National Science Foundation
WHERE DISCOVERIES BEGIN

CPS: Synergy: Collaborative Research: LEAR-CPS: Low-Energy computing for Autonomous mobile Robotic CPS: A Hardware-and-Algorithms Co-design Approach

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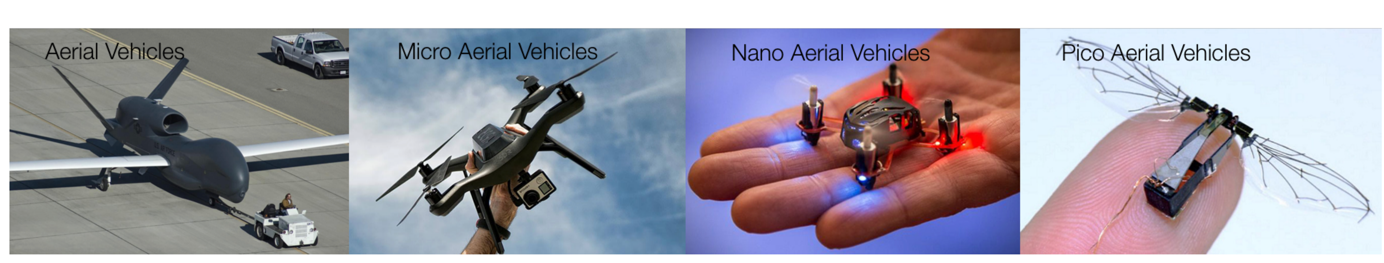
Research Opportunity

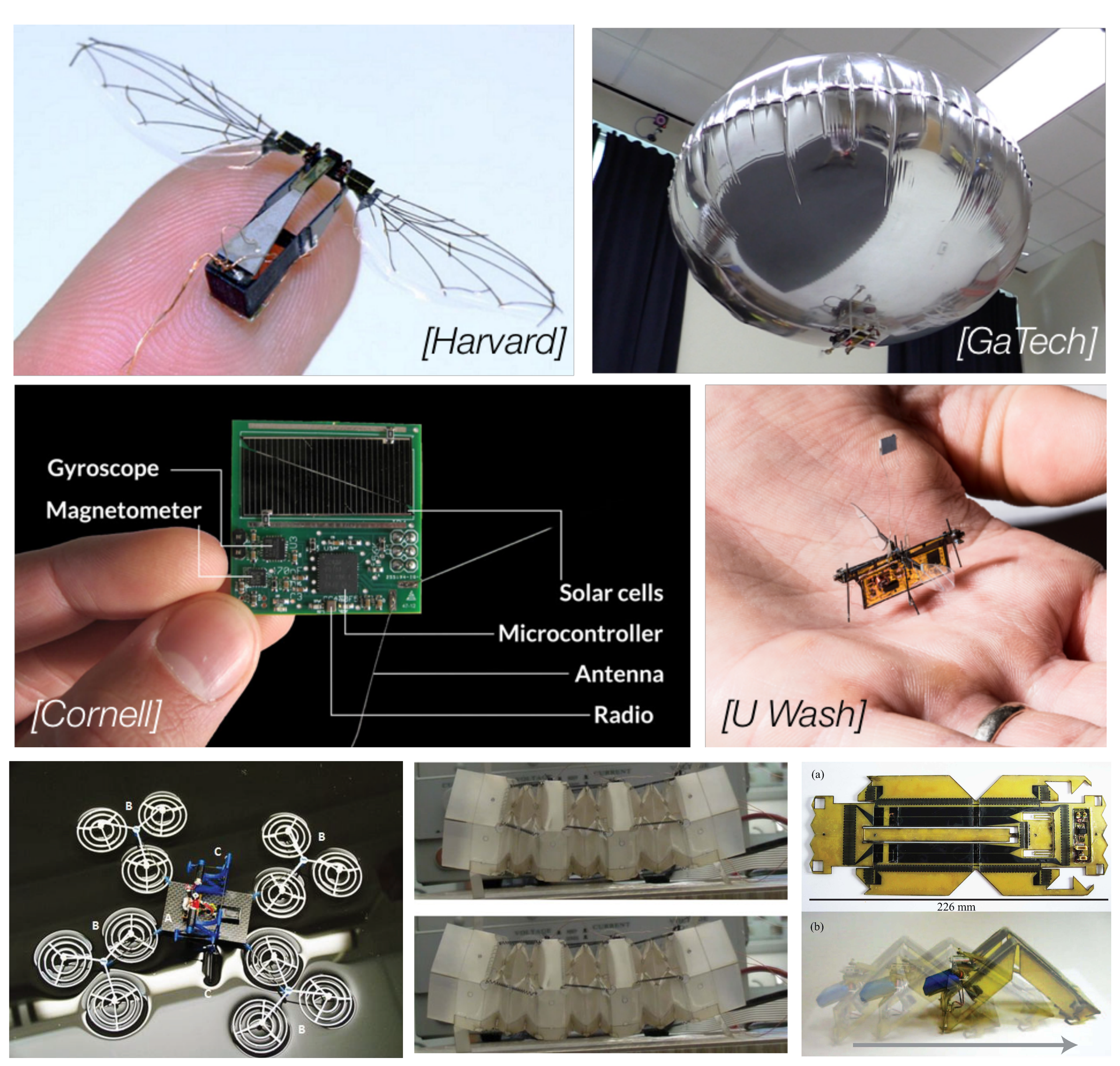
A broad range of next-generation CPS applications will be enabled by low-energy sensing and computing, in particular, by miniaturization. For instance, (i) insect-size drones with swarming capabilities in massive numbers, (ii) pill-size medical robots that can intelligently navigate the human digestion system, (iii) intelligent satellites on chip that can navigate far corners of the Solar system, (iv) low- energy glider drones and underwater vehicles that can operate continuously for months.

In the past decade, there has been tremendous advances in designing and building two of these elements, namely the sensors and actuators. However, powerful computers that modern artificial intelligence and autonomy depend on are still bulky, heavy and energy-hungry. The aforementioned applications require computers that are orders of magnitude smaller, lighter, and more energy-efficient. The current approach of developing algorithms and software that are designed for off-the-shelf general-purpose CPUs and GPUs, fails to deliver. A paradigm shift in computing is necessary towards enabling low-energy, miniature mobile robotic CPS that still provides provable guarantees on completeness, optimality, robustness and safety.

We will develop novel algorithms and computing hardware for low-energy mobile robotic Cyber-Physical Systems.

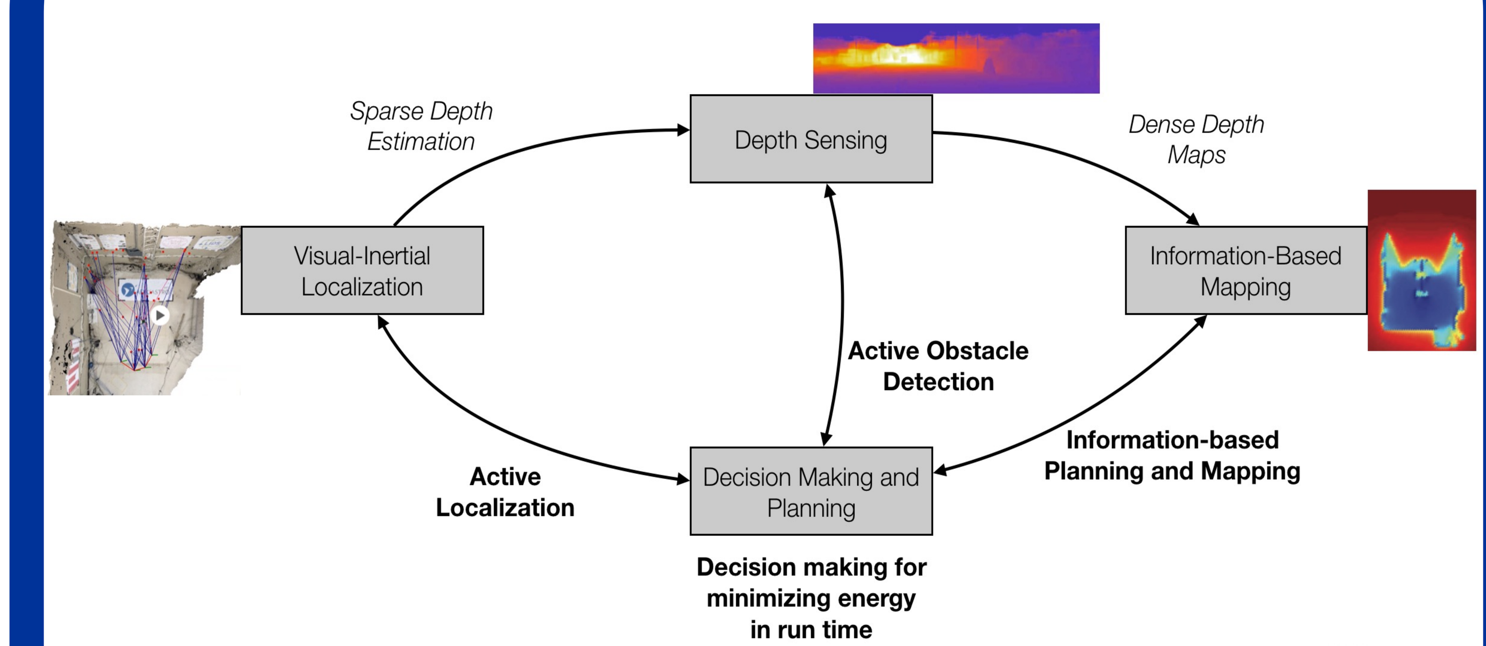


Design of miniature UAVs will be driven not by size/weight but by power.



Example low-energy mobile robotic CPS. Each vehicle consumes less than 1 Watt of electrical power for actuation.

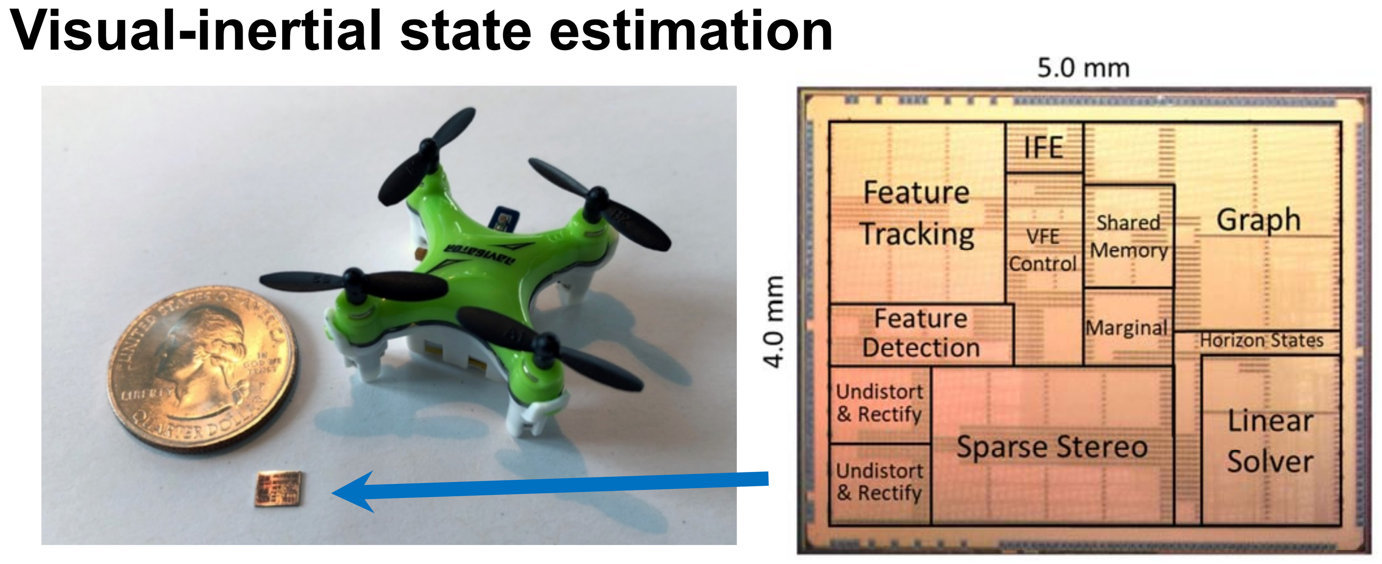
Research Opportunities



An example integrated system for low-energy mobile robotic CPS

Results from previous years

Visual-inertial state estimation

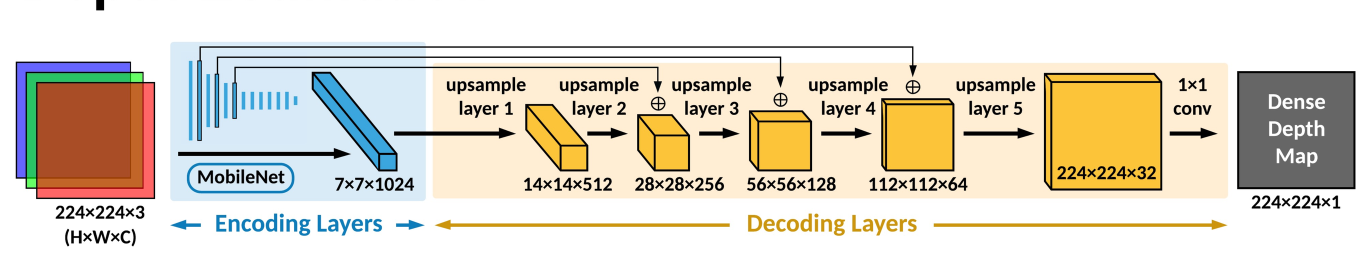


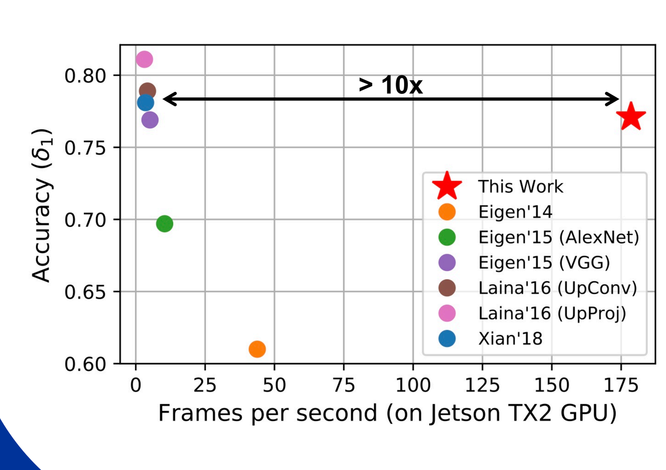
More info at http://navion.mit.edu

Technology	65nm CMOS	Supply	1 V
Chip area (mm²)	4.0 x 5.0	Resolution	752x480
Core area (mm²)	3.54 x 4.54	Camera rate	28 - 171 fps
Logic gates	2,043 kgates	Keyframe rate	16 - 90 fps
SRAM	854KB	Average Power	24 mW
VFE Frequency	62.5 MHz	GOPS	10.5 – 59.1
BE Frequency	83.3 MHz	GFLOPS	1 – 5.7

A. Suleiman, Z. Zhang, L. Carlone, S. Karaman, V. Sze, "Navion: A Fully Integrated Energy-Efficient Visual-Inertial Odometry Accelerator for Autonomous Navigation of Nano Drones," IEEE Symposium on VLSI Circuits, June 2018.
Z. Zhang*, A. Suleiman*, L. Carlone, V. Sze, S. Karaman, "Visual-Inertial Odometry on Chip: An Algorithm-and-Hardware Co-design Approach," Robotics: Science and Systems (RSS), July 2017.

Depth Estimation





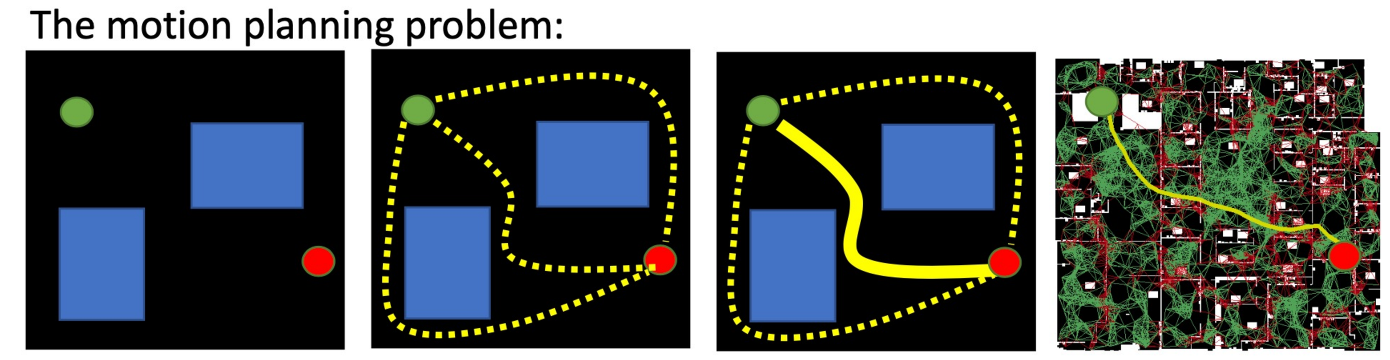
More info at http://fastdepth.mit.edu

D. Wofk*, F. Ma*, T.-J. Yang, S. Karaman, V. Sze, "FastDepth: Fast Monocular Depth Estimation on Embedded Systems," IEEE International Conference on Robotics and Automation (ICRA), May 2019.

Results from This Year

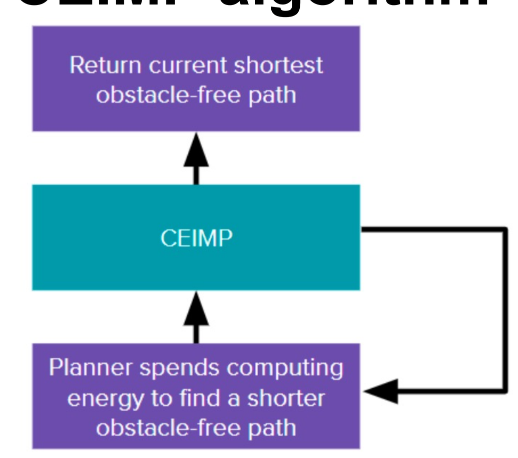
Decision-making and Planning: Balancing Compute Energy and Execution Energy

The motion planning problem:



Compute an obstacle-free path from the start to the goal | Minimize a cost function to select the best path | Select shortest path for conventional cost function (path length) | Planners can monotonically find shorter paths by computing more samples

CEIMP algorithm



We propose CEIMP:

- CEIMP decides whether to continue computing a shorter path or stop computing and return the current best path
- To decide, CEIMP compares its estimates of the future computing energy required and the future actuation energy that will be saved if it continues computing.

Estimating future actuation energy saved:

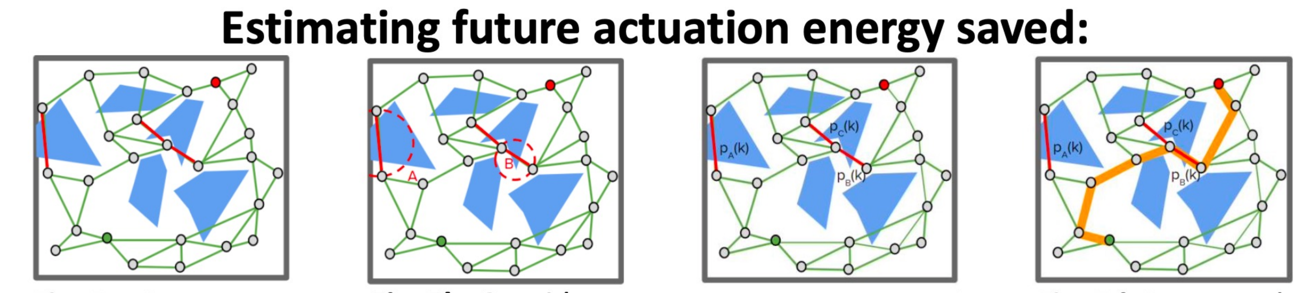


Fig. 5a: Construct a graph with infeasible edges to "probe" the map for new paths

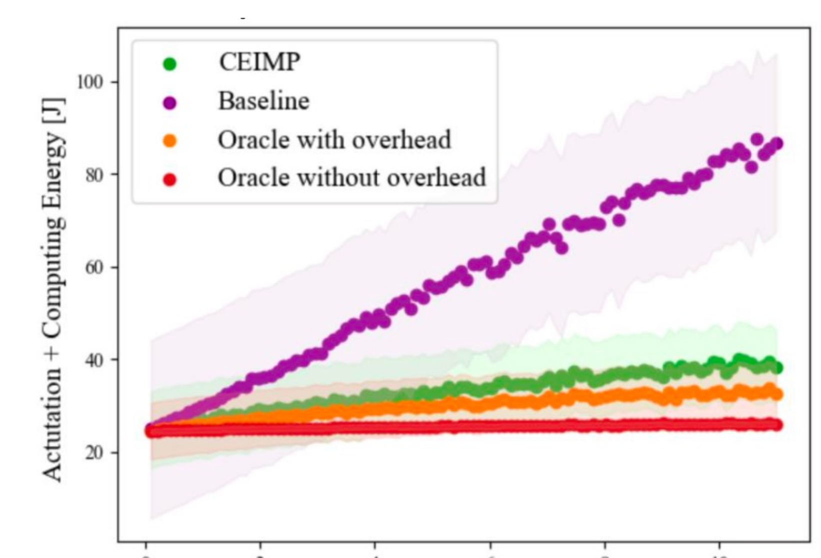
Fig. 5b: Consider sampling as "sensing" whether an edge is repaired (B) or not (A)

Fig. 5c: Estimate the probability each edge is repairable via Bayesian filtering

Fig. 5d: Run search algorithm on graph to return the minimum expected path length

Results

CEIMP yields significant energy savings, especially as the ratio between computation and actuation energy scales.



Key takeaways

Don't think *too* hard: A longer path that we have now can be better than a shorter path that we have to compute a long time to find **Computing is (noisy) sensing:** Sampling nodes in a motion planner can be modeled as a noisy sensor that measures whether a path is open or closed **Inferring from failure:** CEIMP adjusts its beliefs based on which paths have not yet opened, enabling an efficient method to predict future path lengths

S. Sudhakar, S. Karaman, V. Sze, "Balancing Actuation and Computing Energy in Motion Planning," IEEE International Conference on Robotics and Automation (ICRA), May 2020