SMART DUST

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1 author:

Anilkumar C. Suthar
Engineering & Technology (LJ Group of Institutes) ,Gujarat,India

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Smart Dust technology makes it possible to harness the processing power of an IBM desktop computer of 15 years ago in a matchbox-sized machine. We review the key elements of the emergent technology of "Smart Dust" and outline the research challenges they present to the mobile networking and systems community, which must provide coherent connectivity to large numbers of mobile network nodes co-located within a small volume.

PROF. A. C. SUTHAR

In the high-tech industry, less has always been valued as more. That is, the smaller the computational device, the better. Large-scale networks of wireless sensors are becoming an active topic of research. Advances in hardware technology and engineering design have led to dramatic reductions in size, power consumption and cost for digital circuitry, wireless communications and Micro Electro-Mechanical Systems (MEMS). This has enabled very compact, autonomous and mobile nodes, each containing one or more sensors, computation and communication capabilities, and a power supply. The missing ingredient is the networking and applications layers needed to harness this revolutionary capability into a complete system.

History

Smart Dust is the brainchild of Associate Professor Kris Pister and Professor Randy H. Katz, who are currently working out of the University of California, Berkeley. It relies on the convergence of three technologies: digital circuitry, laser-driven wireless communications, and something called MEMS (Micro ElectroMechanical Systems) to pack enough equipment into a space no more than one or two cubic millimeters in size.

Smart dust is the logical product of the ever-decreasing size of electronic equipment. It is now quite possible to harness the processing power of an IBM desktop computer of 15 years ago in a matchbox-sized machine.

Generation of Smart Dust Motes

- Golem motes :Golem motes are solar powered motes with bi-directional communications and

Fig. 1.

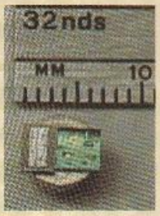

Fig. 2.

Fig. 3.

sensing (acceleration and ambient light).These were having 11.7 mm^3 total circumscribed volume and ~4.8 mm^3 total displaced volume.

- Flashy motes: Flashy motes were 138 mm3 uni-directional communication and sensing (ambient light) mote .
- Draft motes

What is Smart Dust ?

"Smart dust" devices are tiny wireless microelectromechanical sensors (MEMS) that can detect everything from light to vibrations. Thanks to recent breakthroughs in silicon and fabrication techniques, these "motes" could eventually be the size of a grain of sand, though each would contain sensors, computing circuits, bidirectional wireless communications technology and a power supply. Motes would gather scads of data, run computations and communicate that information using two-way band radio between motes at distances approaching 1,000 feet .

A Smart Dust mote is illustrated in Figure. Integrated into a single package are MEMS sensors, a semiconductor laser diode and MEMS beam-steering mirror for active optical transmission, a MEMS corner-cube retroreflector for passive optical transmission, an optical receiver, signal-processing and control circuitry, and a power source based on thick-film batteries and solar cells. This remarkable package has the ability to sense and communicate, and is self-powered!

A major challenge is to incorporate all these functions while maintaining very low power consumption, thereby maximizing operating life given the limited volume available for energy storage. Within the design goal of a cubic millimeter volume, using the best available battery technology, the total stored energy is on the order of 1 Joule. If this energy is consumed continuously over a day, the dust mote power consumption cannot exceed roughly 10 microwatts. The functionality envisioned for Smart Dust can be achieved only if the total power consumption of a dust mote is limited to microwatt levels, and if careful power management strategies are utilized (i.e., the various parts of the dust mote are powered on only when necessary). To enable dust motes to function over the span of days, solar cells could be employed to scavenge as much energy as possible when the sun shines (roughly 1 Joule per day) or when room lights are turned on (about 1 millijoule per day). Techniques for performing sensing and processing at low power are reasonably well understood. Developing a communications architecture for ultra-low-power represents a more critical challenge. The primary candidate communication technologies are based on radio frequency (RF) or optical transmission techniques.

Each technique has its advantages and disadvantages. RF presents a problem because dust motes offer very limited space for antennas, thereby demanding extremely short-wavelength (i.e., high- frequency) transmission. Communication in this regime is not currently compatible with low power operation. Furthermore, radio transceivers are relatively complex circuits, making it difficult to reduce their power consumption to the required microwatt levels. They require modulation, bandpass filtering and demodulation circuitry, and additional circuitry is required if the transmissions of a large number of dust motes are to be multiplexed using time-, frequency- or code-division multiple access. An attractive alternative is to employ free-space optical transmission. Kahn and Pister's studies have shown that when a line-of-sight path is available, well-designed freespace optical links require significantly lower energy per bit than their RF counterparts.

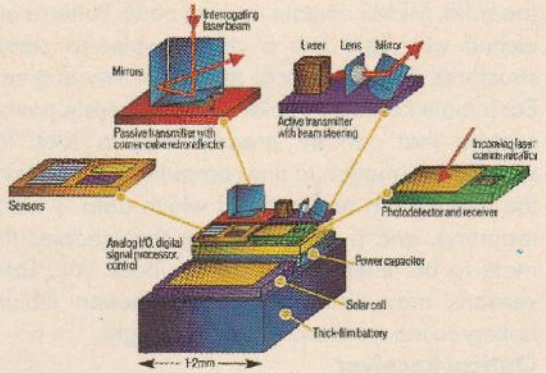

Fig. 4. Smart dust mote, containing microfabricated sensors, optical receiver, passive and active optical transmitters, signal-processing and control circuitry, and power sources

There are several reasons for the power advantage of optical links. Optical transceivers require only simple baseband analog and digital circuitry; no modulators, active bandpass filters or demodulators are needed. The short wavelength of visible or near-infrared light (of the order of 1 micron) makes it possible for a millimeter-scale device to emit a narrow beam (i.e., high antenna gain can be achieved). As another consequence of this short wavelength, a base-station transceiver (BTS) equipped with a compact imaging receiver can decode the simultaneous transmissions from a large number of dust motes at different locations within the receiver field of view, which is a form of space-division multiplexing. Successful decoding of these simultaneous transmissions requires that dust motes not block one another's line of sight to the BTS. Such blockage is unlikely, in view of the dust motes' small size. A second requirement for decoding of simultaneous transmission is that the images of different dust motes be formed on different pixels in the BTS imaging receiver. To get a feeling for the required receiver resolution, consider the following example. Suppose that the BTS views a 17 meter by 17 meter area containing Smart Dust, and that it uses a high-speed video camera with a very modest 256 by 256 pixel imaging array.

Architecture of Smart Dust

Each mote of smart dust is composed of a number of microelectromechanical systems, or MEMS, wired together to form a simple computer. MEMS are made using the same photolithographic techniques used to make computer chips. Once perfected, they are relatively easy and inexpensive to mass-produce. But unlike computer chips, which are solid, MEMS contain moving parts. Patterns are etched with light into a silicon wafer to create structures such as optical mirrors or tiny engines. Each mote contains a solar cell to generate power, sensors that can be programmed to look for specific information, a tiny computer that can store the information and sort out which data is worth reporting, and a communicator that enables the mote to be "interrogated" by the base unit. Later versions may also contain a lilliputian lithium battery so the motes can operate at night.

Optical Receiver

The optical receiver for the smart dust project is being developed by Brian Leibowitz, a student at the University of California. The receiver senses incoming laser transmissions at up to 1 Mbit/s, for a power consumption of 12μW.

CCR (Corner Cube Retro-Reflector)

Corner cube retro-reflectors (CCRs) are 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.

Structure is a corner-cube retroreflector, or CCR. It comprises three mutually perpendicular mirrors of gold-coated polysilicon. The CCR has the property that any incident ray of light is reflected back to the source (provided that it is incident within a certain range of angles centered about the cube's body diagonal). If one of the mirrors is misaligned, this retroreflection property is spoiled. The microfabricated CCR includes an electrostatic actuator that can deflect one of the mirrors at kilohertz rates. It has been demonstrated that a CCR illuminated by an external light source can transmit back a modulated signal at kilobits per second. Since the dust mote itself does not emit light, the passive transmitter consumes little power. 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.

BTS

Successful decoding of these simultaneous transmissions requires that dust motes not block one another's line of sight to the BTS. Such blockage is unlikely, in view of the dust motes' small size. A second requirement for decoding of simultaneous transmission is that the images of different dust motes be formed on different pixels in the BTS imaging receiver. To get a feeling for the required receiver resolution, consider the following example. Suppose that the BTS views a 17 meter by 17 meter area containing Smart Dust, and that it uses a high-speed video camera.

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Suppose that the BTS views a 17 meter by 17 meter area containing Smart Dust, and that it uses a high-speed video camera with a very modest 256 by 256 pixel imaging array. Each pixel views an area about 6.6 centimeters square. Hence, simultaneous transmissions can be decoded as long as the dust motes are separated by a distance roughly the size of a pack of cigarettes.

The BTS contains a laser whose beam illuminates an area containing dust motes. This beam can be modulated with downlink data, including commands to wake up and query the dust motes. When the illuminating beam is not modulated, the dust motes can use their CCRs to transmit uplink data back to the base station. A high-frame-rate CCD video camera at the BTS "sees" these CCR signals as lights blinking on and off. It decodes these blinking images to yield the uplink data. Kahn and Pister's analysis show that this uplink scheme achieves several kilobits per second over hundreds of meters in full sunlight .

At night, in clear, still air, the range should extend to several kilometers. Because the camera uses an imaging process to separate the simultaneous transmissions from dust motes at different locations, we say that it uses space-division multiplexing. The ability for a video camera to resolve these transmissions is a consequence of the short wavelength of visible or near-infrared light. This does not require any coordination among the dust motes, and thus, it does not complicate their design.

Multi-Sensor Emergent

It is useful for sensors to operate in ensembles. Rather than implementing a broad range of sensors in a single integrated circuit, it is possible to simply deploy a mixture of different sensors in a given geographical area and allow them to self organize. Sensors are typically specialized to detect certain signatures. One kind detects motion, another heat, and a third sound. When one sensor detects its critical event signature, it makes other nearby sensors aware of its detection. They then orient their sensing function in a particular, signature specific way.

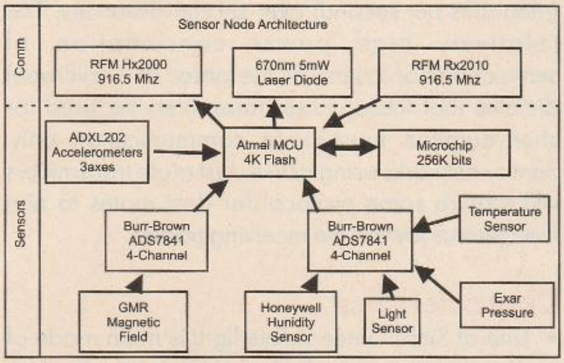

Fig. 5.

For example, a simple motion-detecting sensor might cue more sophisticated sensors detecting thermal or other radiation properties. The array, acting as an ensemble, not only performs the operation of detecting an intruder, but demonstrates more intelligent processing, by distinguishing between one that is a human and another that is a small animal (e.g., the former has a body heat signature spread over a larger volume than the latter).

A more complex sensor cued in this fashion may then increase its own scan rate to obtain a higher-resolution signature, or dedicate its detection energy budget into a particular narrow band or a specific direction. These operations have implications for power consumption. Maximizing detection protection probability and resolution while minimizing power consumption is a key optimization challenge.

Micro-electromechanical Systems and Nanotechnology

The integration of mechanical structures (moving parts) with microelectronics. MEMS devices are "custom" designed for a purpose which requires a mechanical action to be controlled by a computer. The branch of engineering that deals with things smaller than 100 nanometers(especially with the manipulation of individual molecules).

How it Works ?

The sensors -- each one is called a "mote" -- have wireless communications devices attached to them, and if you put a bunch of them near each other, they'll network themselves automatically.

The way the particles operate is as follows:

- Each mote of smart dust is composed of a number of microelectromechanical systems, or MEMS, wired together to form a simple computer.
- MEMS are made using the same photolithographic techniques used to make computer chips. Once perfected, they are relatively easy and inexpensive to mass-produce. But unlike computer chips, which are solid, MEMS contain moving parts.
- Patterns are etched with light into a silicon wafer to create structures such as optical mirrors or tiny engines. Each mote contains a solar cell to generate power, sensors that can be programmed to look for specific information, a tiny computer that can store the information and sort out which data is worth reporting, and a communicator that enables the mote to be "interrogated" by the base unit.

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 looks for an incoming 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 retroreflector or the laser diode, depending on which it has. The corner cube retroreflector 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.

CCR-based passive optical links require an uninterrupted line-of-sight path. Moreover, a CCR-based passive transmitter is inherently directional; a CCR can transmit to the BTS only when the CCR body diagonal happens to point directly toward the BTS, within a few tens of degrees. A passive transmitter can be made more omni directional by employing several CCRs oriented in different directions, at the expense of increased dust mote size.

If a dust mote employs only one or a few CCRs, the lack of omni directional transmission has important implications for feasible network routing strategies a free-space optical network utilizing the CCR-based passive uplink. The BTS contains a laser whose beam illuminates an area containing dust motes. This beam can be modulated with downlink data, including commands to wake up and query the dust motes. When the illuminating beam is not modulated, the dust motes can use their CCRs to transmit uplink data back to the base station. A high-frame-rate CCD video camera at the BTS "sees" these CCR signals as lights blinking on and off. It decodes these blinking images to yield the uplink data. Analysis show that this uplink scheme achieves several kilobits per second over hundreds of meters in full sunlight. At night, in clear, still air, the range should extend to several kilometers. Because the camera uses an imaging process to separate the simultaneous transmissions from dust motes at different locations, we say that it uses space-division multiplexing.

When the application requires dust motes to use active optical transmitters, MEMS technology can be used to assemble a semiconductor laser, a collimating lens and a beam-steering micro-mirror, as shown in figure4. Active transmitters make possible peer-to-peer communication between dust motes, provided there exists a line-of-sight path between them. Power consumption imposes a trade-off between bandwidth and range. The dust motes can communication over longer ranges (tens of kilometers) at low data rates or higher bit rates (megabits per second) over shorter distances. The relatively high power consumption of semiconductor lasers (of the order of 1 milliwatt) dictates that these active transmitters be used for short-duration burst-mode communication only. Sensor networks using active dust mote transmitters will require some protocol for dust motes to aim their beams toward the receiving parties.

Characteristics

- Line of Sight: Since visible light is main mode of communication, thus line of sight is required for data transmission and receiving.
- Optical Communication: Using the Optical Communication is best as comparative to other technologies like infra red technology since it allows the devices to utilizes less power and do the work more efficiently.
- Low power consumption: Power consumption imposes a trade-off between bandwidth and range. Smart dust can "scavenge" energy to make themselves run longer. This includes drawing off the ambient vibration energy generated by an industrial machine or gathering energy from low levels of light.
- Data bit rate(1Mbit/s): The dust motes can mmunication over longer ranges (tens of kilometers) at low data rates or higher bit rates (megabits per second) over shorter distances.
- Intelligent motes: With clever power management techniques, each mote should be able to stay active for several days. The challenge is to ensure that motes distributed in a space can communicate with each other and with a base station called a base-station transceiver (BTS) equipped with a compact imaging sensor.
- Cost: The cost of motes has been dropping steadily. Prices range from $50 to $100 each today, and it is anticipated that they will fall to $1 within five years.
- Logical memory: The motes have a capability of storing upto 1000000 measurements .

How Smart Dust can be released effectively ?

The biggest obstacle right now is the question of how to release the "smart dust" effectively. The most current idea "involves the use of tiny, unmanned aircraft that would spray motes over an area like a miniature crop duster and relay the resulting information back to a base station." One company based in Silicon Valley is already hard at work developing such an aircraft.

Fig. 6.

How to Prepare Smart Dust?

In 1999, a device sent weather information by laser 10 miles from Coit Tower in San Francisco to the Berkeley office of scientist Dr. Pister (Eisenberg, 1999). This marked the beginnings of smart dust. It is a sensor, computer, and communicator rolled

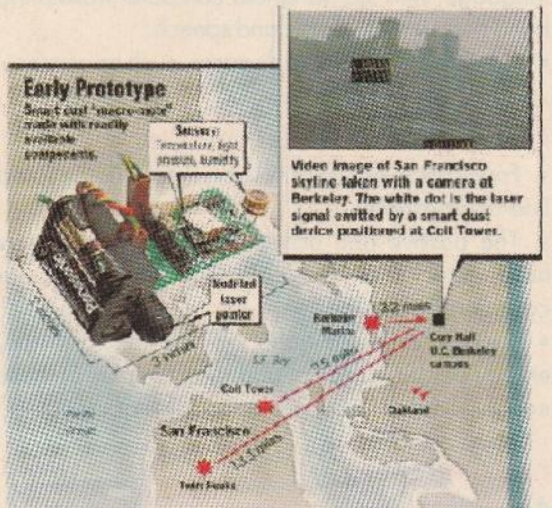

Fig. 7. Laser information send by smart dust from Coit Tower

into a tiny speck. Scientists are creating micro-machines capable of assessing their surroundings, processing information, and relaying to one another. When hundreds are released, smart dust offers a powerful network.

The goal was to create a device that is:

• Minute and airborne: The ideal would was to miniaturize the prototypes down to 1mm2 and 10 microns thick - about 1/10 the diameter of human hair

• Affordable: To economically deploy hundreds of them, creators hope to minimize the costs of each mote, perhaps for as little as 10 cents each. Prototypes currently cost $100 each.

• Energy efficient: Solar energy and batteries now power these motes. To help solve energy costs concerns, engineers intend to create self-powered versions.

• Smart dust represents a combination of digital circuitry, wireless communications, and Micro Electro Mechanical Systems (MEMS). Scientists aren't restricting the types of sensors installed in the motes, except that it is operable by minimal power. Various sensors such as acoustic, vibration, and magnetic sensors could be added.

• Presently, smart dust research faces several obstacles. Providing a power source for something this small is a challenge; a dust mote cannot consume more than microwatt levels. Packing in all the bulk of different technologies to operate a tiny speck makes it difficult as well.

• While it can be created for different purposes (see what smart dust can do), smart dust is of special interest for military use. These devices are expected to significantly impact warfare not only because of its high tech capabilities to gather data. When it is deployed out in the field -- perhaps by micro air vehicles -- it takes the place of military personnel.

Therefore, smart dust will likely be used for military purposes first. After all, the U.S. Defense Advanced Research Projects Agency (DARPA) provided funding of 1.5 million for Smart Dust's project. But eventually, it is expected to be in the market as well. It supplies universities, military, and civil research facilities and businesses for avionics an inch diameter version of the motes. A $950.00 starter kit contains three sensors and a personal computer interface board.

Advantages of Smart Dust

• From User's point of view there are three major advantages

• You do not have to keep track of various motes. The BTS senses where they are present in its locality and other motes keep track by sending and receiving the signals.

• Its cost has been decreasing amazingly from $ 100 to $ 50 and after few years shall be within $ 1.

• You don't have to think about it Smart dust motes find each other and establish communication without any user input.

• Less power consumption, Power consumption imposes a trade-off between bandwidth and range. Smart dust can "scavenge" energy to make themselves run longer. This includes drawing off the ambient vibration energy generated by an industrial machine or gathering energy from low levels of light.

• These Smart mote kits are available for commercial purposes widely in for of the kits which is distributed according to the functionality they perform.

• Can be customized according to its application i. e. the respective functioning sensors can be used according to the work that they have to perform. For example in case of sensing temperature, vibrations etc the smart dust mote will contain that type of sensor.

Practical Examples

The science/engineering goal of the Smart Dust project is to demonstrate that a complete sensor/communication system can be integrated into a cubic millimeter package. This involves both evolutionary and revolutionary advances in miniaturization, integration, and energy management. Here's a sampling of some possible applications, in no particular order:

• Defense-related sensor networks : Battlefield surveillance, treaty monitoring, transportation monitoring, scud hunting.

• 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. QWERTY is the first step to proving the concept, but you can imagine much more useful and creative ways to interface to your computer if it knows where your fingers are: sculpt 3D shapes in virtual clay, play the piano, gesture in sign language and have to computer translate.

• Inventory Control : The carton talks to the box, the box talks to the palette, the palette talks to the truck, and the truck talks to the warehouse, and the truck and the warehouse talk to the internet. Know where your products are and what shape they're in any time, anywhere. Sort of like FedEx tracking on steroids for all products in your production stream from raw materials to delivered goods.

• Product quality monitoring : temperature, humidity monitoring of meat, produce, dairy products , impact, vibration, temp monitoring of consumer electronics.

• 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. No more fighting with your office mates over the thermostat.

Engineers also envision other uses for the Smart Dust project, including:

• Monitoring humidity and temperature to assess the freshness of foods stored in the refrigerator or cupboard.

• Monitoring quadriplegics' eye movements and facial gestures and to assist them in operating a wheelchair or using computational devices.

• Communicating with a handheld computer for games and other forms of entertainment. A user could attach the sensors to his or her fingers to "sculpt" 3D shapes in virtual clay visible on the device's screen. The same idea could be applied to playing the piano or communicating in sign language, with the handheld computer translating hand gestures into music and speech.

• Detecting the onset of diseases, such as cancer.

Limitations and Disadvantages

• Free space optical links requires uninterrupted line-of-sight paths

• The passive and active dust mote transmitters have directional characteristics that must be considered in design.

• There are severe trade offs between bit rate, energy per bit, distance and directionality in these energy - limited free space optical line of sight.

About the author:

A. C. Suthar

Asst. Professor, Electronics & Comm. Dept.

C. U. Shah College of Engg. & Tech.