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Smart Dust

Dr. M.H. Nerkar[1], Nand kumar[2]

Dept of E&TC, Govt College of Engg, Jalgaon, Maharashtra[1,2]

Abstract: Smart dust is a tiny dust size device with extra-ordinary capabilities. Smart dust combines sensing, computing, wireless communication capabilities and autonomous power supply within volume of only few millimeters and that too at low cost. These devices are proposed to be so small and light in weight that they can remain suspended in the environment like an ordinary dust particle. These properties of Smart Dust will render it useful in monitoring real world phenomenon without disturbing the original process to an observable extends. Presently the achievable size of Smart Dust is about 5mm cube, but we hope that it will eventually be as small as pack of dust. Individual sensors of smart dust are often referred to as motes because of their small size. These devices are also known as MEMS, which stands for micro electro-mechanical sensors.

Keywords: Smart dust, millimeters, MEMS.

I. INTRODUCTION

"Smart Dust" is an emerging technology made up from tiny, wireless sensors called as 'Motes'. Eventually these devices would be smart enough to talk with other sensors yet small enough to fit on a head of a pin. Berkeley's Smart Dust project, explores the limits on size and power consumption in autonomous sensor nodes. Size reduction is paramount, to make the nodes as inexpensive and easy-to-deploy as possible. The research team is confident that they can incorporate the requisite sensing, communication, and computing hardware, along with a power supply, in a volume no more than a few cubic millimeters, while still achieving impressive performance in terms of sensor functionality and communications capability. These millimeter-scale nodes are called "Smart Dust." It is certainly within the realm of possibility that future prototypes of Smart Dust could be small enough to remain suspended in air, buoyed by air currents, sensing and communicating for hours or days on end. Smart Dust sensors are networked computer nodes that are just cubic millimeters in volume.

The smart dust project envisions a complete sensor network node, including power supply, processor, sensors and communications mechanisms, in single cubic millimeters. Smart dust motes could run for years, given that a cubic millimeter battery can store 1J and could be backed up with a solar cell or vibrational energy source. The goal of the Smart Dust project is to build a millimeter-scale sensing and communication platform for a massively distributed sensor network. This device will be around the size of a grain of sand and will contain sensors, computational ability, bi-directional wireless communications, and a power supply. Smart dust consists of series of circuit and micro-electro-mechanical systems (MEMS) designs to cast those functions into custom silicon. Micro-electro-mechanical-systems (MEMS) consist of extremely tiny mechanical elements, often integrated together with electronic circuitry.

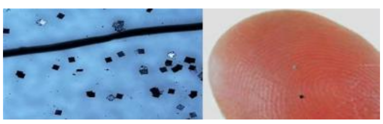

Figure 1.a: Smart Dust particles

2. LITERATURE REVIEW

The current ultramodern technologies are focusing on automation and miniaturization. The decreasing computing device size, increased connectivity and enhanced interaction with the physical world have characterized computing's history. Recently, the popularity of small computing devices, such as hand held computers and cell phones; rapidly flourishing internet group and the diminishing size and cost of sensors and especially transistors have accelerated these strengths. The emergence of small computing elements, with sporadic connectivity and increased interaction with the environment, provides enriched opportunities to reshape interactions between people and computers and spur ubiquitous computing researches. This section describes smart dust, beginning with a summary of early development work at UC Berkeley. Also presented are two notable smart dust applications completed in the beginning stages of smart dust history. [6]

2.1: History

Smart dust was conceived in 1998 by Dr. Kris Pister of the University of California, Berkeley. He set out to build a device with a sensor, communication device and small computer, integrated into single package. In early stages of the projects, the team gained experience by building relatively large motes using components available. One such mote named RF mote has sensors for "Humidity, Temperature, Barometric Pressure, Light intensity, Tilt and Vibration and Magnetic field." And it is capable of communicating distances of 60 feet using RF communication. If the mote operated continuously its battery would last upto 1 week.

One issue the team faced in building smaller motes involved powering the device. Small batteries help

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minimize the size of the resulting mote but they contain less energy than traditional, larger batteries and thus they have shorter life span. However long battery life is critical to application where it would be costly, inconvenient or impossible to retrieve a smart dust mote in order to replace its batteries. The Smart dust project website states that "The primary constraint in the design of smart dust motes is volume, which puts a severe constraint on energy since we do not have much room for batteries or large solar cells." However to conserve the available energy one approach taken by Dr. David Culler was to design a "software that enabled the motes to 'sleep' most of the time yet 'wake up' regularly to take readings and communicate. " This allows for energy conservation during the sleep period.

2.2: Early Applications

Smart dust was used to detect the vehicles traveling through an isolated dessert area in Palm Springs California. In doing so the experiment proved how smart dust can be used by military and Law enforcement personnel to monitor movement in the region. Next scientists approach smart dust from a biotechnology perspective to produce motes from chemical compounds rather than electrical circuitry. One experiment demonstrated the use of smart dust to detect the presence of hydrocarbon vapors from approximately 65 feet away. While the experiment was limited to hydro carbon vapors the researchers predict that with appropriate chemical modification the smart dust sensors used can specifically detect bimolecular, explosives chemical war fare agent such as 'Sarin'. There is a need to better understand the routing trends and connectivity performance of the "Smart Dust" network. On this front, further analysis and more systematic tests will be conducted to detect the effect due to traffic interference and environment factors on the network performance. By varying frequency of transmission, distance and layout between motes and test environment (i.e., outdoor versus indoor, foggy/rainy/icy conditions), a more in-depth understanding of"Smart Dust" capabilities in real-world applications will be achieved. In addition, the embedding of an ice detection algorithm would help decrease the packet loss by decreasing the data sent. Instead of sending all the sensors readings, a 2-bit signal representing the road condition will be sent. The robustness and survivability of the proposed sensor-road button will be further investigated and its design will be improved. [1]

3. PROBLEM ANALYSIS

The development and use of smart dust raises some problems and concerns for stake holder these include privacy issue, potential system security weaknesses, need for standards and the environmental impacts of smart dust.

3.1: Privacy

It's easy to imagine that tiny smart dust sensors could be use for mischievous, illegal or unethical purposes. Corporations, government and individual who use motes to monitor people without their knowledge and smart dust could become the tool of choice for corporate espionage. Though the issues are not easily resolved but as smart dust becomes smaller, cheaper and more prevalent privacy concerns are likely to increase.

3.2: Security

Smart dust motes as network computing devices are susceptible to security concern similar of that of computers on internet. One of these susceptibilities is due to the fact that motes in the network are reprogrammable. This feature allows an administrator to update software on single mote and then command it to pass the update along all the other motes in the network.

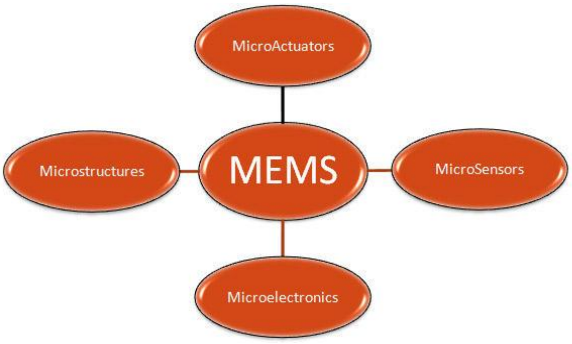
3.3: Environmental impacts

After smart dust is sprinkle in a remote or desolate area to accomplish a monitoring function it is not easily or inexpensively retrieved. If mote fails and it consequently abandoned bytes owner, there is an environmental impact. Motes environmentally unfriendly components include integrated circuit, battery, PCB. Clearly motes have main environmental impacts that should be consider by users such as protecting a forest from protecting fires. Some environmental concern might be raised about motes that draw on radioactive power sources. An atomic scientist said in an article that motes with these types are batteries "aren't likely to be way dangerous unless you ate them or threw them in fire and inhaled the smoke."

4. IMPLEMENTATION

4.1: The MEMS Technology in Smart Dust

Smart dust requires mainly revolutionary advances in miniaturization, integration & energy management. Hence designers have used MEMS technology to build small sensors, optical communication components, and power supplies. Micro-electro-mechanical-systems consist of extremely tiny mechanical elements, often integrated together with electronic circuitry. They are measured in micrometers, which are millions of a meter. They are made in a similar fashion as computer chips. The advantage of this manufacturing process is not simply that small structures can be achieved but also that thousands or even millions of system elements can be fabricated simultaneously. This allows systems to be both highly complex and extremely low-cost.



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Micro-Electro-Mechanical Systems (MEMS) is the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through micro-fabrication technology. While the electronics are fabricated using integrated circuit (IC) process sequences, the micromechanical components are fabricated using compatible "micromachining" processes that selectively etch away parts of the silicon wafer or add new structural layers to form the mechanical and electromechanical devices. MEMS realize a complete System On chip technology. Microelectronic integrated circuits can be thought of as the "brains" of a system and allow Microsystems to sense and control the environment. Sensors gather information from the environment through measuring mechanical, thermal, biological, chemical, optical, and magnetic phenomena. The electronics then process the information derived from the sensors and through some decision making capability direct the actuators to respond by moving, positioning, regulating, and filtering, thereby controlling the environment for some desired purpose. Because MEMS devices are manufactured using batch fabrication techniques similar to those used for integrated circuits, unprecedented levels of functionality, reliability, and sophistication can be placed on a small silicon chip at a relatively low cost. The deep insight of MEMS is as a new manufacturing technology, a way of making complex electromechanical systems using batch fabrication techniques similar to those used for integrated circuits, and uniting these electromechanical elements together with electronics. Historically, sensors and actuators are the most costly and unreliable part of a sensor-actuator-electronics system. MEMS technology allows these complex electromechanical systems to be manufactured using batch fabrication techniques, increasing the reliability of the sensors and actuators to equal that of integrated circuits. The performance of MEMS devices and systems is expected to be superior to macro scale components and systems; the price is predicted to be much lower.

4.2: Smart Dust Technology

Integrated into a single package are:

1. MEMS sensors
2. MEMS beam steering mirror for active optical transmission
3. MEMS corner cube retro reflector for passive optical transmission
4. An optical receiver
5. Signal processing and control circuitry
6. A power source based on thick film batteries and solar cells

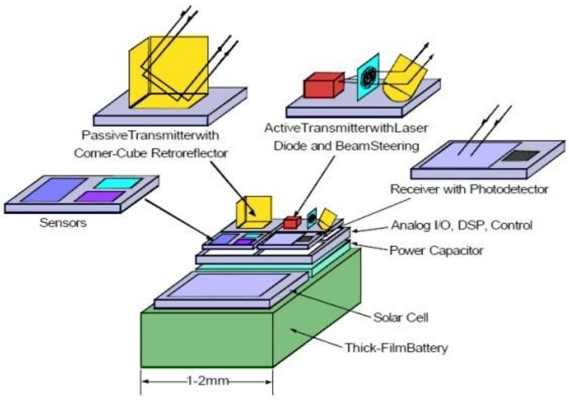
This remarkable package has the ability to sense and to communicate and to self power. A major challenge is to incorporate all these functions while maintaining very low power consumption.

- Smart dust employs 2 types of transmission schemes:

Passive transmission: It uses corner cube retro reflector to transmit to base stations.

Active transmission: It uses a laser diode & steerable mirrors for mote to mote communication.

- The photo diode allows optical data reception.
- Signal processing & control circuitry consists of analog I/O, DSPs to control &process the incoming data.
- The power system consists of a thick film battery, a solar cell with a charge integrating capacitor for a period of darkness.



The Smart Dust mote is run by a microcontroller that not only determines the tasks performed by the mote, but also controls power to the various components of the system to conserve energy. Periodically the microcontroller gets a reading from one of the sensors, which measure one of a number of physical or chemical stimuli such as temperature, ambient light, vibration, acceleration, or air pressure, processes the data, and stores it in memory. It also occasionally turns on the optical receiver to see if anyone is trying to communicate with it. This communication may include new programs or messages from other motes. In response to a message or upon its own initiative the microcontroller will use the corner cube retro reflector or laser to transmit sensor data or a message to a base station or another mote.

The primary constraint in the design of the Smart Dust motes is volume, which in turn puts a severe constraint on energy since we do not have much room for batteries or large solar cells. Thus, the motes must operate efficiently and conserve energy whenever possible. Most of the time, the majority of the mote is powered off with only a clock and a few timers running. When a timer expires, it powers up a part of the mote to carry out a job, then powers off. A few of the timers control the sensors that measure one of a number of physical or chemical stimuli such as temperature, ambient light, vibration, acceleration, or air pressure.

When one of these timers expires, it powers up the corresponding sensor, takes a sample, and converts it to a digital word. If the data is interesting, it may either be stored directly in the SRAM or the microcontroller is powered up to perform more complex operations with it. When this task is complete, everything is again powered down and the timer begins counting again.

Another timer controls the receiver. When that timer expires, the receiver powers up and look for an incoming

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packet. If it doesn't see one after a certain length of time, it is powered down again. The mote can receive several types of packets, including ones that are new program code that is stored in the program memory. This allows the user to change the behavior of the mote remotely. Packets may also include messages from the base station or other motes. When one of these is received, the microcontroller is powered up and used to interpret the contents of the message. The message may tell the mote to do something in particular, or it may be a message that is just being passed from one mote to another on its way to a particular destination.
In response to a message or to another timer expiring, the microcontroller will assemble a packet containing sensor data or a message and transmit it using either the corner cube retro-reflector or the laser diode, depending on which it has. The laser diode contains the onboard laser which sends signals to the base station by blinking on and off. The corner cube retro-reflector transmits information just by moving a mirror and thus changing the reflection of a laser beam from the base station.
This technique is substantially more energy efficient than actually generating some radiation. With the laser diode and a set of beam scanning mirrors, we can transmit data in any direction desired, allowing the mote to communicate with other Smart Dust motes.

5. COMMUNICATING FROM A GRAIN OF SAND

Smart Dust's full potential can only be attained when the sensor nodes communicate with one another or with a central base station. Wireless communication facilitates simultaneous data collection from thousands of sensors. There are several options for communicating to and from a cubic-millimeter computer.
Radio-frequency and optical communications each have their strengths and weaknesses. Radio-frequency communication is well under-stood, but currently requires minimum power levels in the multiple milliwatt (mW) range due to analog mixers, filters, and oscillators. If whisker-thin antennas of centimeter length can be accepted as a part of a dust mote, then reasonably efficient antennas can be made for radio-frequency communication. While the smallest complete radios are still on the order of a few hundred cubic millimeters, there is active work in the industry to produce cubic-millimeter radios.
Semiconductor lasers and diode receivers are intrinsically small, and the corresponding transmission and detection circuitry for on/off keyed optical communication is more amenable to low-power operation than most radio schema. Perhaps most important, optical power can be collimated in tight beams even from small apertures. Diffraction enforces a fundamental limit on the divergence of a beam, whether it comes from an antenna or a lens. Laser pointers are cheap examples of milliradian collimation from a millimeter aperture. To get similar collimation for a 1-GHz radio-frequency signal would require an antenna 100 meters across, due to the difference in wavelength of the two transmissions. As a result, optical transmitters of millimeter size can get antenna gains of one million or more, while similarly sized radio frequency antennas are doomed by physics to be mostly isotropic.
Collimated optical communication has two major drawbacks. Line of sight is required for all but the shortest distances, and narrow beams imply the need for accurate pointing. Of these, MEMS technology and clever algorithms can solve the pointing accuracy, but an optical transmitter under a leaf or in a shirt pocket is of little use to anyone. We have chosen to explore optical communication in some depth due to the potential for extreme low-power communication.

5.1 Optical Communications

We have explored two approaches to optical communications:

- Passive reflective systems
- Active-steered laser systems.

5.2.1: Passive reflective systems

The passive reflective communication is obtained by a special device called CCR (Corner cube retro reflector) consists of three mutually orthogonal mirrors. Light enters the CCR, bounces off each of the three mirrors, and is reflected back parallel to the direction it entered. In the MEMS version, the device has one mirror mounted on a spring at an angle slightly askew from perpendicularity to the other mirrors.
In this position, because the light entering the CCR does not return along the same entry path, little light returns to the source a digital 0. Applying voltage between this mirror and an electrode beneath it causes the mirror to shift to a position perpendicular to other mirrors, thus causing the light entering the CCR to return to its source a digital 1. The mirror's low mass allows the CCR to switch between these two states up to a thousand times per second, using less than a nano-joule per $0 \rightarrow 1$ transition. A $1 \rightarrow 0$ transition, on the other hand, is practically free because dumping the charge stored on the electrode to the ground requires almost no energy.

Our latest Smart Dust device is a 63-mm3 autonomous bidirectional communication mote that receives an optical signal, generates a pseudorandom sequence based on this signal to emulate sensor data, and then optically transmits the result. The system contains a micro machined corner-cube reflector, a 0.078-mm3 CMOS chip that draws 17 microwatts, and a hearing aid battery. In addition to a battery based operation, we have also powered the device using a 2-mm2 solar cell. This mote demonstrates Smart Dust's essential concepts, such as optical data transmission, data processing, energy management, miniaturization, and system integration.
A passive communication system suffers several limitations. Unable to communicate with each other, motes rely on a central station equipped with a light source to send and receive data from other motes. If a given mote does have a clear line of sight to the central station, that mote will be isolated from the network. Also, because the CCR reflects only a small fraction of the light emitted from the base station, this system's range cannot easily extend beyond 1 kilometer.

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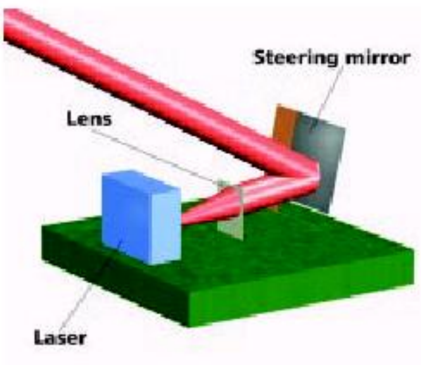
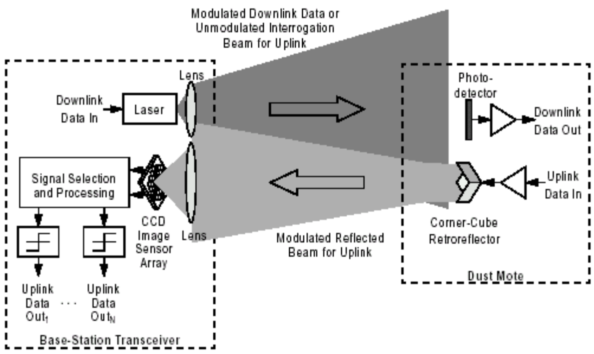
5.2.2: Active-steered laser systems

For mote-to-mote communication, an active-steered laser communication system uses an onboard light source to send a tightly collimated light beam toward an intended receiver. Steered laser communication has the advantage of high power density; for example, a 1-milliwatt laser radiating into 1 milliradian (3.4 arcseconds) has a density of approximately 318 kilowatts per steradian (there are 4 steradians in a sphere), as opposed to a 100-watt light bulb that radiates 8 watts per steradian isotropically. A Smart Dust mote's emitted beam would have a divergence of approximately 1 milliradian, permitting communication over enormous distances using milliwatts of power. Each mote must carefully weigh the needs to sense, compute, communicate, and evaluate its energy reserve status before allocating precious nanojoules of energy to turn on its transmitter or receiver. Because these motes spend most of their time sleeping, with their receivers turned off, scheduling a common awake time across the network is difficult. If motes don't wake up in a synchronized manner, a highly dynamic network topology and large packet latency result. Using burst mode communication, in which the laser operates at up to several tens of megabits per second for a few milliseconds, provides the most energy-efficient way to schedule this network. This procedure minimizes the mote's duty cycle and better utilizes its energy reserves. The steered agile laser transmitter consists of a semiconductor diode laser coupled with a collimating lens and MEMS beam-steering optics based on a two degree-of-freedom silicon micro mirror. This system integrates all optical components into an active 8-mm3 volume as the figure shows



Active-steered laser systems



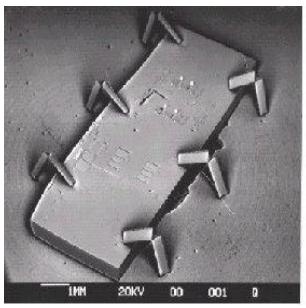
6. CURRENT ADVANCEMENTS

6.1: Computing at the Millimeter Scale

Computing in an autonomous cubic-millimeter package must focus on minimizing a given task's energy consumption. Smaller, faster transistors have reduced parasitic capacitance, thereby resulting in diminished dynamic power consumption. Constant electric field scaling has reduced supply voltages, producing dramatic power reductions for both high-performance and low-energy computing because dynamic power has a quadratic dependence on supply voltage. However, constant electric field scaling also calls for a reduction in the threshold voltage. This will result in larger leakage currents, which are already a concern in the high performance processors to be released in 2001 that will leak amps of current. The process engineers need to keep leakage currents low, which will also benefit low-energy designers. In millimeter-scale computing, the shrinking transistor's size lets designer's compact significant computing power into this small area. [2]

6.2: Microbotics

Add legs or wings to smart dust and we get micro robots. Like smart dust, these synthetic insects will sense, think, and communicate. In addition they will have the ability to move about and interact physically with their environment. Micro machining can be used to build micro actuators and micro mechanisms, forming legs and wings, which are integrated with other smart dust components. The crawling microbot consume only tens of micro watts of power; the motors can lift more than 130 times the robot's own weight. The flying microbot have a wing span of 10-25 mm and will sustain autonomous flight. Developers folded 50 micron thick stainless steel into desired shape to create the wings and exoskeleton. Piezoelectric motors attached to the exoskeleton actuate the wings. These legged and winged microbots will consume a total power of less than 10 milliwatts, provided by onboard solar cells.[4]



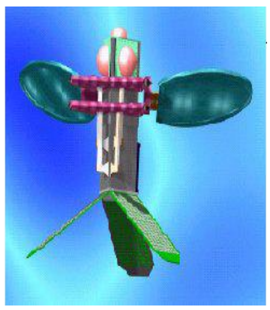


Figure 6.a: Crawling microbot Figure 6.b: Flying microbot

6.3: Cots Dust

They are large scale bodies for models for smart dust and they are devices that incorporate communications, processing, sensors and batteries into a package about a cubic inch in size. COTS dust was designed with the intention of testing out communication and sensing capabilities of large number of nodes. Potential

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applications are limitless! They can range from fire detectors to espionage, from earthquake monitoring to people tracking. The basic structure of COTS dust consists of an Atmel microcontroller with sensors and communication unit. The communication unit is one of the following: an RF transceiver, a laser module, a corner cube reflector. Devices can have one or all of the following sensors: temperature, light, humidity, pressure, 3axis magnetometer, 3axis accelerometers.[4]

7 APPLICATIONS

- Civil and military applications where chemical & biological agents in a battle field are detected.

Figure 7.a: Soldier-wearable shooter localization system

- Virtual keyboard Glue a dust mote on each of your fingernails. Accelerometers will sense the orientation and motion of each of your fingertips, and talk to the computer in your watch. Combined with a MEMS augmented-reality heads-up display, your entire computer I/O would be invisible to the people around you.

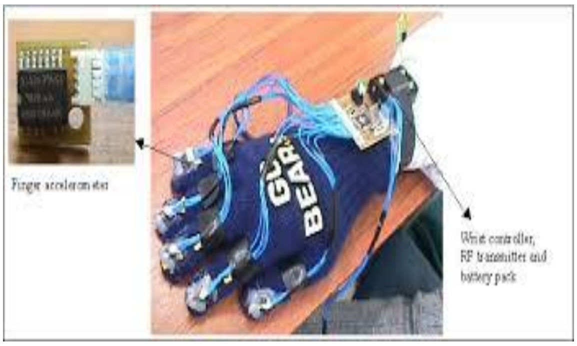

Figure 7.b: Virtual keyboard

- Inventory Control Smart office spaces The Center for the Built Environment has fabulous plans for the office of the future in which environmental conditions are tailored to the desires of every individual. Maybe soon we'll all be wearing temperature, humidity, and environmental comfort sensors sewn into our clothes, continuously talking to our workspaces which will deliver conditions tailored to our needs.
- Individual dust motes can be attached to the objects one wishes to monitor or a large number of dust motes may be dispersed in the environment randomly.

Figure 7.c: Dust motes attached to various objects

- Dust motes may be used in places where wired sensors are unusable or may lead to errors. Example: Instrumentation of semiconductor processing chambers, wind tunnels, rotating machinery etc.
- May be used in biological research example: to monitor movements & internal processes of insects.

Figure 7.d: Biological applications of Smart Dust

- Smart Contacts

The idea of "smart contact" lenses, the kind that can superimpose information on the wearer's field of view has been around for a while. But contact lenses are also being developed that use embedded sensors and electronics to monitor disease and dispense drugs. Such devices may eventually be able to measure the level of cholesterol or alcohol in your blood and flash up an appropriate warning.

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By adding tiny light-emitting elements to contact lenses, it is becoming possible to map digital images directly onto the wearer's field of vision to create a heads-up display or augmented-reality overlay that requires no glasses, screen or headset. The first iteration of smart contact lenses is already on the market. The Triggerfish, created by Sensimed, a spin-off from the Swiss Federal Institute of Technology in Lausanne, is a wirelessly powered contact lens designed to help people with glaucoma manage their treatment. It does this by continuously measuring the curvature of the eye over a 24-hour period using a tiny strain gauge, built using micro-electromechanical system (MEMS) technology, which is incorporated into the lens.

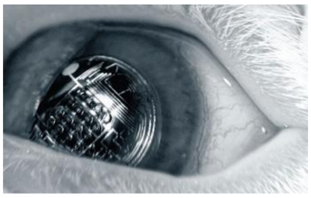

Figure 7.e: Smart Contacts

8. FUTIRE TRENDS

How far they have been implemented

1. The optical receiver for the smart dust project is being developed. The receiver senses incoming laser transmissions at up to 1Mbit/s, for a power consumption of 12µW. Although this is too high for continuous use in smart dust, it is a reasonable figure for the download of small amounts of data such as a 1Kbit program.
2. For data transmission, the team is using corner cube retro-reflectors (CCRs) built using MEMS techniques. CCRs are produced by placing three mirrors at right angles to each other to form the corner of a box that has been silvered inside. The key property of a CCR is that light entering it is reflected back along the path it entered on. For the smart dust system, the CCR is being built on a MEMS process with the two vertical sides being assembled by hand. When a light is shone into the CCR, it reflects back to the sending position. By modulating the position of one of the mirrors, the reflected beam can be modulated, producing a low-energy passive transmission.
3. The analog-digital convertor (ADC) the 8bit ADC has so far demonstrated with an input range of 1V, equal to the power supply, and a 70kHz sampling rate. The converter draws 1.8µW when sampling at that rate, or 27pJ for an 8bit sample.
4. The latest smart dust mote, with a volume of just 16cu mm, has been tested. It takes samples from a photo-detector, transmits their values with the CCR and runs off solar cells. So smart dust is on the way.

9 ADVANTAGES AND DISADVANTAGES

Advantages:

- Dramatically reducing system and infrastructure costs increasing productivity improving safety and compliance
- Takes into consideration the needs of the crop, therefore there is a better fertilization management.
- It gives farmers a better management of time.
- Better for the environment.
- Reduction of inputs and Increase of outputs = Increase in productivity.

Disadvantages:

- Privacy issues
- High cost
- Adverse use of technology
- Environmental problems

10. CONCLUSION

Smart dust is made up of thousands of sand-grain-sized sensors that can measure ambient light and temperature. The sensors each one is called a "mote" which has wireless communications devices attached to them, and if you put a bunch of them near each other, they'll network themselves automatically. These sensors, which would cost pennies each if mass-produced, could be plastered all over office buildings and homes. Each room in an office building might have a hundred or even a thousand light- and temperature-sensing motes, all of which would tie into a central computer that regulates energy usage in the building. Taken together, the motes would constitute a huge sensor network of smart dust, a network that would give engineers insight into how energy is used and how it can be conserved. In a dust-enabled building, computers would turn off lights and climate control in empty rooms. During peak energy usage times, air conditioners that cool servers -- which drain a lot of the tech world's power would be automatically shut off, and then turned on again if the servers get too hot. Thus it can very lead to world's energy conservation solutions. Research in the wireless sensor network area is growing rapidly in both academia and industry. Most major universities and many companies now have sensor networking projects, and some products are appearing on the market. Innovative research includes short-range micro power radio, energy scavenging from thermal gradients and vibration, operating systems, networking and signal processing algorithms, and applications. While the raw power of future computing environments will enable more massive and amazing hardware and software networks, a growing community will be pushing the limits on the lower end, building smaller hardware and writing

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