Micrite: A Sub-100-Micron Distributed Sensor System

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Sensor Systems

- Becoming smaller, better integrated.
- Driven by improving technology.

- Less expensive + more on-board functionality = wider deployment and more applications!
- Pervasive sensing, pervasive computing.

Design Goals for Micrites

- 100 microns or less
- Fully integrated
- Built using off-the-shelf IC processes

- Sample application: Surveillance
  - Narrows selection of sensing and data manipulation tasks.
- Emphasis on hardware design

Presentation Outline

- Introduction
- Existing small integrated sensor projects
- Surveillance task description/requirements
- Hardware requirements
- Existing hardware projects (starting point)

Tiny Sensor Motes

- cm-scale:
  - COTS Dust (UCB)
  - Push-Pin Computer (MIT)
- mm-scale:
  - Industrial Sensor Tag (MUEM)
  - Smart Dust (UCB)
- Sub-mm-scale:
  - Hitachi RFID

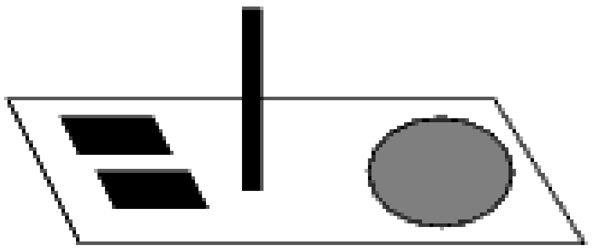
COTS Dust (UCB)

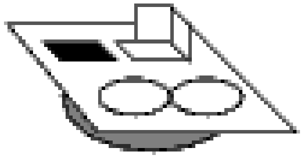
- Small printed circuit board with batteries.
  - Intended as test bed for Smart Dust systems.

- Identifies key sensor mote functions:
  - Power
  - Computation
  - Sensing
  - Communications

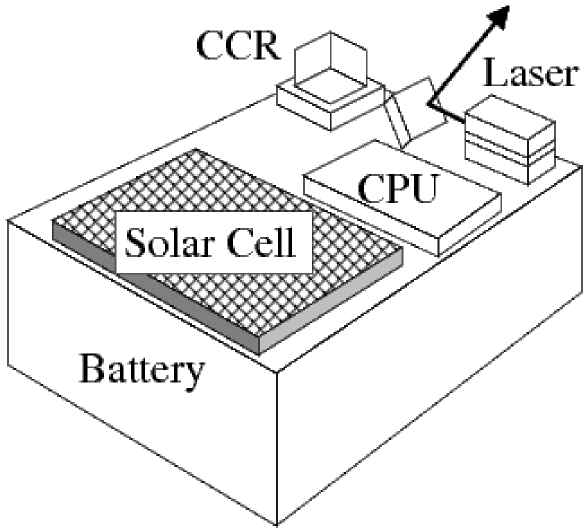
COTS Dust (UCB)

- RF Mote
  - Weather station + short range RF
- Laser Mote
  - Weather station + long range optical link
- CCR Mote
  - MEMS technology testbed





Smart Dust (UCB)



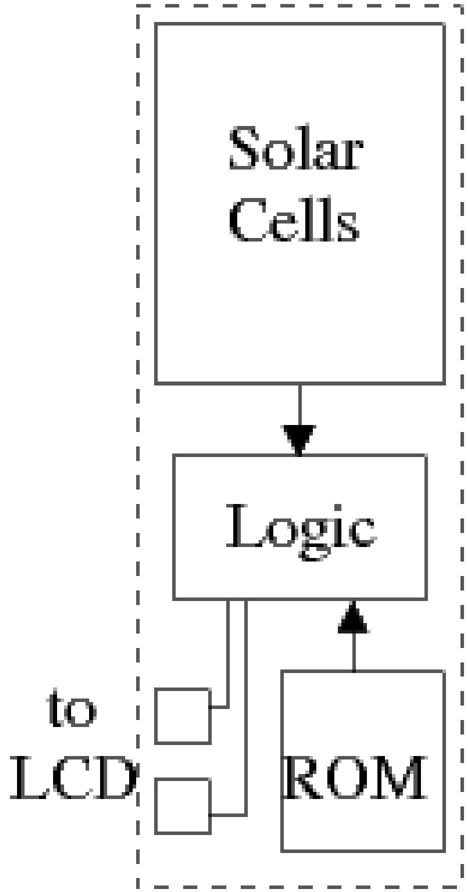
- Goal is self-contained device under $1mm^3$.
- Assembled from multiple components.
  - Each is highly-integrated, but made with a different process.

Smart Dust (UCB)

- Power from a photovoltaic cell.
- Power storage and smoothing from thick-film battery and capacitor.
- Transmitter via MEMS CCR or by diode laser with steerable mirror.
- CMOS process for logic and analog circuits.

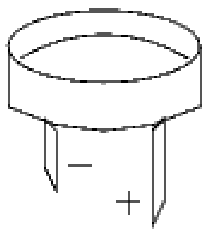
Industrial Sensor Tag (MUEM)

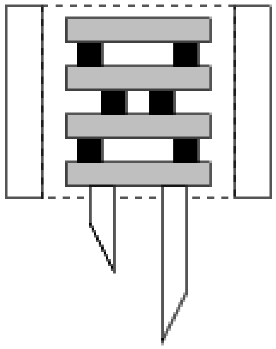
- Functionally similar to RFID.
- Interrogated by laser rather than RF; output to an LCD patch.
- Monolithic fabrication on standard SOI process.



Push-Pin Computing (MIT)

- Small devices powered by substrate, communicating by IR.
- Intended as distributed sensing mock-up system.
- Later work: communicating through substrate.
  - Substrate is unpatterned; acts as a broadcast medium.

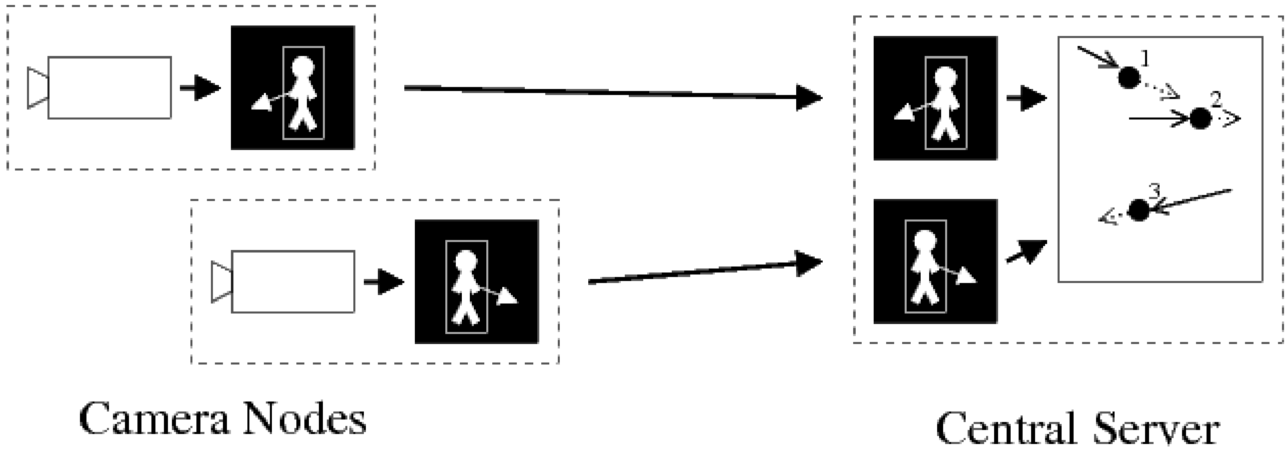




Hitachi uChip RFIDs

- Standard offering is 300-400 micron die.
  - Smaller devices on market.
- Coil is usually much larger.
- Devices demonstrated with 400 micron coil for use in smart cards and similar.
  - Reader must be very close to device; within a few millimetres.

Task: Surveillance



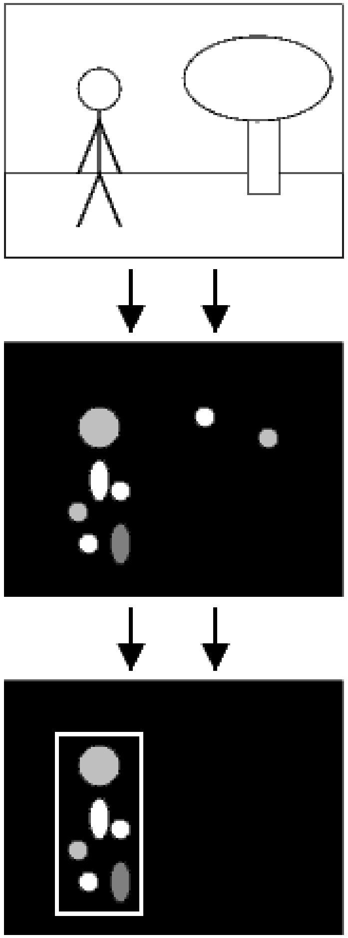
- 3rd Generation systems are distributed networks with hierarchical processing.
- Smart Cameras detect, track, and characterize foreground objects. Server aggregates and refines data.

Foreground Object Detection

- Background model method
  - Pixels are assumed to be background; characterized by a colour model.
  - Deviating values mean a pixel is now foreground.
- Time differencing method
  - Changing pixels are assumed to be foreground
- Convolution method
  - Haar wavelets, Hough kernels

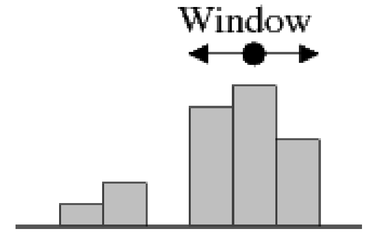
Background Models

- Goals:
  - Segment image into FG/BG.
  - Build BG model unsupervised.
- Approach:
  - Build statistical model of pixel colour over time. Outlying values are FG.
  - FG pixel “blobs” are clustered, and clusters are treated as objects to track.

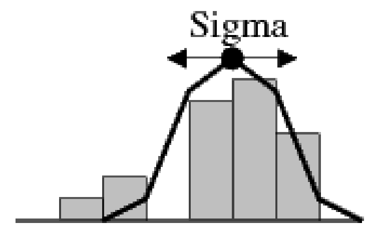


Background Models

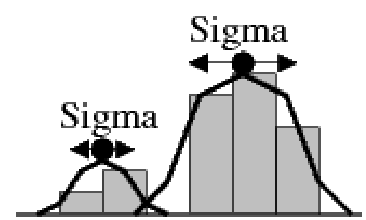
- All operate on a single pixel’s time-varying colour (possibly transformed).
- Histogram:
  - Anything close to central value is background.



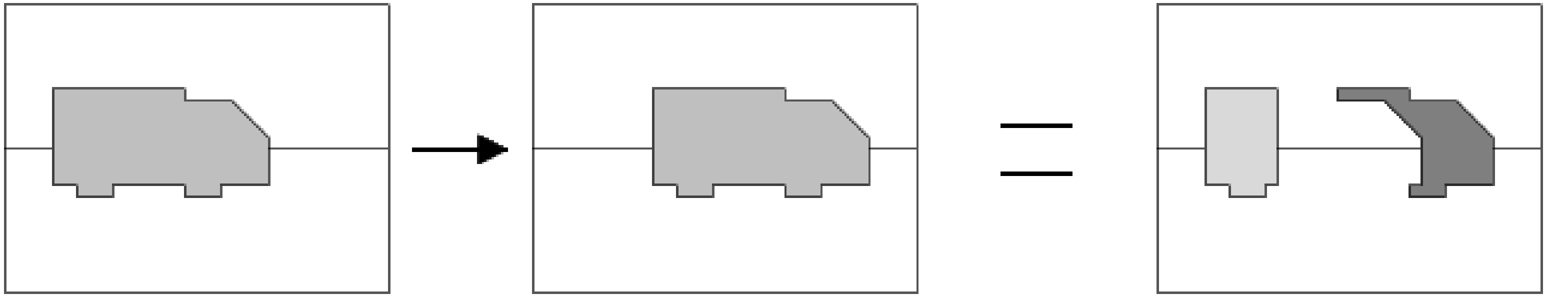
- Gaussian:
  - Anything within some number of deviations is background.



- Gaussian Mixture:
  - Anything within N most common gaussians is background.



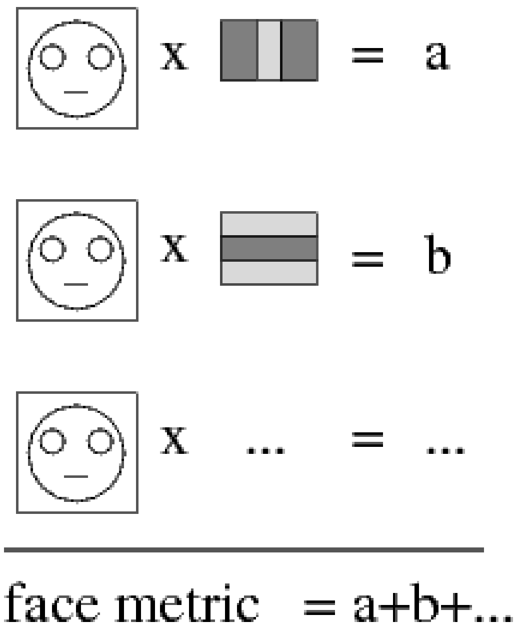
Time Differencing



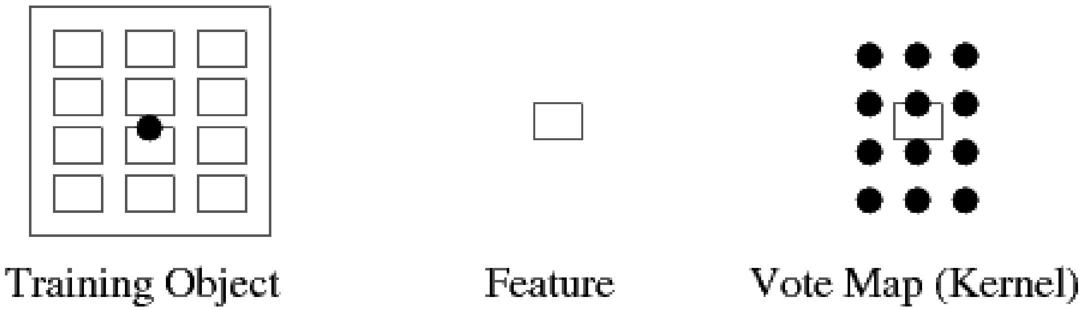
- Compute difference of pixel value and moving-window average.
- Moving objects produce “head” and “tail” disturbances.
- Approaches: Flag as object, or trace path.

Convolution

- Haar wavelets
  - Used for face recognition.
  - Fast to compute.
  - Large number of wavelet comparisons needed.
  - Performed for a large number of sub-windows.



Convolution



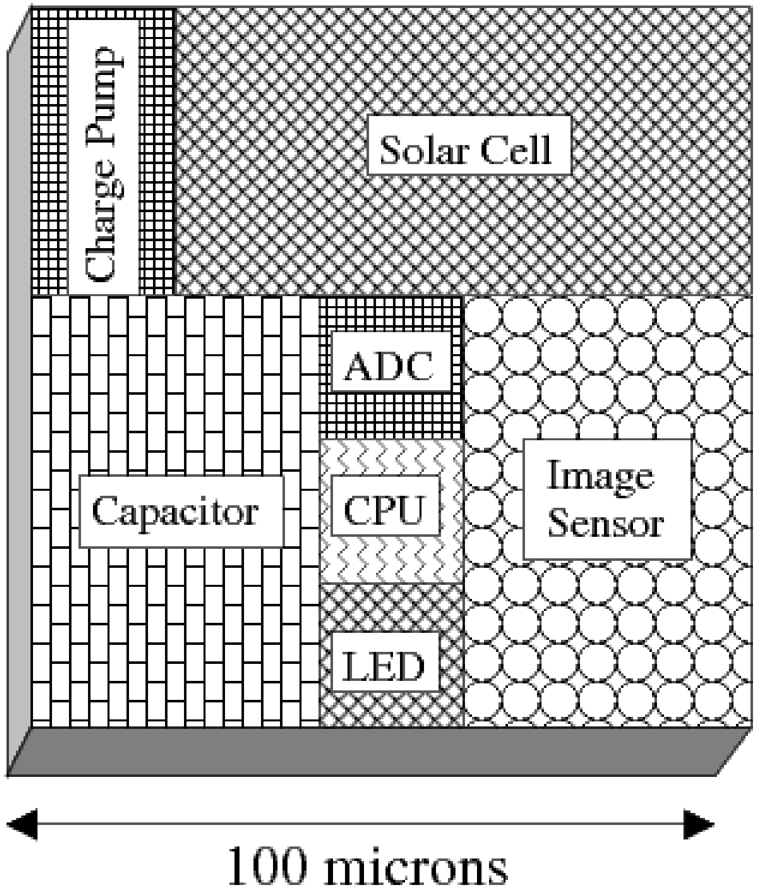
- Hough kernels
  - Variant of Generalized Hough Transform.
  - Image is preprocessed into quantized features.
  - Each feature casts “votes” on where prototype object is likely to be, given feature location.
  - True location accumulates many votes.

Object Tracking

- Salient information:
  - Object location or bounding box
  - Object identity fingerprint (usually colour)
- Tracking:
  - Usually use a Kalman filter to model trajectory
  - Allows graceful handling of occlusion
- Server interaction:
  - Server fuses data from multiple views.
  - Server may give tracking hints to cameras.

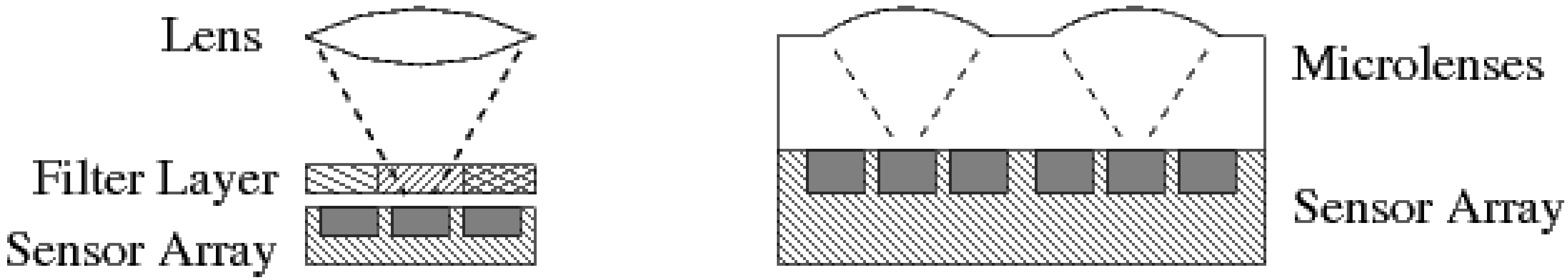
Micrite Component Implementation

- Hardware Subsystems:
  - Imaging
  - ADC
  - Image Processing
  - Power
  - Communication



- Design Constraints:
  - Made with vanilla CMOS or near variants.
  - Energy budget of 1-10 pJ.

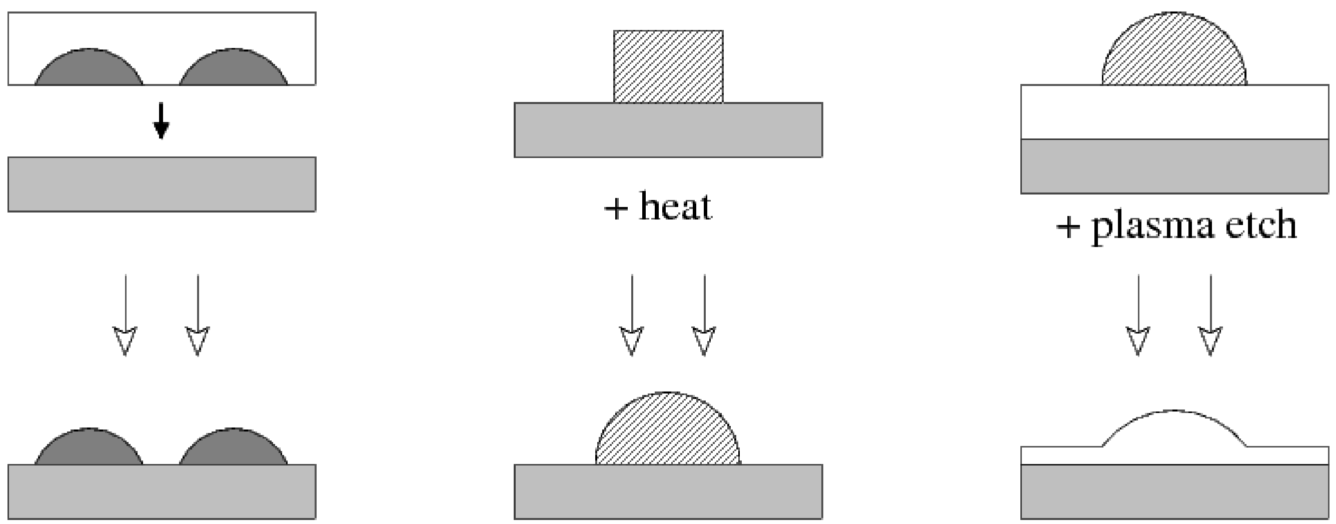
Imaging Systems



- Consist of optics over a photosensor, possibly with filters.
- Usually discrete optics; want integrated into same process as photosensor.
- Colour sensing without filters, if possible.

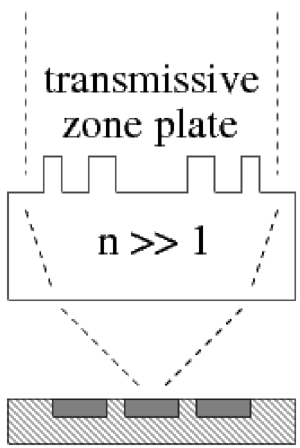
Integrated Optics

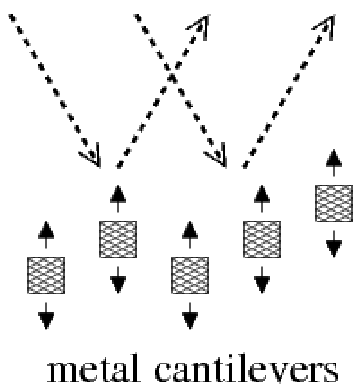
- Refractive optics: Microlenses
  - Widely used as concentrators.
  - Made by molding, reflow, or etching.

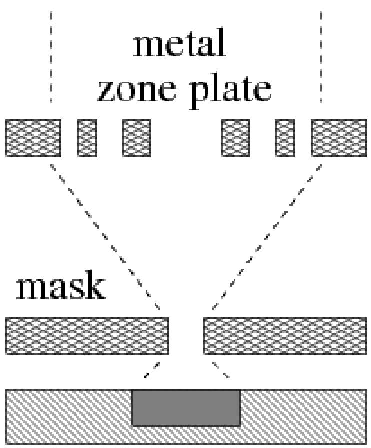


Integrated Optics

- Diffractive optics: Experimental
  - Phase-shift zone plates
  - Metal zone plates
  - MEMS reconfigurable gratings
  - Wavelength-sensitive!





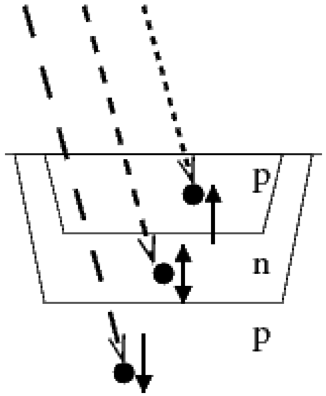


Integrated Optics Projects

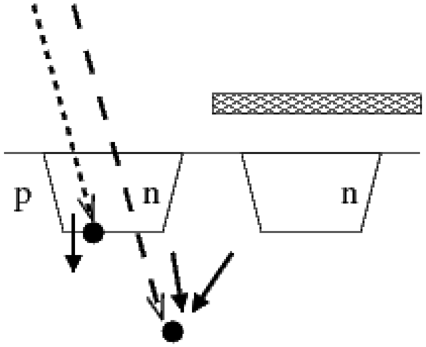
- MEMS gratings
  – Sagberg et. al.; IR spectroscopy
- Holographic gratings
  – Enguehard and Hatfield; etched fiber faces, MEMS micromirrors, LCD gratings
- TOMBO
  – Tanida et. al.; imaging with microlenses
- Very Small Array
  – Micrite precursor; imaging with metal ZPs

Colour Sensors

- Different wavelengths penetrate different distances into silicon.
- Vertical multi-junction sensor:
  - Directly detects carriers from different depths.
- Lateral diffusion sensor:
  - Deep carriers leak to adjacent shielded pixels.
  - Electric field may enhance effect.



Vertical Sensor

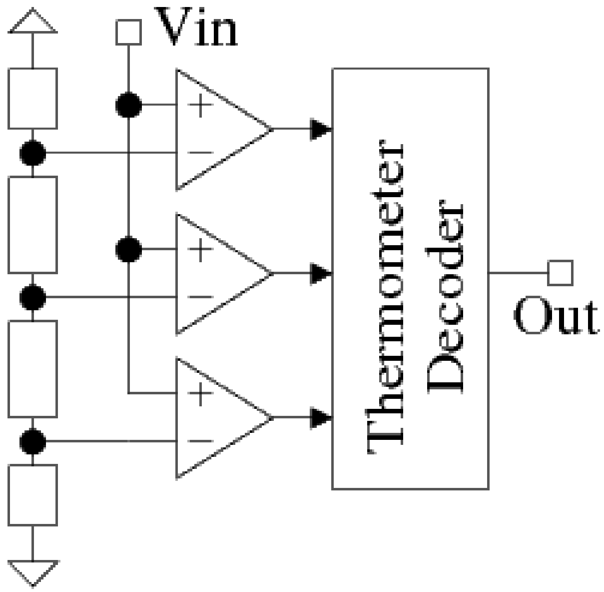


Lateral Sensor

Analog to Digital Conversion

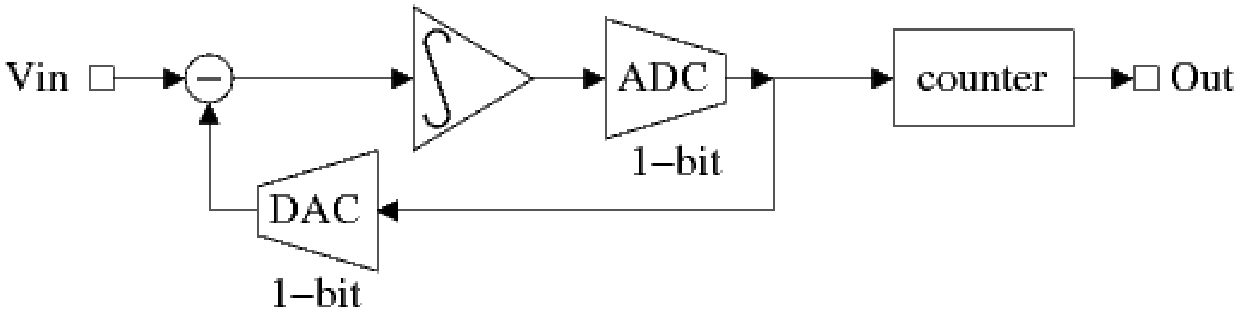
- Many approaches to ADC implementation.
- Design elements traded off:
  - Power
  - Area
  - Speed
  - Precision
- Micrite concern is low power foremost, followed by small area.

Analog to Digital Conversion



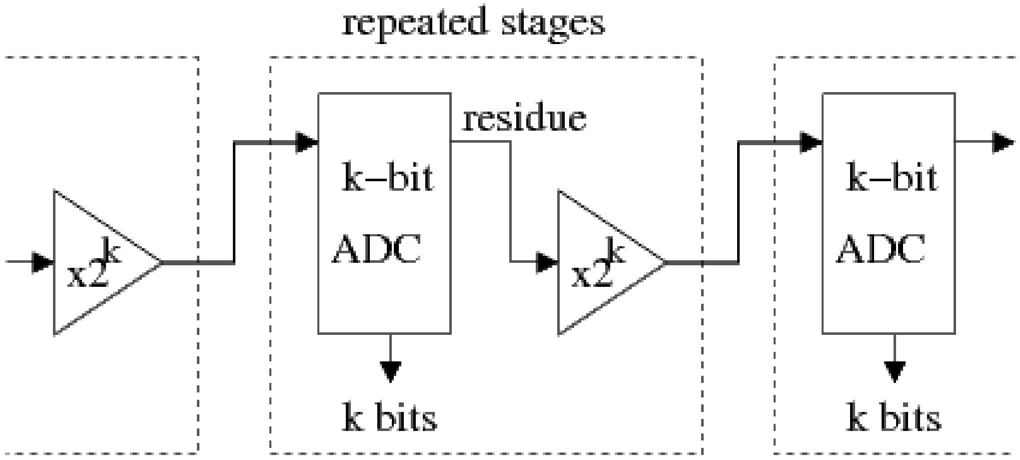
- Flash ADC
  - String of comparators (2^n for n bits).
  - Large area and power.

Analog to Digital Conversion



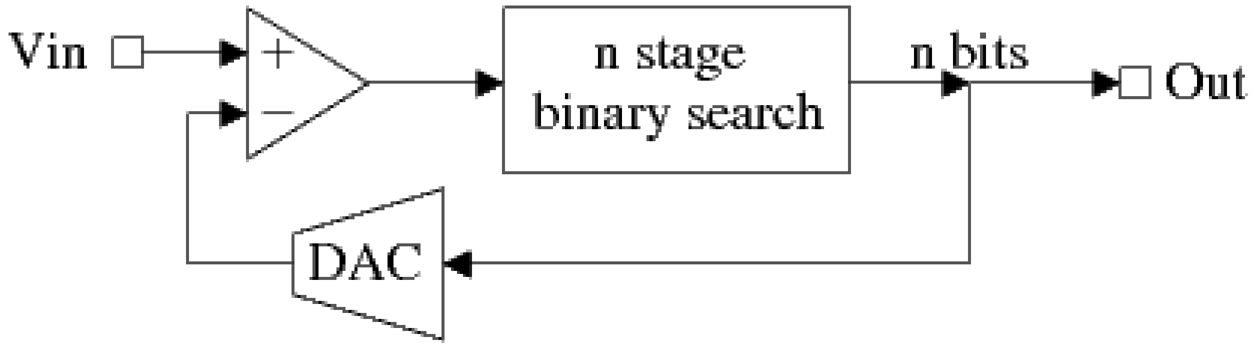
- Sigma Delta ADC
  - Subtracts quantized integrated signal from input signal.
  - Quantization noise shaped to high frequencies and filtered.
  - Compact but $2^{n/k}$ operations per n-bit sample.

Analog to Digital Conversion



- Sub-Ranging ADC
  - Each stage converts k bits, feeding residue into the next stage.
  - O(n) stages, but requires high-precision residue amplifier.

Analog to Digital Conversion



- Successive Approximation ADC
  - Binary searches output values, using DAC to compare with input.
  - Fast (n steps), but DAC takes either large area (charge redistribution) or high power (current-steering).

Analog to Digital Conversion

- Typical sub-ranging:
  – 200 pJ/sample (0.18 micron) (10 bits)
  – 45 pJ/sample (65 nm) (10 bits)
- Typical successive approx:
  – 31 pJ/sample (0.25 micron) (8 bits)
  – 19 pJ/sample (65 nm) (10 bits)
- Best reported results:
  – 1 pJ/sample in the 4-9 bit range

Image Processing Hardware

- Fundamental operation: MAC
  - Used in FIR, used for kernel operations.
- Auxiliary operation: FFT
  - Allows convolution in O(n log n) steps.
  - Can be implemented with MAC.

- Implementation is beyond the scope of this Micrite prototype.

Image Processing Hardware

- Example: Kerneltron
  - Mixed-signal, with analog MAC unit
  - 4-bit args, 8-bit accumulator
  - 0.9 pJ/MAC (0.5 micron); 2 fJ claimed later
- Example: TSMC process info
  - 1 fF/square micron (0.18 micron)
  - est. 1 pJ/MAC digital

Power

- Power sub-tasks:
  - Collection
  - Storage
  - Conversion to working voltages
- Micrite is power-limited.
  - Must store enough power for one ADC operation.
  - Must store enough power for one bit transmission.

Power Collection

- Inductive Power Collection
  - Widely used for RFID.
  - Voltage is proportional to coil area!
  - Smallest demonstrated coil is 400 microns, and had to be within millimetres of transmitter.
  - Boosting transformers demonstrated for other applications (communication).

Power Collection

- Photovoltaic Power Collection
  - Proposed for Smart Dust and other projects.
  - Bootstrapping PV system demonstrated for laser product tag.
  - Supplied by ambient light or base station laser.
  - One light source can supply power and communication.

Power Storage

- Smart Dust
  - Proposes thick-film battery and thick-film capacitor.
  - Prototype uses discrete battery and capacitor.
- Other Systems
  - Integrated typically need constant illumination.
  - Discrete typically use separate batteries and capacitor.

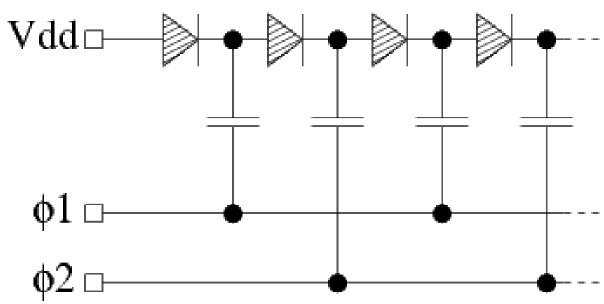
Power Conversion

- Photocell voltage typically 0.5 V.
- Analog needs > $2V_{th}$ (about 1 V).
- LEDs/diode lasers need about 2.5-5V.

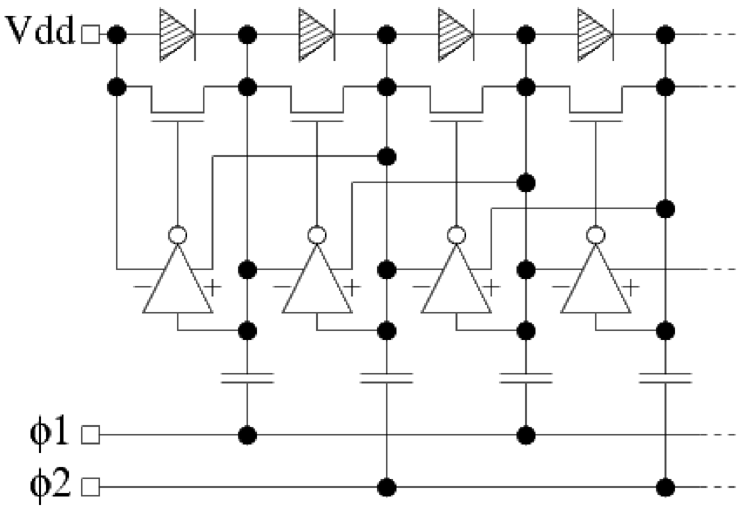
- SOI photodiodes can be strung in series.

- Bulk CMOS: Need charge pump.

Power Conversion



Dickson Charge Pump



Wu Charge Pump

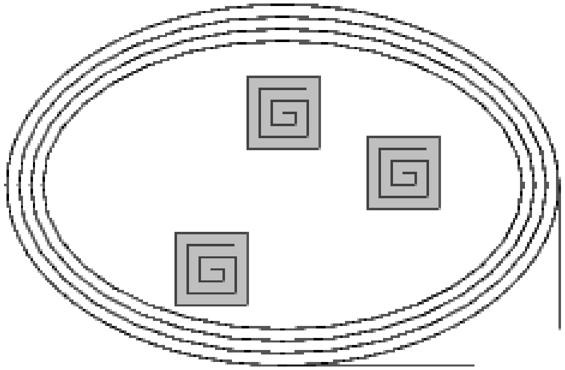
- Dickson pump
  - Widely known early design.
  - Loses V_{th} per stage.
- Wu pump
  - Typical advanced pump with active switches.

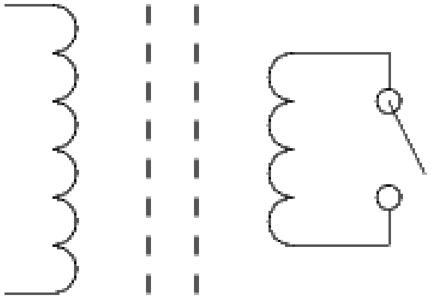
Communication Hardware

- Concerned with front-end physical layer.
- Far field RF:
  - Widely used for centimetre-scale and up.
- RF load modulation:
  - Widely used for RFID.
- Near field inductive and capacitive:
  - Proposed for MCM and 3D chip interconnects.
- Optical:
  - Waveguides, free-space, one-way, two-way.

RF Load Modulation

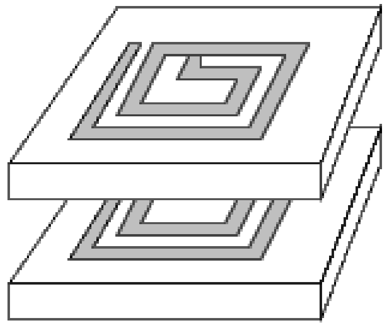
- Pickup coil on mote.
  - Opened or shorted to vary power draw.
- Base station senses changing load.
- Problems:
  - Only works in transmitter's near field.
  - Smaller motes mean smaller changes in load.



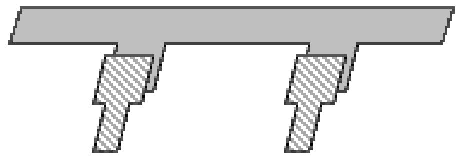


Near Field Interconnects

- Inductive Interconnect
  - Published for 3D chips.
  - Coils must have spacing comparable to diameter.



- Capacitive Interconnect
  - Published for MCMs.
  - Gap between pad and bus must be small.

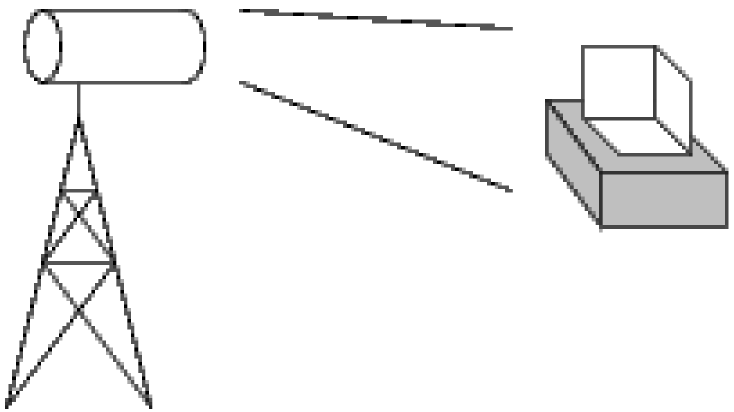


Optical Communication

- Several proposed aproaches:
  - One-way from base station
  - CCR retroreflector
  - Two-way with waveguides
  - Two-way free-space

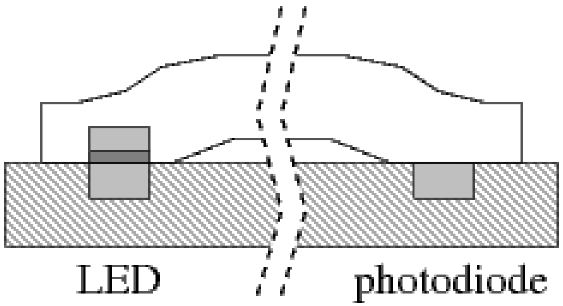
- MEMS needed for CCR.
- LEDs or lasers needed for two-way.

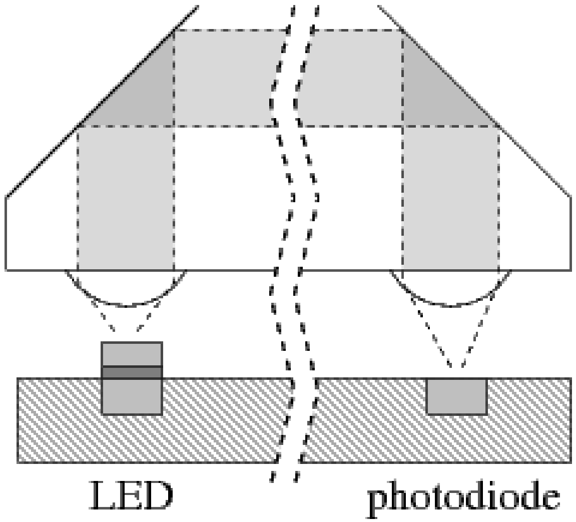
Optical Communication



- CCR retroreflector:
  - Corner cube retroreflector.
  - Bottom mirror tilted to spoil retroreflection.
  - Interrogated by base station laser.

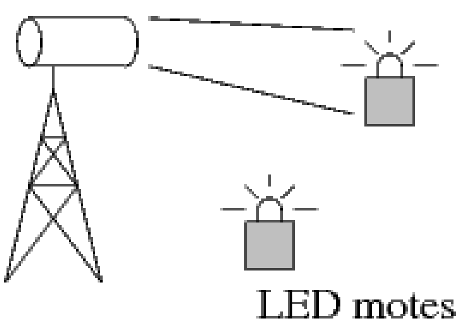
Optical Communication

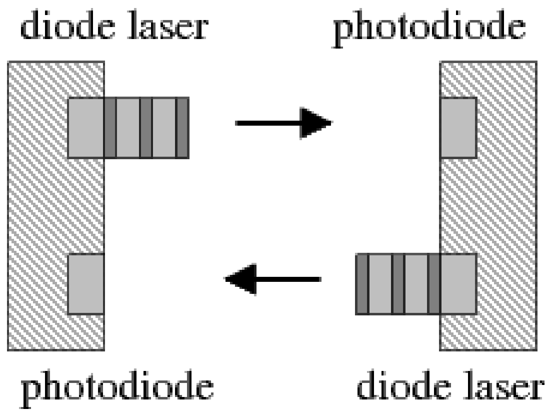




- Optical waveguides:
  – Nitride waveguide on silicon reported.
  – Discrete prism waveguide reported.

Optical Communication





- Free space optical:
  - LEDs reported for COTS dust.
  - Array of photodiode and VCSEL lasers proposed.

LEDs on Micrites

- LEDs and diode lasers are similar structures.
- LEDs and diode lasers are hard to make on silicon.
  - Can instead make logic on LED substrate.
  - Can wafer-bond.
  - Can grow epitaxially using buffer layers.
  - Can use exotic silicon-based LEDs.
- LEDs and diode lasers are complex structures taking many process steps.

LEDs on Micrites

- Wafer bonding has been demonstrated for GaAs (AlGaInP) on Si and sapphire (GaN) on Si.
  - Labour-intensive.
- Epitaxial growth of GaN on Si has been widely reported.
  - Requires care to get high quality.
- Epitaxial growth of AlGaInP on Si has been reported.
  - Requires a series of buffer layers for approximate matching. Matching is still poor.

LEDs on Micrites

- Silicon avalanche diodes
  - Emit light during avalanche breakdown.
  - Efficiency very poor.

- Silicon nanocrystal LEDs
  - Encourage radiative recombination.
  - Low efficiency.
  - High voltage.

Concluding Remarks

- A trend towards miniature devices exists, but 100 micron scale is still new.
- Surveillance is a good proof of concept application.
- Work on the needed components has already been performed for other purposes.
- Implementation of a device on this scale appears feasible.