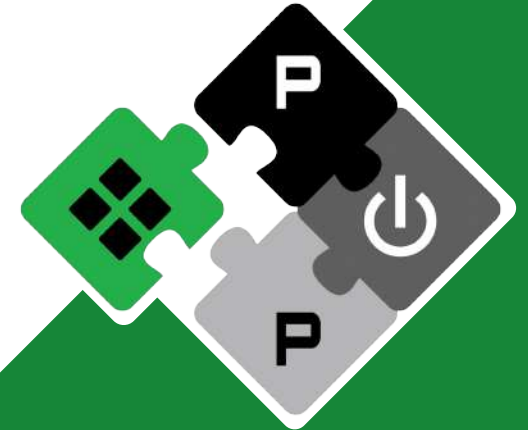


Progress on PULP-based Nano-drones

D. Palossi^{‡§}, L. Lamberti^{*}, L. Bompani^{*}, M. Pourjabar^{*}, V. Niculescu[‡], H. Müller[‡], Victor J. Kartsch Morinigo[‡], T. Polonelli[‡], M. Rusci[†], F. Conti^{*}, L. Benini^{‡*}

[‡]ETH Zürich, [§]IDSIA USI-SUPSI, ^{*}University of Bologna, [†]KU Leuven

Daniele Palossi dpalossi@iis.ee.ethz.ch



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Team effort



Lorenzo



Mahyar



Luca



Vlad



Hanna



Victor



Tommaso



Manuele



Francesco



Daniele

Thank you all!

(and many bachelor/master students)



Everything started 10 years ago



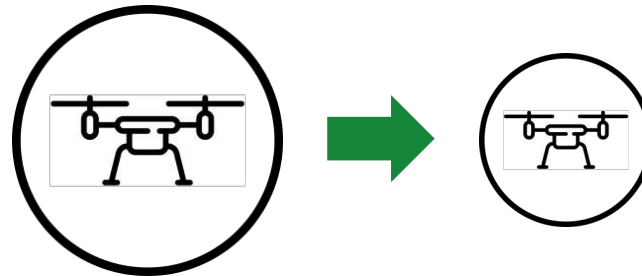
Autonomous drones: Applications



Surveillance & Inspection



Rescue missions
Disaster management



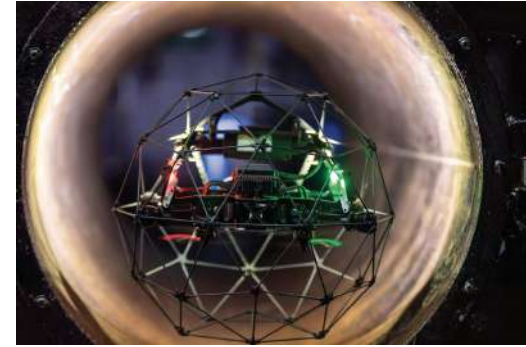
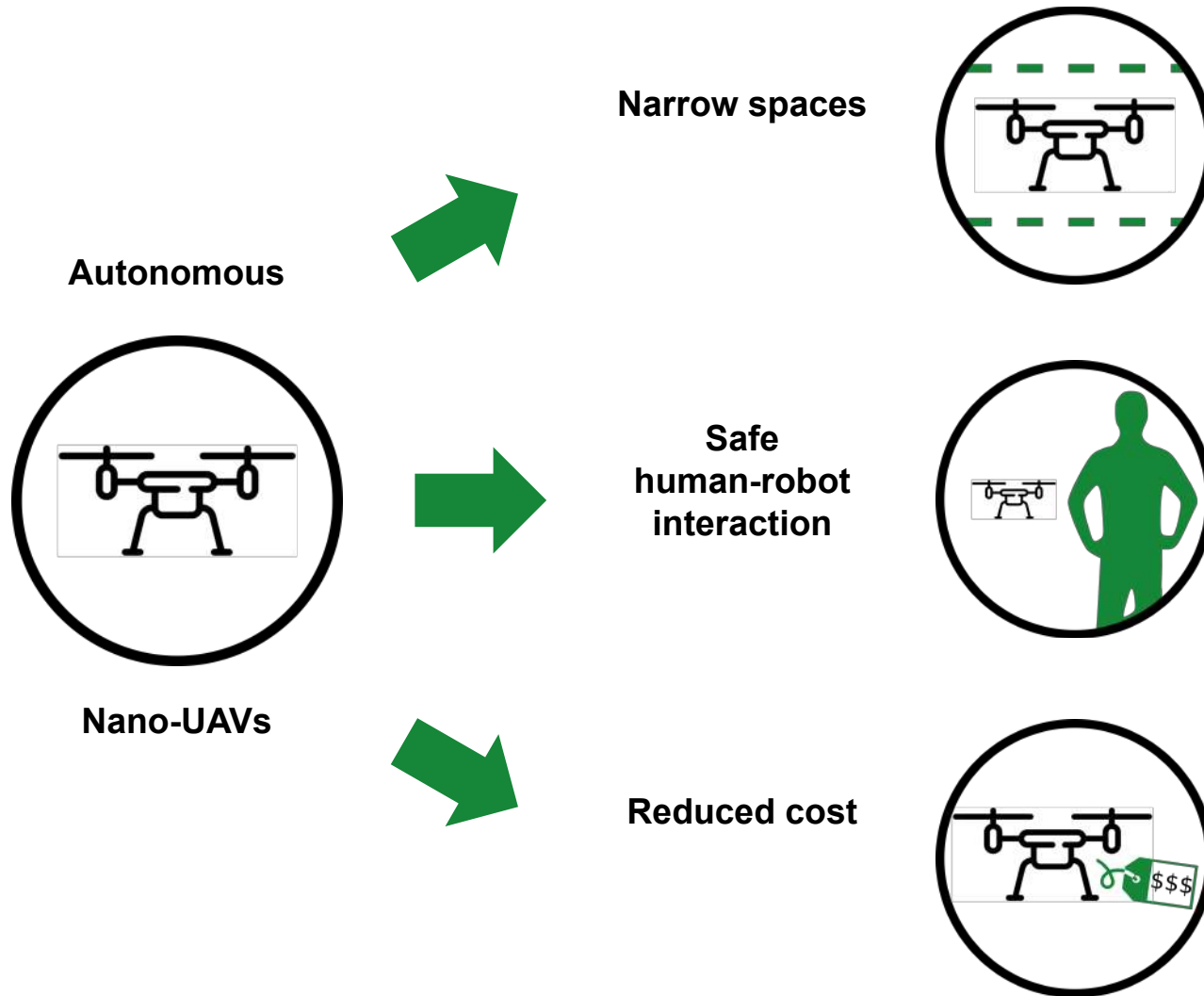
Precise agriculture



Entertainment



Autonomous palm-sized drones: Advantages



Crazyflie 2.1

SKU: 114991551


\$225.00 | \$281.25 inc VAT



Research challenge




standard-size UAV



~20 cm

A


micro-size UAV



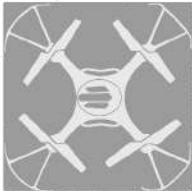
~10 cm

B


2D visual comparison



A



B




C

D

10 cm


nano-size UAV



~5 cm

C

pico-size UAV



~2 cm

D

Vehicle class	Weight	Onboard
A 	+1 Kg	
B 	0.5 Kg	
C 	10 g	
D 	1 g	

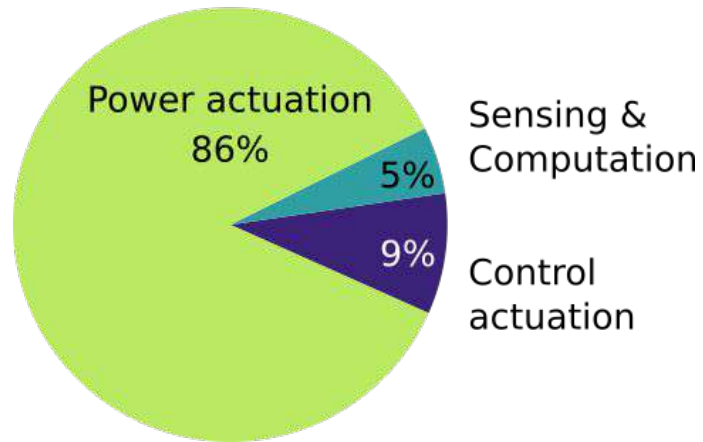


Research challenge

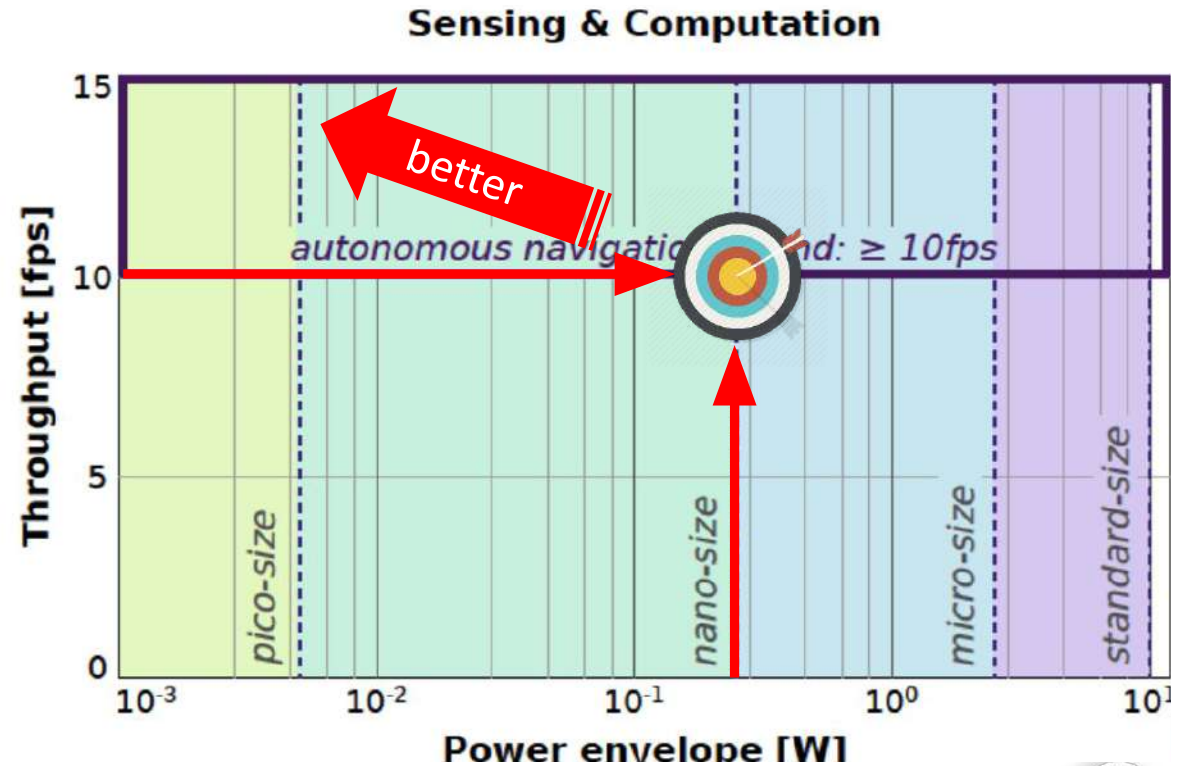


Vehicle class	∅ : Weight [cm:Kg]	Power [W]	Onboard Device
standard-size	≥ 50 : ≥ 1	≥ 100	Desktop
micro-size	~25 : ~0.5	~50	Embedded
nano-size	~10 : ~0.01	~5	MCU
pico-size	≤ 2 : ≤ 0.001	≤ 0.1	ULP

Power envelope break-down:



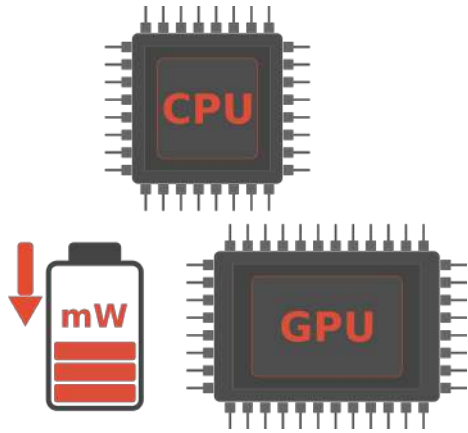
Challenging trade-off between power consumption and onboard processing



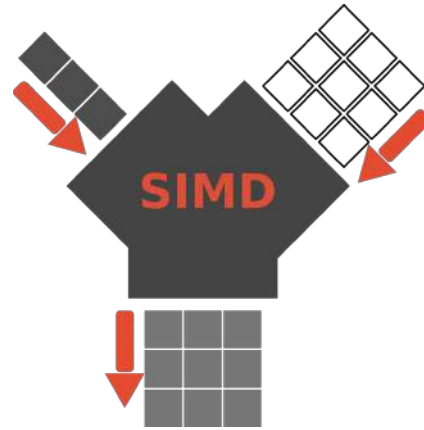
How to enable high energy efficiency



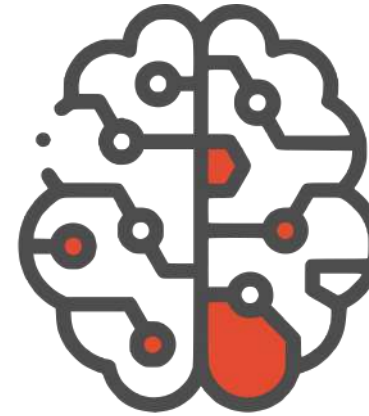
Ultra-low power heterogeneous model



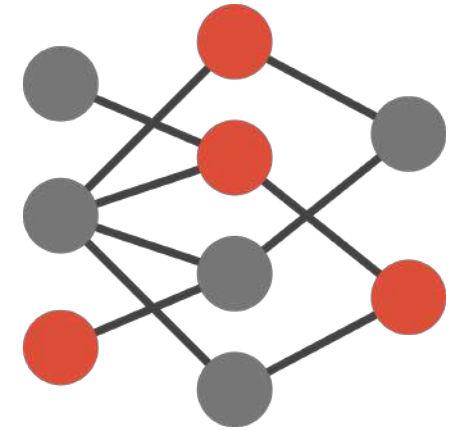
Parallel execution



Approximate computing



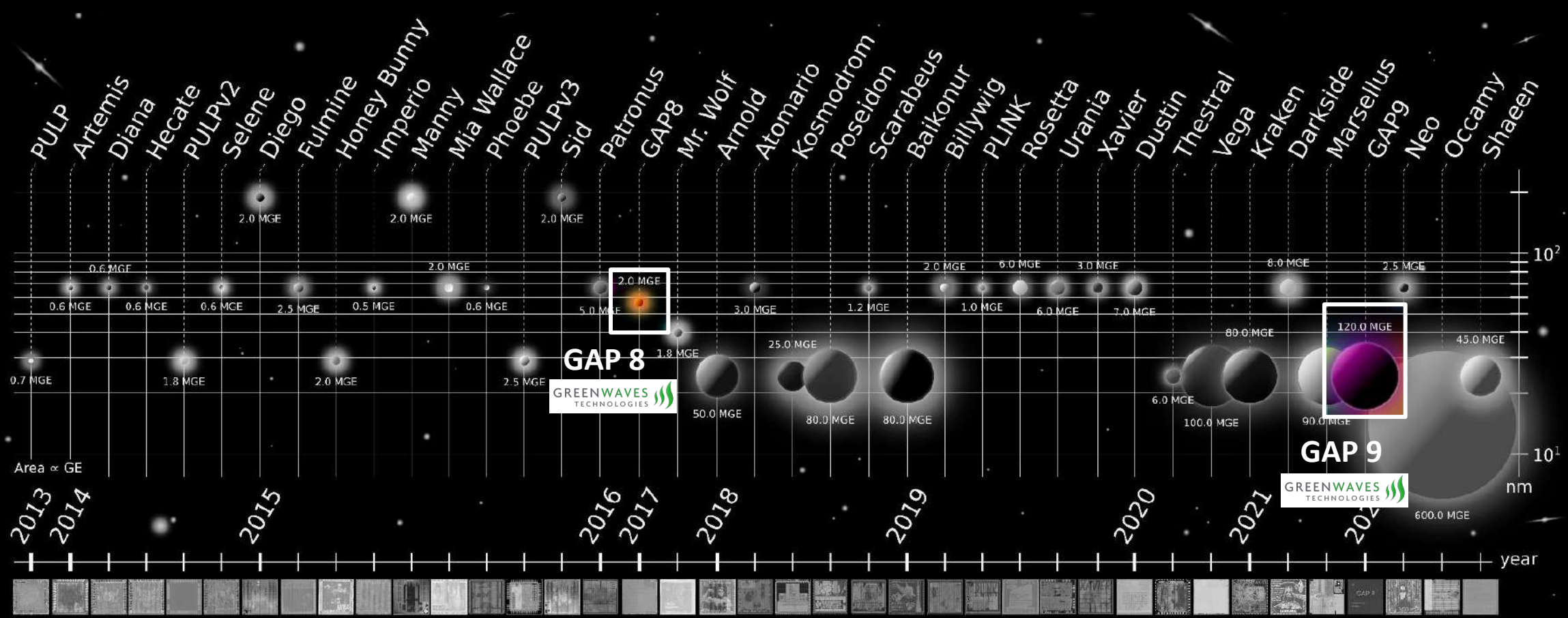
Artificial intelligence



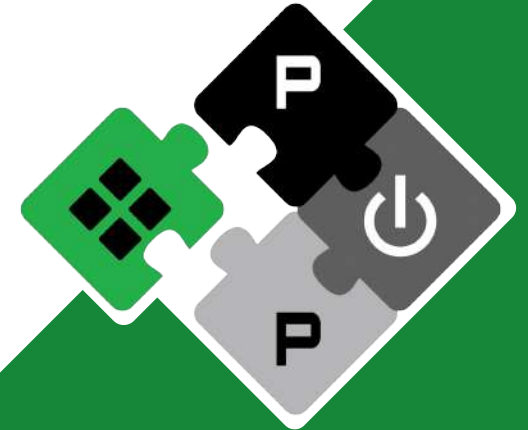
PULP
Parallel Ultra Low Power



History of the PULP



Multitasking nano-drone



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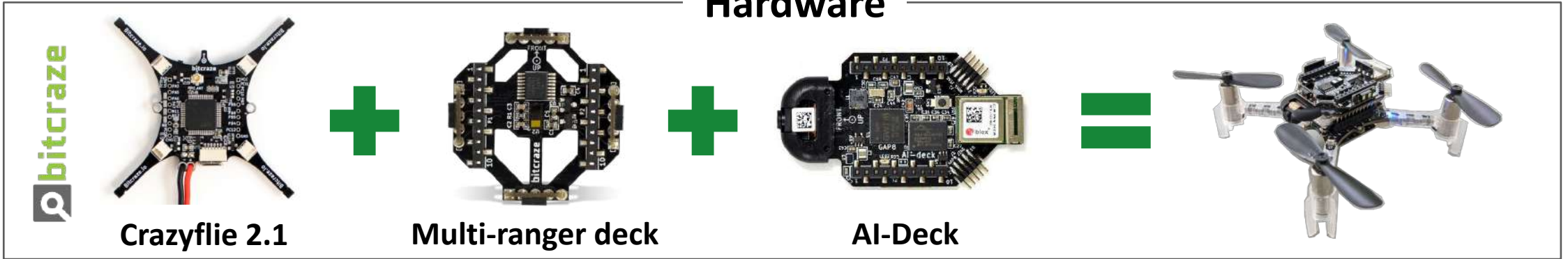
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Multitasking on nano-drone [1]



Hardware



STM32F4 MCU

Control-based tasks
Sensor interfacing



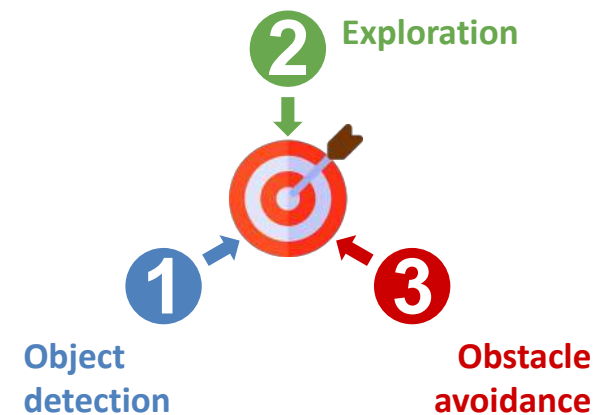
VL53L1x

5x Time-of-Flight (ToF) ranging sensors (single beam)



GAP8 SoC

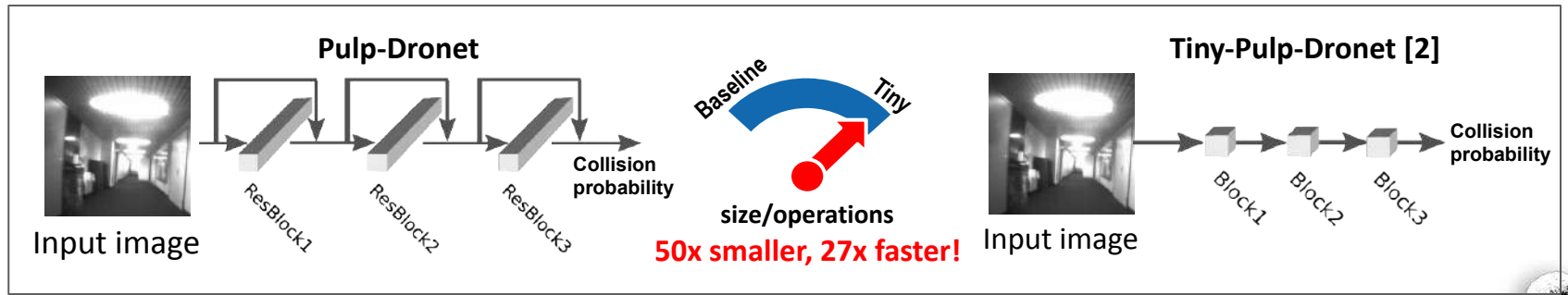
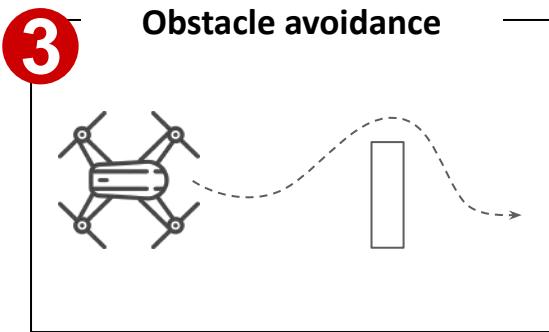
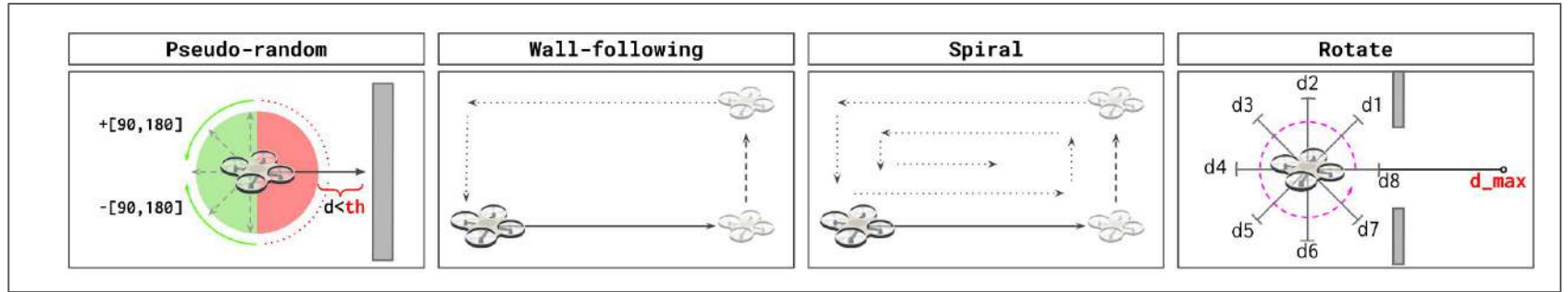
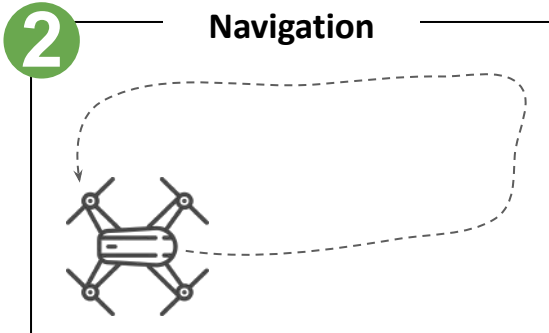
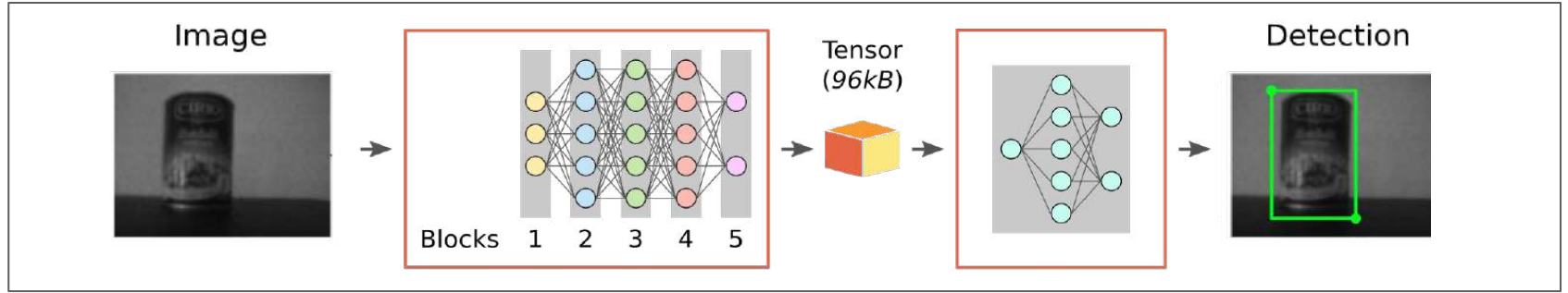
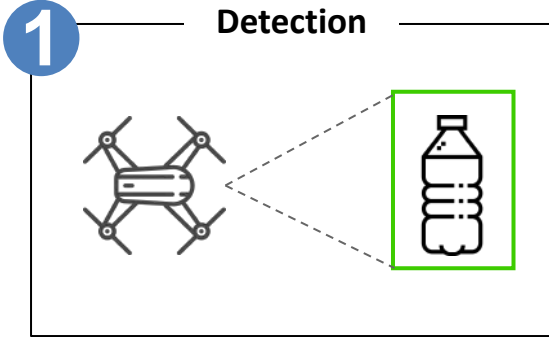
8 parallel ULP cores
QVGA camera



[1] L. Lamberti et al., "Bio-inspired Autonomous Exploration Policies with CNN-based Object Detection on Nano-drones," DATE, 2023



Multitasking on nano-drone [1]



[1] L. Lamberti et al., "Bio-inspired Autonomous Exploration Policies with CNN-based Object Detection on Nano-drones," DATE, 2023

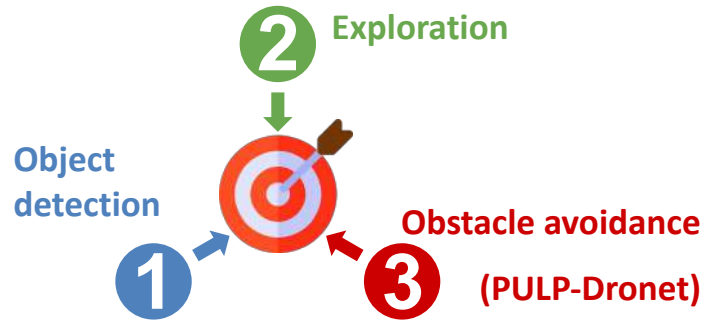
[2] L. Lamberti et al., "Tiny-pulp-dronets: Squeezing neural networks for faster and lighter inference on multi-tasking autonomous nano-drones," AICAS, 2022



Multitasking on nano-drone [1]



Results



	GAP8	GAP9
PULP-Dronet	19 Hz	145 Hz
Tiny-PULP-Dronet	160 Hz	424 Hz
Object detection	1.6 Hz	11 Hz

Bio-inspired Autonomous Exploration Policies with CNN-based Object Detection on Nano-drones

Lorenzo Lambertini, Luca Bompani, Victor Javier Kartsch,
Manuele Rusci, Daniele Palossi, Luca Benini



[1] L. Lambertini et al., "Bio-inspired Autonomous Exploration Policies with CNN-based Object Detection on Nano-drones," DATE, 2023



Multitasking nano-drones swarm



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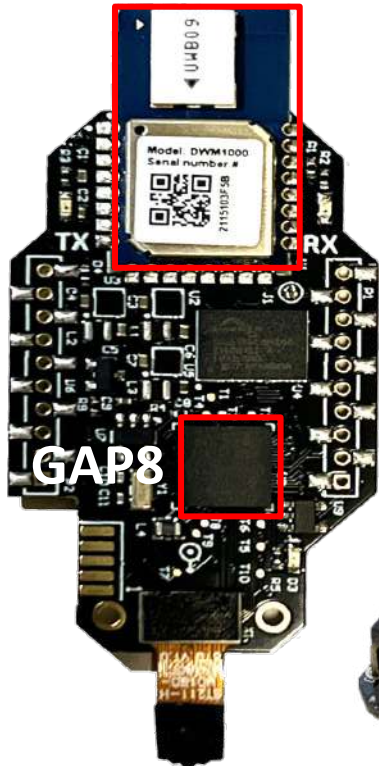
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Multitasking nano-drones swarm [3]



PULP-UWB shield

UWB radio



UWB module

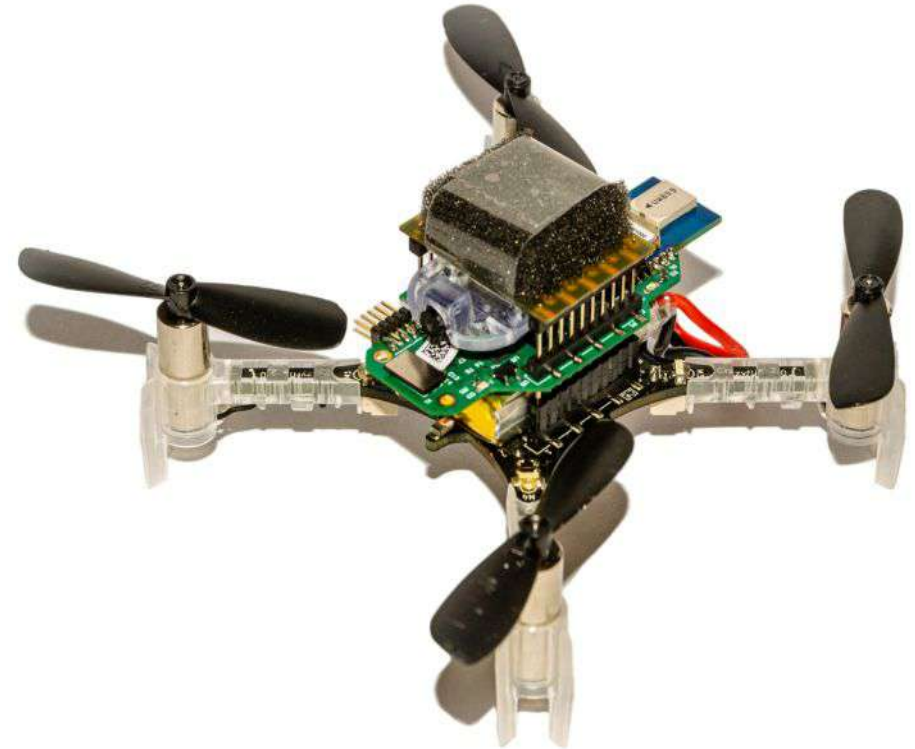
Ranging used to avoid collision with other nano-drones

GAP8 SoC

- Object detection CNN
- PULP-Dronet collision avoidance

Multiranger deck

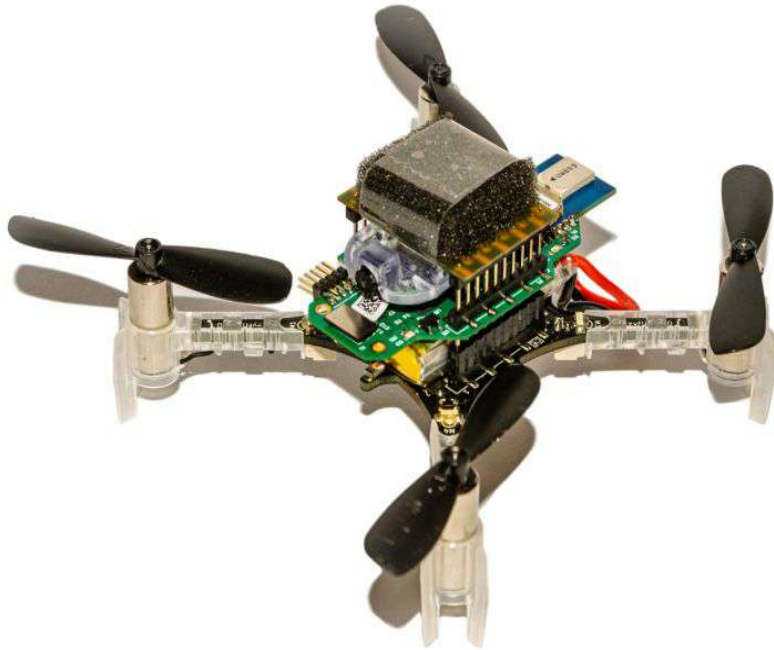
ToF-based collision avoidance



[3] M. Pourjabar et al., "Land & Localize: An Infrastructure-free and Scalable Nano-Drones Swarm with UWB-based Localization," *DCOSS*, 2023



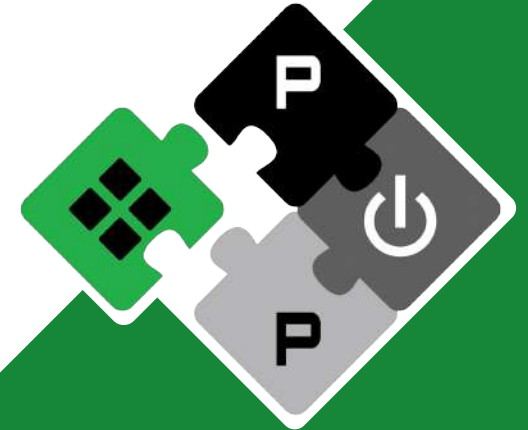
Multitasking nano-drones swarm [3]



[3] M. Pourjabar et al., "Land & Localize: An Infrastructure-free and Scalable Nano-Drones Swarm with UWB-based Localization," *DCOSS*, 2023



GAP9 SoC and Depth map sensor



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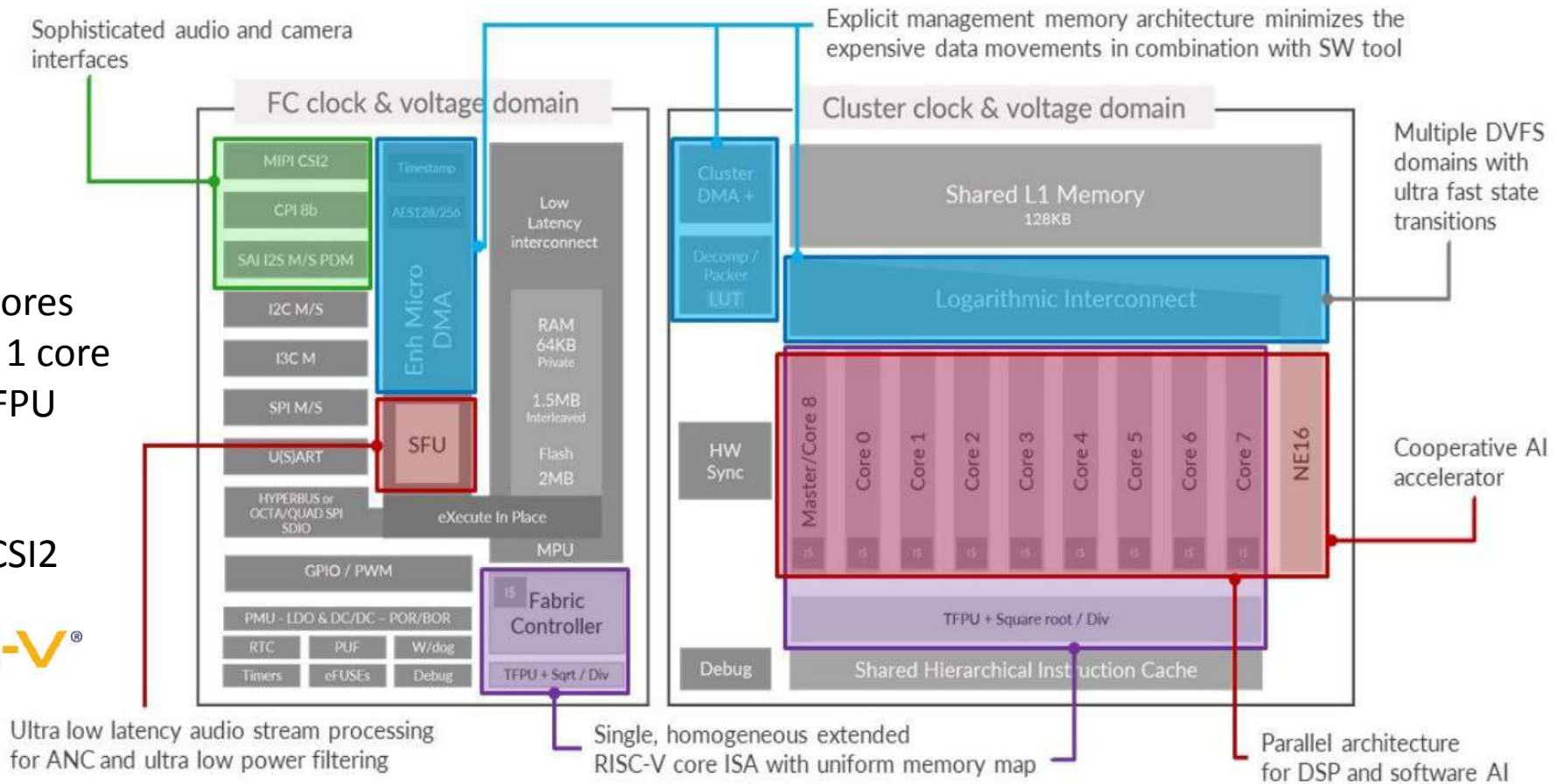
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GAP9-based nano-drone

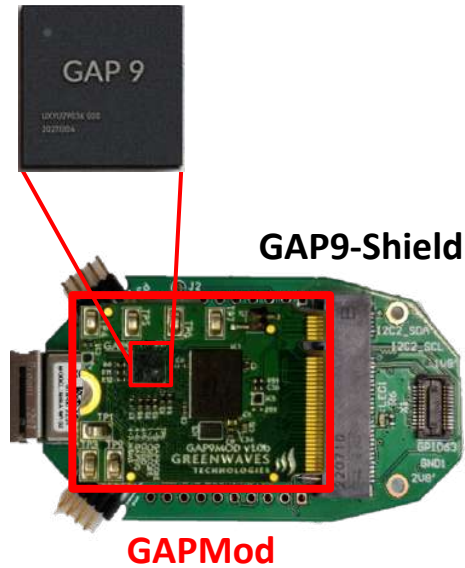


GAP9

- Cluster: 9 cores
- Fabric Ctrl: 1 core
- Hardware FPU
- L1: 128 KB
- L2: 1.5 MB
- Interface: CSI2



GAP9-based nano-drone



10 mm



OV5647
Camera

Camera connector



GAPMod
connector

NINA WiFi

Crazyflie + GAP9-Shield



GAP9-Shield:

- Additional board for the Crazyflie nano-drone
- NINA WiFi module
- 5MP CSI2 color camera (VGA)
- Currently developing V2, with GAP9 on the same PCB



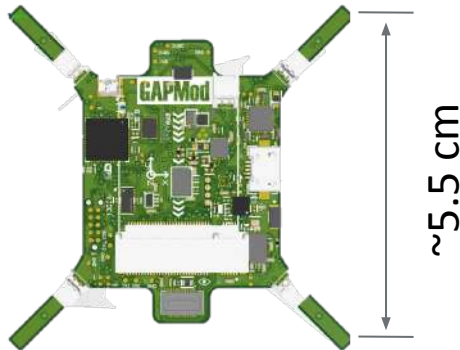
Onboard images



GAP9-based nano-drone



GAP9-Shield



GAP9-Drone:

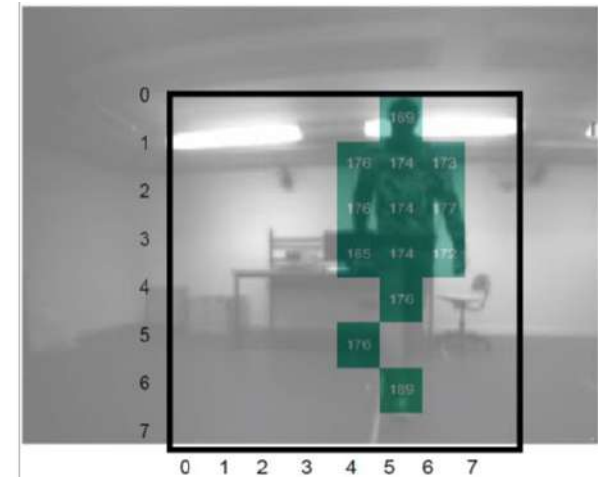
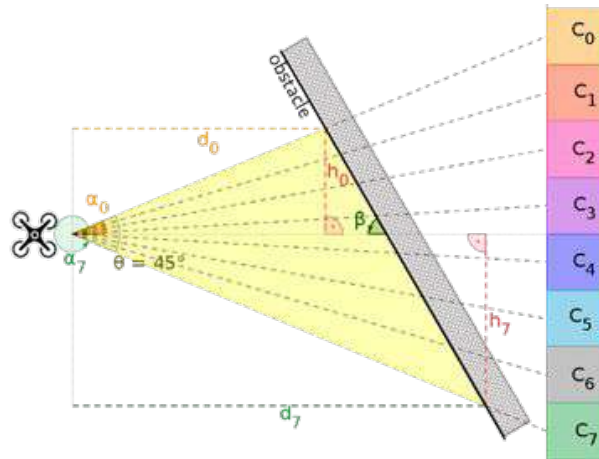
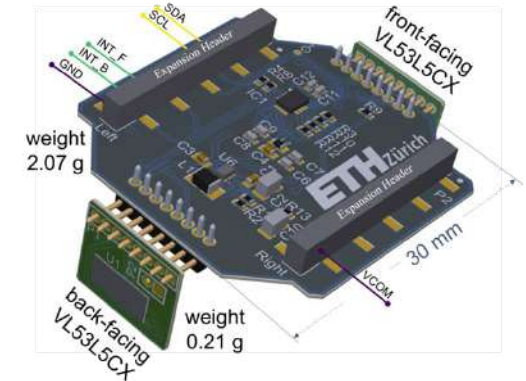
- Only one GAP9 SoC (for all tasks)
- NINA WiFi module
- 5MP CSI2 color camera
- Multiple sensors: IMU, barometer, Optical-flow camera



Novel multi-zone ToF depth sensor



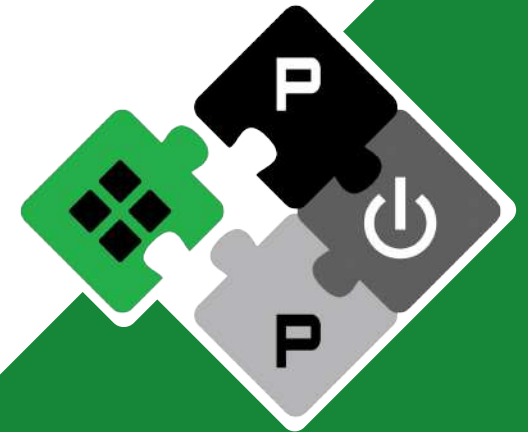
- VL53L5CX sensor from STMicroelectronics
- Maximum resolution configuration: **8x8 @ 15 Hz.**
- The sensor provides a depth maps up to 2m range (validity 90%)
- Error **<4 cm** for ranges up to 1.8m



Localization

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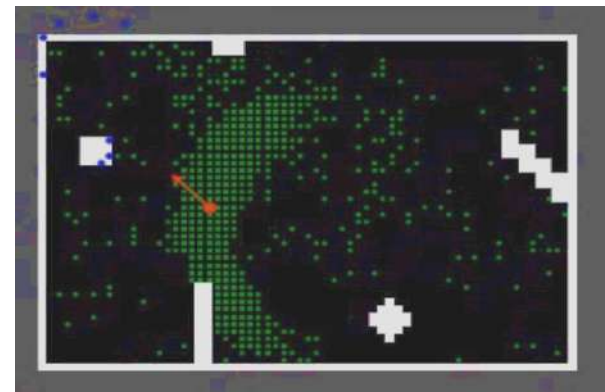
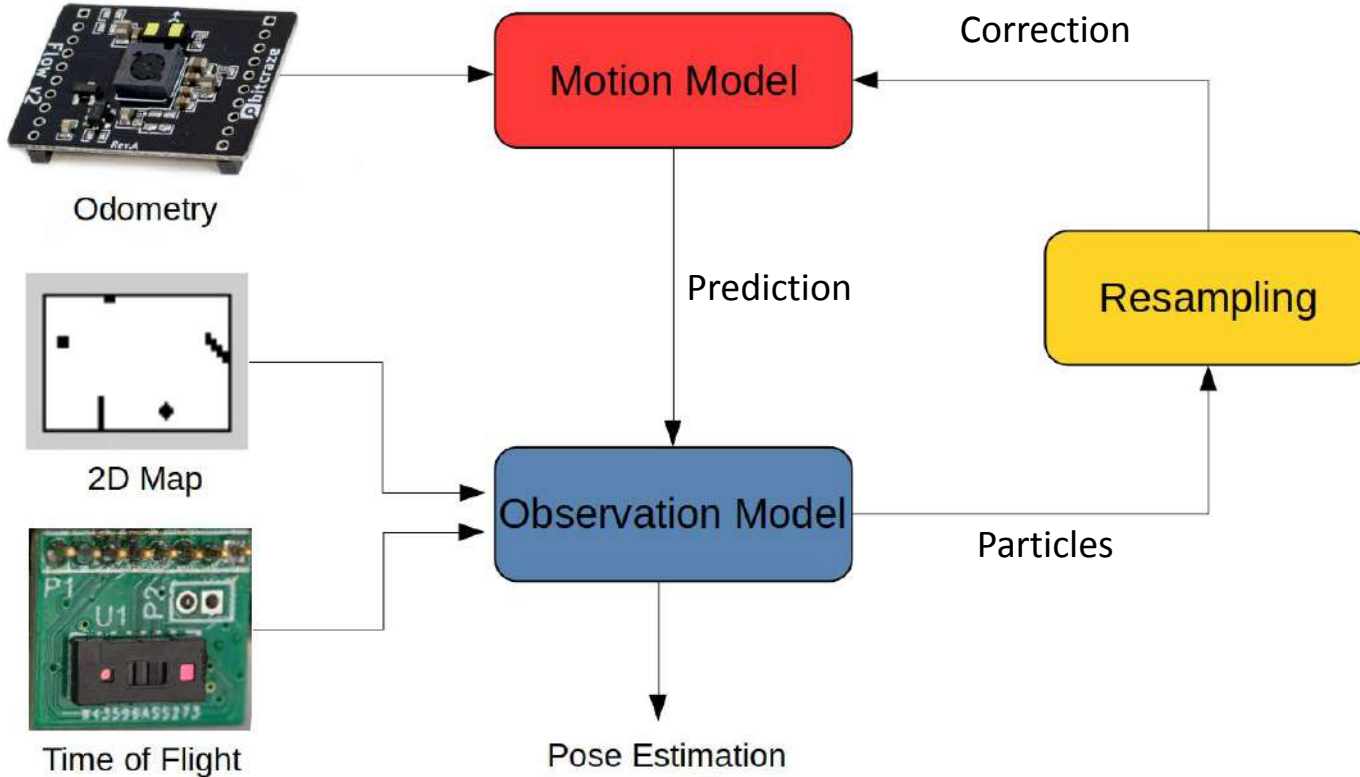
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Particle filter localization [4]



Monte Carlo localization running on GAP9



●●● Particles ●●● Observations
↗ Pose prediction

[4] H. Mueller et al., "Fully On-board Low-Power Localization with Multizone Time-of-Flight Sensors on Nano-UAVs," DATE, 2023



Particle filter localization [4]

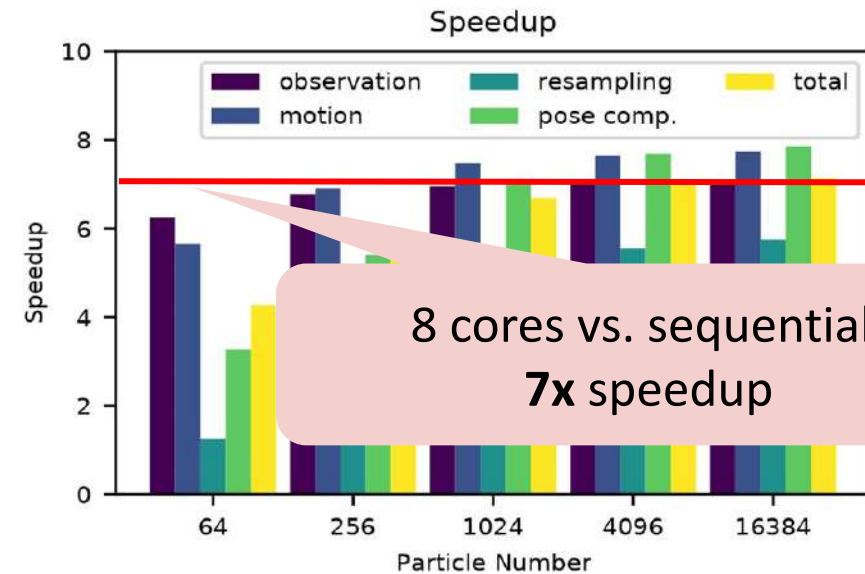
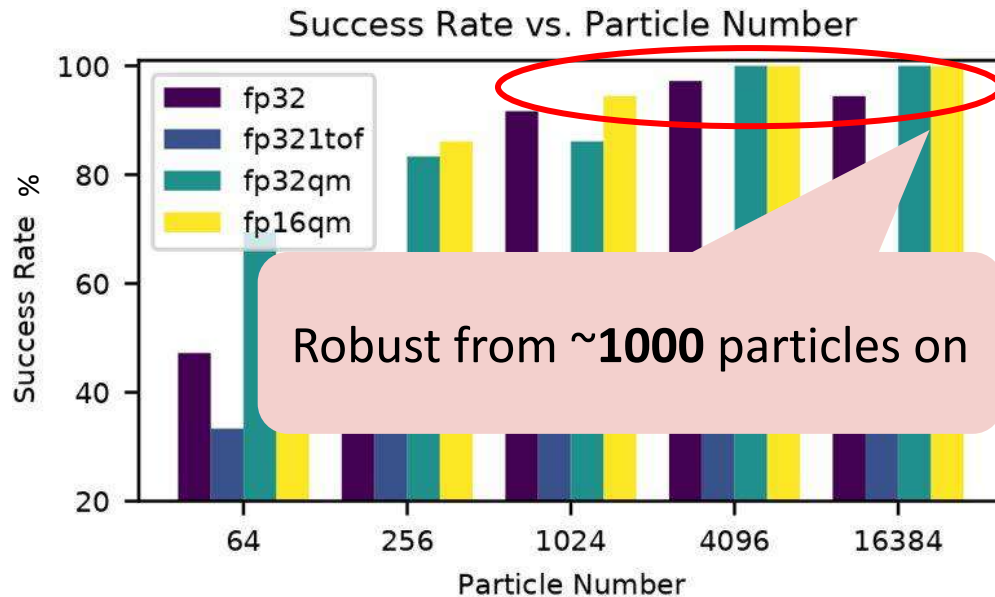


Setup

- Tested on 6 flight sequences
- Motion model float32 vs. 8-bit quantized
- Particles float32 vs. float16

Results with 1024 particles

- 0.15 m accuracy with 95% success rate
- 60 ms real-time execution
- 13 mW power consumption



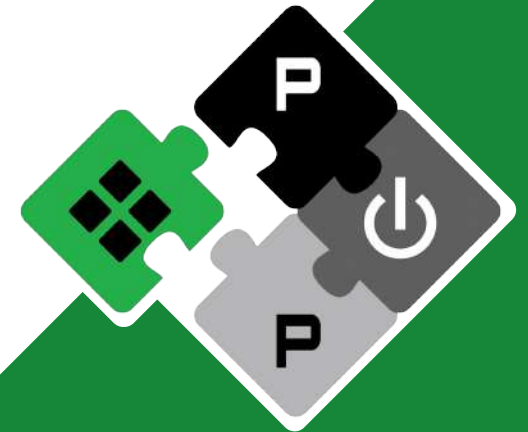
[4] H. Mueller et al., "Fully On-board Low-Power Localization with Multizone Time-of-Flight Sensors on Nano-UAVs," DATE, 2023



Mapping

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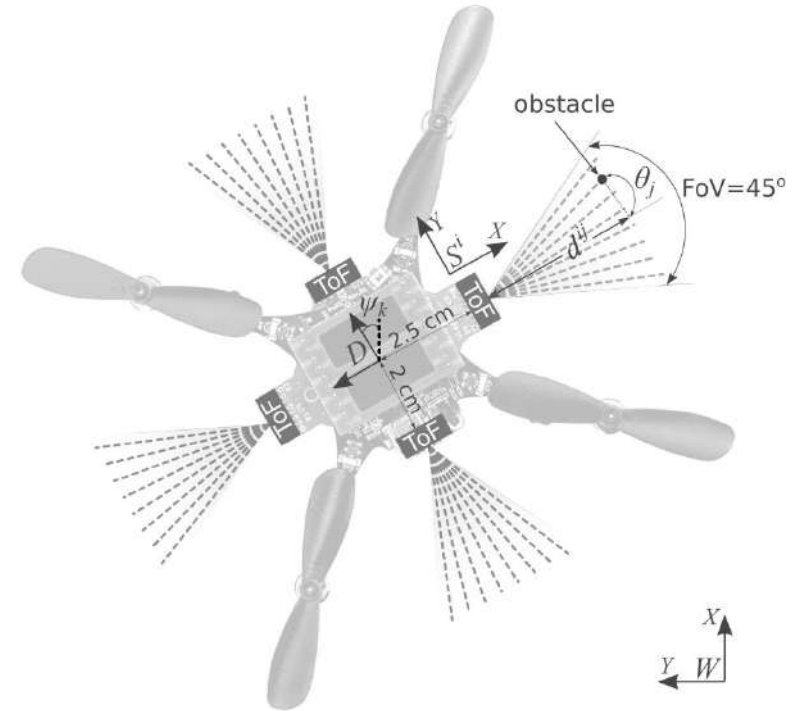
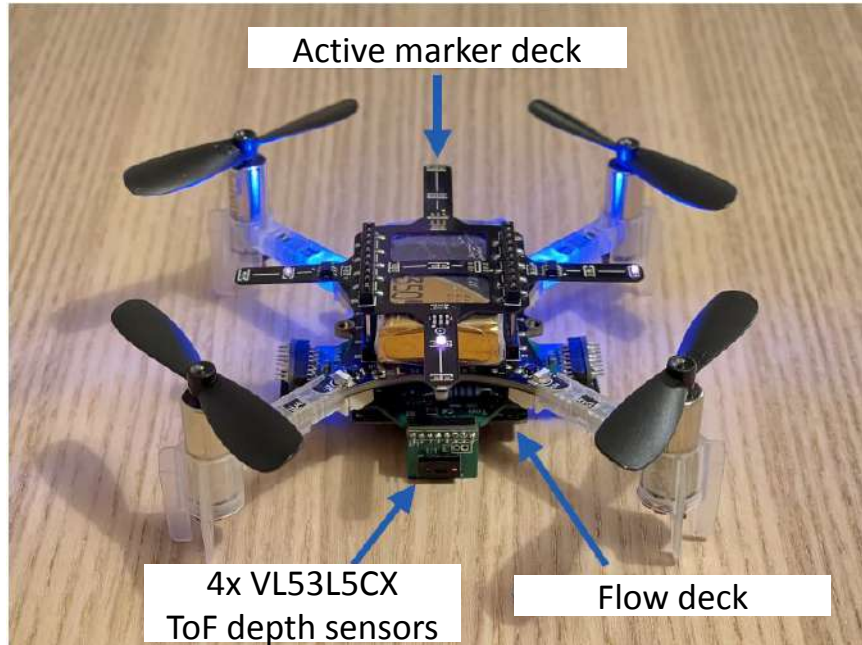


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Mapping: single-drone [5]



- 4x 64-pixels depth sensors @ 15Hz
- STM32 controller (Crazyflie)
- Flow-deck (state estimation)
- GAP9 SoC

Total FoV $\rightarrow 180^\circ \rightarrow$ the nano-UAV has unobservable blind angles

At each scan it rotates 45° to reach a cumulative 360° FoV

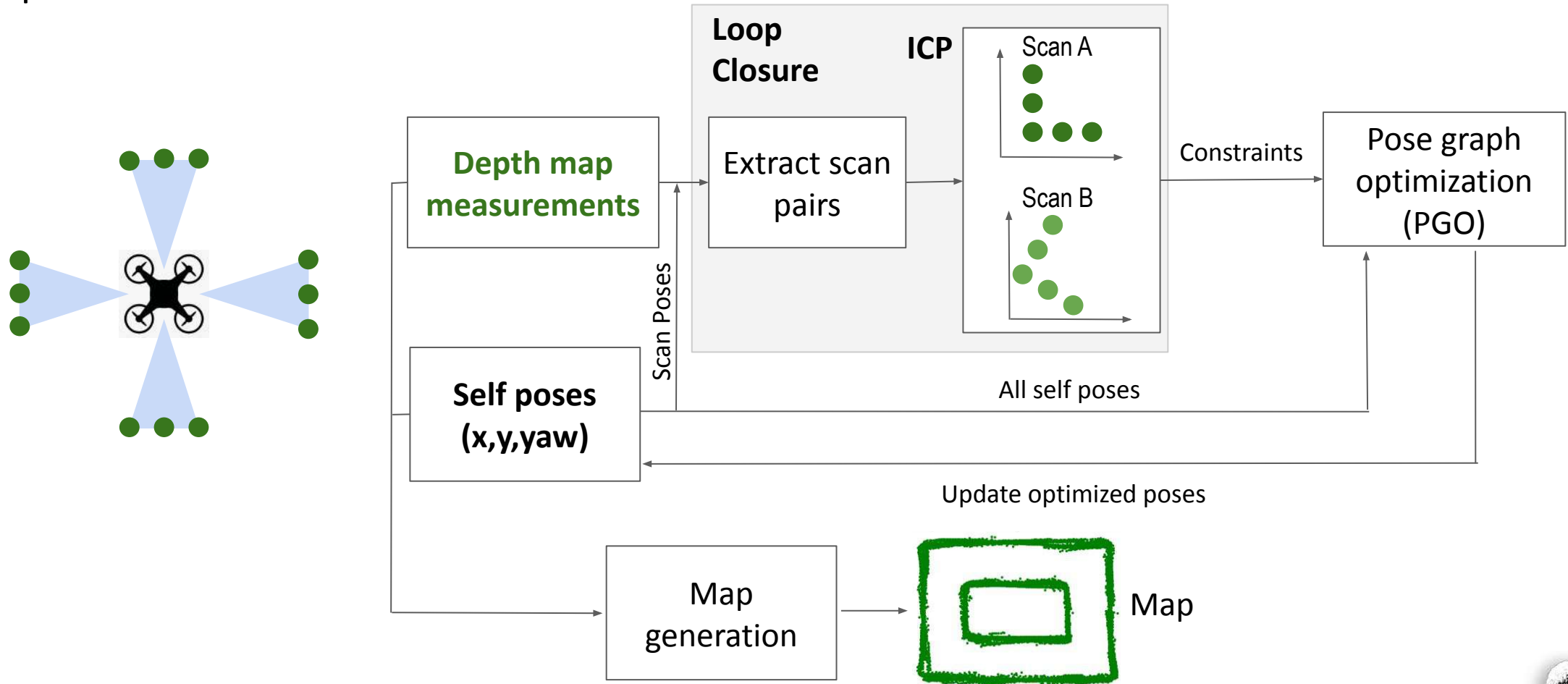
[5] C. Friess et al., "Fully Onboard SLAM for Distributed Mapping with a Swarm of Nano-Drones," CODES ISSS, 2023



Mapping: single-drone [5]



Pipeline



[5] C. Friess et al., "Fully Onboard SLAM for Distributed Mapping with a Swarm of Nano-Drones," *CODES ISSS*, 2023

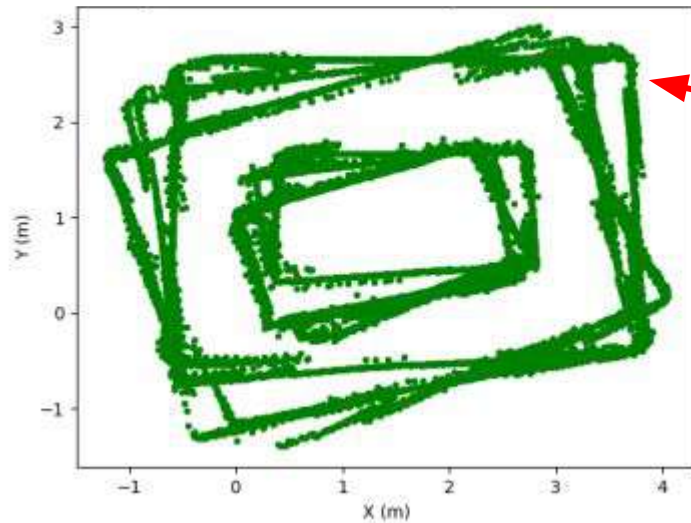


Mapping: single-drone [5]



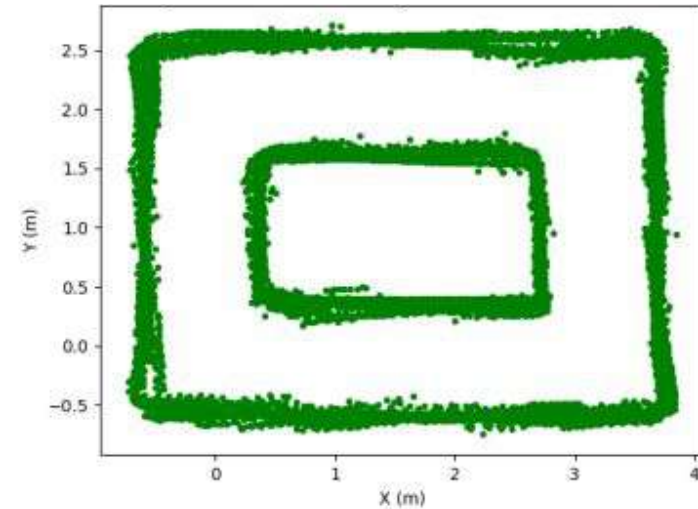
Results

Without ICP and PGO: **RMSE=26cm**



Due to
odometry drift

With ICP and PGO: **RMSE=14cm**



- Runs onboard in tens of milliseconds
- Reduces the mapping error by up to 46%

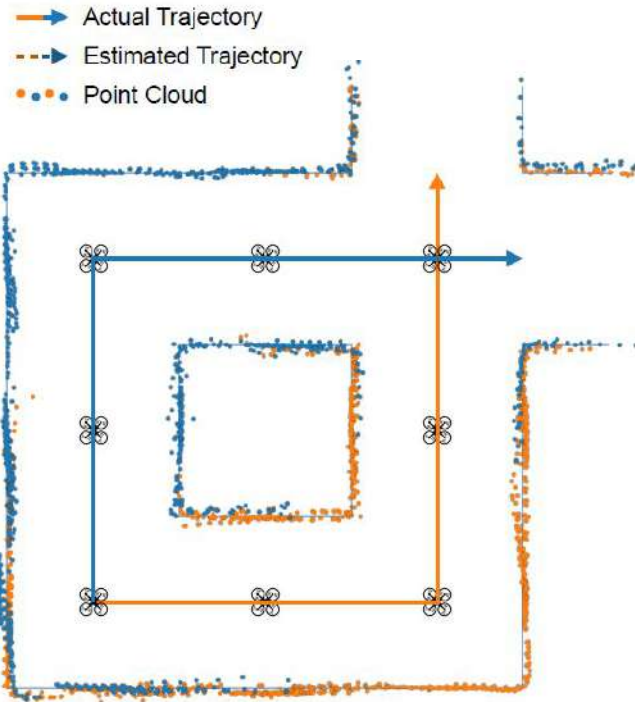
[5] C. Friess et al., "Fully Onboard SLAM for Distributed Mapping with a Swarm of Nano-Drones," *CODES ISSS*, 2023



Mapping: swarm



Mapping with 4 drones



Nanoco²pter AI Challenge 2022



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Nanocoaster AI Challenge @ IMAV'22



PULP Team:



Challenge:

autonomous navigation in an 8x8 m unknown flight arena, with static/dynamic obstacles and gates.

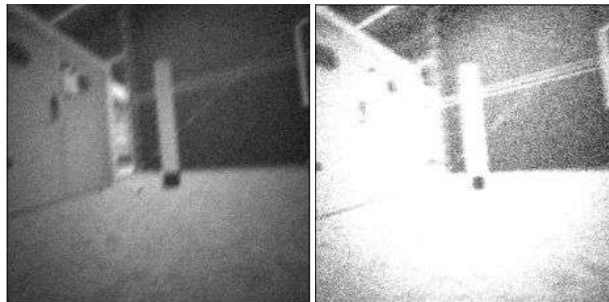
Training: only simulated data

CNN: visual obstacle avoidance (30FPS)

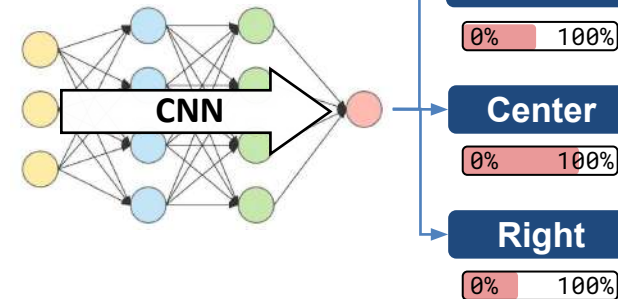
Simulator



Photometric augmentation



Synthetic dataset



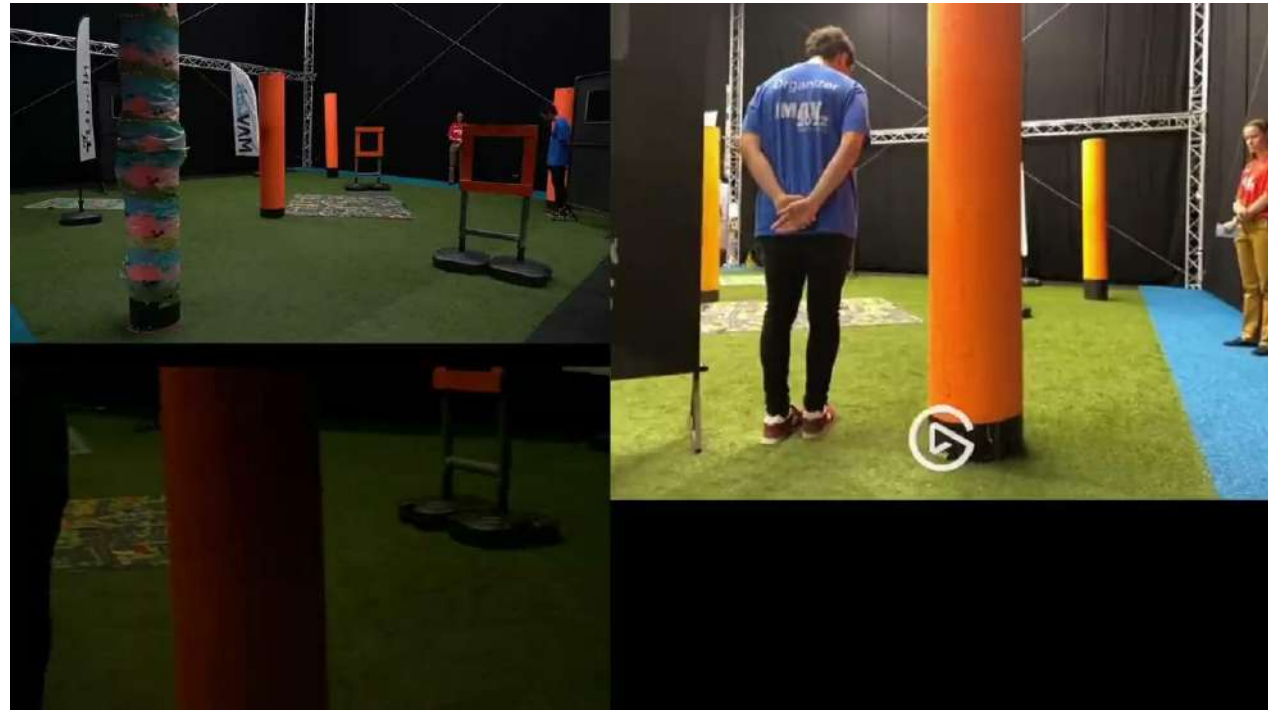
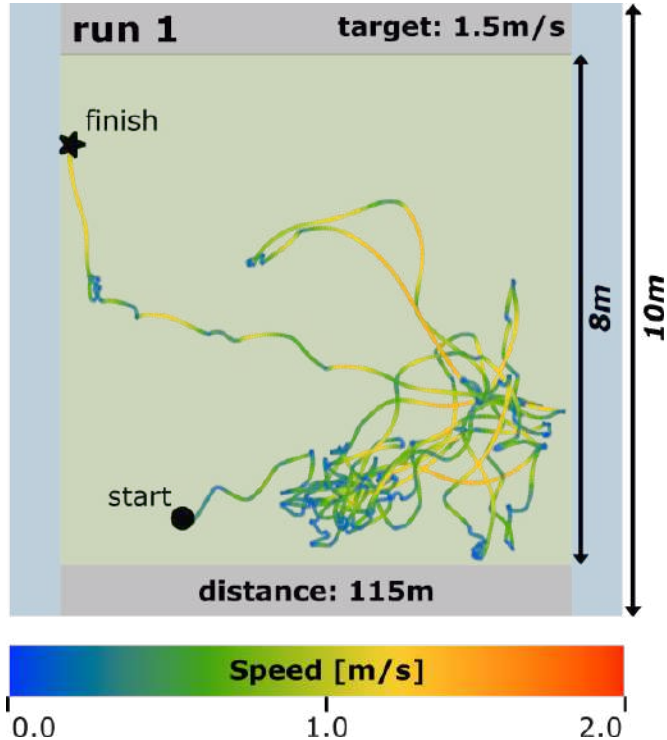
collision probability



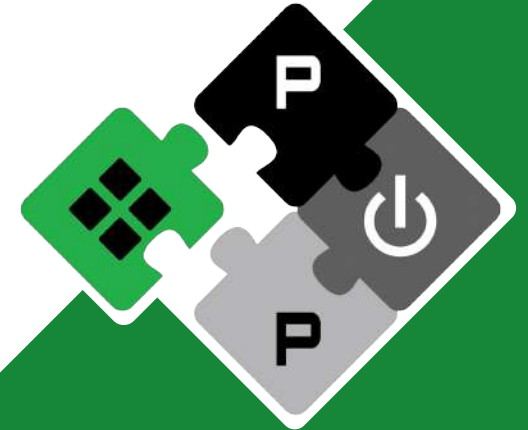
Nanocoaster AI Challenge @ IMAV'22



We won the challenge with the best run of 115 m flight in 5 min without any collision and never leaving the flight arena.



Depth map-based gate navigation



PULP Platform

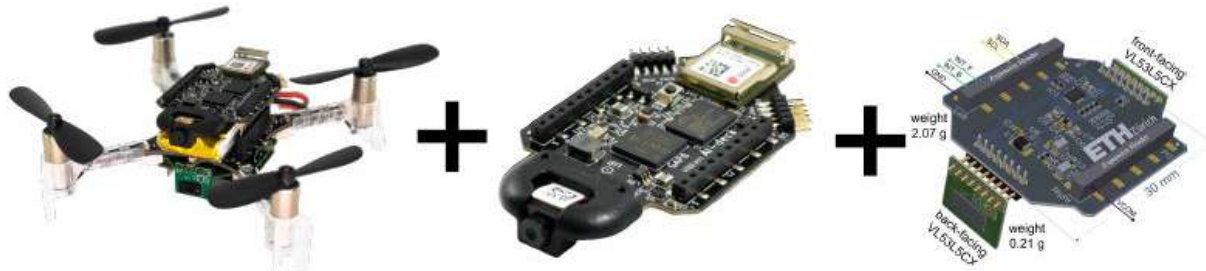
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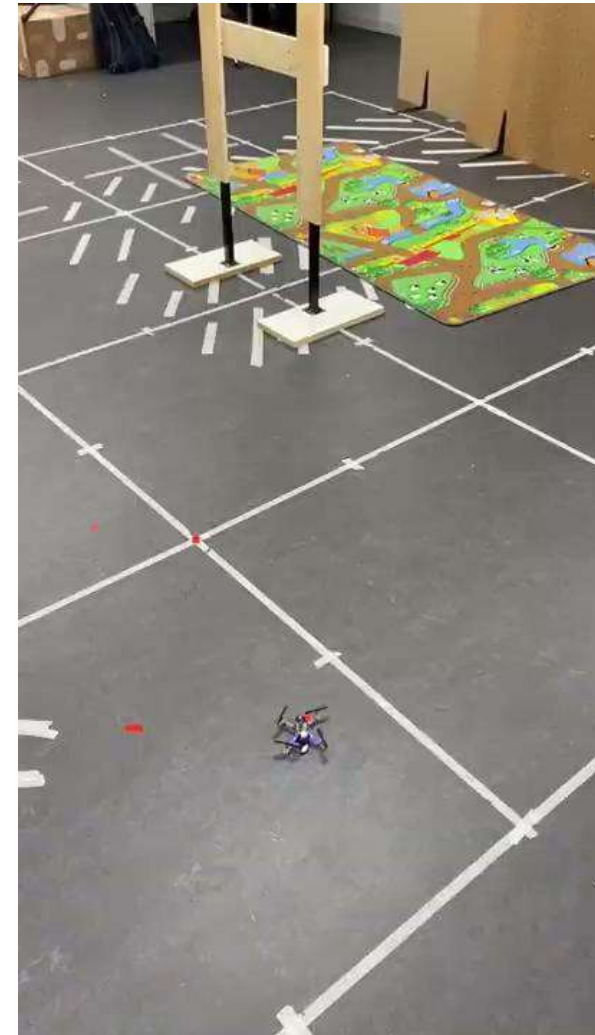
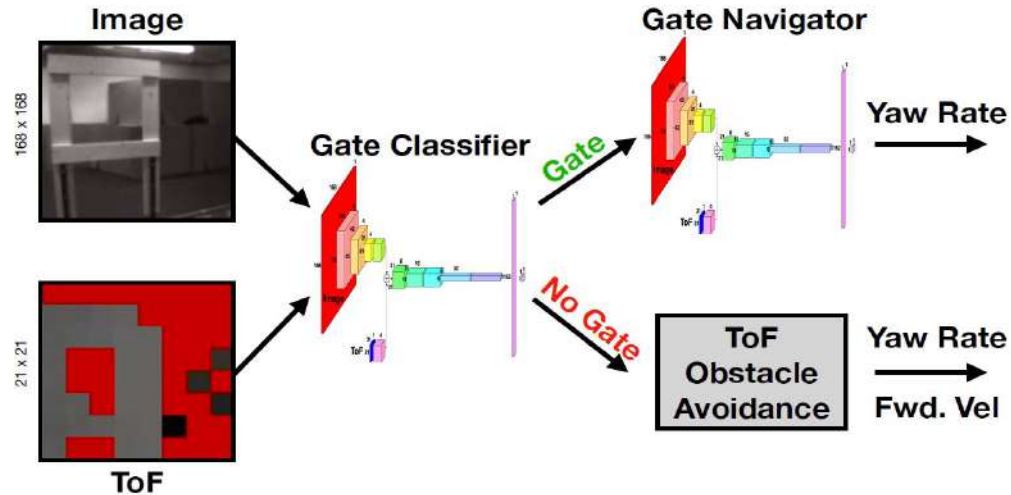
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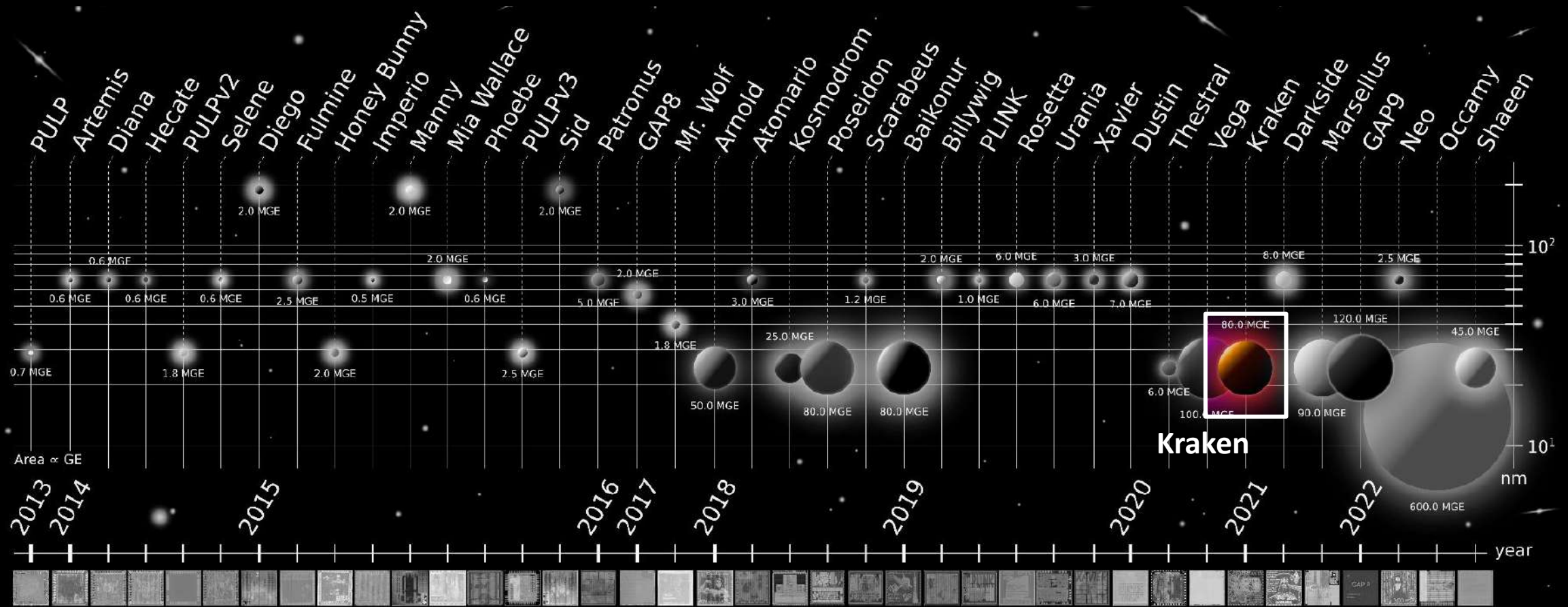
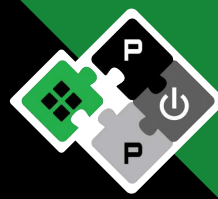
Depth map-based gate navigation



Training only in simulation



History of the PULP



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<http://asic.ethz.ch/applications/Pulp.html>

Credit: Danfele Palossi



Conclusion: what's next

Neuromorphic-based nano-drone racing



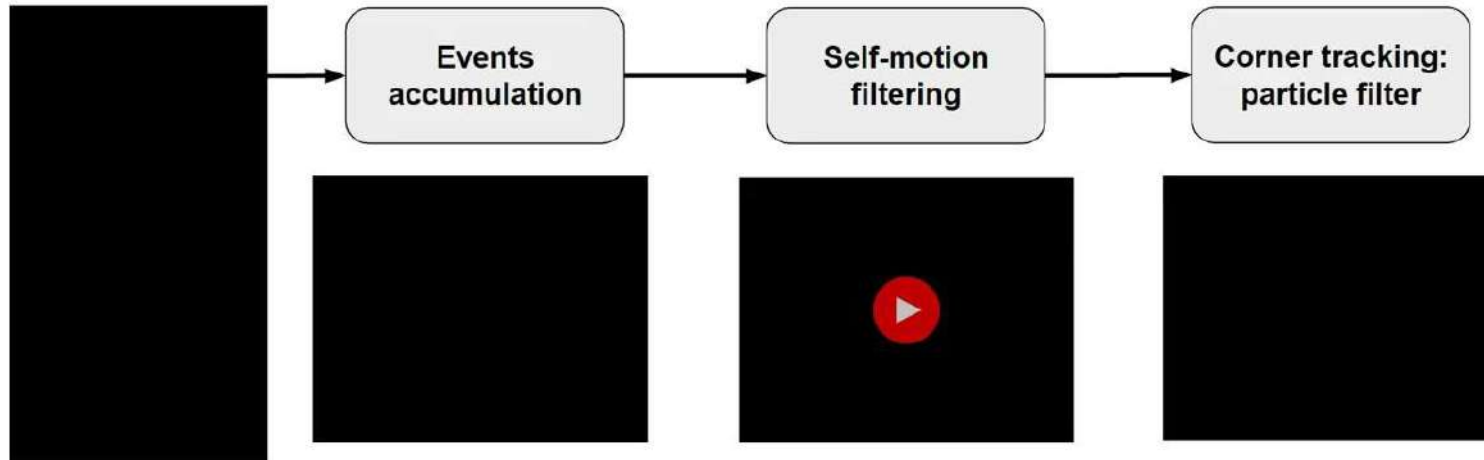
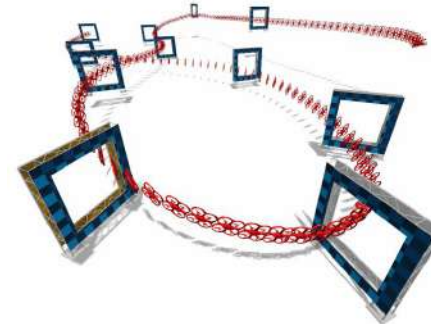
PULP Kraken



Event-based camera



High-speed gate-based navigation

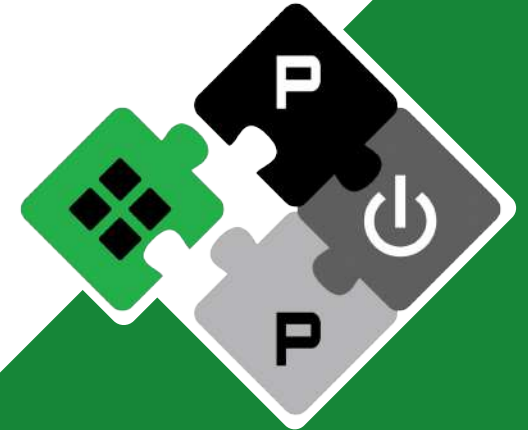


Latency	
Camera	Processing
~ 1000 fps	few ms

... and many more



Live demo: Autonomous nano-drone



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Thank you!

Q&A