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UNIVERSITÄT BONN

Fully On-board Low-Power Localization with Multizone Time-of-Flight Sensors on Nano-UAVs

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Why On-board Localization on (Nano-)UAVs?

- **Nano-UAV**
  - **Suitable for cluttered indoor environment**
- **Localization**
  - **Crucial capability for mobile autonomous systems**
  - **Foundation for complex tasks**
- **On-board localization**
  - **Independent of infrastructure**
  - **Reduces security risks**

Intelligent Nano-UAV - Challenges

Vehicle class	Ø : 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	~10	MCU
pico-size	≤ 2 : ≤ 0.001	≤ 0.1	ULP

- Require lightweight, low-power sensors
- Require low-power but high computational power

Crazyflie 2.1

27g

\+

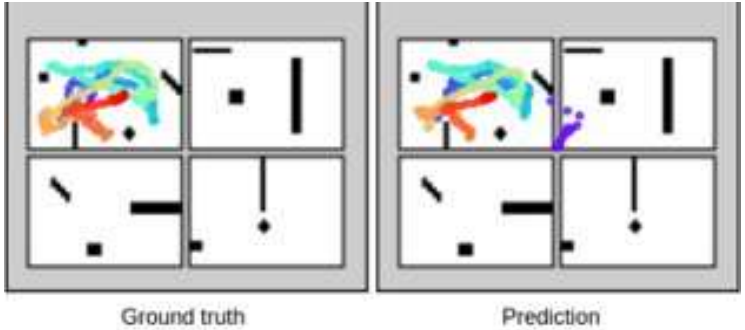
<15g

- Open source
- Modular – extension with own decks possible
- State estimation with extended Kalman filter
- Based on STM32F405 (192kB RAM, 168MHz ARM Cortex M4)

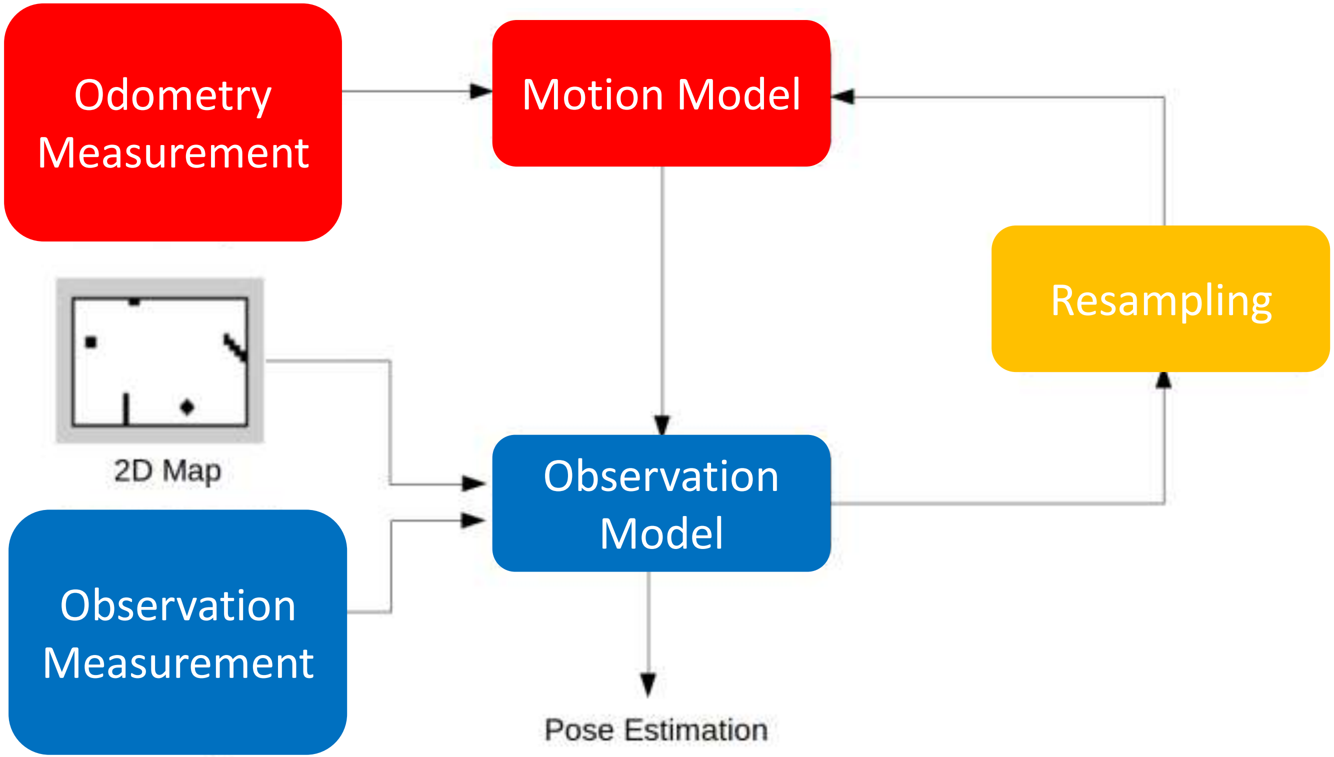
On-board Localization

Our contributions:

- On-board localization
- 0.15m accuracy, 95% success rate
- Reduced memory by quantization/f16
- Reduced latency by parallelization (7x)
- Sensing and processing <7% of power consumption



Monte Carlo Localization



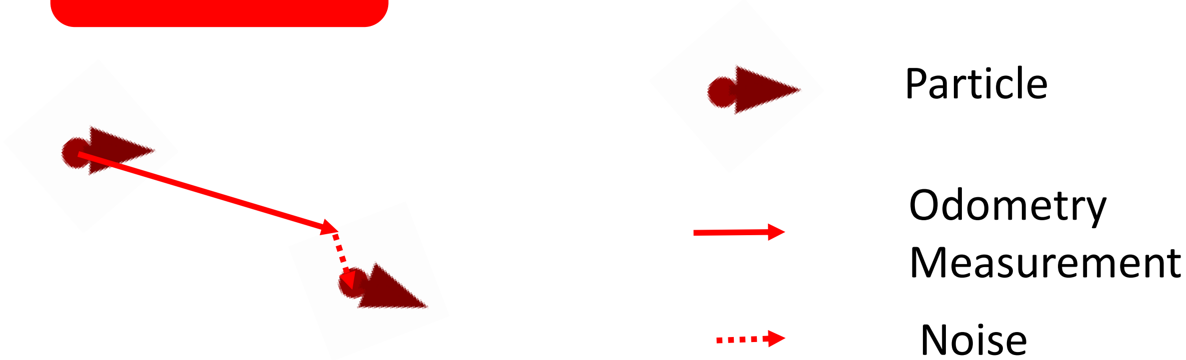
Monte Carlo Localization

Odometry Measurement

Extended Kalman Filter @100Hz

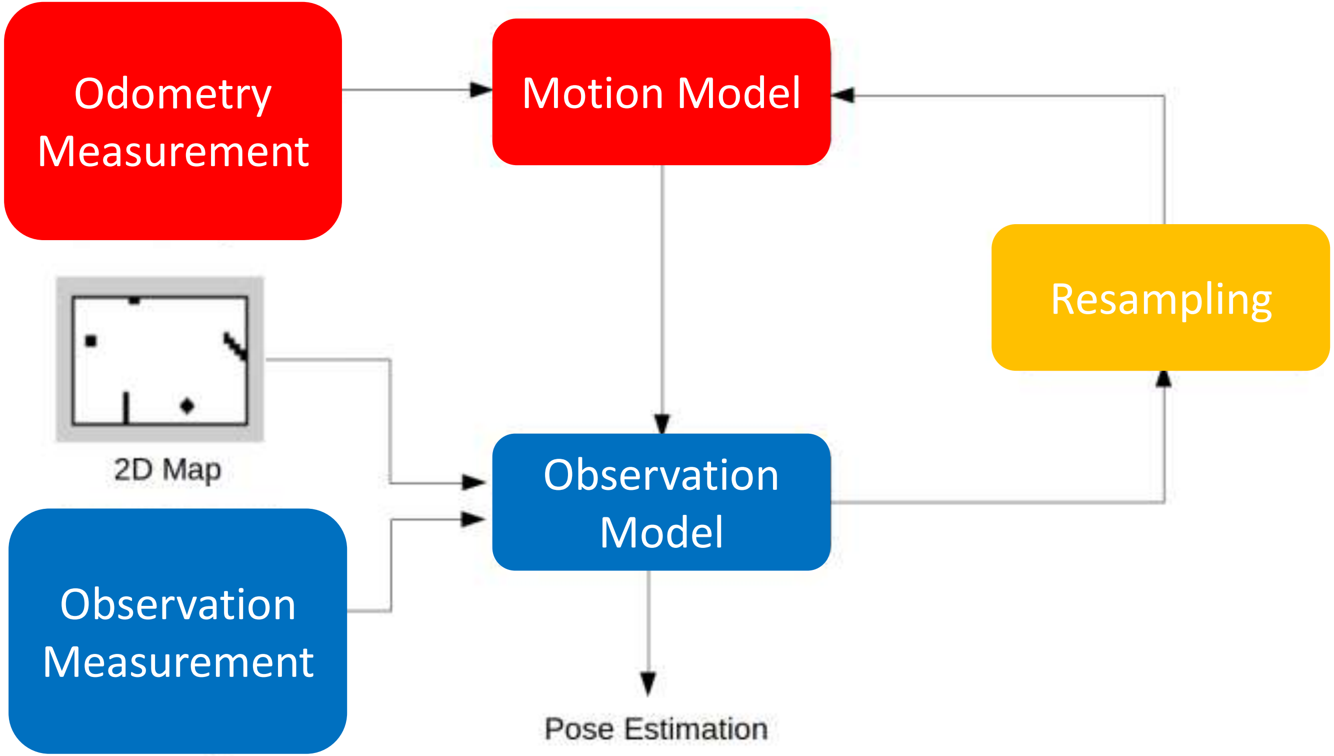
6-axis IMU: BMI088
Optical Flow: PMW3901
Downward ToF: VL53L1

Motion Model



A particle represents a hypothesis about the robot's state

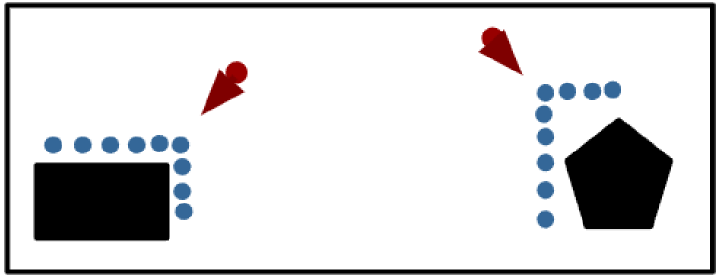
Monte Carlo Localization



Monte Carlo Localization

Observation Measurement

Multizone ToF:
VL53L5
@15Hz




Particle


Observation

Observation Model

Particle state

Observation

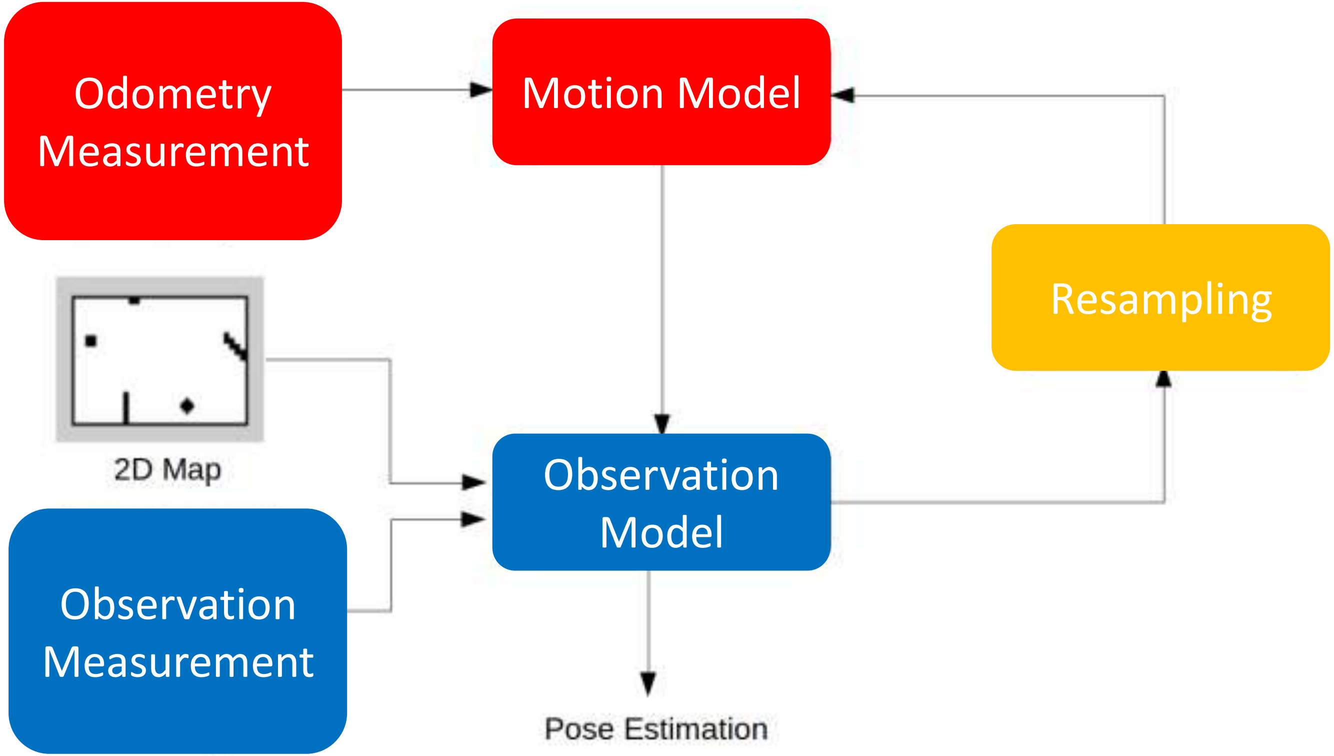
Map

$$p(z_t^k \mid x_t, m) = \frac{1}{\sqrt{2\pi\sigma_{\text{obs}}}} \exp\left(-\frac{EDT(\hat{z}_t^k)^2}{2\sigma_{\text{obs}}^2}\right)$$

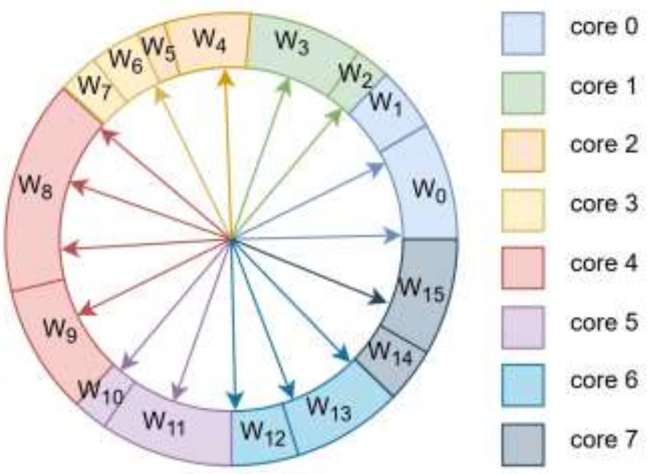
Euclidean Distance Transform of observation

Standard deviation of observation

Monte Carlo Localization

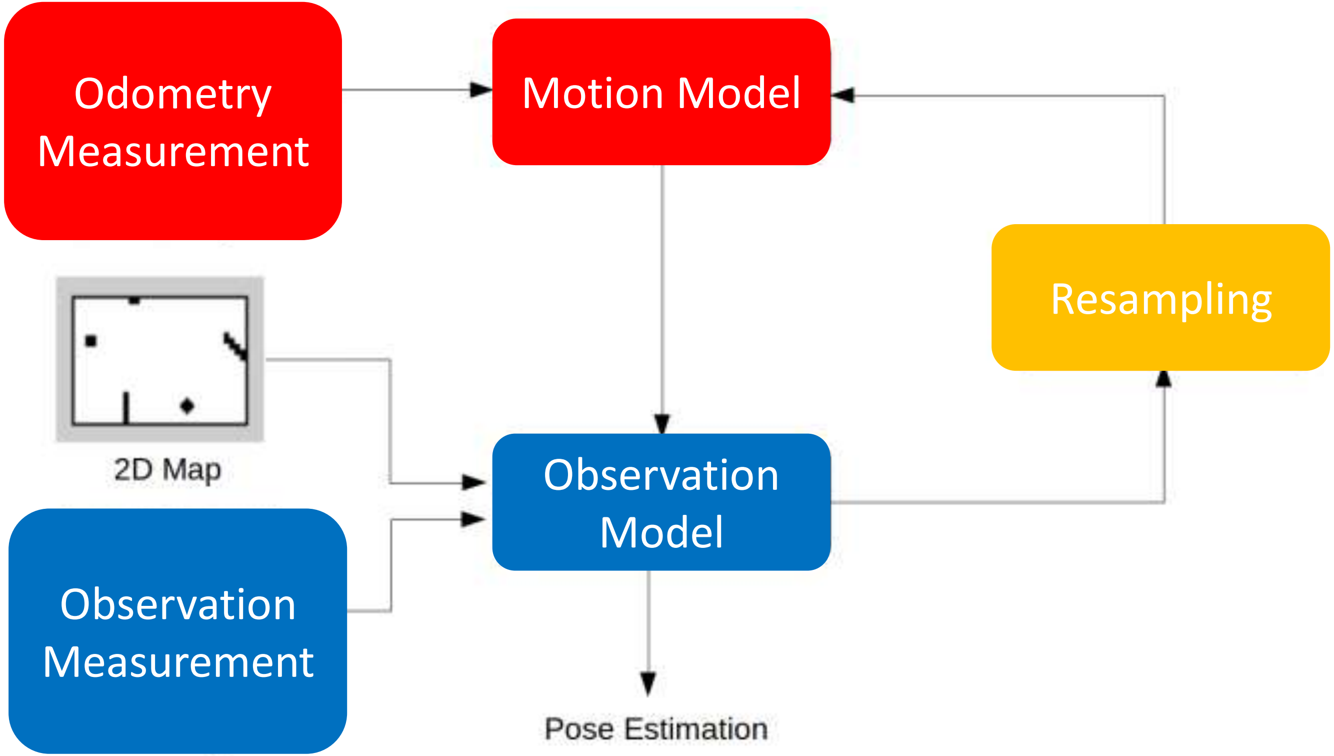


Monte Carlo Localization



Resampling

Monte Carlo Localization



Key Hardware Components

Odometry Measurement

Extended Kalman Filter @100Hz

6-axis IMU: BMI088
Optical Flow: PMW3901
Downward ToF: VL53L1

Flight Controller

ARM Cortex M4: STM32F405

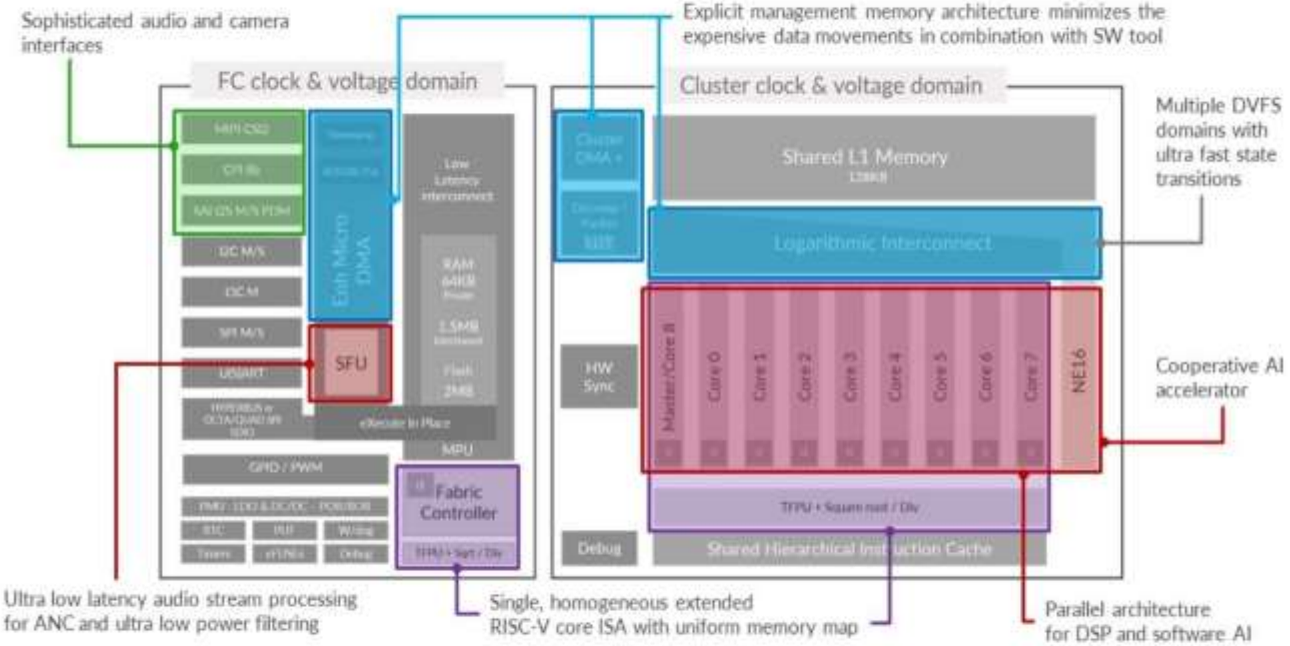
Observation Measurement

Multizone ToF: VL53L5 @15Hz

Monte Carlo Localization

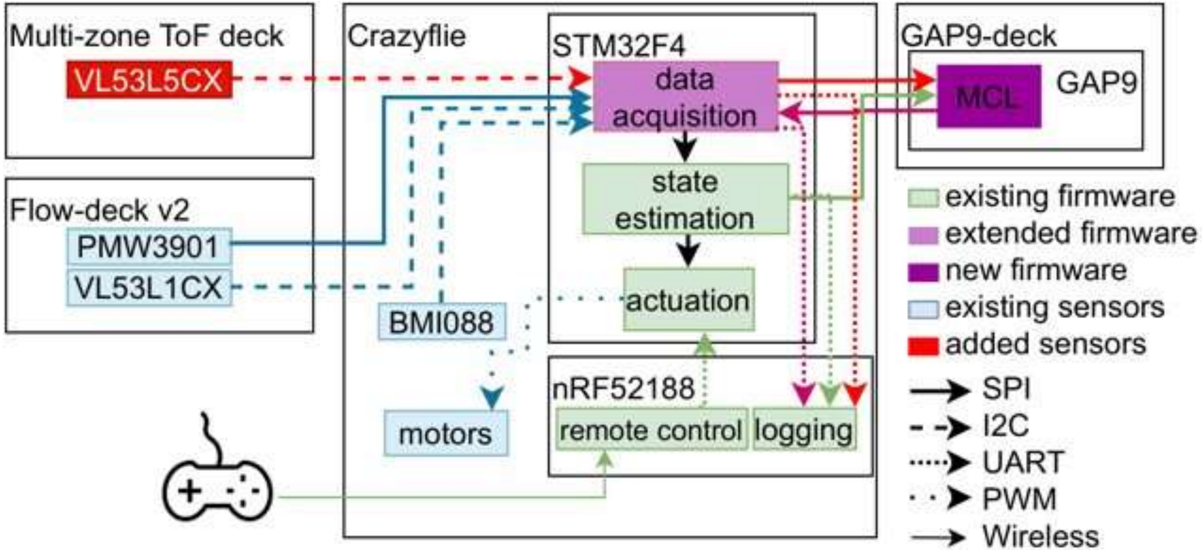
Parallel Ultra Low-Power SoC: GAP9

GAP9 Architecture

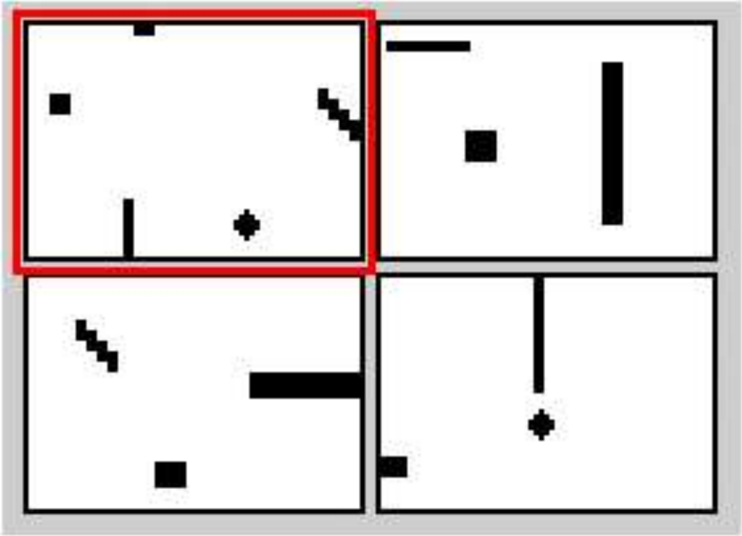


https://greenwaves-technologies.com/gap9_processor/

System Architecture



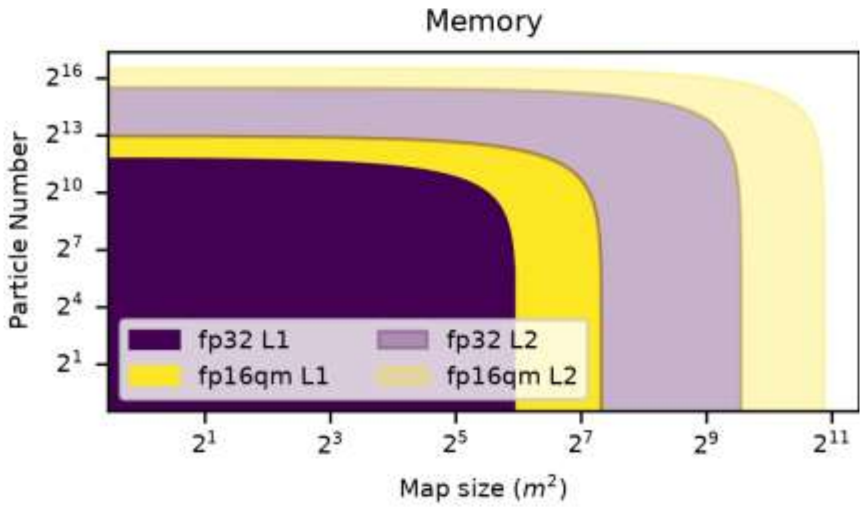
Experimental Evaluation - Setup



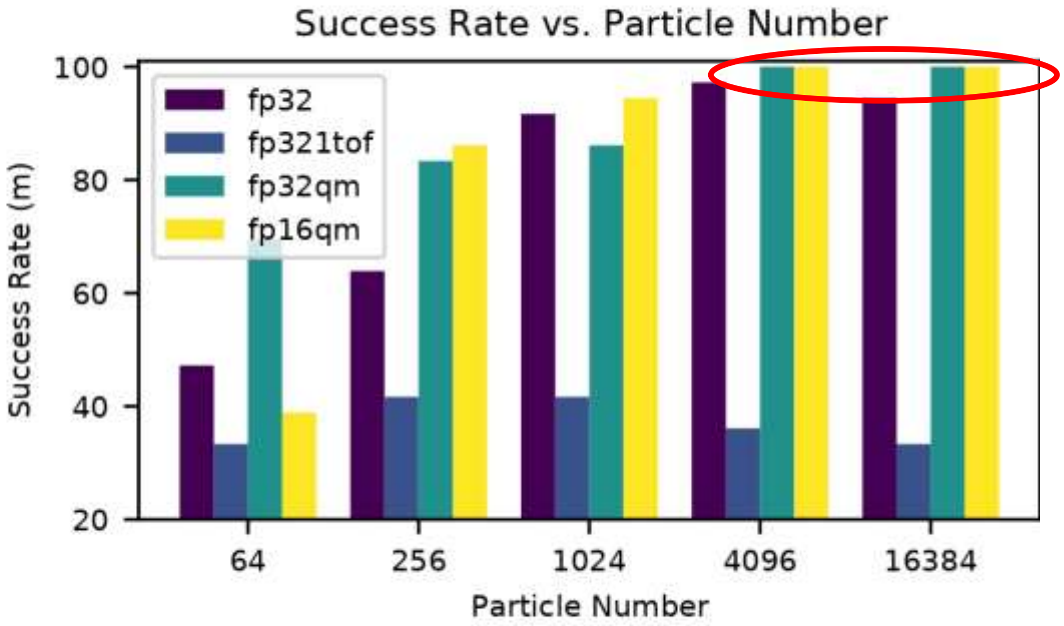
MCL Parameters

- 1 (front) vs 2 (front and rear) ToF sensors
- #particles (64, 256, 1024, 4096, 16384)
- full precision vs quantized map, lower accuracy particles

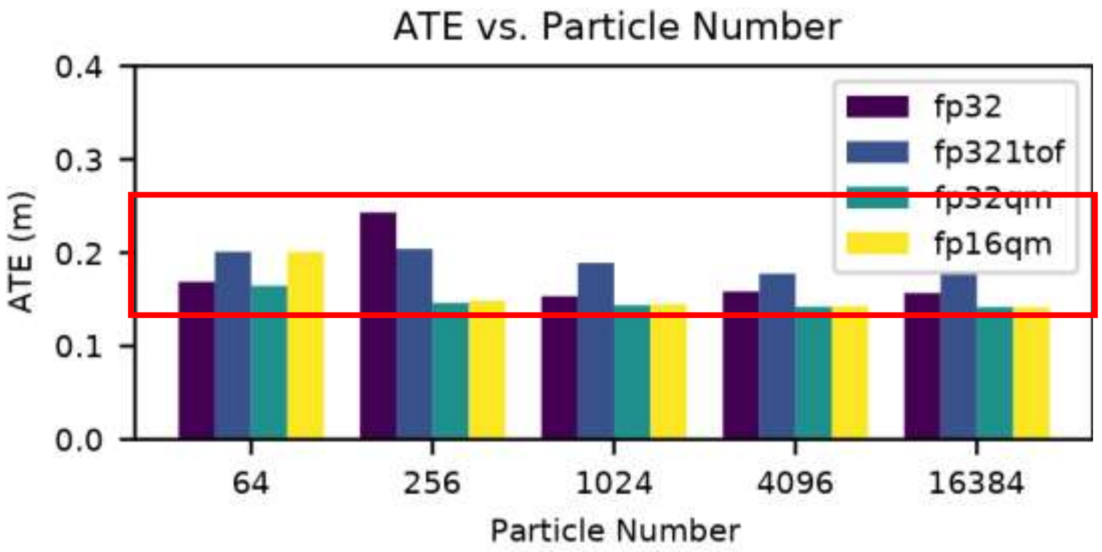
each particle:
- x position
- y position
- yaw angle
- weight



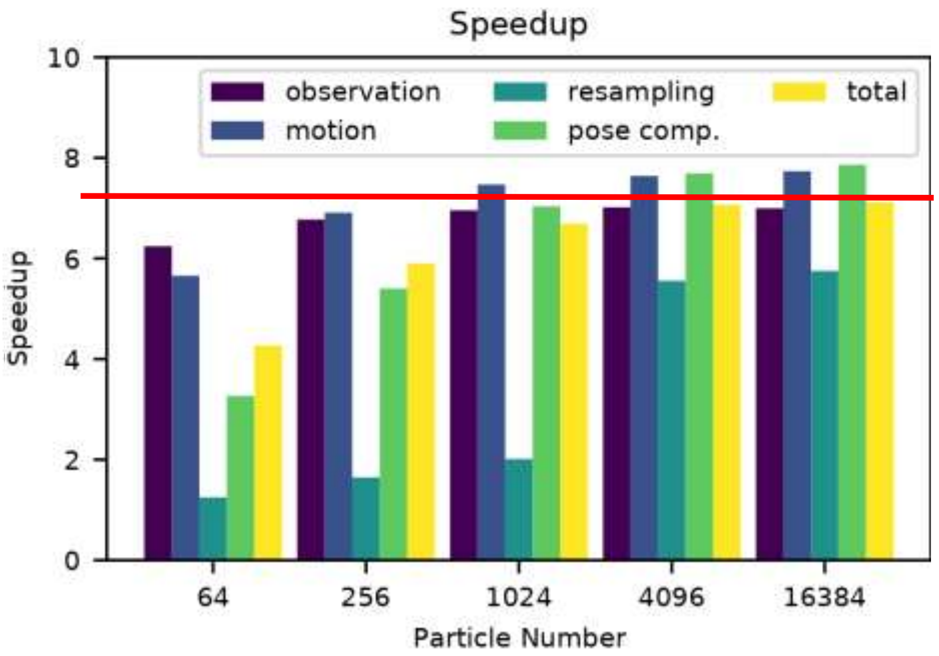
Experimental Evaluation – Robust Localization



Experimental Evaluation – Robust Localization



Experimental Evaluation – Real-time



Experimental Evaluation – Real-time/Power

	Avg. Power consumption	Execution time
GAP9@400MHz/1,024 particles	61mW	1.901ms
GAP9@12MHz/1,024 particles	13mW	59.898ms
GAP9@400MHz/16,384 particles*	61mW	30.880ms
GAP9@200MHz/16,384 particles*	38mW	61.524ms

*particles stored in L2

Measurement update: 15Hz

Conclusion

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- Open source