Powering (autonomous) sensors and systems

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Autonomous Computing: what it is

- A standalone (in so far as possible) SOC with the sensors, actuators, controllers communications and storage.
- Capable of realizing complete communications, sense, analysis, recognition and motor actions.
- Must be more than simple sense and communicate; analysis to create information.
- Ensemble computing, cumulative intelligence

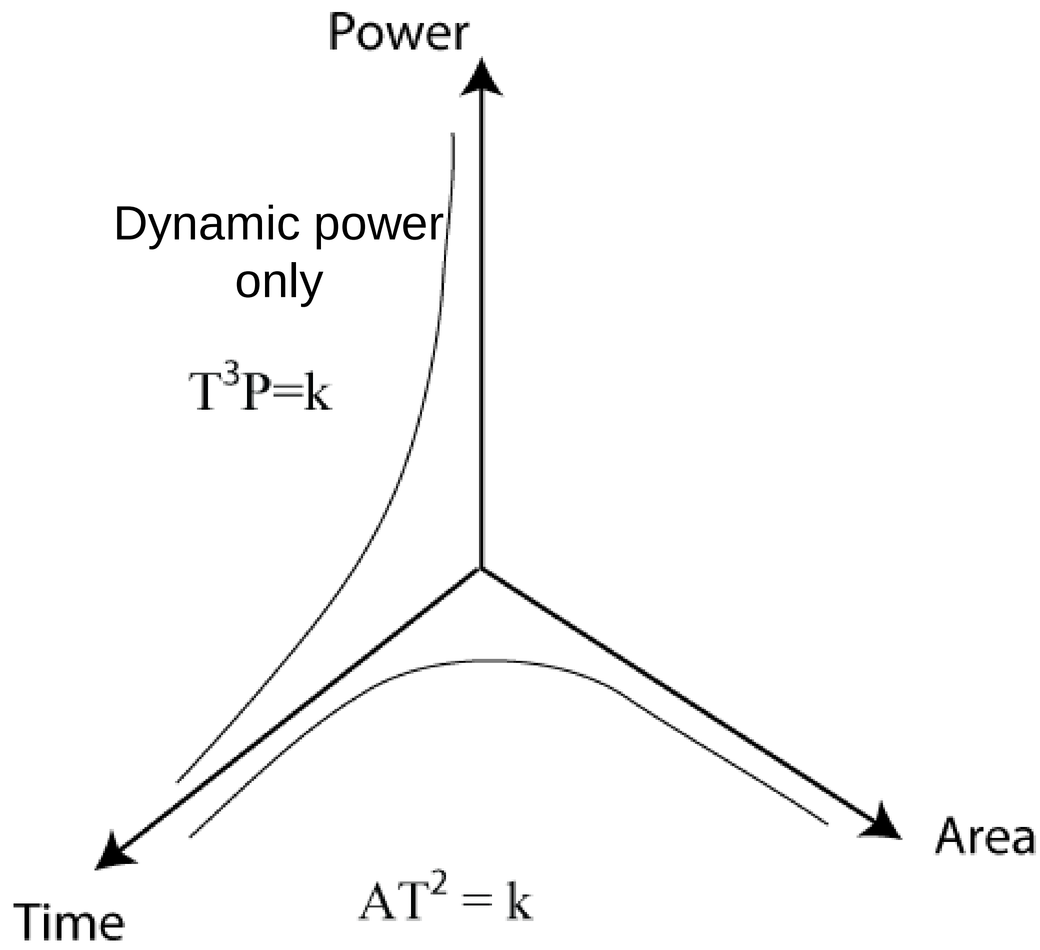
Untethered Computing, RFID vs. Autonomous Computing

System	*Passive id*	*Active id*	*RF sensor*	*AC*
Example	RFID, Smart Card (simple)	Smart card, Active RFID	Smart Dust; RFID + sensor	
Power source	None	Short term battery	Battery	Integrated Battery
Maximum Memory	ROM ID (1KB)	R/W ID + parameters (2KB)		R/W extensive (100 MB)
RF range (meters)	Passive; order of 1 meter (M)	Active 1-10 M	10 - 20 M	10+M
Compute	None	FSM or controller	FSM	More than one CPU

Autonomous Computing basics

- Small size (basic die type: $\mathcal{O}$(1/4 -1 cm^2 x ½ mm)
- *Note, long term: could be printed on an ultra thin base*
- Power and energy, self contained
- Persistent storage
- Communications with environment (network)
- One or more types of sense and reaction
- Networked ensemble.

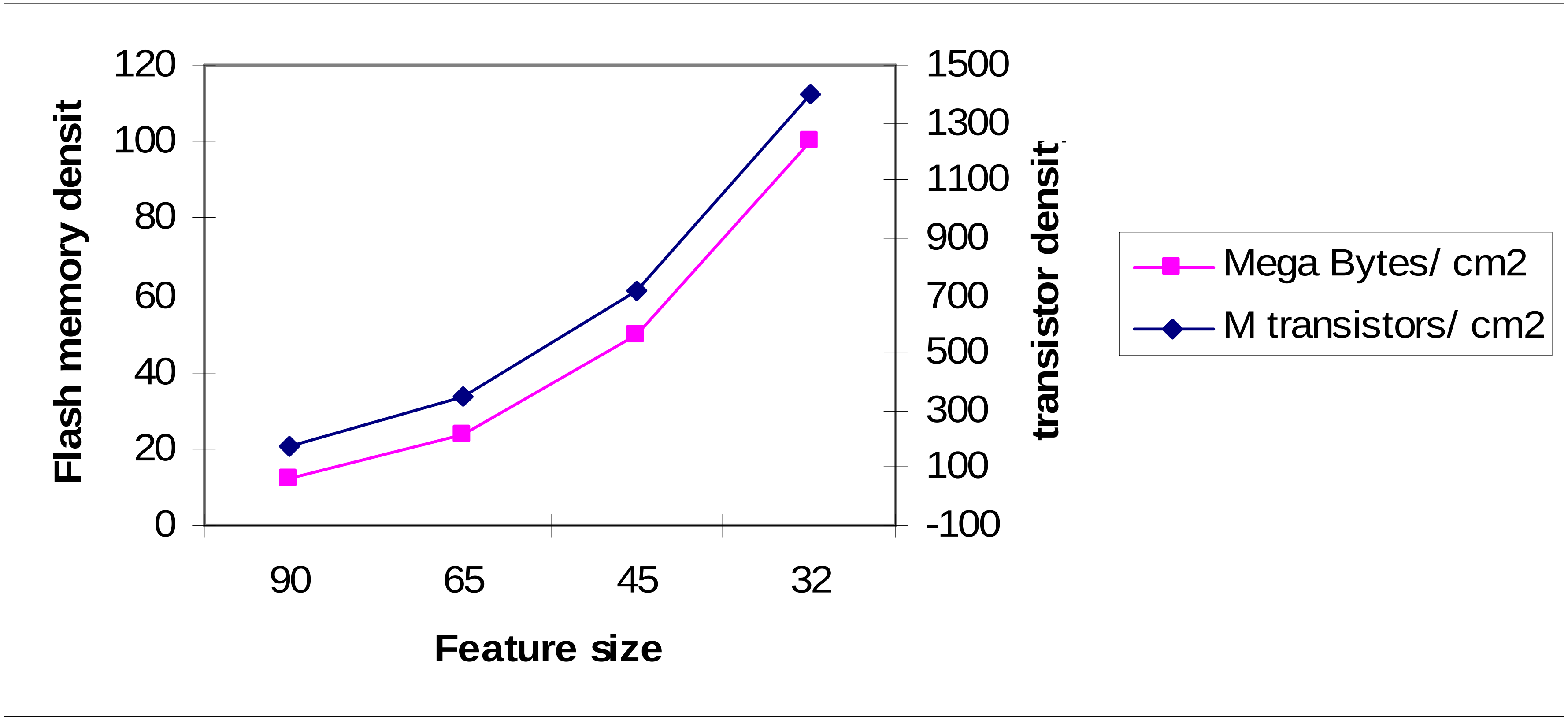
Area, Time (Performance) and Power Design Tradeoffs



Area

- Cost of processed silicon is \$1-10/cm^2.
- Most designs target 1 cm^2 or a little less in area; the sweet spot. Gives 90% + yield.
- Larger dies have lower yields and fewer dies / wafer. Costs can be 10x for a doubling of die size.
- Small dies aren’t much cheaper; limited by testing and packaging.

Silicon device density scaling



Net: there's either a 1 billion transistors or 100 Mega Bytes of Flash on a $1cm^2$ die

Power and batteries

- Eliminating the external battery is one key technology for autonomous computing; no pins or distribution problems
- Must print or deposit battery on reverse side of die.
- Can scavenge power but source may be unreliable and adds on die complexity.

Battery technology

Type	*Energy (J)*	*Recharge Y/N*	*Thickness (micron)*
Printed [1]	2 / cm^2	N	20
Thin film [2]	10 /cm^2	Y	100
Button	200	Y	500 (stand alone)

[1] PowerID, Power Paper Corp. www.powerpaper.com

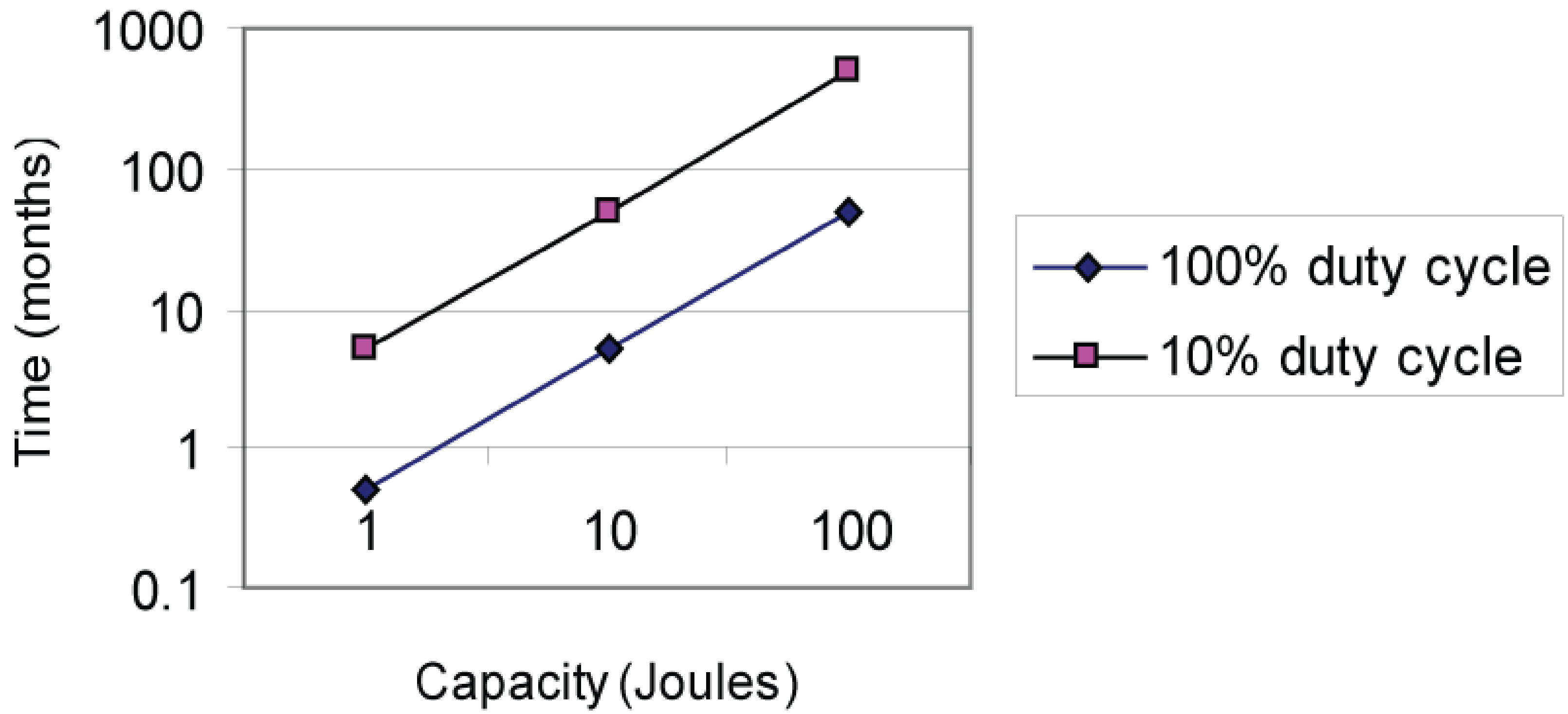
[2] The POWER FAB (Thin Film Lithium Ion Cell) battery system,. http://www.cymbet.com

Scavenging Energy

Source	*Charge rate*	*Comment*
Solar	65 (milliwatts)/ cm^2	
Ambient light	2 (milliwatts)/ cm^2	
Strain and acoustic	A force (sound) changes alignment of crystal structure, creating voltage; 2 (milliwatts)/ cm^2	Piezoelectric effect About 2-4% efficient See [SOD]
RF	An electric field of 10^V/m yields 16μW/cm^2 of antenna	See [YEA]
Temperature difference (Peltier effect)	40 (microwatts/5^0C difference)	Needs temperature differential.

[YEA] E.M. Yeatman, “Advances in power sources for wireless sensor nodes,” Proceedings of 1st International Workshop on Body Sensor Networks, London, 2004
[SOD] Sodano et al, ” Electric power harvesting using piezoelectric materials,” 10th SPIE Conference on Smart Structures and Materials, 2003

Energy capacity at 1 μw usage



Net: an on die battery will have only 10 Joules unless energy is scavenged. At a 10% duty cycle this gives better than a 3 year lifetime.

Power and performance

- With a power budget of 1 μw how to provide meaningful performance?
- If today's processor offers 5 GHz at 100w, then by the cubic rule 1 μw (dynamic power) should offer 10.5 MHz ($(10^{-8})^{1/3} = 2.1 \times 10^{-3}$).
- But with lots of transistors we need to use them to recover performance.

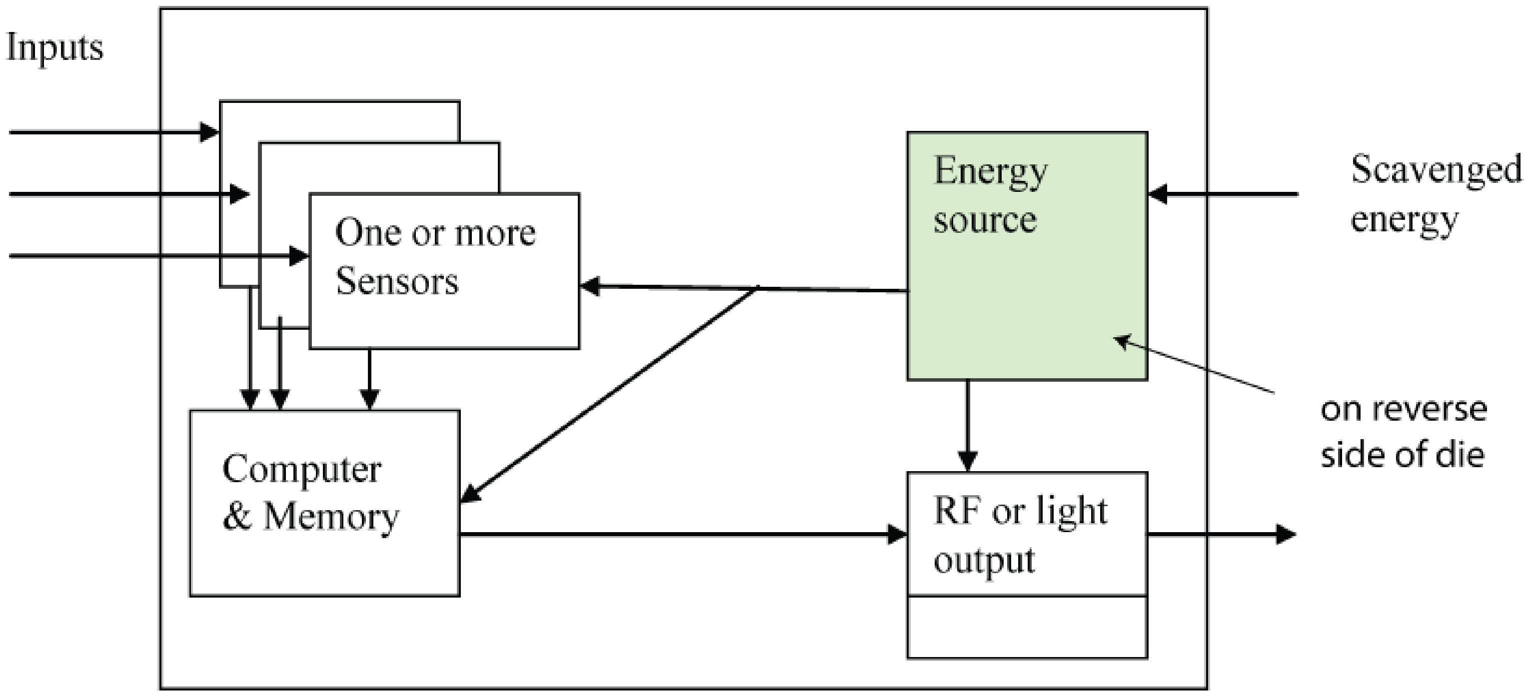
Power and performance

- With a power budget of 1 μw how to provide meaningful performance?
- Static power is also a big issue. Must be of the $\mathcal{O}$(0.1) μw. Sub threshold circuits, power islands, sleep transistors, SOIAS (SOI active substrate), each can contribute to substantial static power reduction.

Performance with low clock rate

- No clock: asynchronous logic; no unnecessary state transitions.
- Minimum or no cache system; backed by compatible *Flash*.
- VLIW and specialized multi processors to recover performance.

The Autonomous die



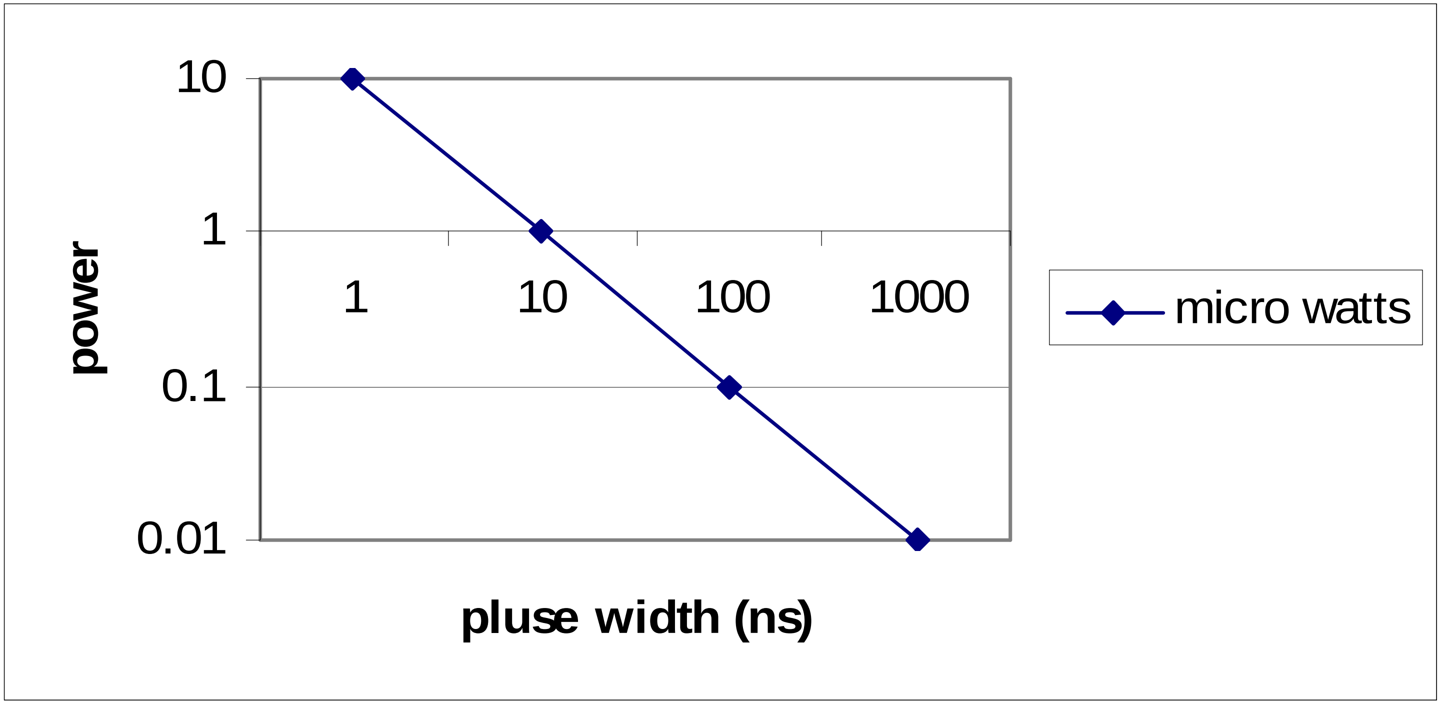
Networking: it’s the ensemble that produces the action

- No individual die is expected to produce a definitive recognition or a definitive action.
- Recognitions are passed to neighbors; can be sent to higher level for action or through *swarm* computing arrived at via the network.
- Our current software models are inadequate in this regard.
- For hardware communications is the key.

Untethered inter die communications

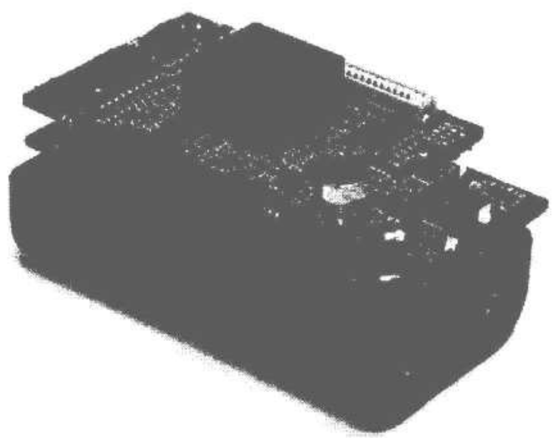
- Light or RF
- Modulated light can be low power
  - Relatively easy to focus/ defocus
  - Free space signals are non interfering
  - But, must have line of sight.
- RF, components well understood
  - RFID technology
  - Can require power; especially at high frequency
  - Antenna focuses power based on carrier frequency

On die Lasers for communications

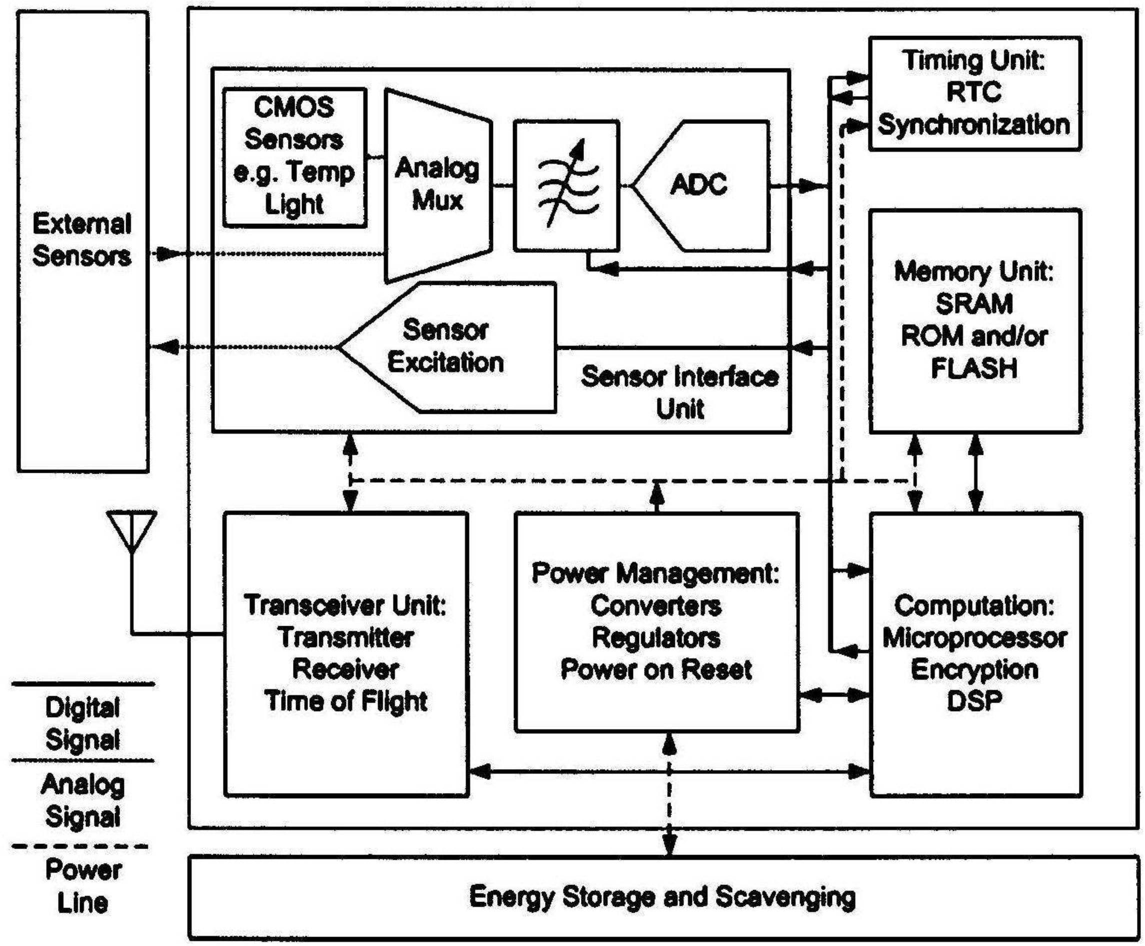


It's possible to achieve 100 Mbps with 1μwatt without noise
But: ambient light is noise; need 10x signal over noise; also distance requires optics to collimate the beam for low divergence

RF, *smart dust*:10^{11} bits/Joule/ Meter.

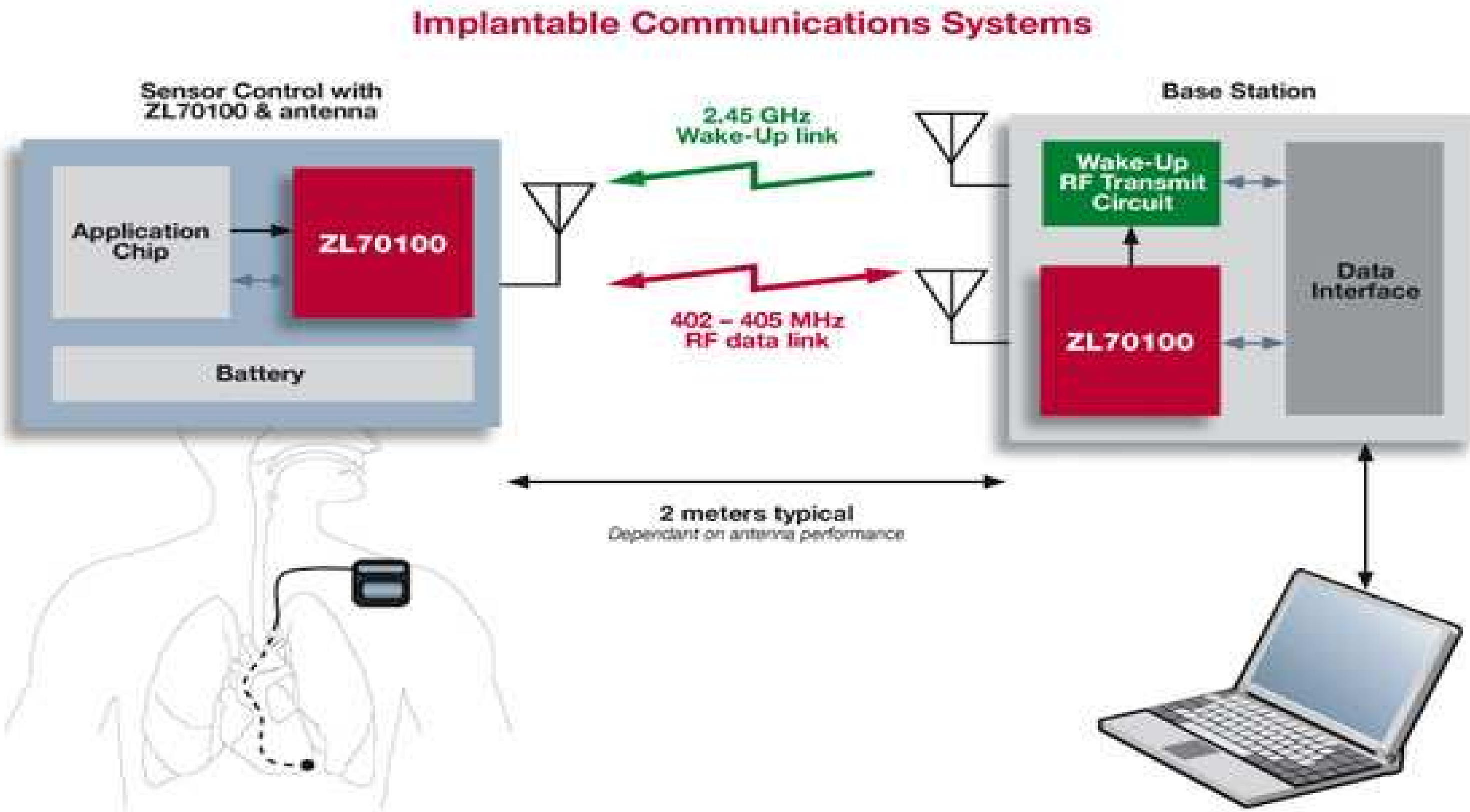


65x30x25 mm
Prototype;
Target 2 mm^3



Ref: [Coo] B. W. Cook et al, "SOC Issues for RF Smart Dust," Proc IEEE June 2006

Today's autonomous die; implantable RF 5 mw (peak), 2 meters, 1 Mbps

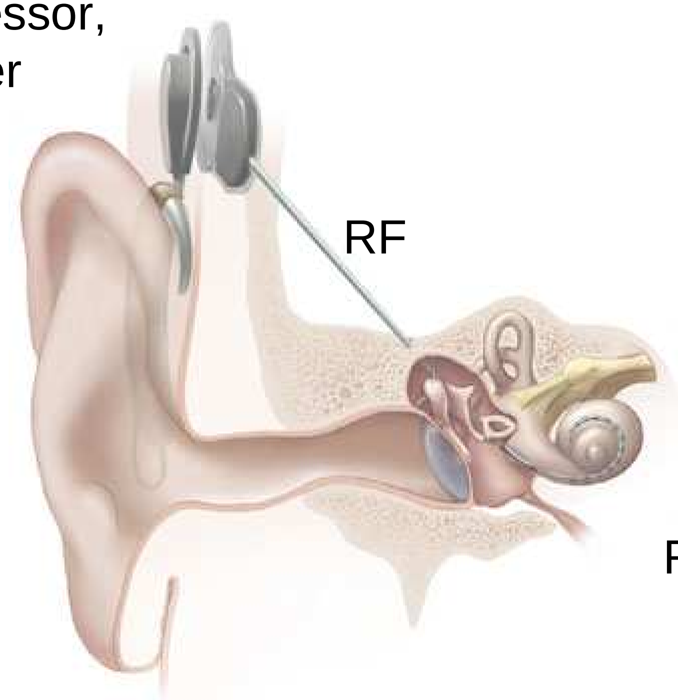


Ref: Zarlink's medical implantable RF

Audio sensors

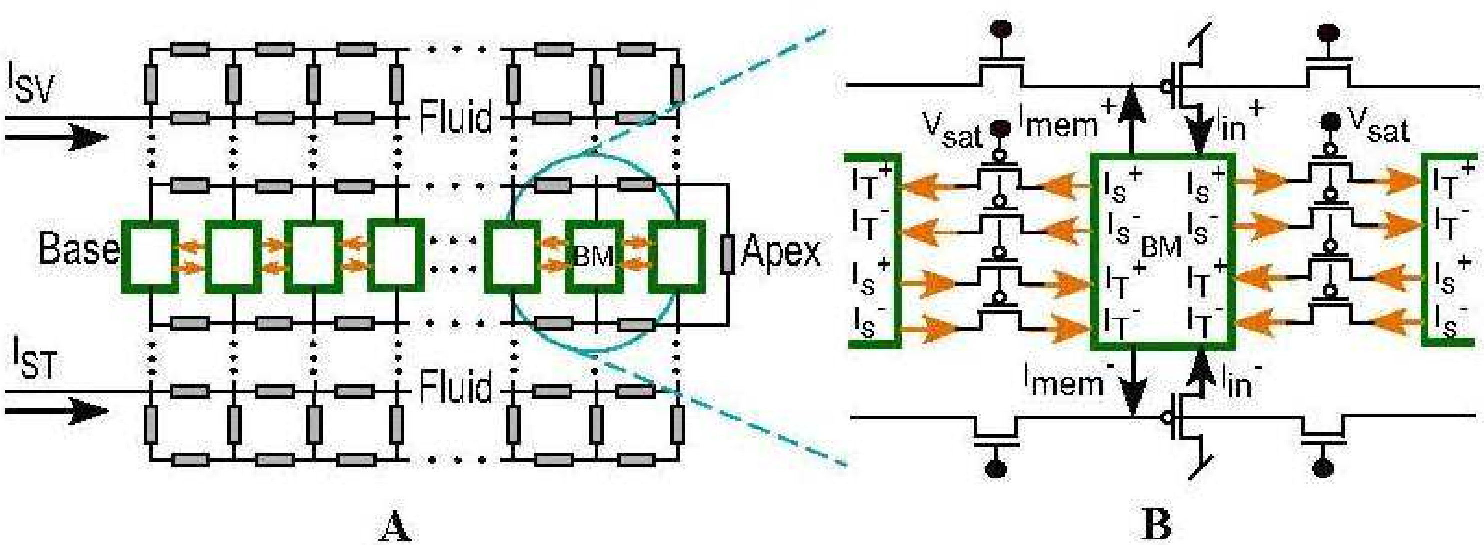
- Time or frequency domain
- Ear uses frequency domain
- Need sensitive chip mounted crystal transducers to provide signal (voltage) to sensor.

Audio sensors: Cochlear implant



Ref: Wikipedia

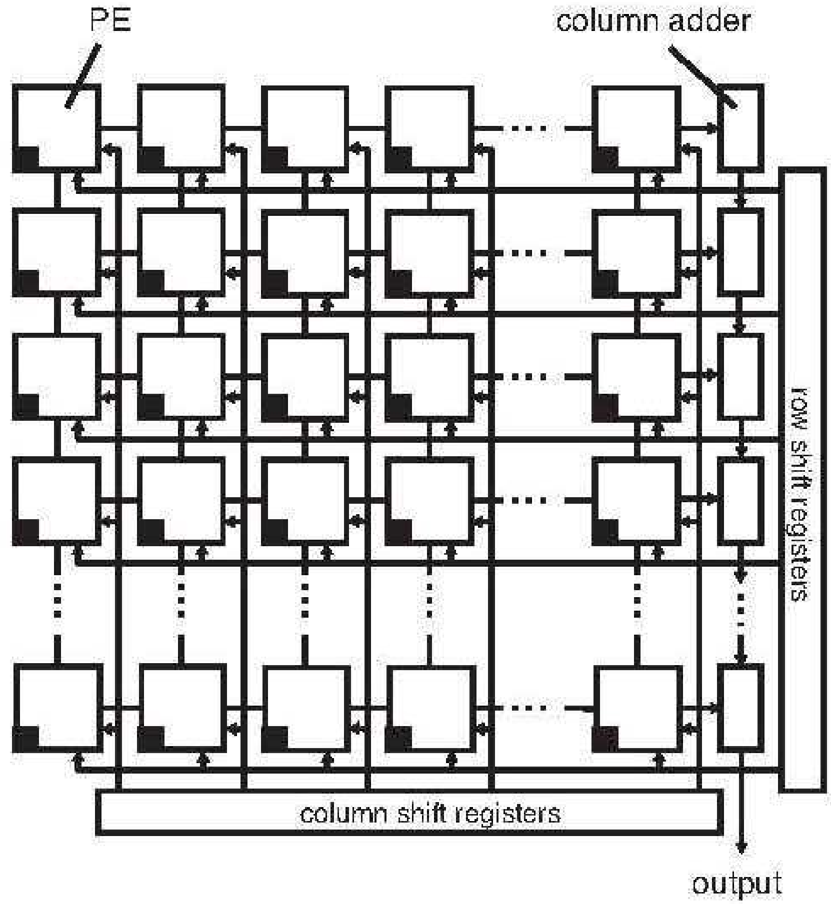
Audio sensors; cochlear chip; series of frequency bandpass filters



Ref: B. Wen et al "Active Bidirectional Coupling in a Cochlear Chip" Advances in Neural Information Processing Systems 17, Sholkopf Ed., MIT Press, 2006

Vision and recognition: edges

64x64 pixel array (PEs) with reconfiguration; PE chaining and fast summation for edge detection

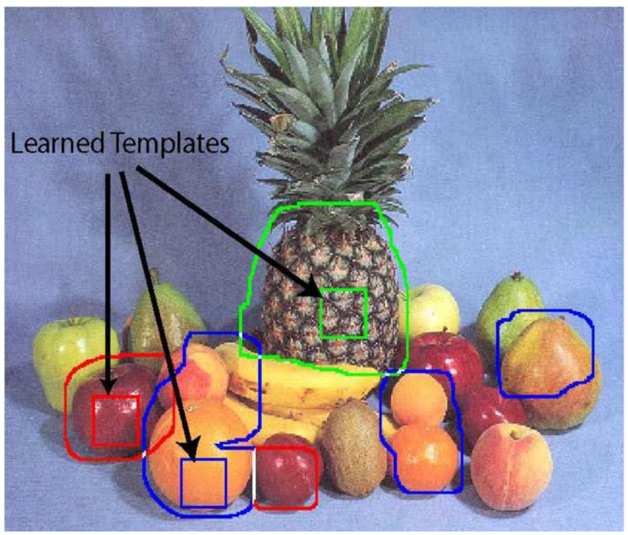


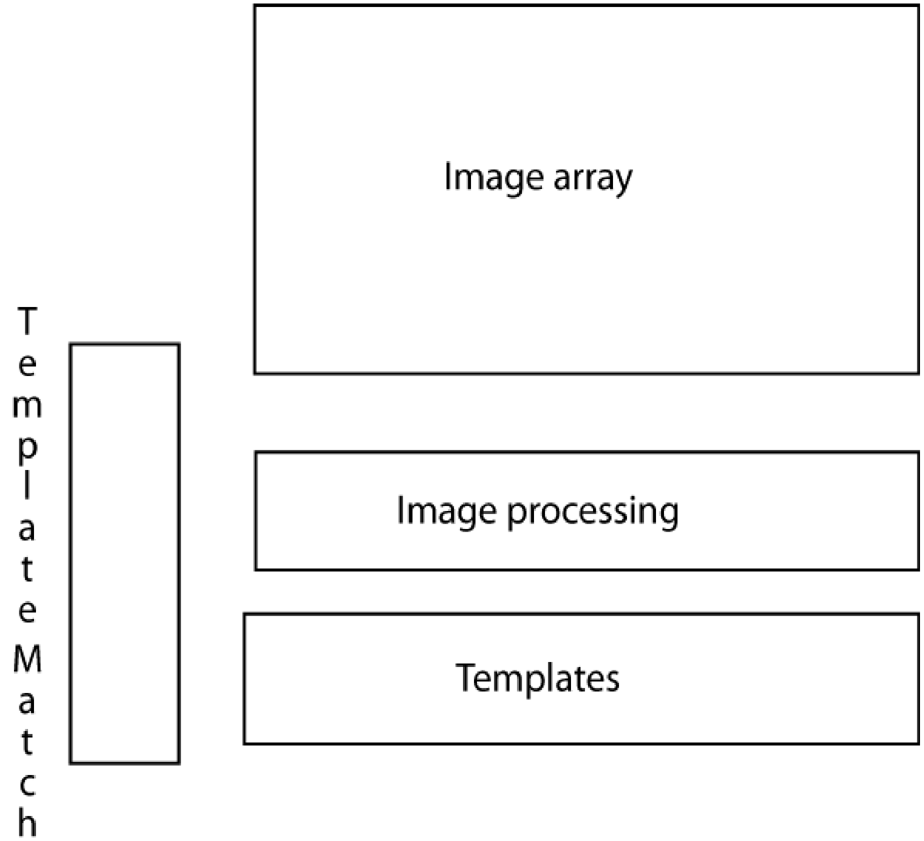
Ref: T. Komuro, “SIMD Processor for Vision“ IEEE JSSC, VOL. 39, NO. 1, JAN 2004

Vision and recognition: templates

Object recognition with color (RGB to HIS)
128 x 64 pixel element array
Uses SAD array scan to match against 32
Templates (432 b each)

Achieves 30 frames per second with 1 mw





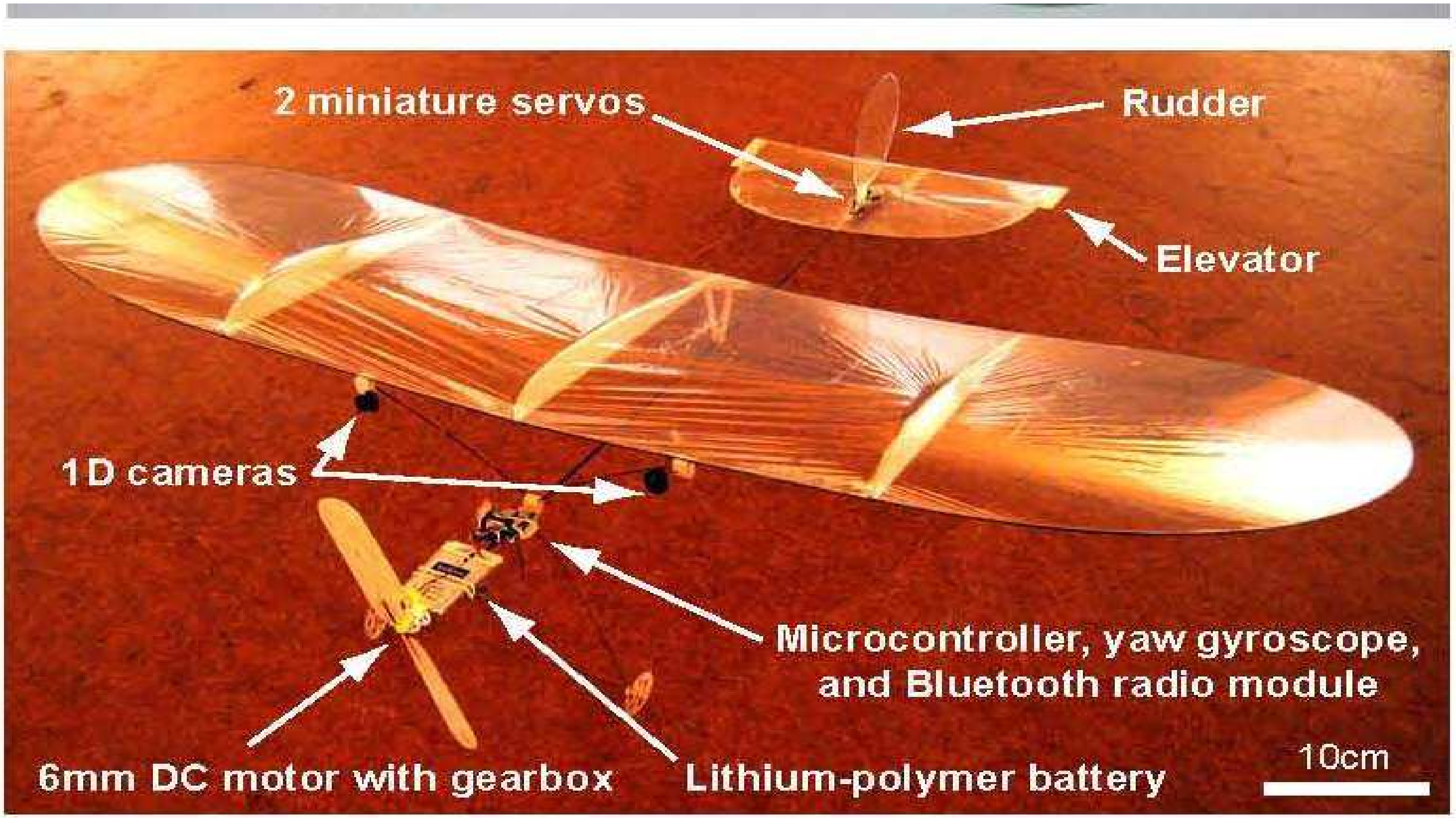
Ref:Etienne-Cummings, “A Vision Chip for Color Segmentation and Pattern Matching,” EURASIP Journal on Applied Signal Processing 2003:7, 703–712

Movement: 2D

- An autonomous die is 10x10x0.6mm and weights about 200 mg.
- With 1 Joule of energy (10^7 ergs); lifting 200mg 1 cm requires 20 ergs or 2 μw-sec.
- So as long as speed is slow (order of cm / sec) or duty cycle is low, simple motion using nano motors shouldn't be a problem

Movement: Flight

Toward 30-gram Autonomous Indoor Aircraft: Vision-based Obstacle Avoidance and Altitude Control



J. Zufferey and D. Floreano," Toward 30-gram Autonomous Indoor Aircraft: Vision-based… Control," Laboratory of Intelligent Systems, EPFL

Movement: Flight

Toward 30-gram Autonomous Indoor Aircraft: Vision-based Obstacle Avoidance and Altitude Control

http://www.youtube.com/watch?v=Lv6amv0yDIg

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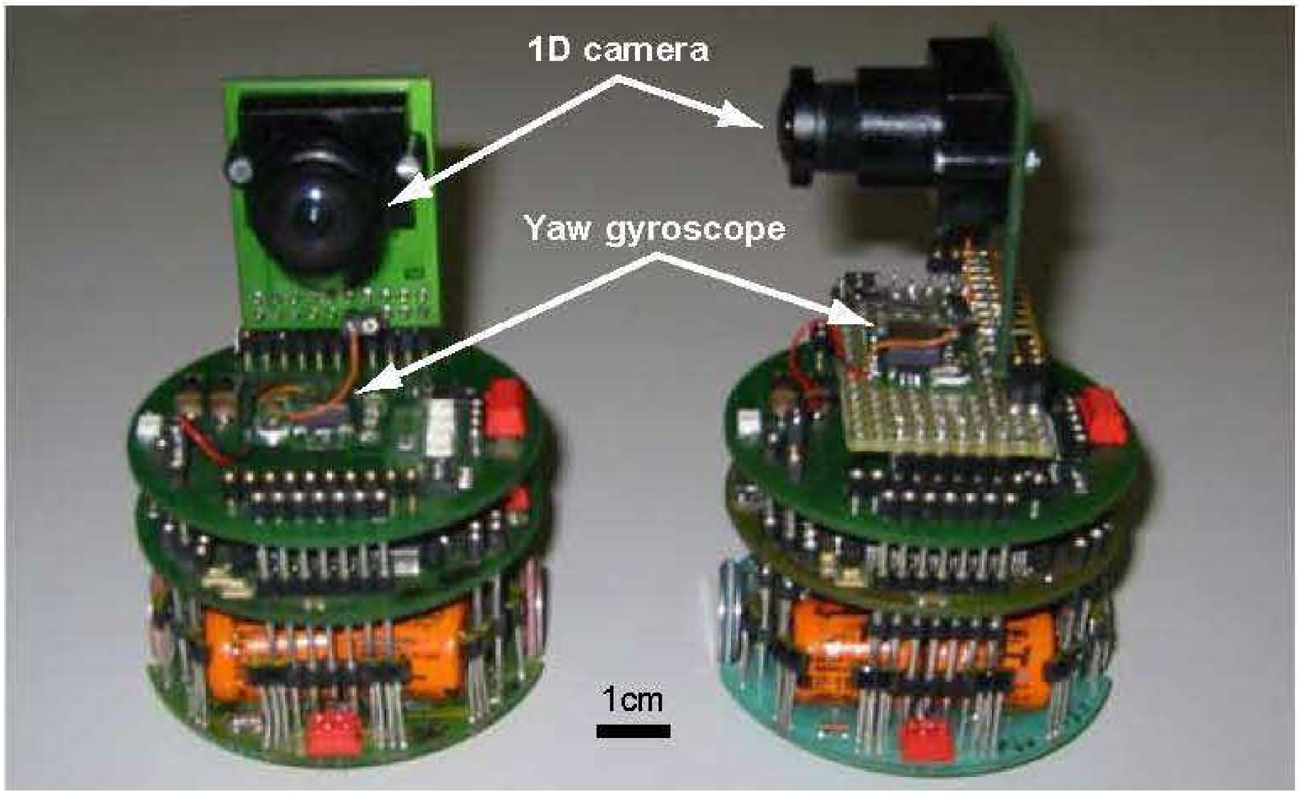
Movement: flight



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Movement: the fruit fly

Drosophila melanogaster

Fruit fly

- Length 2.5 mm; volume 2 mm^3
- 0.65 milligram; 1 month lifetime
- Vision: 800 units each w 8 photoreceptors for colors thru the UV (200k neurons); 10x better than human in temporal vision
- Also olfaction, audition, learning/memory
- Flight: wings beat 210x /sec; move 10 cm/sec; rotate 90^0 in 50 ms.

Summary

- The goal is to create a catalog of powering techniques, sensors, controllers, transceivers and processors together with an interconnection and design methodology for an application
- System can be one or many die; with external units as required by system. Networked *swarm* computing is a key technology.
- We're a long way in Cost-Time-Power from a fruit fly; but we're making progress!