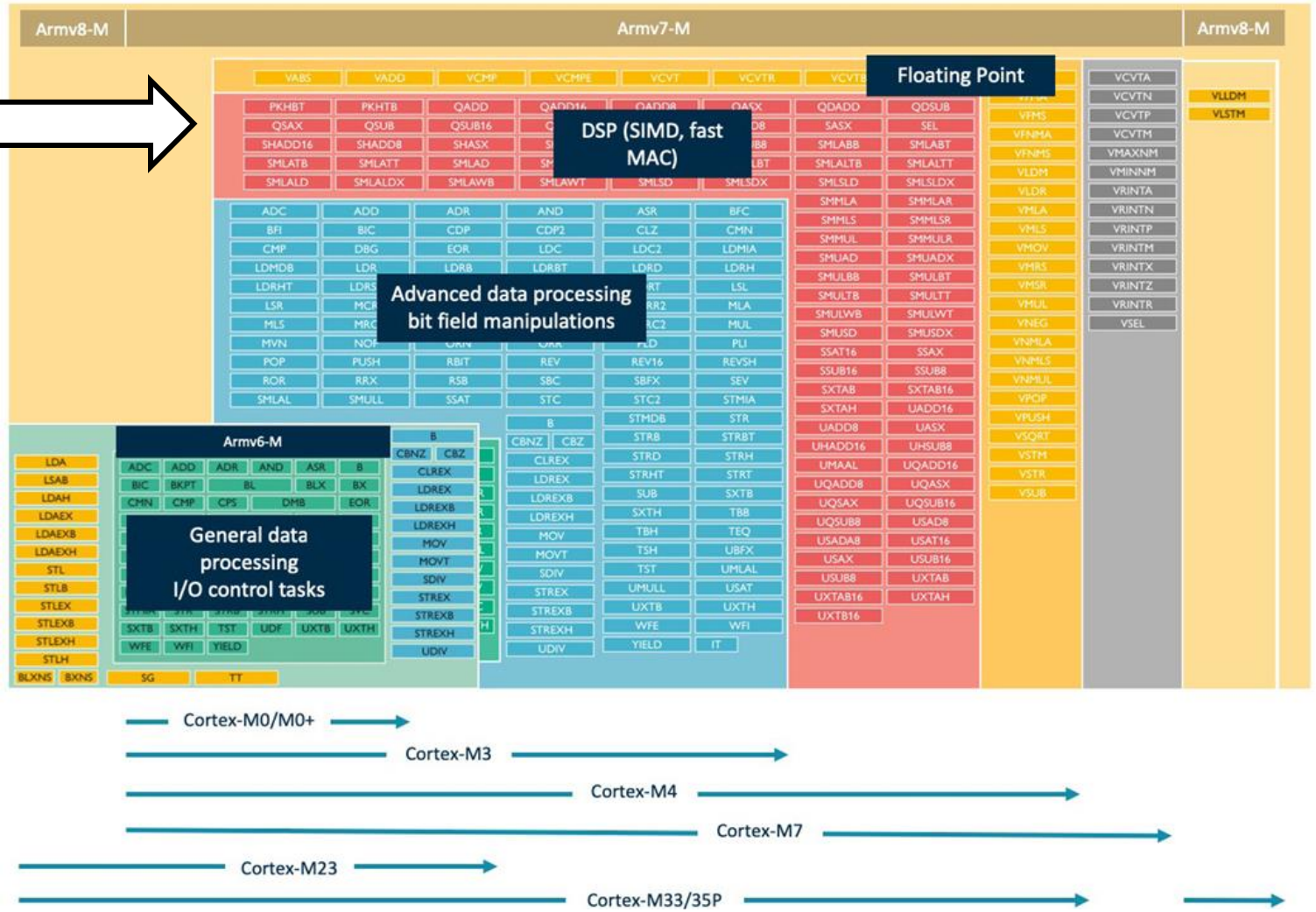


Less time spent in active ➔ lower total energy consumed.

We can do so by using optimization techniques.

The DSP extension instruction set (ARM)

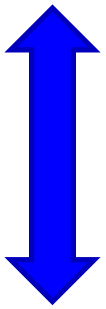
This provides a level of parallel processing where the register is still 32-bits, allowing more performance to be squeezed out of the processor.



You need to know your Architecture!

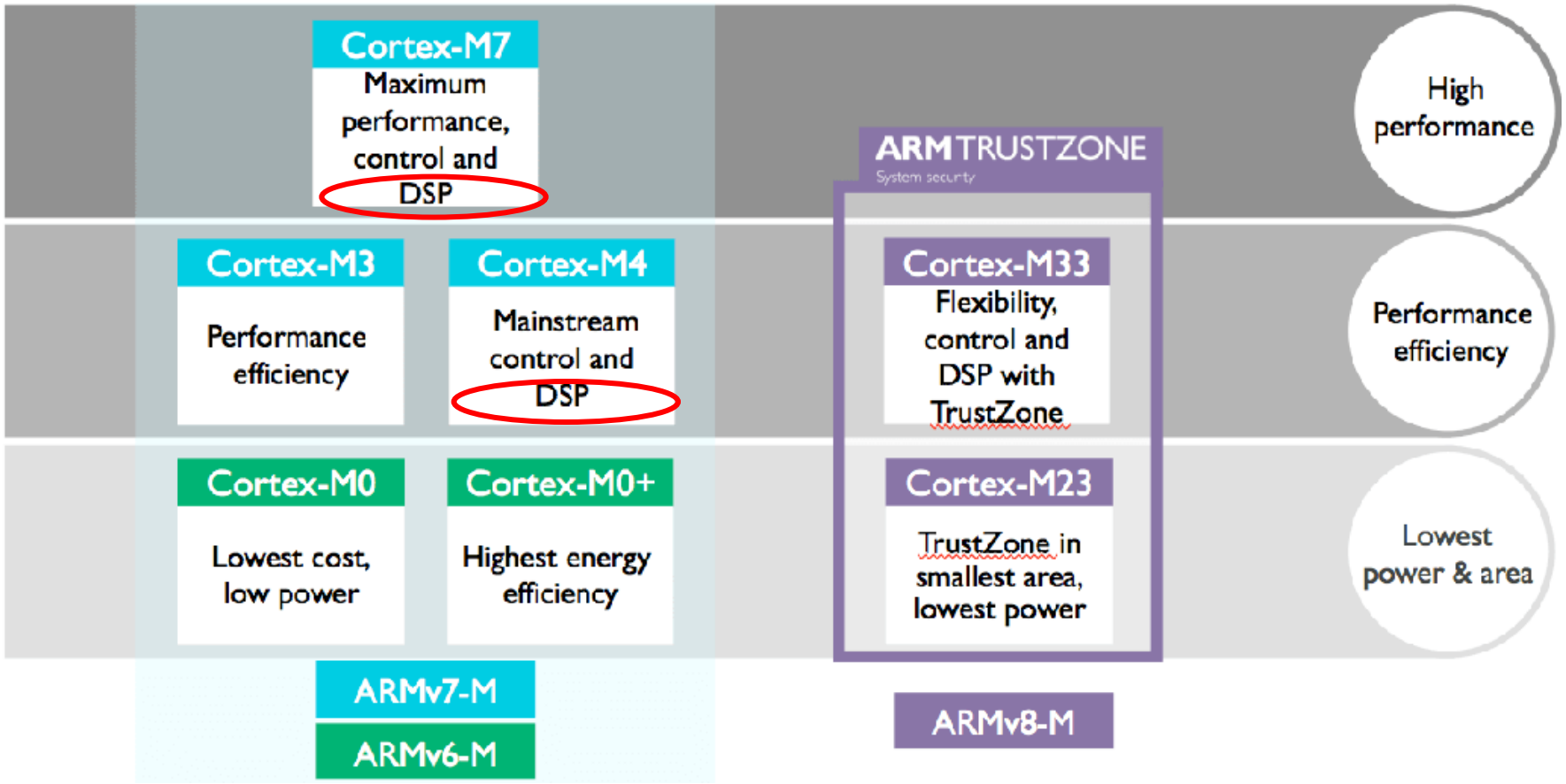
FPU Double precision

SIMD Instructions



No FPU

No DSP



Cortex® DSP instructions

The Cortex®-Mx cores feature several instructions that result in efficient implementation of DSP algorithms.

Collection of 61 algorithms including

- Basic mathematical functions with vector operations
- Fast mathematical functions, like sine and cosine
- Complex mathematical functions like calculating magnitude
- Filtering functions like FIR or IIR
- Matrix computing functions
- Transform functions like FFT
- Controller functions like PID controller
- Statistical functions like calculating minimum or maximum
- Support functions like converting from one format to another
- Interpolation functions

CMSIS-DPS mandatory for M4 and M7 and ML

There are a number of arithmetic instructions for integer and fractional datatypes supported by the Cortex-M4 and Cortex-M7 which are most frequently used in DSP algorithms

- Accellerating the Multiply ACcumulate (MAC) operation
- Enabling the SIMD (Single Instruction Multiple Data) instructions

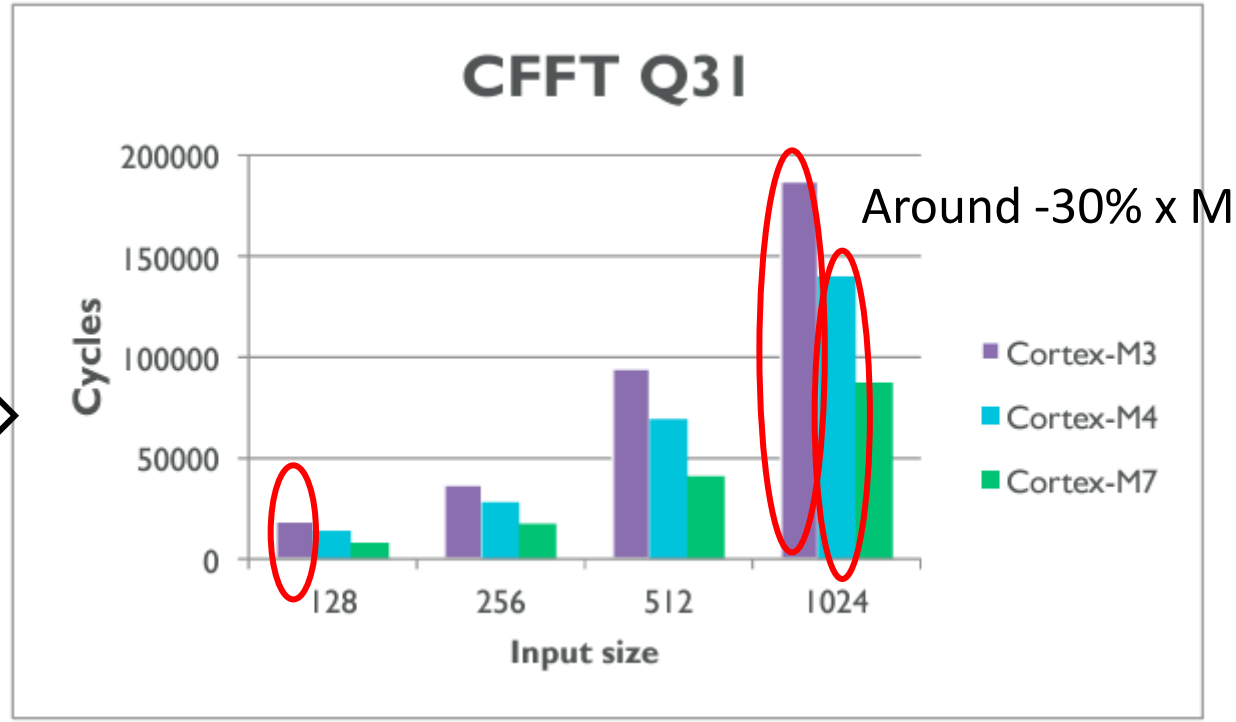
Fast Fourier Transforms (FFT) - ARM DSP.

Table Present the results for a running a Complex FFT for 32-bit input data (Q31) with block size varying from 32 to 1024

CFFT Q31	Block Size					
	32	64	128	256	512	1024
Cortex-M3	3374	6695	18549	36779	94267	187204
Cortex-M4	2577	5282	13823	28000	69253	139898
Cortex-M7	1497	3235	8050	17235	41076	87128

Cycle counts (hence small values are better).

Architecture is CRUCIAL



Source: The DSP capabilities of ARM® Cortex®-M4 and Cortex-M7 Processors

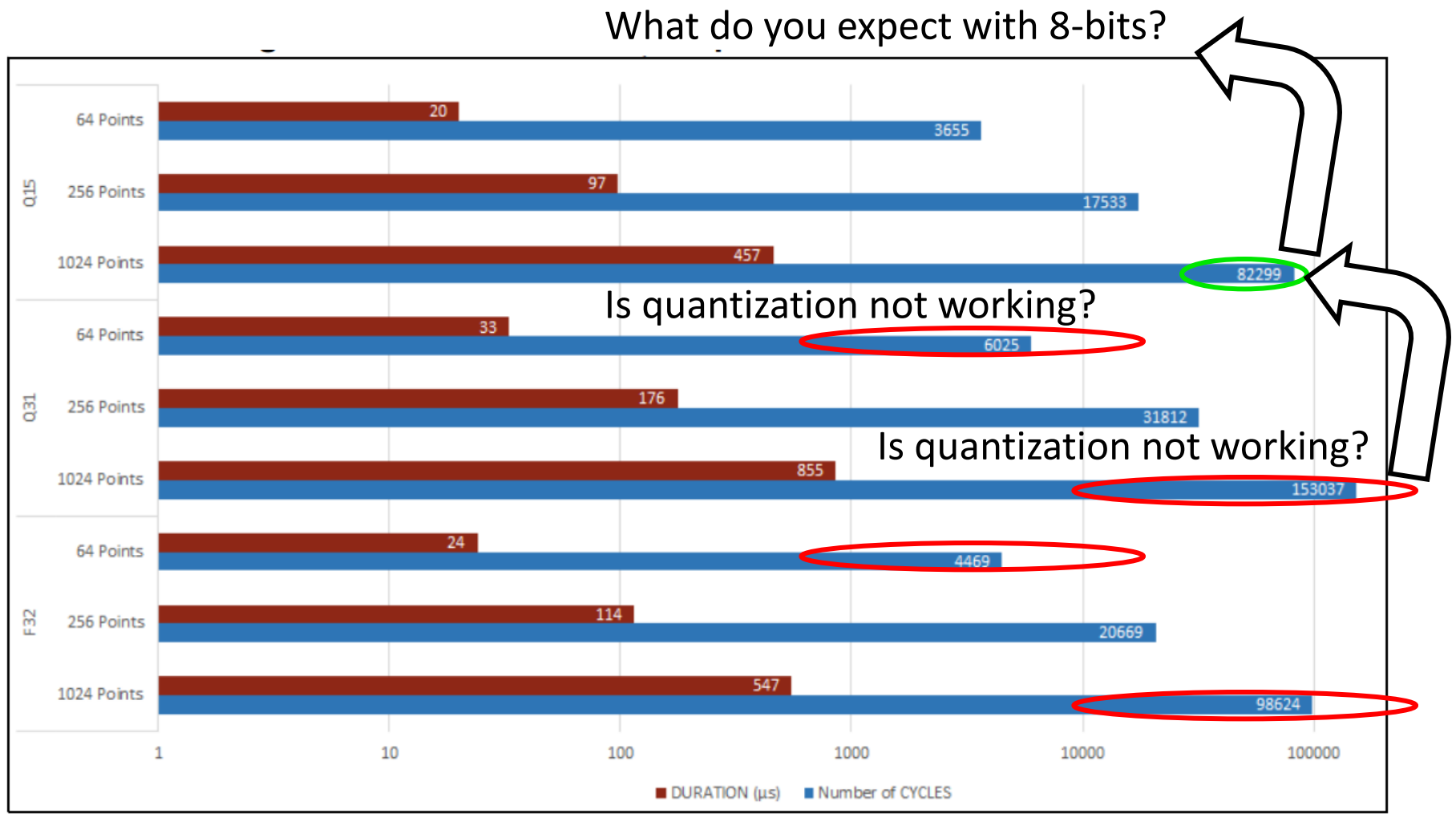
Cortex-M7 can execute up to two instruction per clock cycle (dual issue capability)

- Cortex-M7 has dynamic branch predication

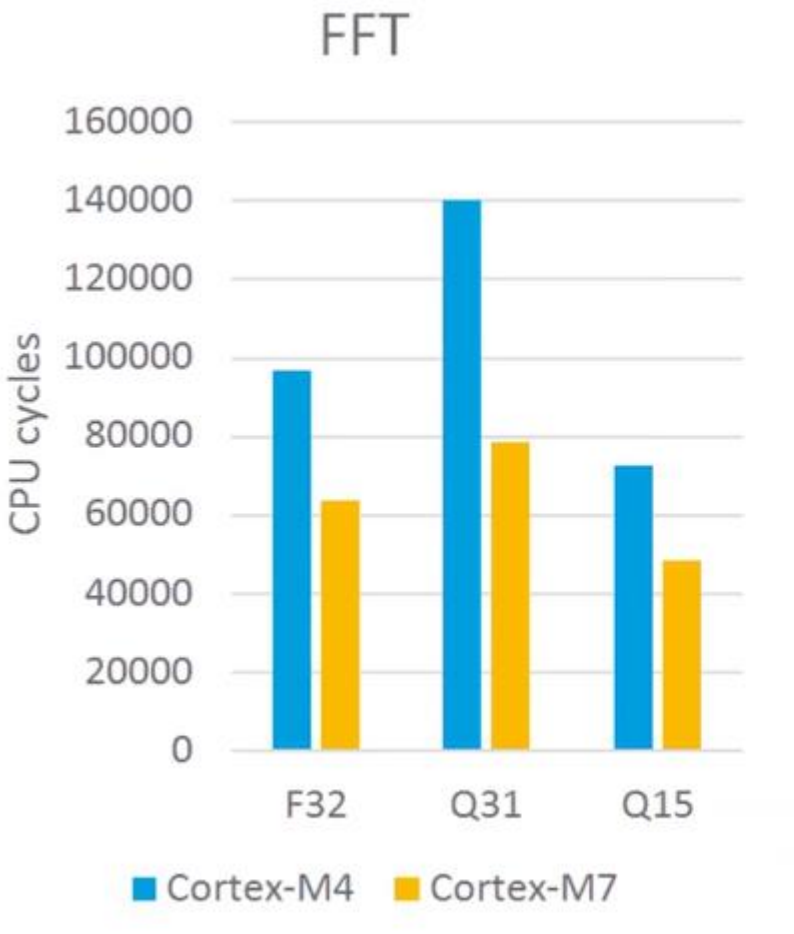
- The floating-point unit in Cortex-M7 is designed to support higher floating point processing capability

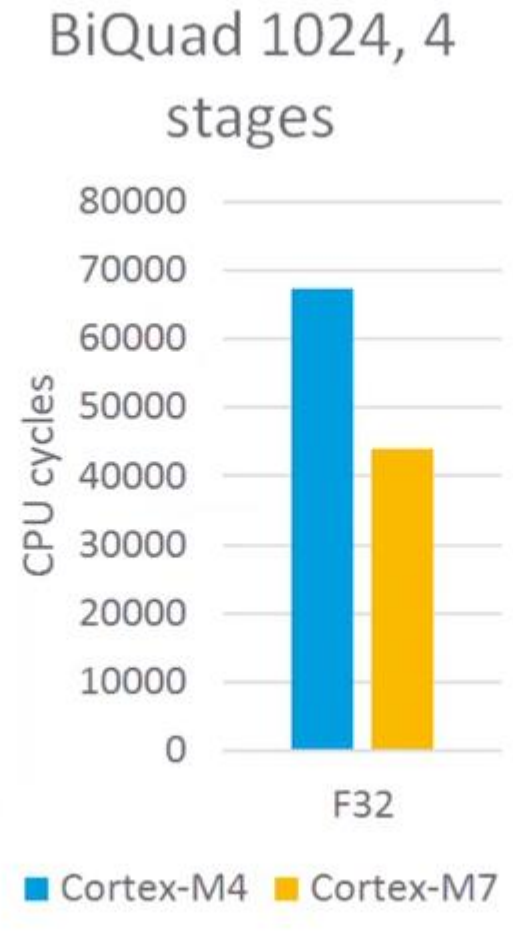
DSP and Fix vs Float

FFT size calculation performance ARM Cortex-M4F



Comparison M4 Vs M7 vs Operations and tasks





Quantifying the energy saving

- **Comparison of Energy Consumption:**

1. **Cycle Count Reduction:**
    1. Without DSP (or with NOT optimized code): 200 instructions.
    2. With DSP (or with optimized code): 50 instructions.
    3. **Reduction:** 75% fewer instructions executed.

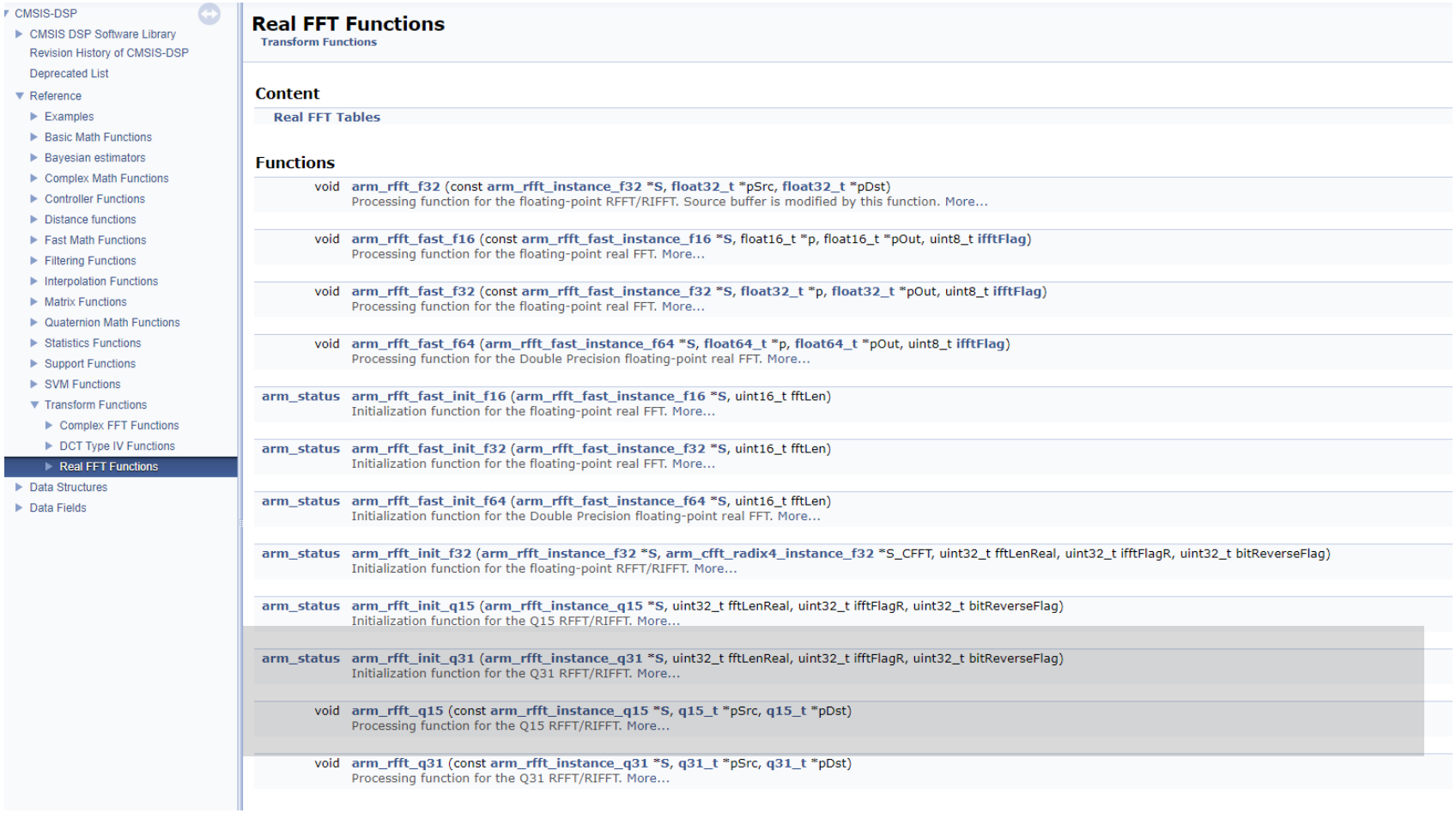
2. **Energy Savings:** Energy consumption is proportional to the number of instructions executed.
    1. If the microcontroller consumes $E_{xClockPeiod} = P_{ActiveMode}\, N_{instructios}$
    2. Energy Without DSP: 200× $E_{xClockPeiod}$
    3. Energy With DSP: 50× $E_{xClockPeiod}$
    4. Assuming $E_{xClockPeiod}$ Doesn't change with the use of DSP instructions
    5. **Energy Saved: 75% reduction**

CMSIS-DSP (LAB)

Example Real FFT function (LAB)

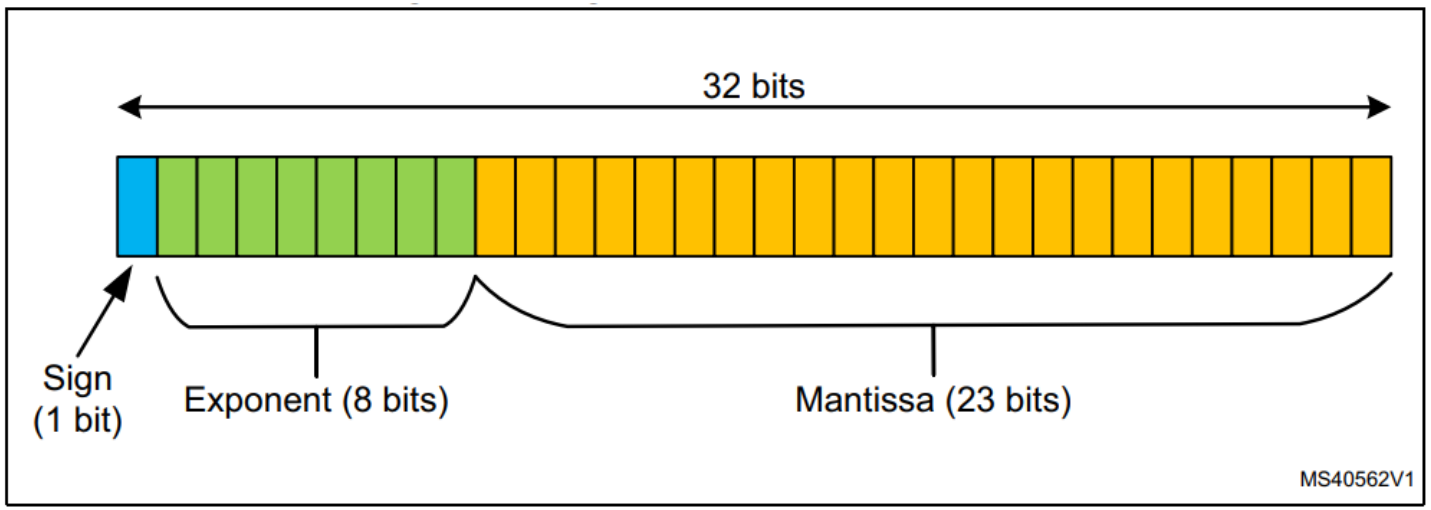
What is doing arm_rfft

What is Q15??



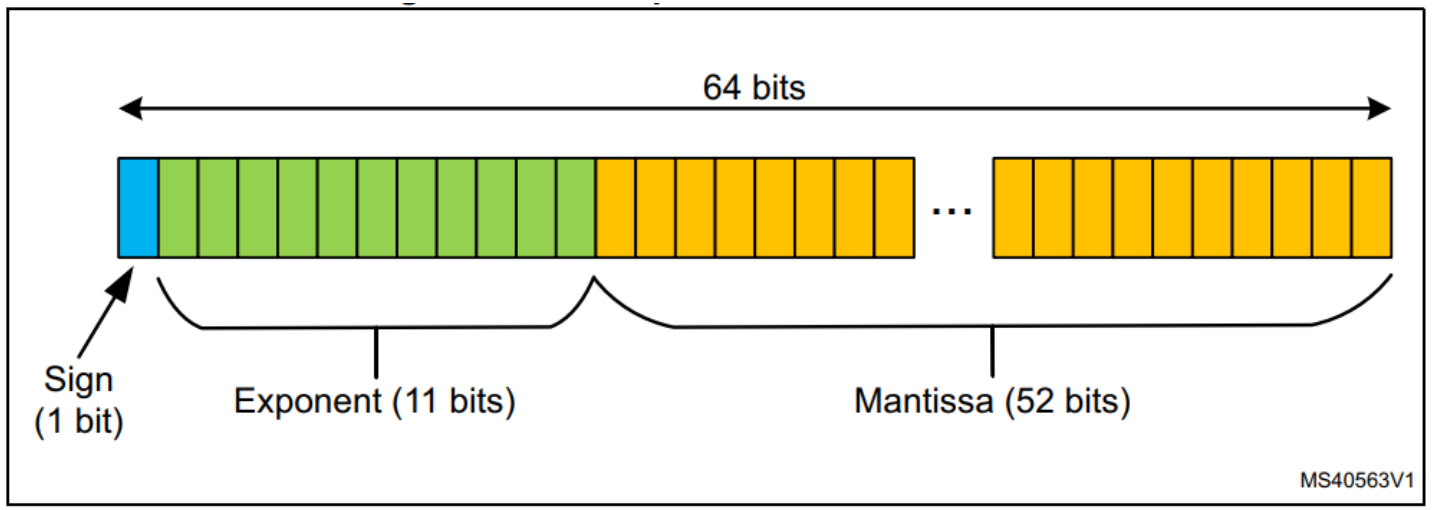
DSP operations can use either floating-point or fixed-point formats.

Single Precision



$$Value = (-1)^{s} \times M \times 2^{(E-127)}$$

Double Precision

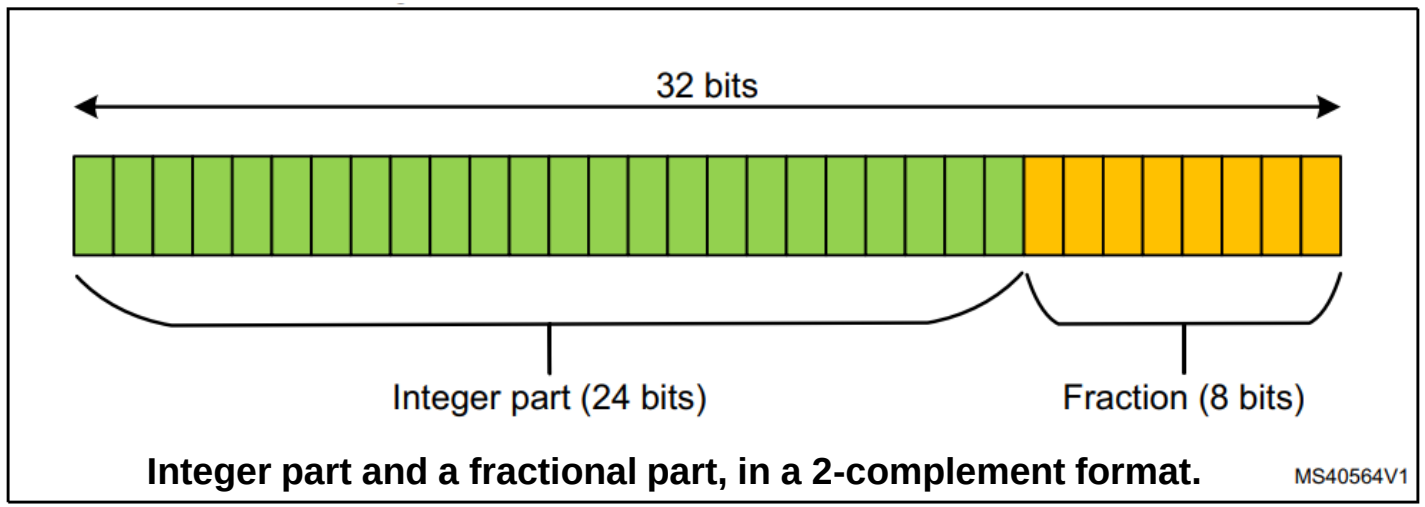


$$Value = (-1)^{s} \times M \times 2^{(E-1023)}$$

Fix Point Representation (LAB)

Most common format for DSP QX:
Q7, Q15 and Q31

Where X is the number of fractional bits



32-bit fixed point representation.

$$Value = (-1)^{b_S} \times (b_{14} \times 2^{-1} + b_{13} \times 2^{-2} + \ldots + b_1 \times 2^{-14} + b_0 \times 2^{-15})$$

The range of numbers supported in a Q15 number is comprised between -1.0 and 1.0, corresponding to the smallest and largest integers that can be represented, respectively

Avoiding Overflow

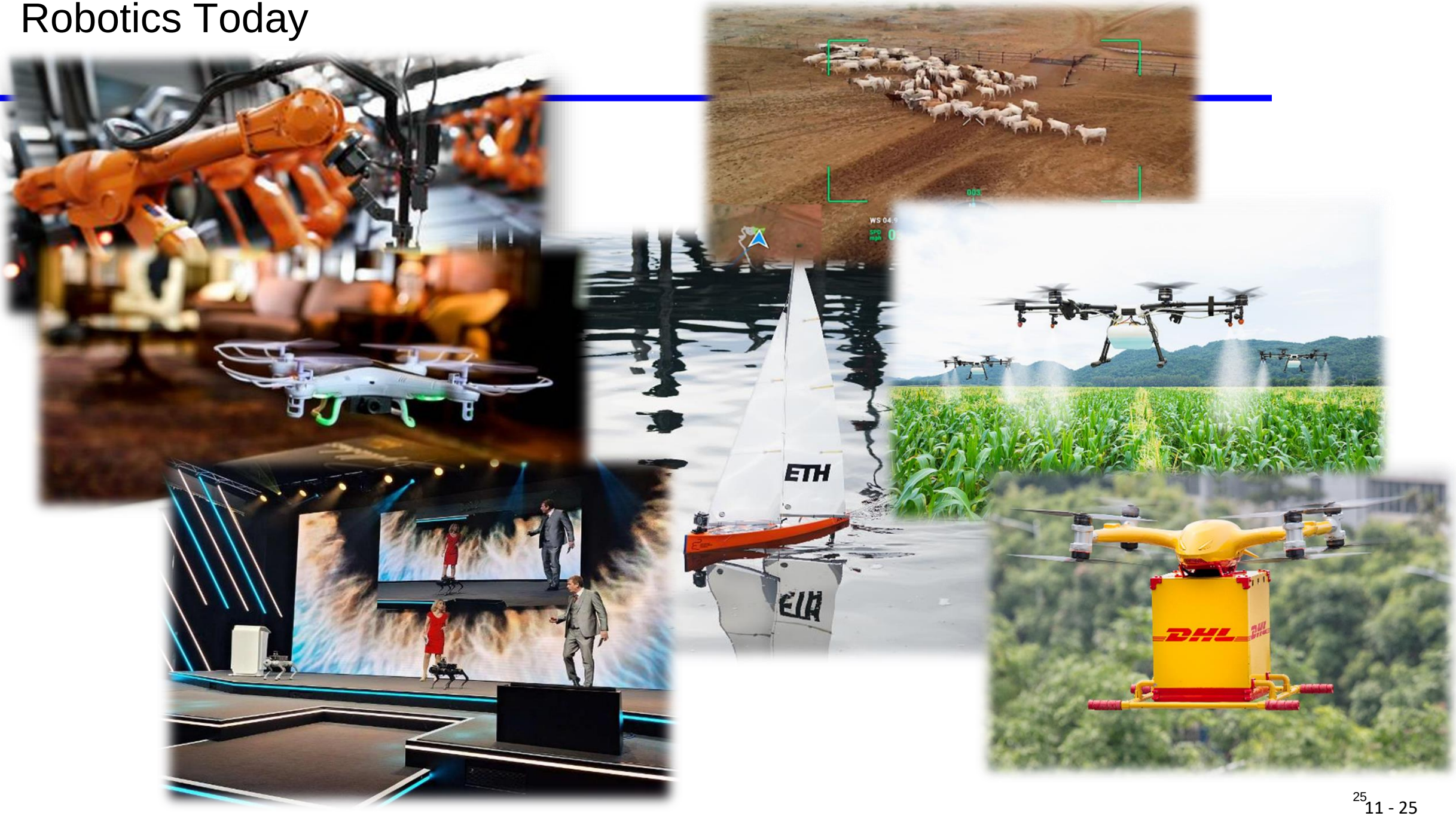
-32768 and 32767.

What Did You Learn?

- ✓ Embedded Systems relies on Hardware and Software co-design
- ✓ Implementation techniques
  - ✓ Understand the hardware architecture
  - ✓ DSP instruction on ARM Cortex-m
- ✓ Speed-up improvement with software programming

Time for Demo!! ☺

Robotics Today



From Edge to Extreme Edge Challenges

Advanced autonomous drone and vehicles

[1] A. Bachrach, “Skydio autonomy engine: Enabling the next generation of autonomous flight,” IEEE Hot Chips 33 Symposium (HCS), 2021

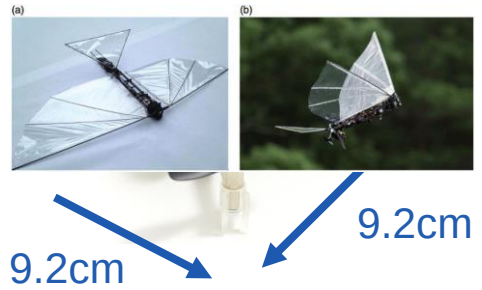
https://www.skydio.com/skydio-2-plus

- 3D Mapping & Motion Planning
- Object recognition & Avoidance
- 0.06m2 & **800g of weight**
- Energy Capacity (Battery) **5410mAh**

Deployment in tight spaces?

Nano-drone

https://www.bitcraze.io/products/crazyflie-2-1



- Smaller form factor of 0.008m2
- Weight of **27g** (30X lighter)
- Battery capacity of **250mAh** (20X smaller)

Can we fit sufficient “intelligence” in a **30X** smaller payload and **20X** lower energy budget?

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Credits: Luca Benini

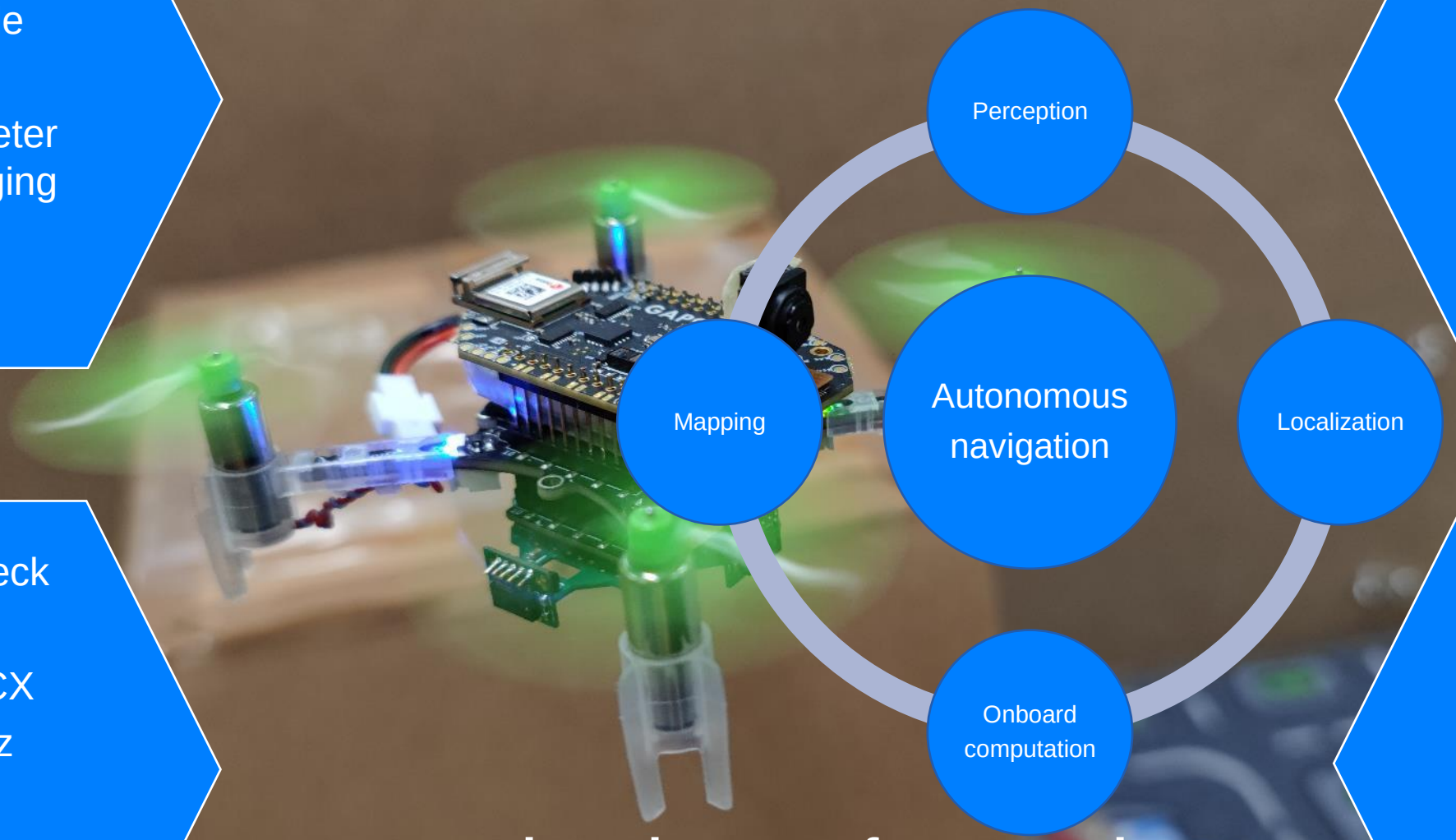
•Miniturized Drone

•WiFi module

•UWB centimeter precision ranging

•GAP9 SoC
•9+1 Cores
•1.5 MB RAM
•~ 100 mW

•total mass
•5.86 g



•Quad ToF Deck

•4x VL53L5CX
•up to 60 Hz

•~300 mW

•4.2 g

•OmniVision
•OV5647 camera

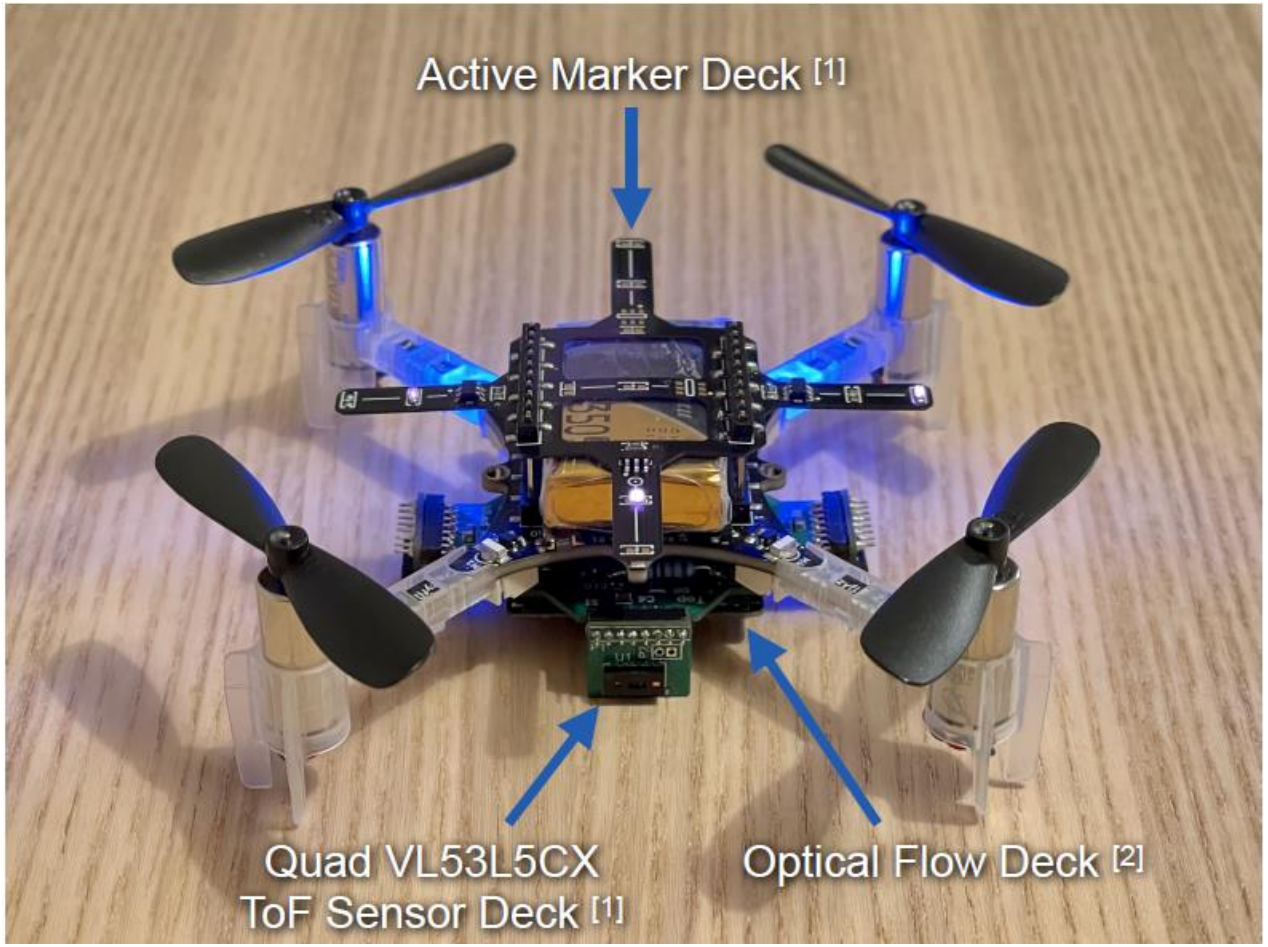
•RGB - 5 MPixel
•45 fps

•~90 mW

•search and rescue fast-mapping

•for emergency response

Fully Onboard Autonomous navigation, with mapping, planning , object avoidance and landing (LIVE DEMO!)



Each nano-UAV is equipped with:

1. 4x 64-pixels depth sensors
2. STM32 - controller
3. GAP9 - co-processor
4. NRF51 transceiver - intra-swarm communication
5. Active marker - ground truth

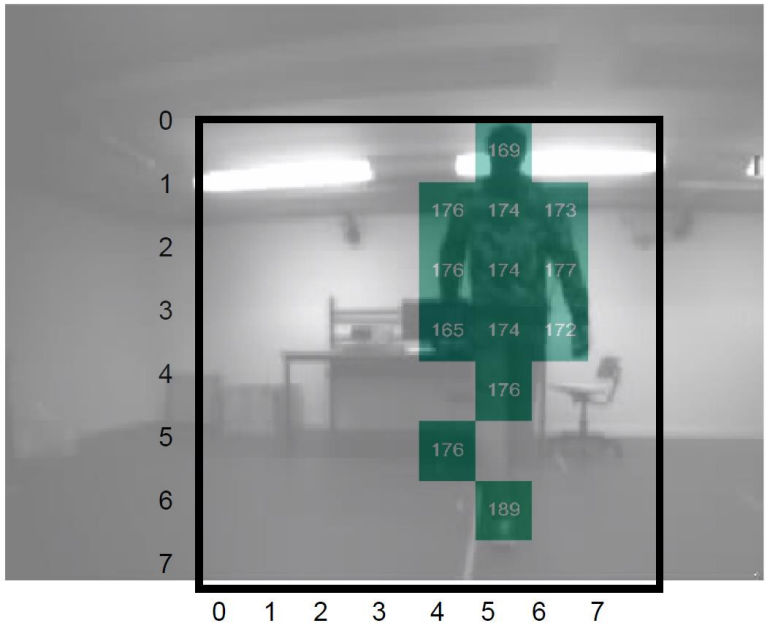
[1] Custom

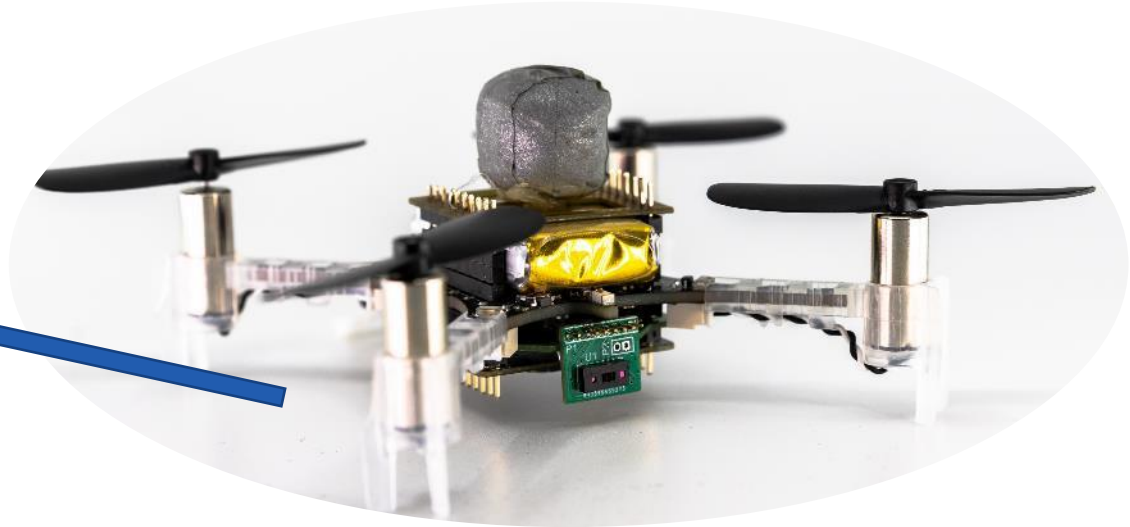
[2] Commercially available

Sensor Fusion – RGB + Depth

8x8 VL53L8CX ToF sensor

- 8x8 or 4x4 multi-zone ranging
- weight 42 mg
- 2 cm – 4 m range
- automatic noise detection
- 215 mW @ 60 Hz



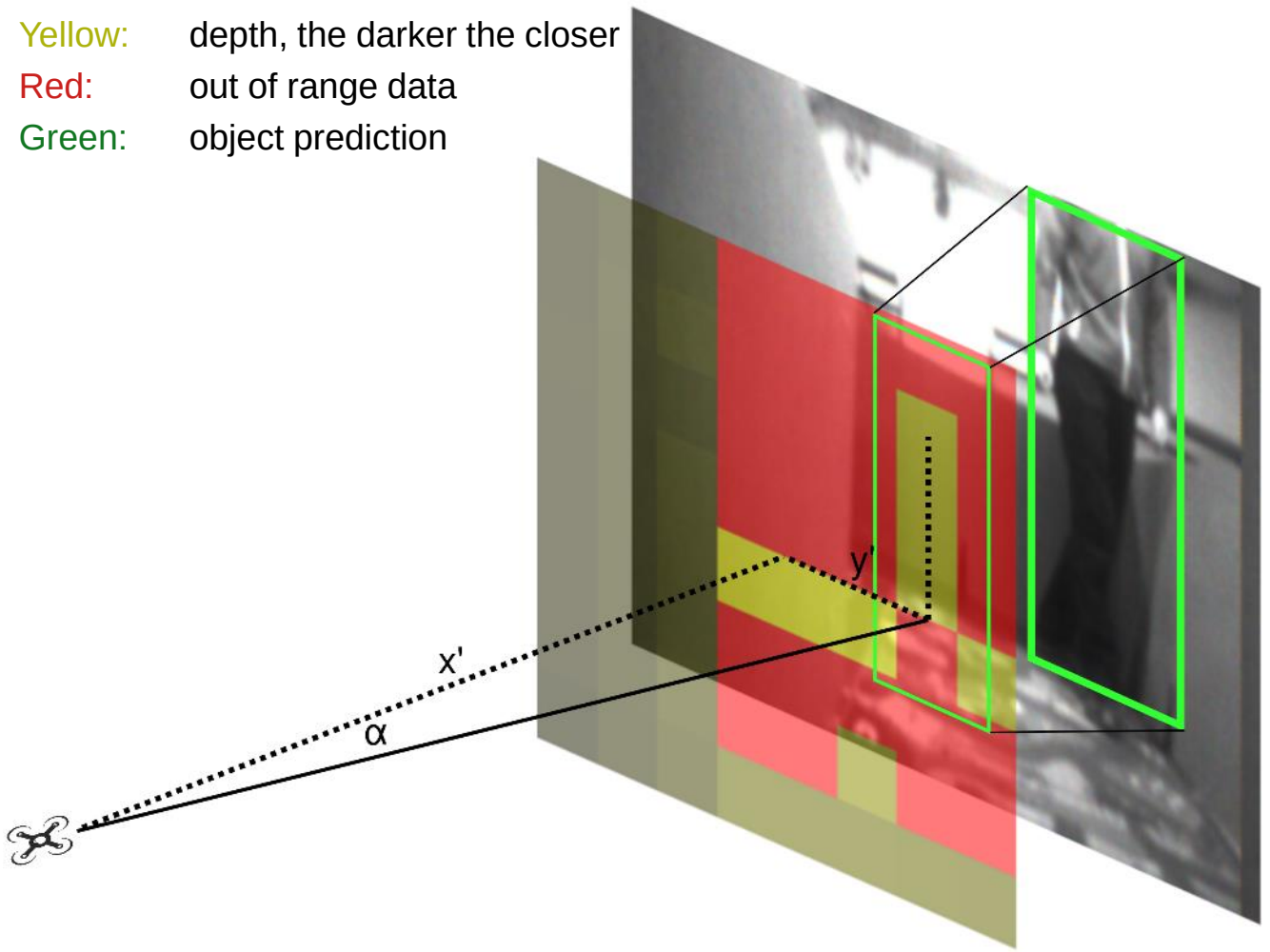


Sensor Fusion – RGB + Depth

8x8 VL53L8CX ToF sensor

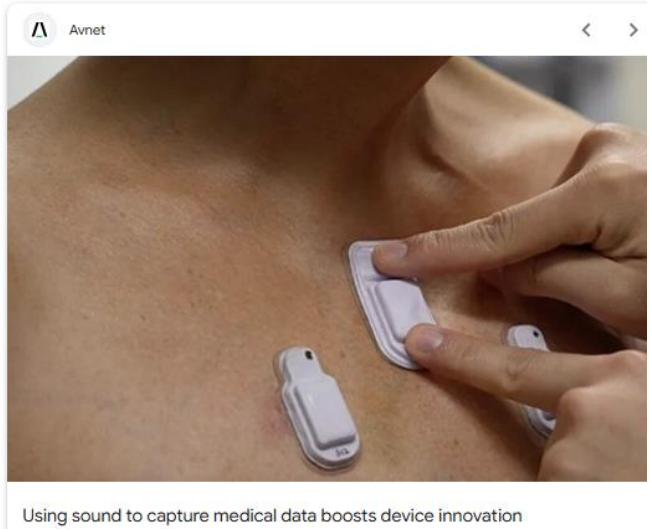
- 8x8 or 4x4 multi-zone ranging
- weight 42 mg
- 2 cm – 4 m range
- automatic noise detection
- 215 mW @ 60 Hz

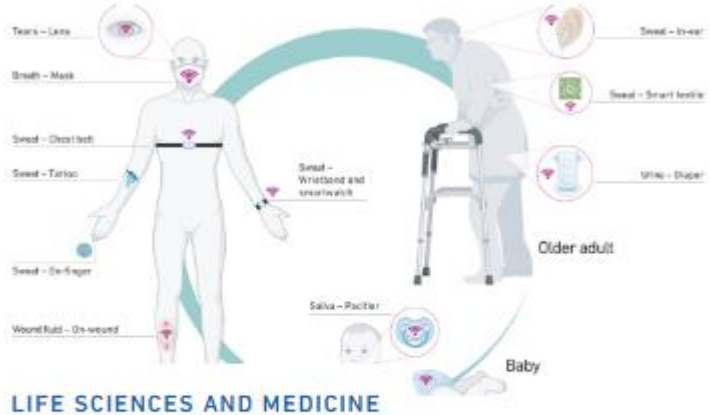
Yellow: depth, the darker the closer
Red: out of range data
Green: object prediction



If the demo did not work….

PBL Mini-Project





LIFE SCIENCES AND MEDICINE

How the latest sensors analyse body fluids

04.12.2024

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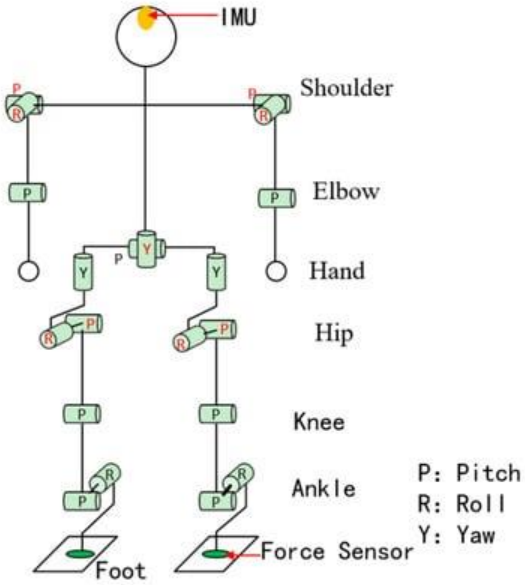
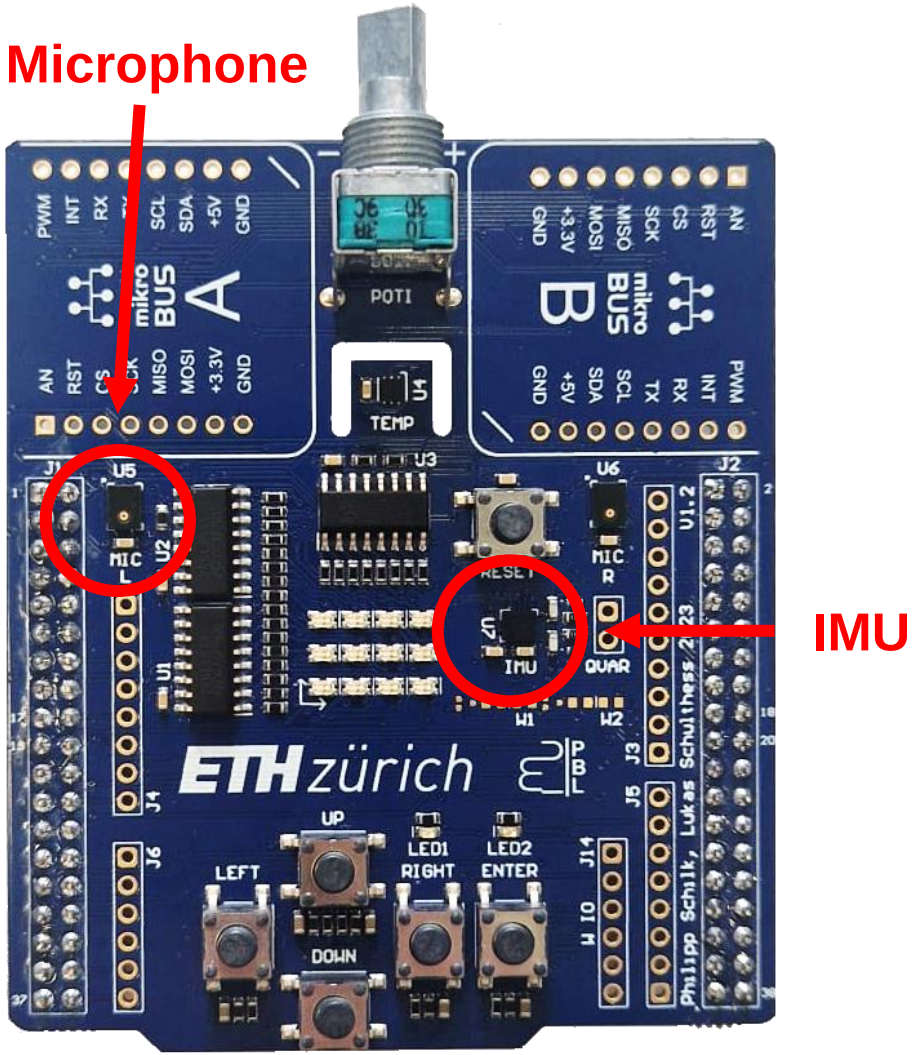


Embedded Systems PBL Mini-Project



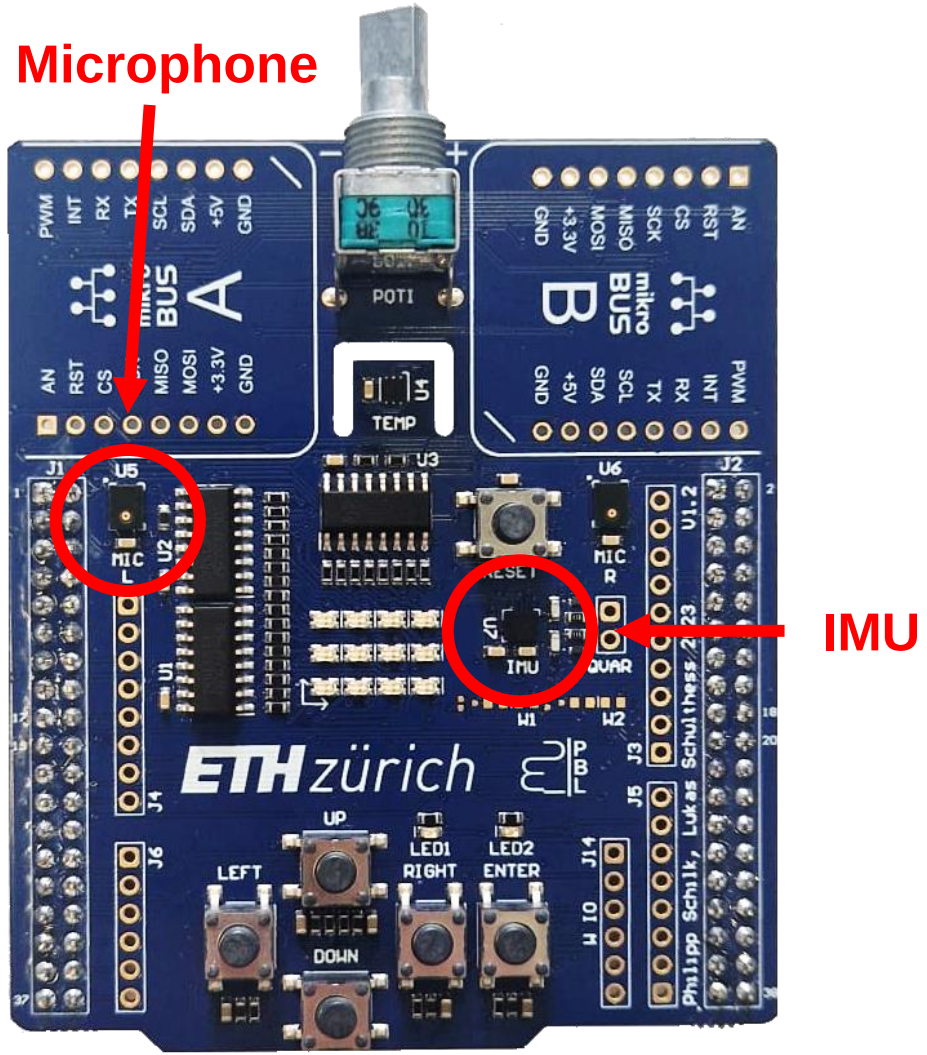
Goal: have a small real-world application running on your STM32 platform

- A few different ideas in **the task assignment**, but you may also realize an idea of your own, working with either the IMU or the microphone **(LAB helps here)**
- All applications will consist of **active mode** and **sleep mode**:
  - Collect sensor data (e.g. for 1 second)
  - Apply at least two signal processing algorithms on the data, so you can compare the performance
  - Giving the result to the user, then go to sleep mode

→**How much energy will your application consume? And how fast will it process? To optimize, don't forget SIMD commands or the CMSIS-DSP library**

– **But you can also play easy ☺ (i.e Time domain processing vs FFT)**

Embedded Systems PBL Mini-Project



How to get the 0.25 bonus points?

- Collect data from at least one sensor and process it using a fixed sample rate and period.
- Provide a clear performance comparison of the two algorithms implemented in terms of speed and energy consumption.
- Include energy consumption calculations based on active and sleep phases.
- Submit a concise, half-page report summarizing the findings.
- Submit a 30sec to max. 60sec video of the developed application, showing its correct operation.
- Submit the code used to create the results

→ **Deadline for hand-in on Moodle:**
Dec. 20th 2024 23:59