

# UBIQUITOUS COMPUTING

Summer 2004



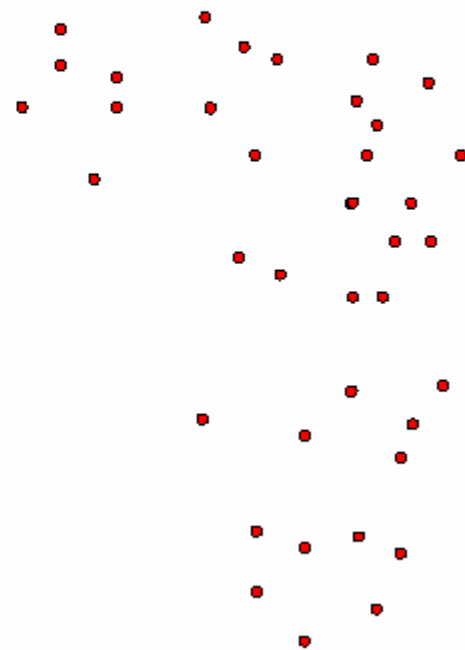
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## Wireless Sensor Networks

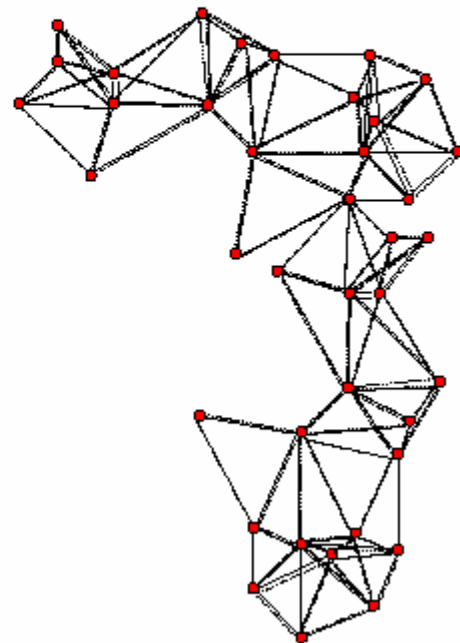
- Embed numerous distributed devices to monitor the physical world



F. Ma. 47

## Wireless Sensor Networks

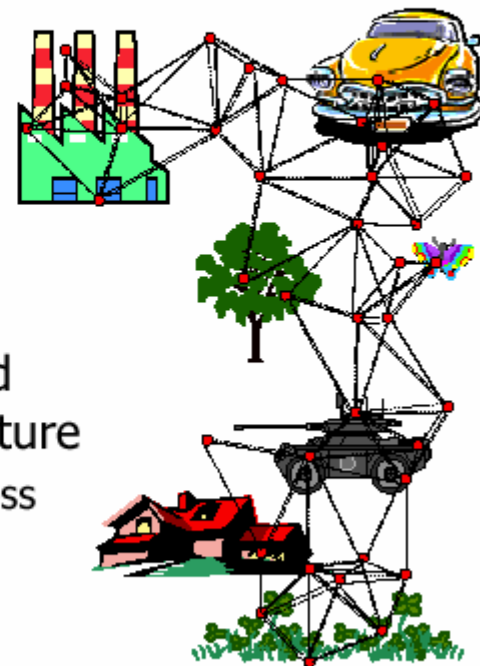
- Embed numerous distributed devices to **monitor the physical world**
- Network these devices so that they can **coordinate** to perform **higher-level tasks**



F. Ma. 48

## Wireless Sensor Networks

- Embed numerous distributed devices to **monitor the physical world**
- Network these devices so that they can **coordinate** to perform **higher-level tasks**
- Combine **sensing, communication** and **computation** into a complete architecture
  - possible by advances in low power wireless communication technology
  - MEMS bringing rich array of cheap, tiny sensors

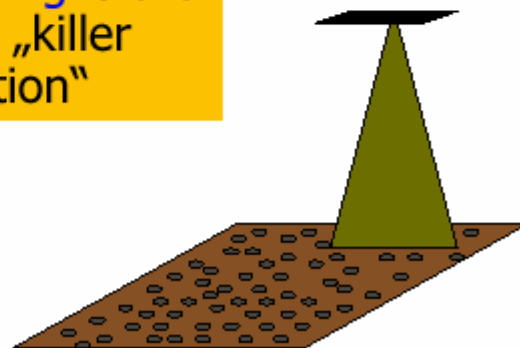


F. Ma. 49

## Sensor Networks – Vision

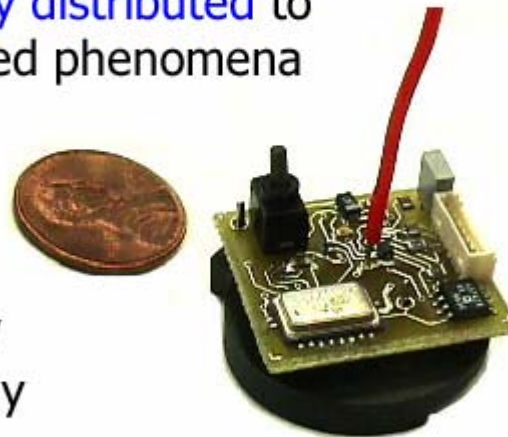
- Dense instrumentation by massively distributed networks of tiny processing elements
  - computationally-augmented environments („smart spaces“)
  - environmental, in situ monitoring
  - surveillance and security
  - military
  - emergency analysis
  - traffic monitoring
  - medical monitoring
  - condition-based maintenance
- SF
  - smart paint?
  - ingestible device networks?

Monitoring is the generic „killer application“



## Challenges

- Small-form-factor nodes, **densely distributed** to achieve physical locality to sensed phenomena
- Design **constraints**
  - energy
  - bandwidth
  - node size and cost
  - robustness, node and link reliability
- Devices must **adapt** automatically to the environment
  - too many devices for manual configuration
  - environmental conditions are unpredictable



Berkeley COTS  
smart dust motes

## Challenges – Massive Parallelism

- Large numbers of unattended device
  - individual devices are not important
- Tolerate device failures and irregularity
  - exploiting redundancy
  - graceful system degradation
- Self-organization
  - ad-hoc
  - healing
  - clustering, configuration
  - team formation
  - routing
- Information aggregation, in-network processing
- OS, middleware, infrastructure, services,...

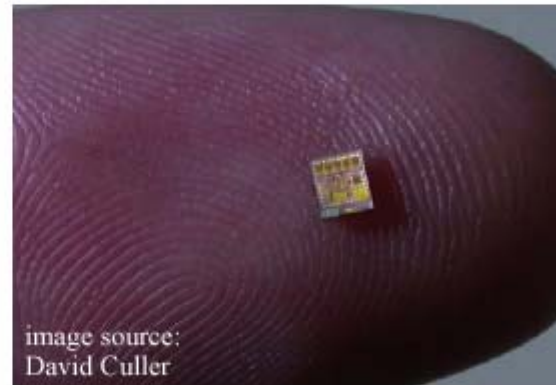
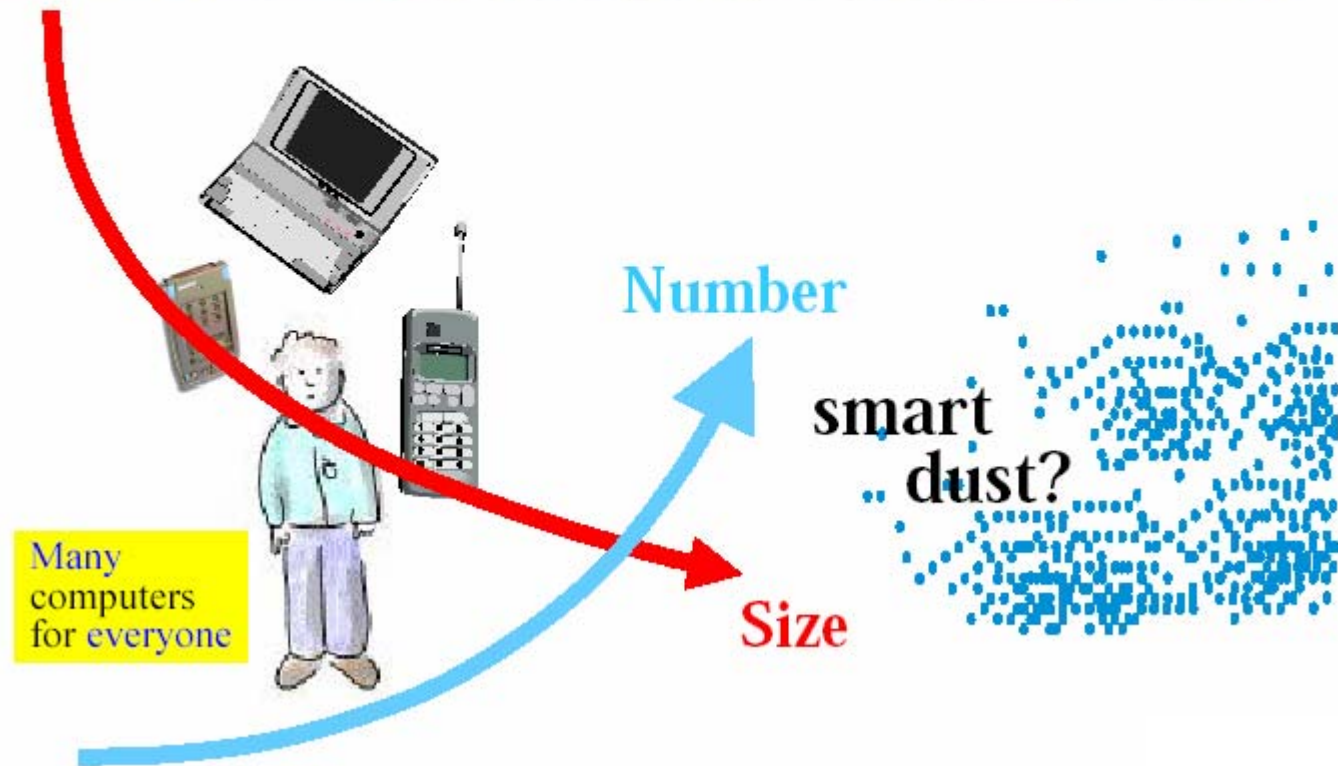


image source:  
David Culler



# SENSOR NETWORKS

## The Trend... What's Next?



Source: Friedemann Mattern (ETH Zurich)



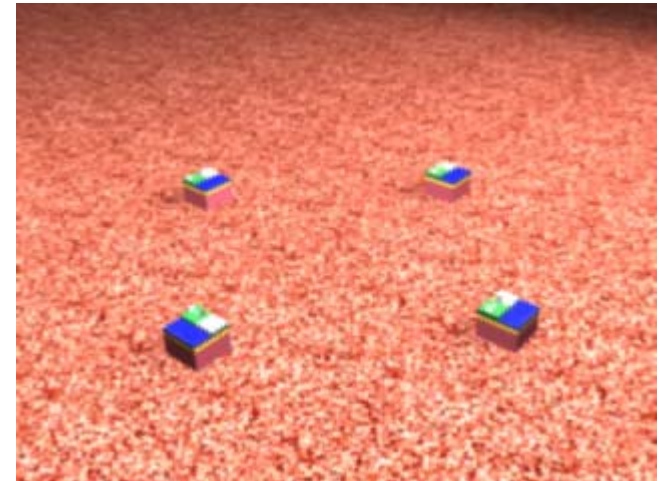
# SENSOR NETWORKS

## What are **Sensor Networks**?

- ❑ Sensor Networks consist of a large number of autonomous Sensor Nodes
- ❑ Allows to monitor (automatically and in real-time) huge amount of data without disturbing the physical processes

## What are **Sensor Nodes**?

- ❑ Sensor Nodes are autonomous devices consisting of
  - sensors  
(acoustic, visual, luminance, velocity, temperature, humidity, etc.)
  - (embedded) processors
  - small memory modules
  - (wireless) communication means
  - power supplies
  - mechanical parts to allow movements  
(arms, legs, wings, etc. : nano-robots)
- ❑ Goal: sub-mm size (Smart Dust)



# SENSOR NETWORKS



## Goals

- ☐ Measure or monitor real world information
- ☐ A sensor's operation is usually quite simple
- ☐ The complex functions of a sensor network are created by the **cooperation of a high number of sensor nodes in a dynamic system**
- ☐ Some aspects of real world effects can only be detected and monitored through cooperation of sensors for different aspects (e.g. location, direction, size, form, etc.) over time



## Applications (Examples)

- ☐ Life and Medical Science: study animal behaviour in the natural environment (in situ monitoring)
- ☐ Military: observe enemy locations and movements
- ☐ Environment: monitoring air and water pollution
- ☐ Architecture: monitor the influence of seismic activities on the structural integrity of bridges or buildings
- ☐ Medicine: detailed monitoring of body functions
- ☐ Security: analysis and detection of emergency situations
- ☐ Business: production plant monitoring to ensure perfect conditions

***The killer application of Sensor Networks is Monitoring***



# SENSOR NETWORKS



## Examples (Biology)

### ☐ Great Duck Island

- ☐ Small island off the coast of Maine (USA)
- ☐ Wireless sensor networks for habitat monitoring
- ☐ College of the Atlantic (COA), Bar Harbor, Maine
- ☐ Intel Research Laboratory & University of California, Berkeley, California
- ☐ Goal: non-intrusive/non-disruptive monitoring of sensitive wildlife and habitats



Source: <http://www.greatduckisland.net>



# SENSOR NETWORKS

## Examples (Biology)

### ☐ Great Duck Island

#### ☐ Habitants:

Leach's Storm Petrel

(*oceanodroma leucorhoa*)

Seabird in the western North Atlantic

Spend most of their lives in soft peaty soil, and are active around breeding colonies only during the dark – typically after 10pm.

#### ☐ Questions:

- What is the usage pattern of nesting on a daily basis?
- What changes during the season?
- What are the differences in the micro-environments with and without large numbers of nesting petrels?



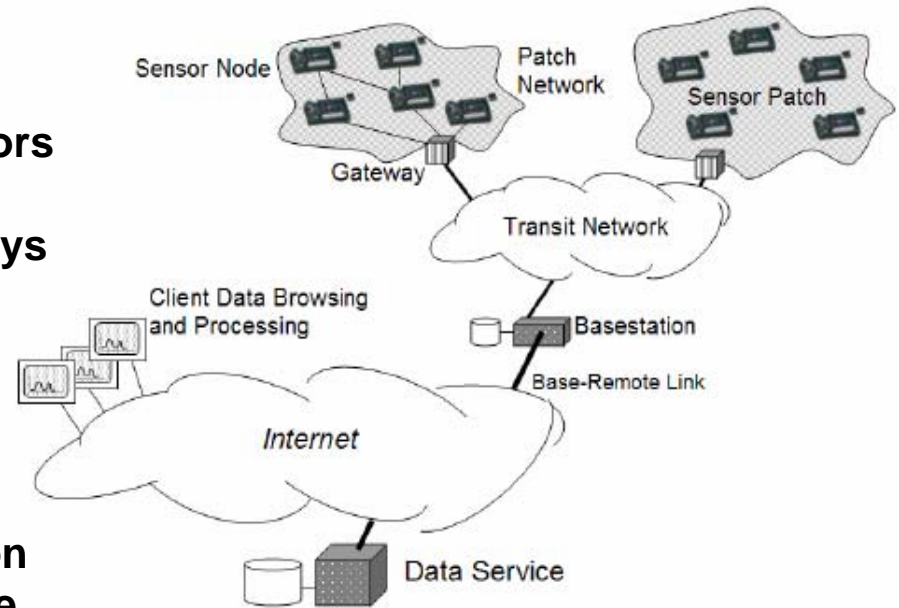
# SENSOR NETWORKS

## Examples (Biology)

### ❑ Great Duck Island

#### ❑ System Architecture:

- Tiered Architecture
- Lowest level: sensor nodes
- Sensor patch: group of sensors
- Patches are connected to transit network via gateways
- Gateways forward data to basestations
- Basestations send data over long distances to the data service module (data base) using satellite communication
- Clients can read data over the (wired) Internet



# SENSOR NETWORKS

## Examples (Biology)

- ❑ **Great Duck Island**
- ❑ MICA sensors boards are based on Berkeley **notes**
- ❑ Single channel communication with 40kbps, 4 MHz processor, 512KB memory
- ❑ Sensors are enclosed in acryl to protect against environmental disturbance



The MICA Hardware Platform



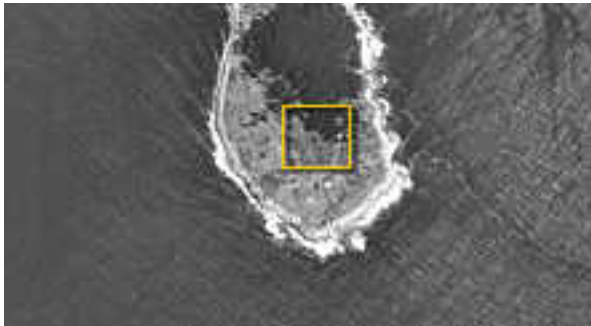
Source: <http://www.greatduckisland.net>



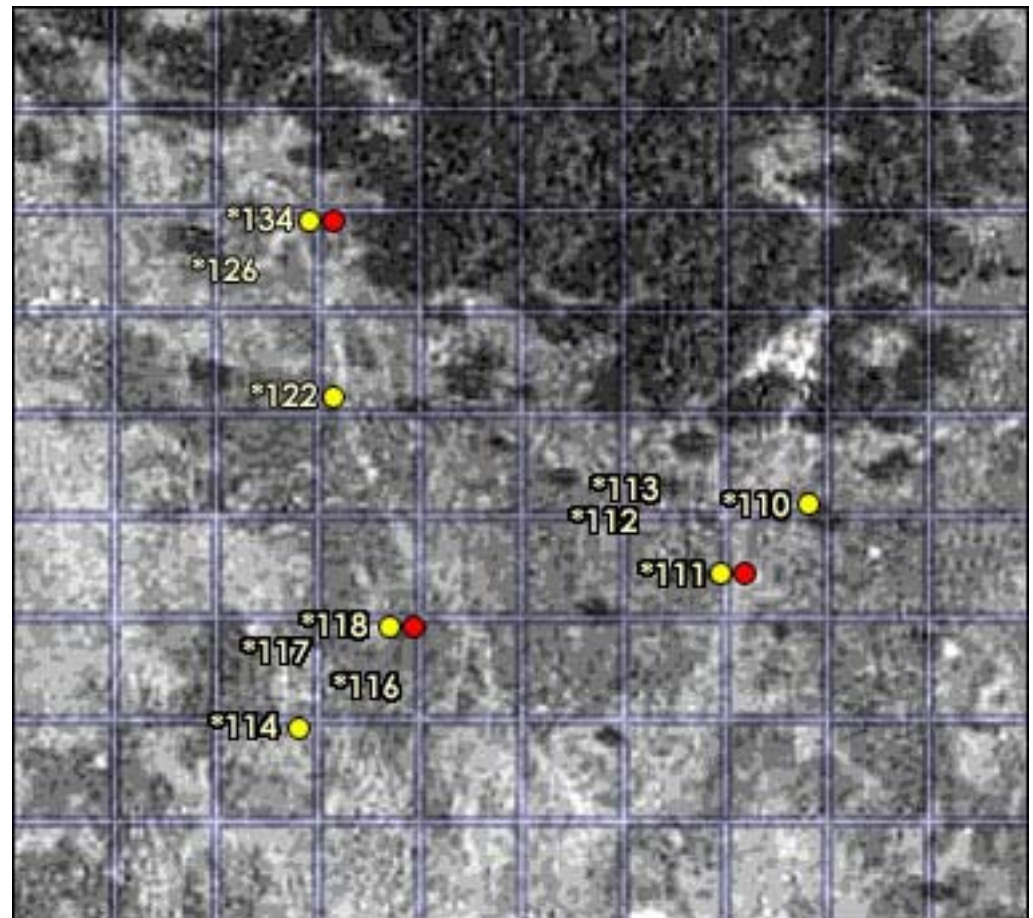
# SENSOR NETWORKS

## Examples (Biology)

- ❑ **Great Duck Island**
- ❑ 42 sensors (motes) distributed on island



- Microphone
- Camera



Source: <http://www.greatduckisland.net>

# SENSOR NETWORKS



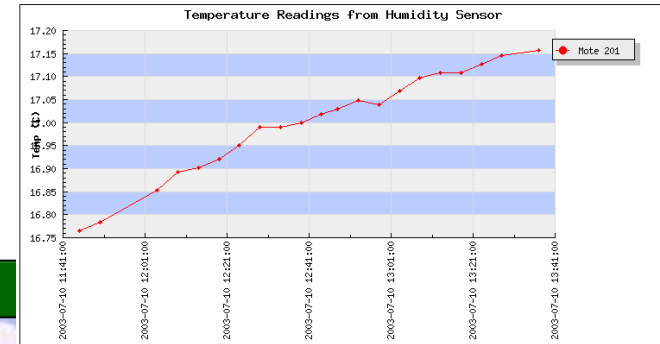
## Examples (Biology)

- ❑ **Great Duck Island**
- ❑ Charts of sensors data available online at <http://www.greatduckisland.net/charting.php>

**Habitat Monitoring on Great Duck Island**



Homepage	<b>Live Sensor Readings</b>  Last Update Time : 2003-07-13 5:57:36 <table border="1"><thead><tr><th>AutoUpdates</th><th>Charts</th><th>Notes to View</th></tr></thead><tbody><tr><td>No Auto Updates <small>If autorefresh is set, end time will be set to current time.</small></td><td>Temperature (Pressure) Temperature (Humidity) Barometer Pressure (HG) Barometer Pressure (MBar) Relative Humidity Total Solar Radiation Defused Solar Radiation Direct/Defused Solar Radiation Direct PAR Defused PAR Direct/Defused PAR</td><td>Weather Motes <input checked="" type="checkbox"/> Burrow Motes <input checked="" type="checkbox"/> 101 102 103 108 121 122 123 124 125 126 127 128</td></tr><tr><td><b>Interval</b></td><td></td><td></td></tr><tr><td>End Time 2003-07-13 5:57:36</td><td></td><td></td></tr><tr><td>Duration (minutes) 120</td><td></td><td></td></tr><tr><td colspan="3"><input type="button" value="Make Charts"/></td></tr><tr><td colspan="3"><b>Please select one or more Notes</b> <b>Please select one or more Charts</b> <b>Please enter a valid date that follows the format (YYYY-MM-DD HH:MM:SS) (2003-06-04 13:41:52)</b></td></tr><tr><td colspan="3">Related Links: <a href="#">College of the Atlantic</a>, <a href="#">University of California at Berkeley</a>, <a href="#">Intel Research Laboratory at Berkeley</a></td></tr></tbody></table>	AutoUpdates	Charts	Notes to View	No Auto Updates <small>If autorefresh is set, end time will be set to current time.</small>	Temperature (Pressure) Temperature (Humidity) Barometer Pressure (HG) Barometer Pressure (MBar) Relative Humidity Total Solar Radiation Defused Solar Radiation Direct/Defused Solar Radiation Direct PAR Defused PAR Direct/Defused PAR	Weather Motes <input checked="" type="checkbox"/> Burrow Motes <input checked="" type="checkbox"/> 101 102 103 108 121 122 123 124 125 126 127 128	<b>Interval</b>			End Time 2003-07-13 5:57:36			Duration (minutes) 120			<input type="button" value="Make Charts"/>			<b>Please select one or more Notes</b> <b>Please select one or more Charts</b> <b>Please enter a valid date that follows the format (YYYY-MM-DD HH:MM:SS) (2003-06-04 13:41:52)</b>			Related Links: <a href="#">College of the Atlantic</a> , <a href="#">University of California at Berkeley</a> , <a href="#">Intel Research Laboratory at Berkeley</a>		
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Photo Gallery																									
Biology																									
Technology																									
People & Contacts																									
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# SENSOR NETWORKS

## Examples (Biology)

### ☐ Great Duck Island

### ☐ Advantages of Sensor Networks for habitat monitoring

- Localized measurements and detailed information hard to obtain through traditional instrumentation
- Complex filtering and triggering functions through local processing and storage means
- Application-specific or sensor-specific data compression algorithms
- Statistical sampling, data aggregation, and system health and status monitoring through communication between nodes
- Nodes can adapt their operation over time, in response to changes in the environment, the condition of the network itself, etc.
- In contrast to human observers, potential impacts on monitoring plants and animals is reduced significantly
- Sensor networks provide a substantially more economic method for conducting long-term studies
- realtime availability of data for large user group (web access)

Source: <http://www.greatduckisland.net>



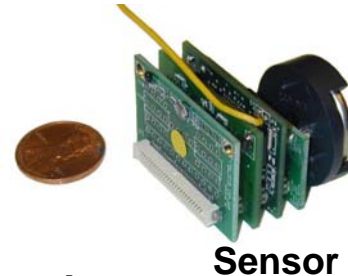
# SENSOR NETWORKS

## Examples (Military)

### 29 Palms

#### Goals of the experiment:

- Deploy a sensor network onto a road from an unmanned aerial vehicle (UAV)
- Establish a time-synchronized multi-hop communication network among the nodes on the ground
- Detect and track vehicles passing through the network by using magnetometers
- Transfer vehicle track information from the ground network to the UAV
- Transfer vehicle track information from the UAV to an observer at the base camp



Vehicle



Base Camp



Packed Sensor for dropping

Sources: <http://www.isi.edu/scadds/pictures/29palms.html>, <http://www-bsac.eecs.berkeley.edu/~pister/29Palms0103/>,  
<http://basics.eecs.berkeley.edu/sensorwebs/29palms/>

# SENSOR NETWORKS

## Challenges of Sensor Networks

- ❑ **Size Reduction**: create sensor nodes, that are small (several cubic millimeters), cheap, long-lasting, and robust against environmental exposures
- ❑ Due to size restriction, **the power supply is a major issue**
  - Hardware (sensors, processors, communication technology) and Software (Operating system, communication protocols, etc.) must be tailored to minimize power consumption
  - Efficient power supplies (solar panels, etc.) and power storage devices must be created
  - Design of protocols and distributed algorithms (to minimize energy-consumption of nodes and of the complete network)
- ❑ **Scalability**: support of thousands or even millions of sensors in a network
- ❑ **Robustness**: lost nodes (exhausted batteries, etc.) should be tolerable
- ❑ **Mobility**: mobile nodes (wind, water movements) should be supported
- ❑ **Self-Configuration**: create a sensor network without a central infrastructure (Ad-hoc Networking: network nodes create infrastructure automatically)
- ❑ **Security**: protection against disturbed nodes or attacks (e.g. intruder nodes)
- ❑ **Addressing**: classical explicit addressing of nodes not optimal or necessary
- ❑ **Operating Systems**: tailored to specific application requirements and energy restrictions (Example: **TinyOS** (Tiny Operating System), Berkeley)

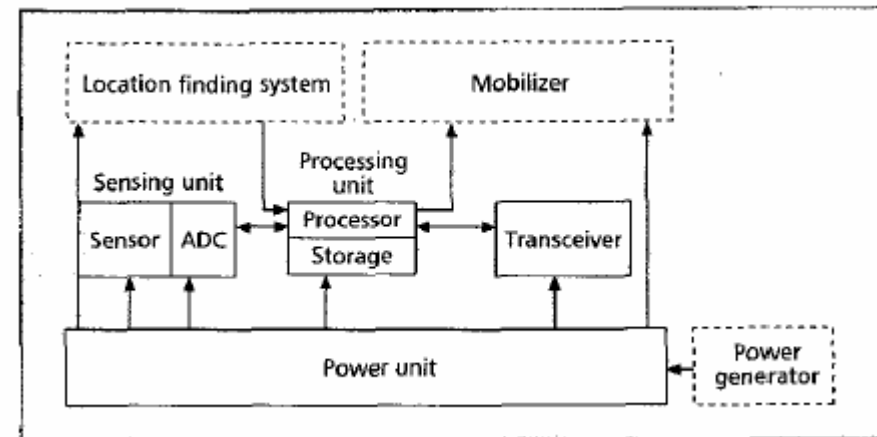
# SENSOR NETWORKS

## Components of a Sensor Node

- ❑ **Sensing units** are usually composed of two subunits: Sensors & ADCs. Analog signals of the measurement are digitized and fed into the processor
- ❑ The **processor** unit has a small memory unit and is responsible for the data processing and collaboration with other nodes
- ❑ The **transceiver** connects the node to the network
- ❑ The **power unit** is one of the most important modules of the node sometimes combined with a power generator (e.g. solar panel)

Other units are optional:

- ❑ The **location finding system** enables routing techniques and location-based sensing tasks
- ❑ The **mobilizer** can be used to change the location



Components of a sensor node



# SENSOR NETWORKS

## ■ Sensor Node Examples (COTS)

### □ MIT: **μAMPS** (**μ**Adaptive **M**ulti-Domain **P**ower aware **S**ensors)

- <http://www-mtl.mit.edu/research/icsystems/uamps/>
- μAMPS v1 : COTS
- μAMPS v2 : dedicated ASICs for the digital processing and for the analog/RF part of the radio



μAMPS I

### □ Berkeley: **Motes**

- Manufactured by Crossbow:  
[http://www.xbow.com/Products/Wireless\\_Sensor\\_Networks.htm](http://www.xbow.com/Products/Wireless_Sensor_Networks.htm)

### □ ETH Zurich: **BTnodes**

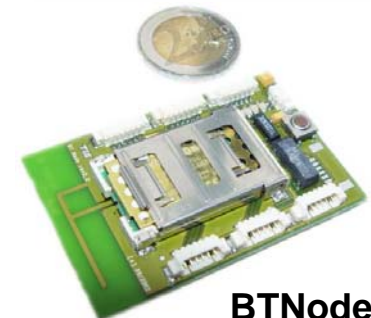
- <http://www-mtl.mit.edu/research/icsystems/uamps/>

### □ Typical COTS (commercial off the shelf) devices:

- several cubic centimeter volume
- several MIPS DSP
- several 100kB program space
- <100KB RAM
- several 100kbps over some meters
- energy consumption between 50μW (sleep mode) and 200 mW



Motes



BTNodes

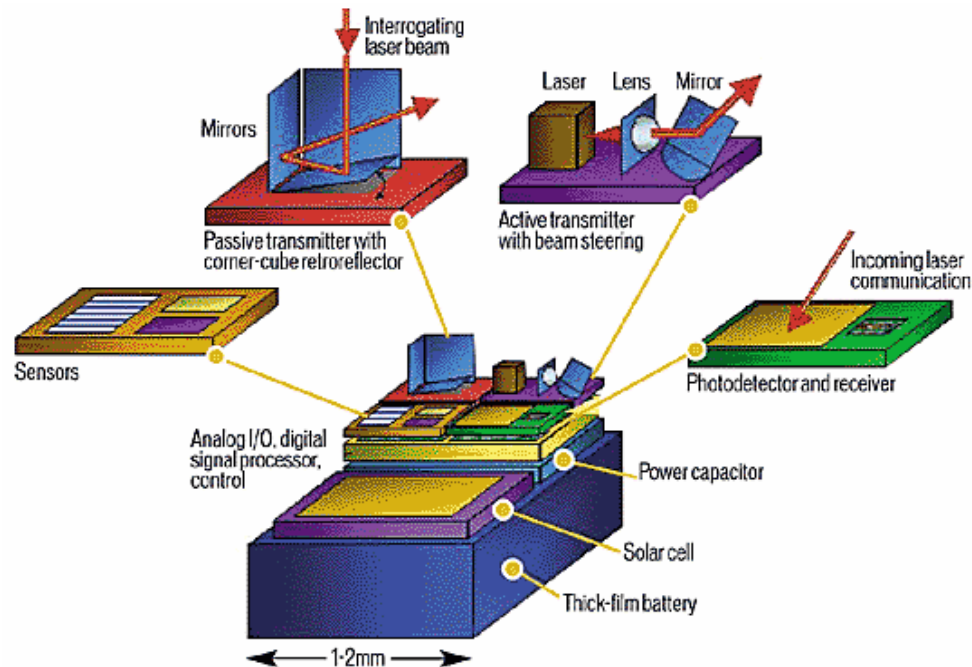
# SENSOR NETWORKS

## MEMS (MicroElectro-Mechanical Systems)

### ❑ Smart Dust (Berkeley)

<http://robotics.eecs.berkeley.edu/~pister/SmartDust/>

- ❑ Goal: self-contained, millimeter-scale sensing and communication platforms, the size of a grain of sand, cheap, with sensors, computational ability, bi-directional wireless communications and power supply



# SENSOR NETWORKS

## MEMS (MicroElectro-Mechanical Systems)

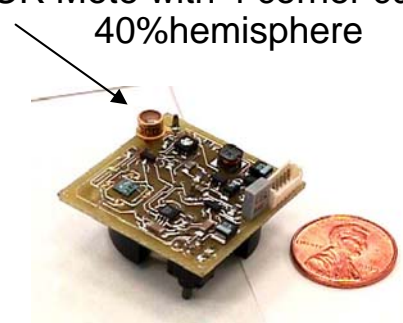
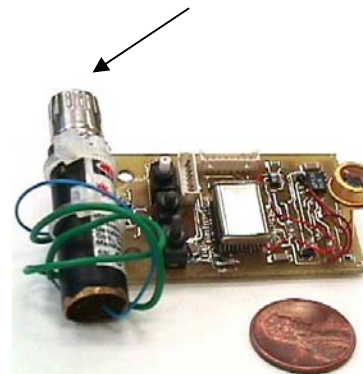
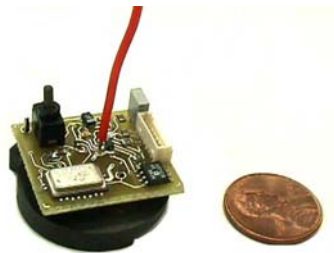
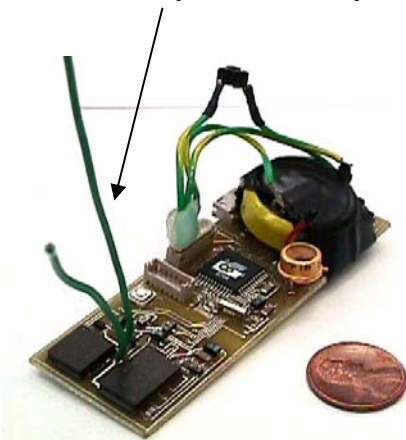
- ❑ **Smart Dust** (Berkeley)
- ❑ Thick-film battery, solar cell with a charge-integrating capacitor or both
- ❑ Various sensors, including light, temperature, vibration, magnetic field, acoustic, and wind shear depending on objectives
- ❑ Integrated circuit provides sensor-signal processing, communication, control, data storage and power management

Atmel Microprocessor  
RF Monolithics transceiver  
916MHz, ~20m range, 4800 bps  
1 week fully active, 2 yr @1%

### Early Prototypes (COTS)

Laser Mote with  
650nm laser pointer

CCR Mote with 4 corner cubes,  
40%hemisphere



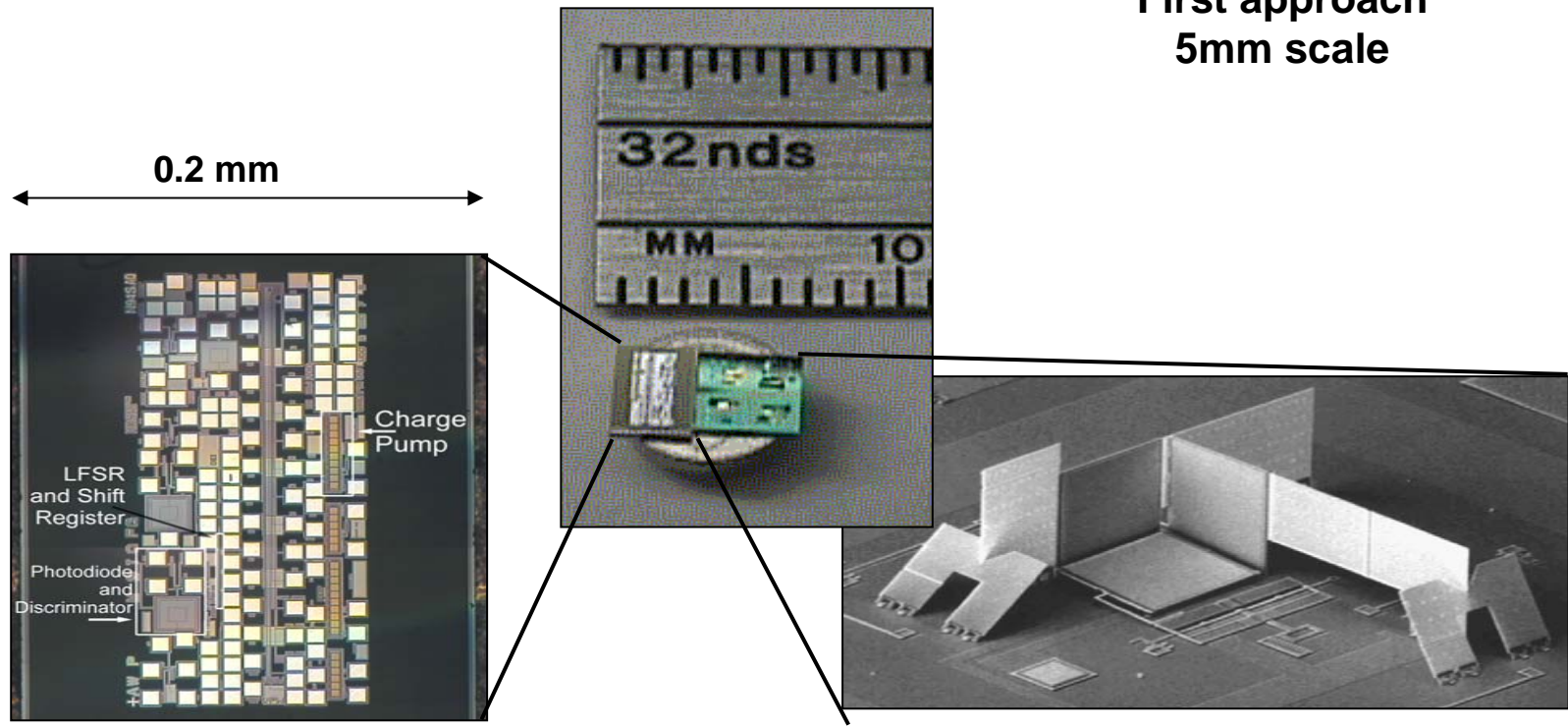
Source: <http://eecs.berkeley.edu/~pister/SmartDust>

# SENSOR NETWORKS

## MEMS (MicroElectro-Mechanical Systems)

- ❑ **Smart Dust** (Berkeley)
- ❑ The next step: **Micro Motes**

First approach  
5mm scale

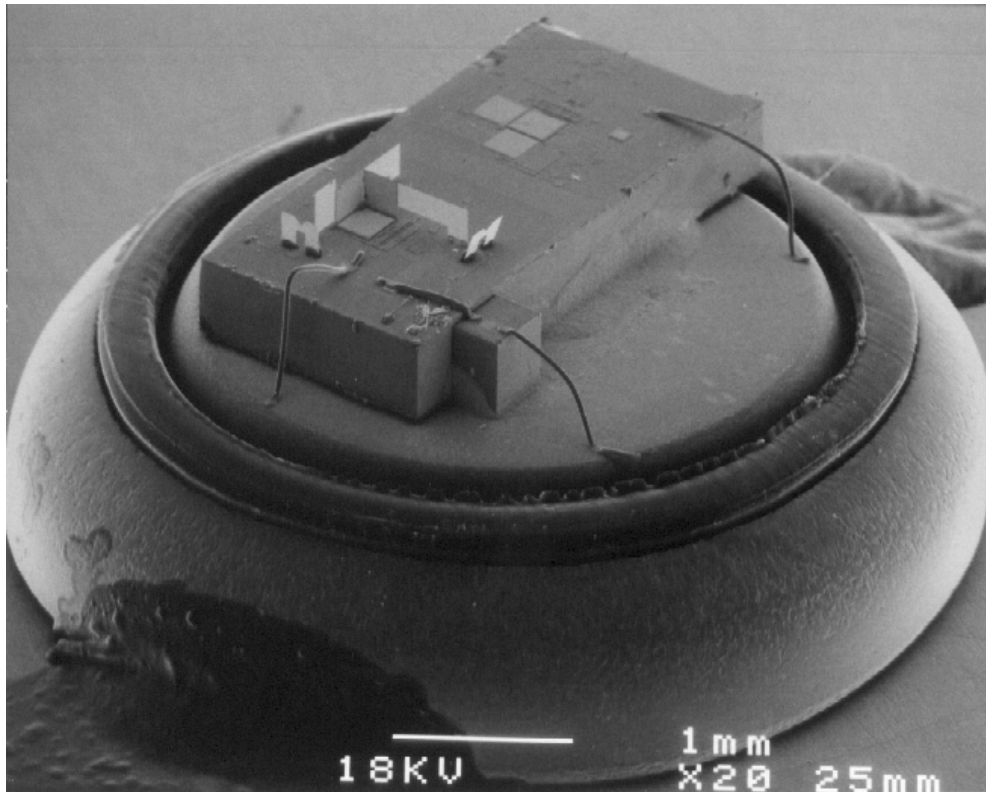




# SENSOR NETWORKS

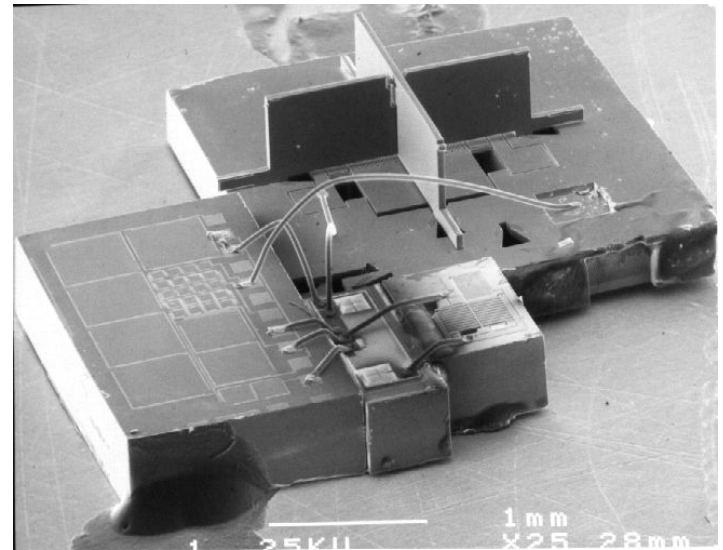
## MEMS (MicroElectro-Mechanical Systems)

- ❑ **Smart Dust** (Berkeley)
- ❑ The next step: **Micro Motes**



X20 63 mm<sup>3</sup> bi-directional communication mote

The next version  
1mm scale



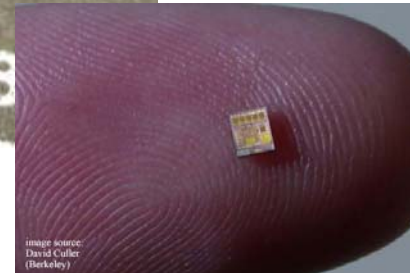
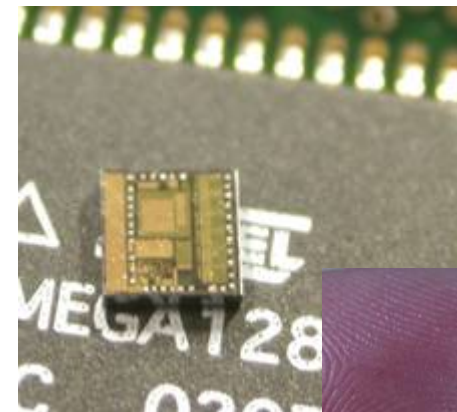
X25

# SENSOR NETWORKS

## MEMS (MicroElectro-Mechanical Systems)

- ❑ **Smart Dust** (Berkeley)
- ❑ The next step: **Micro Motes**

The current version  
(March 2003):  
Sensors, Processing  
and Communication  
in 1-mm scale





# SENSOR NETWORKS

## MEMS (MicroElectro-Mechanical Systems)

### ☐ **Smart Dust** (Berkeley)

#### ☐ Communication Principles

##### ▪ Radio-frequency communication

- Well understood
- Minimum power level in multiple milliwatt range
- Size of antennas and senders restricted by physics

##### ▪ Light

- Can be collimated in tight beams even from small apertures
- Optical transmitters of millimeter size can get antenna gains of one million or more compared to radio
- But line of sight necessary (sensor below a leaf is useless!)
- Dangerous for Eyes!

#### ☐ Passive Optical Communication

- Dust Mote does not require on-board light source
- Light bouncing at the sensor is either reflected or not reflected

#### ☐ Active Optical Communication

- Active steered laser communication

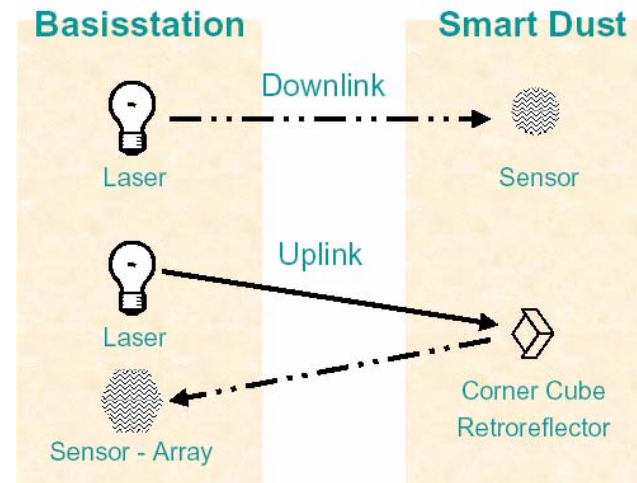
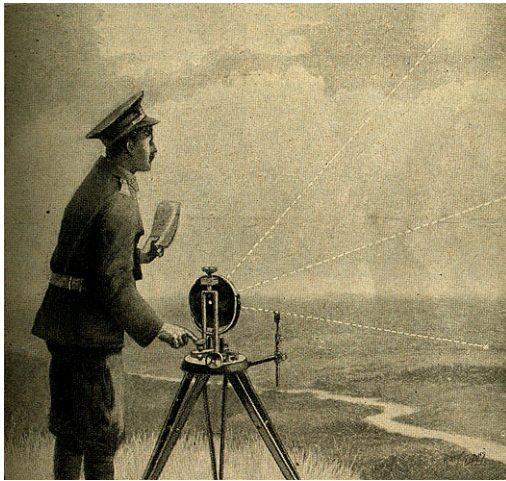
# SENSOR NETWORKS

## MEMS (MicroElectro-Mechanical Systems)

### Smart Dust (Berkeley)

#### Passive Optical Communication

- Resembles how a heliograph operator bounces sunlight off a mirror to flash a Morse code message to ships – an idea of the fifth century BC
- Laser beam from base station is received by sensor for downlink
- A special construction of mirrors on the device is used to either reflect or not reflect the base station laser for the uplink



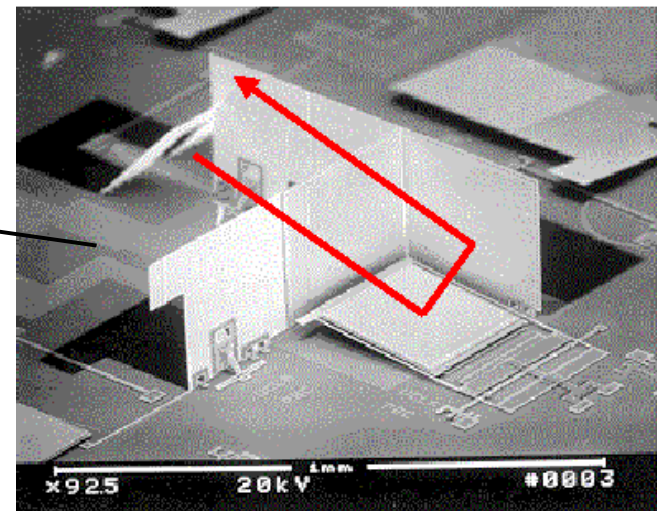
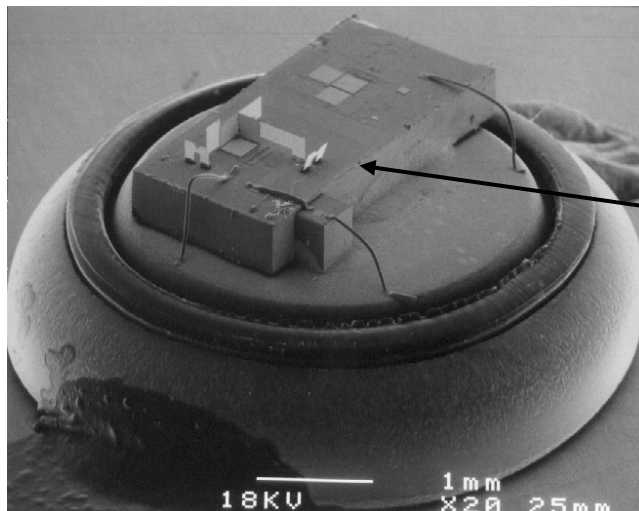
# SENSOR NETWORKS

## MEMS (MicroElectro-Mechanical Systems)

### Smart Dust (Berkeley)

#### Passive Optical Communication

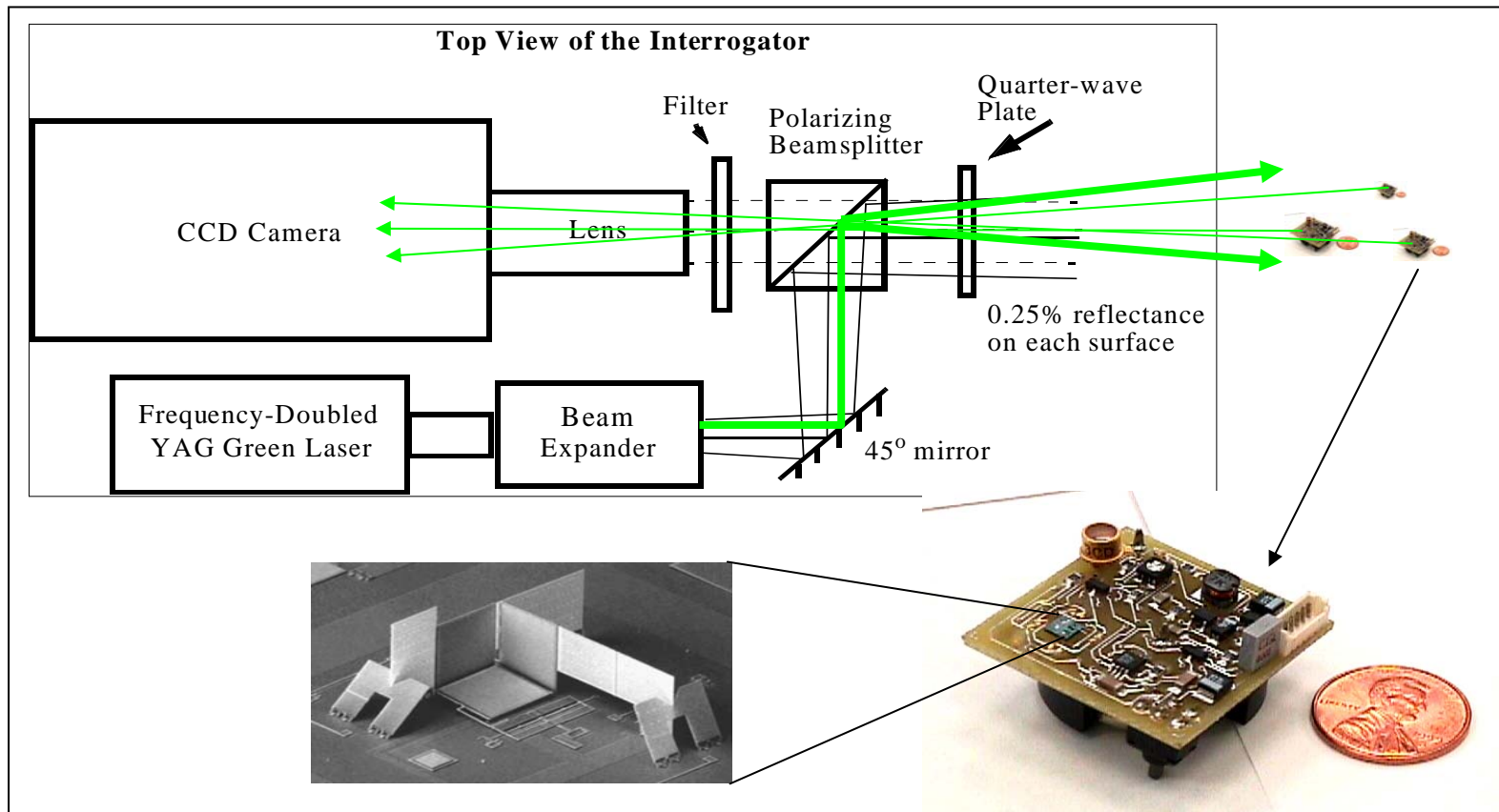
- Corner Cube Retroreflector (CCR) consists of 3 mutual orthogonal mirrors
- Light enters the CCR, bounces off each the 3 mirrors and is reflected back parallel to the direction it entered
- One mirror can be adjusted with a motor to an angle slightly askew (MEMS system, 1nJ per adjustment , kHz frequency)



# SENSOR NETWORKS

## MEMS (MicroElectro-Mechanical Systems)

- ❑ **Smart Dust** (Berkeley)
- ❑ CCR Interrogator



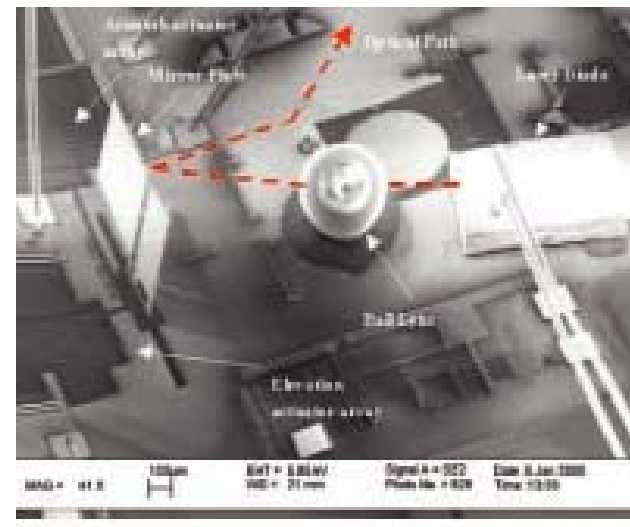
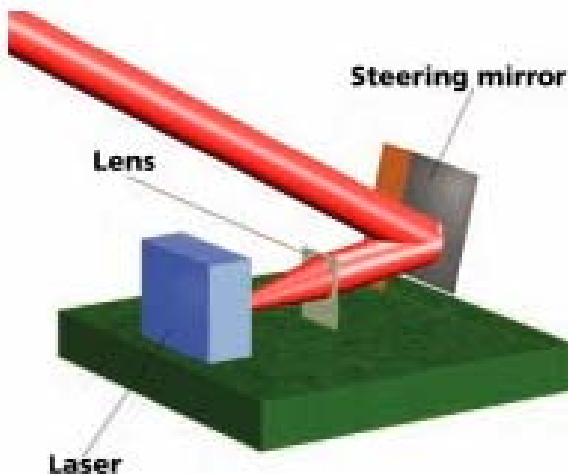
# SENSOR NETWORKS

## MEMS (MicroElectro-Mechanical Systems)

### Smart Dust (Berkeley)

#### Active Optical Communication

- Laser with MEMS controlled mirror on the sensor node
- Advantage: high power - 1mW laser with 1 milliradian (3.4 arcsec) has a density of ~318kW per steradian (40000 times of 100W light bulb)
- Challenge: beam direction and synchronization in multi-hop networks



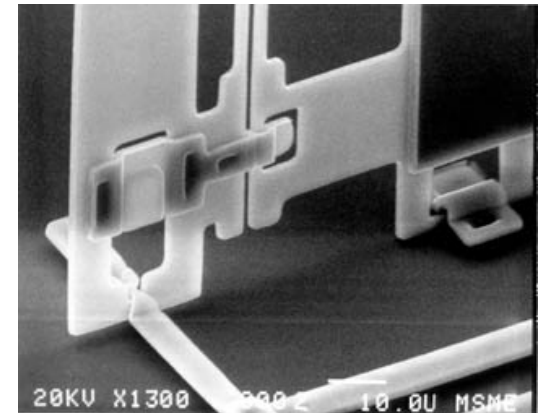
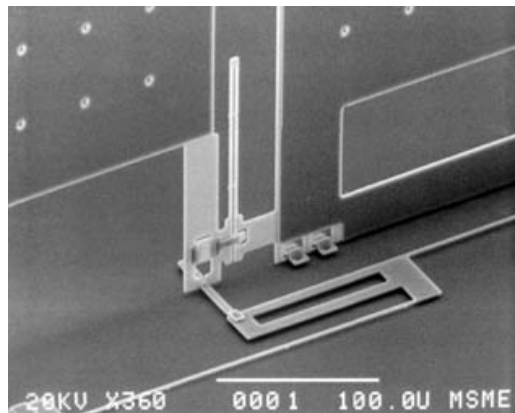
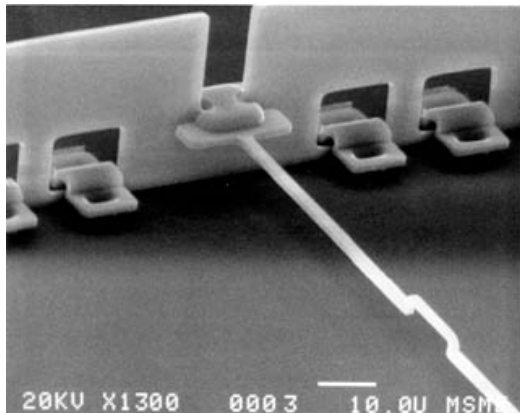
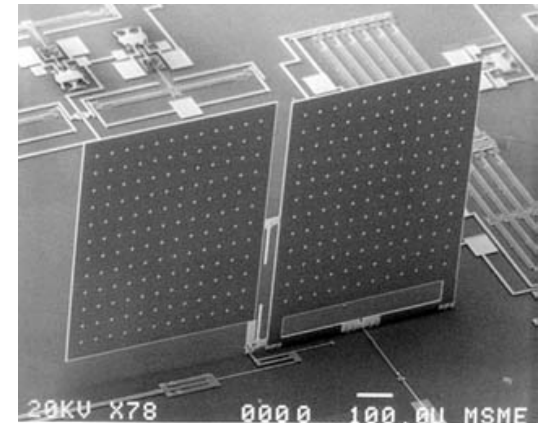
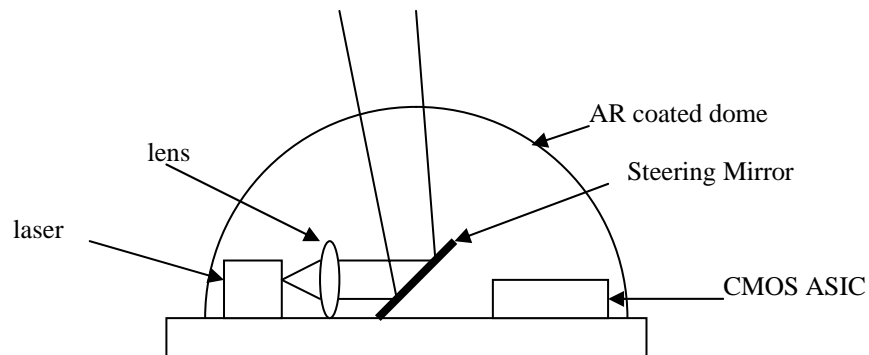


# SENSOR NETWORKS

## MEMS (MicroElectro-Mechanical Systems)

### Smart Dust (Berkeley)

#### 2D Beam Scanning

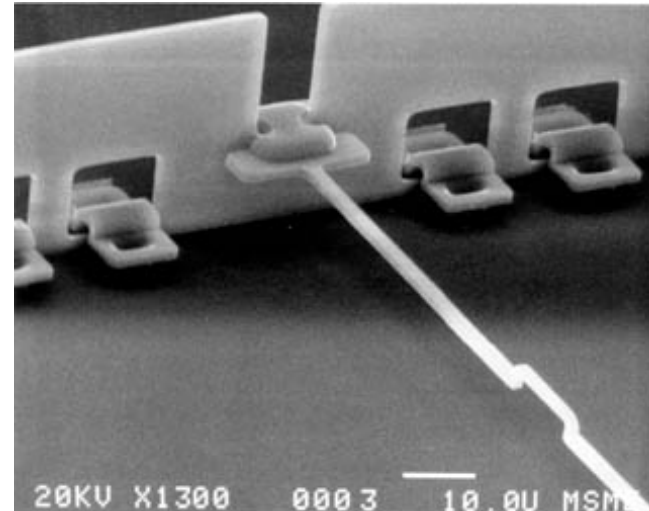
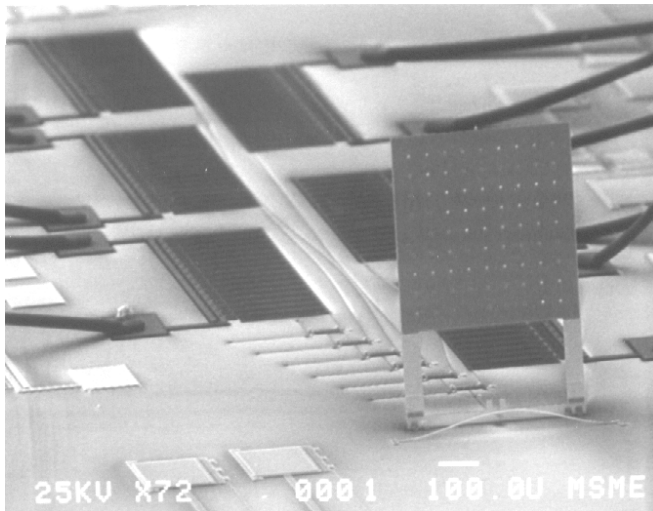
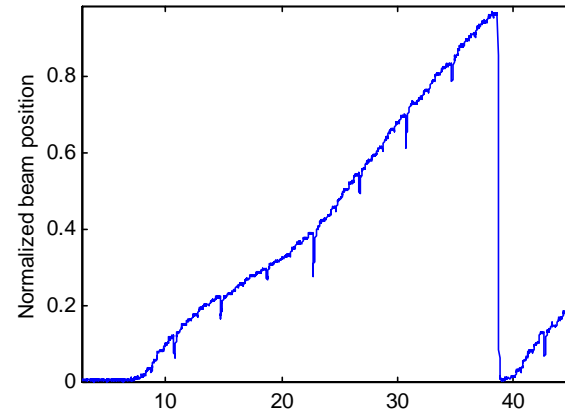




# SENSOR NETWORKS

## MEMS (MicroElectro-Mechanical Systems)

- **Smart Dust** (Berkeley)
- 6 bit DAC Driving Motor
  - open loop control
  - Insensitive to disturbance
  - potentially low power

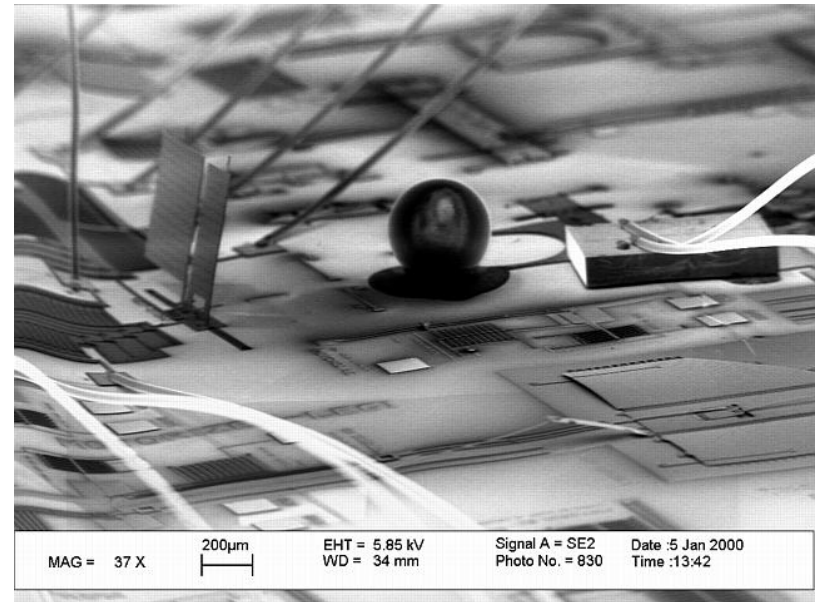
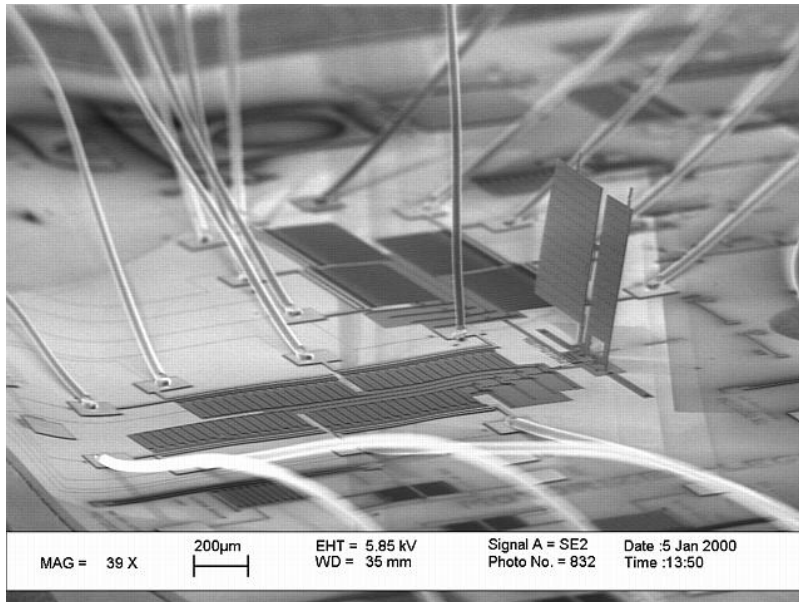


Source: <http://eecs.berkeley.edu/~pister/SmartDust>

# SENSOR NETWORKS

## MEMS (MicroElectro-Mechanical Systems)

- ❑ **Smart Dust** (Berkeley)
- ❑ 8mm<sup>3</sup> laser scanner
- ❑ Two 4-bit mechanical DACs control mirror scan angles
- ❑ 6 degrees azimuth, 3 elevation



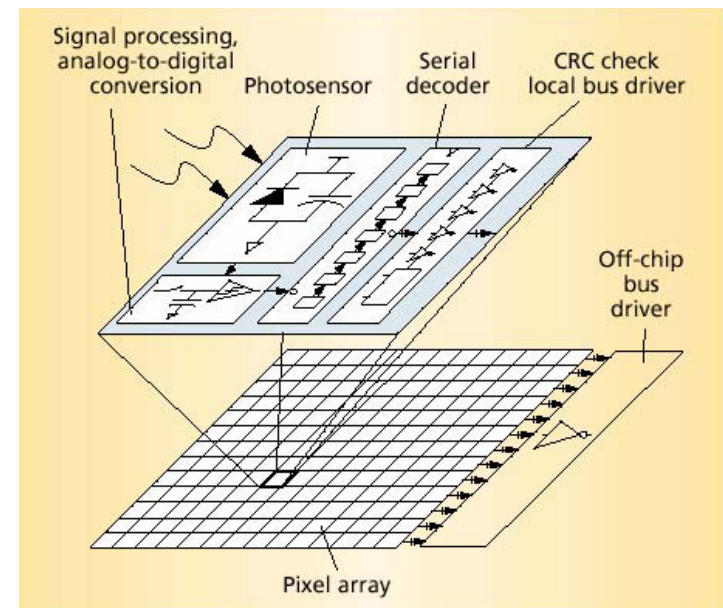
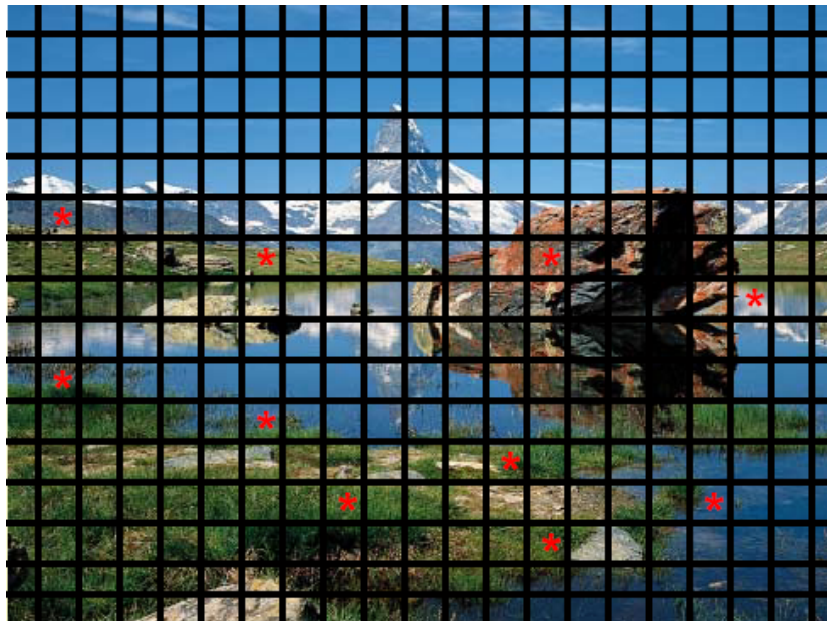
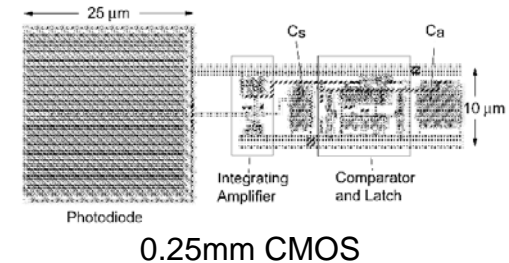
# SENSOR NETWORKS

## MEMS (MicroElectro-Mechanical Systems)

### Smart Dust (Berkeley)

#### Integrated Imaging Receiver

- Each pixel of an array contains complete asynchronous receiver circuit
- Allows for parallel communication with many sensors (few Mbps)



# SENSOR NETWORKS

## MEMS (MicroElectro-Mechanical Systems)

### ☐ **Smart Dust** (Berkeley)

#### ☐ Energy Considerations:

#### ☐ Supply:

- Battery:  $\sim 1\text{J}$  per  $1\text{mm}^3$
- Capacitor:  $\sim 10\text{mJ}$  per  $1\text{mm}^3$
- Solar Cell:
  - Sunlight:  $\sim 1\text{J}$  per  $\text{mm}^2$  & day,
  - Indoor:  $\sim 1\text{-}10\text{mJ}$  per  $\text{mm}^2$  & day

#### ☐ Consumption:

- Bluetooth (330mW):  $1\text{J}$  lasts for 3 sec,  $1\text{J} / 3000 \text{ bit} = 0.33\text{mJ} / \text{bit}$
- Optical Receiver:  $0.1 \text{ nJ} / \text{bit}$
- CCR:  $1\text{nJ} / \text{bit}$
- A/D-Converter:  $1\text{nJ} / \text{sample}$
- Computation:  $1\text{pJ} / \text{instruction}$

☐  $1\text{mJ} / \text{day}$  is sufficient to sensor, process and transmit data each second

☐ But also: for each sample, 1000 8-bit instructions can be performed

Therefore: spend extra computation before transmitting is advantageously



# SENSOR NETWORKS

## MEMS (MicroElectro-Mechanical Systems)

- ☐ **Smart Dust** (Berkeley)
- ☐ Test system in San Francisco
- ☐ 2 weather sensors at Twin Peaks and Coit Towers using active laser communication

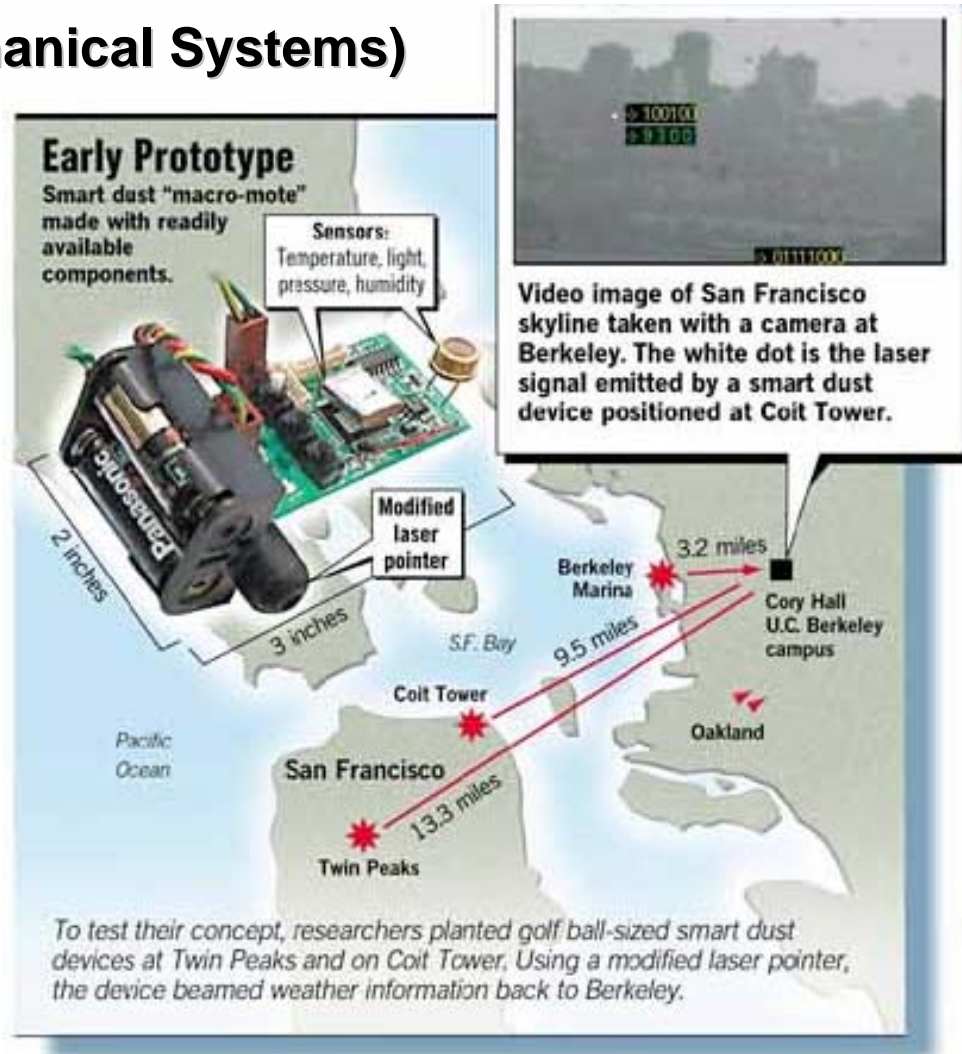
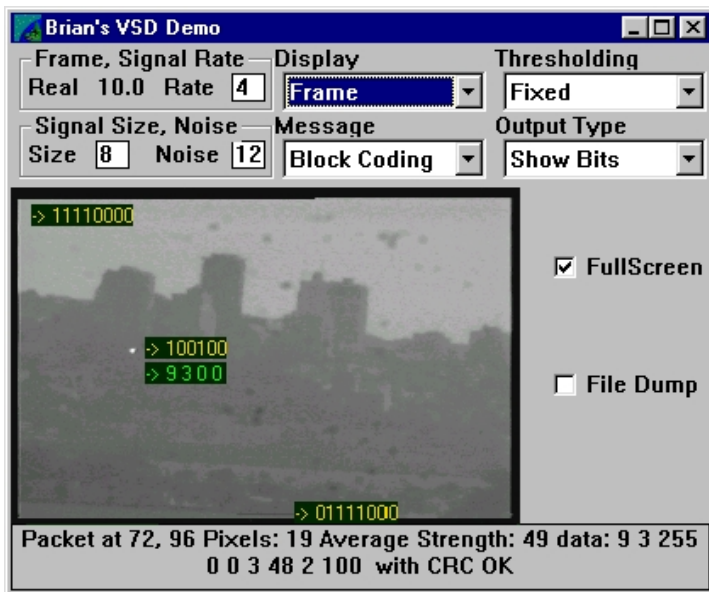


Image Source: John Blanchard, The San Francisco Chronicle

# SENSOR NETWORKS

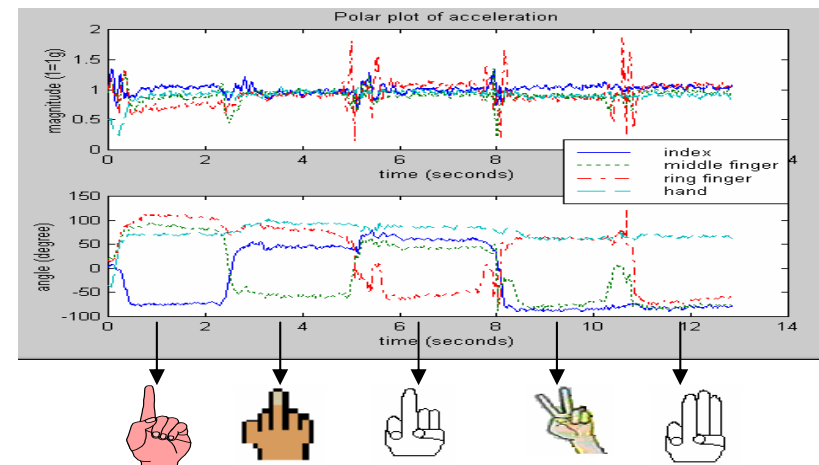
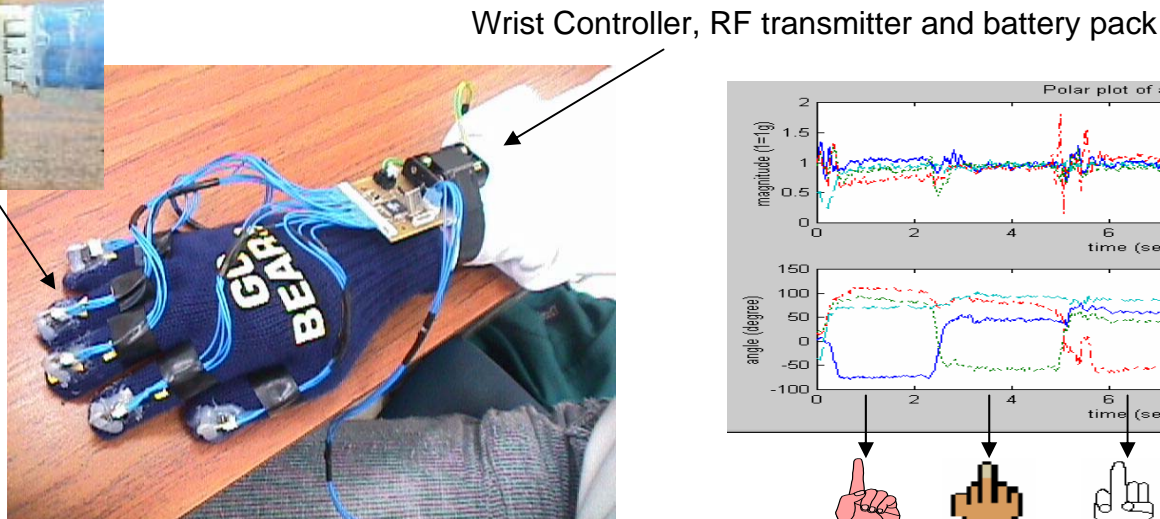
## MEMS (MicroElectro-Mechanical Systems)

### Smart Dust (Berkeley)

- Usage example: virtual sensing keyboard
- 2 axis ADXL 202 accelerometer is placed on top of each finger on the glove
- Additionally, a sixth accelerometer is placed on the back of the hand
- The signals from the accelerometers are digitized and send to a computer
- Allows gesture recognition which can be used as pointer, keyboard, etc.



Finger Accelerator Meter



# SENSOR NETWORKS

## MEMS (MicroElectro-Mechanical Systems)

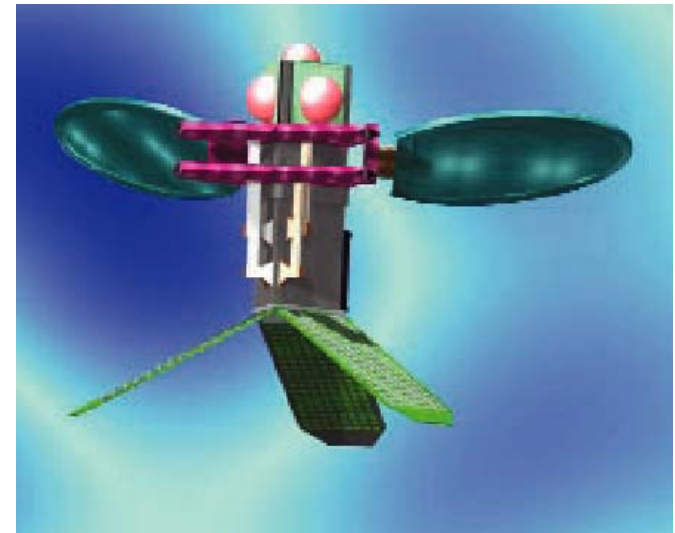
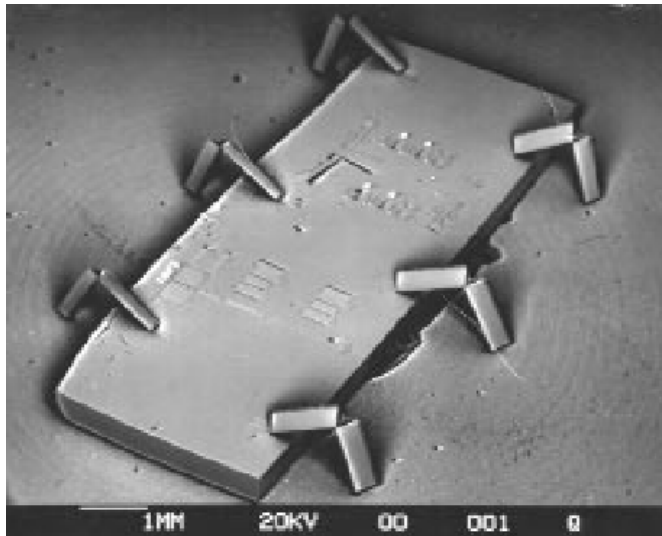
- ❑ **Smart Dust** (Berkeley)
- ❑ Mobility through mechanical enhancements:
  - Silicon maple seeds
  - Silicon dandelions
- ❑ Enhances time to reach ground after release from airplane (factor 3: 15 hours)



# SENSOR NETWORKS

## Microrobotics

- ☐ Richard Yeh (Berkeley)
- ☐ Synthetic insects constructed using microactuators and micromechanisms, forming legs and wings
- ☐ Crawling microrobot (less than one cubic centimeter) with legs of 2-micron with silicon tendons to couple each leg to electrostatic motors on the body
- ☐ Piezoelectric motors attached to the exoskeleton actuate wings made of 50-micron-thick stainless steel
- ☐ Total power consumptions less than 10 mW, provided by on-board solar cells



Source: <http://www-bac.eecs.berkeley.edu/~yeh/currentbot.html>, <http://robotics.eecs.berkeley.edu/~ronf/mfi.html>