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

- 3\textsuperscript{rd} 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.

\[
\begin{align*}
\text{face metric} & = a + b + \ldots
\end{align*}
\]
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.
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.
• **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 approaches:
  – 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 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.