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Smart Dust Technologies

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Abstract This paper is a review of smart dust technologies. The work discussed the smart dust technology, its components and different areas of applications of the smart dust technology to encourage its widespread use, especially in wireless sensor networks. The work also identified some of the current challenges preventing its widespread use. Smart dust has numerous remarkable applications in almost all fields of science and engineering. Research in wireless sensor networks is geared towards producing compact devices that consume minimal power while having functionalities such as sensing, computing, and communication capabilities. The tiny size of smart dust makes it suitable for this and other novel applications. The areas of applications identified in this work include space, traffic monitoring and control, health and wellness monitoring, military applications, environmental monitoring, and IoT to mention a few. Research is encouraged towards mitigating the identified challenges especially in the area of power consumption and security.

Keywords wireless sensor networks (WSN), MEMS, Motes, Smart dust, retroreflector

Introduction

Computing history has been characterized by the need to decrease computing device size, increase connectivity, and enhance interaction with the physical world. 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 research [1]. In the advancing technology industry, less has always been valued as more [2-3]. That is, the smaller the tech device, the better. Hence, the continued search towards miniaturization of tech devices. Advances in wireless communications and microelectronic mechanical system technologies have enabled the development of networks of a large number of small inexpensive low-power, multifunctional sensors [4]. A sensor network is designed to detect events or phenomena, collect and process data, and transmit sensed information to interested users.

Progressive advancement in wireless communications and microelectronic mechanical system technologies has enabled the design of networks of a high number of minute low-cost, low-power, multifunctional sensors. These networks nicknamed "Smart Dust" present a very fascinating and challenging area and have numerous potential applications. Research and commercialization of wireless sensor networks are growing exponentially. This drive is towards the production of affordable minute hi-tech devices with the capabilities of sensing, wireless communication, sustained autonomous power supply within a compact structure. Wireless sensor networks consist of a large number of sensor nodes that may be deployed randomly and densely.

Many researchers have proven that it is feasible to combine sensing, communication, and power supply into an inch-scale device using only off-the-shelf technology [2]. This drastic reduction in size, power consumption, and cost for digital circuitry is aided by the advances in hardware technology and engineering design brought about by the active research into large-scale networks of wireless sensors. Digital circuitry, wireless communication, and micro Electro-Mechanical Systems are three technologies that greatly enabled compact, autonomous nodes, having sensing, computation, and communication capabilities and a power supply.

The term Smart Dust coined in 1997 was a research proposal to DARPA written by Kris Pister, Joe Kahn, and Bernhard Boser, all from the University of California, Berkeley, to examine whether autonomous sensing, computing, and communication system can be packed into a cubic-millimeter mote (a small particle or speck) to form the basis of integrated, massively distributed sensor networks [5-6]. A Distributed sensor network can consist of hundreds to thousands of dust motes and one or more interrogating transceivers. Each of these dust motes consists of a power supply, a sensor or sensors, analog and digital circuitry, and a system for receiving and transmitting data. The size of a dust mote may vary from $1mm^3$ to as large as a sugar cube depending on whether the source of power is a solar cell, thick-film battery, or commercially available battery.

Smart Dust will engender innovative ways of interacting with the environment, providing more information from more places less intrusively, combining both evolutionary and revolutionary advances in miniaturization, integration, and energy management. The goal of this paper is to present some of the technological opportunities and challenges of smart dust technology to capture the interest of systems-level researchers in this critical area.

MEMS Technology

Smart dust requires revolutionary advances in miniaturization, integration, and energy management [7]. To this end, micro-electromechanical systems (MEMS) technology is used by designers to build small sensors, optical communication components, and power supplies. Made in the same way as computer chips, MEMS consists of extremely tiny mechanical elements, often integrated with electronic circuitry. The smart dust mote is an integrated single package of MEMS sensors, a semiconductor laser diode and MEMS beam-steering mirror for active optical transmission, a MEMS corner-cube retro-reflector for passive optical transmission, an optical receiver, signal processing, and control circuitry, and a power source based on thick film batteries and solar cells. A key constraint in the design of the mote owing to its size is energy management. Consumption of the most minimum energy is necessary to drive the circuits and MEMS devices. Confining the entire mote within a $1mm^3$ volume, the energy density of the power supply is the principal concern. The potential of the smart dust is attained when the sensor nodes communicate with one another or with a central base station. There are different options for communicating to and from a cubic millimeter computer.

The Smart Dust

Smart Dust is millimeter-scale sensing and communication platform [8]. It was described that Smart dust as an assemblage of small sensor-equipped leaves with the ability to send information to two or more receivers. According to Arief et al [9] Smart dust is a network of micro-electro-mechanical devices (also known as *motes*), which are typically composed of a processing unit, some memory, and a radio chip, which allows them to communicate wirelessly with other smart dust devices within range. In the words of Quart et al [10] a Smart Dust is a Femto-spacecraft with an external surface coated with electrochromic material, which exploits the solar radiation pressure to produce a propulsive acceleration. It can also be seen as a propellant-less Femto-satellite, with a characteristic side length of a few millimeters and a high value of its area-to-mass ratio. It exploits the solar radiation pressure to create a propulsive acceleration sufficient enough to substantially affect its orbital dynamics [11]. It is a huge network that contains several wireless portable mobile smart dust nodes which animatedly broadcast information amongst themselves without dependence on a base station [12].

Smart Dust is an autonomous or self-contained network of tiny sensors called motes, each with the ability to sense and monitor environmental conditions. The motes have computational ability and can communicate with base stations or with other motes depending on their application. Signal transmission is carried out by microscopic devices called Micro Electromechanical Systems (MEMS). Smart dust combines sensing, computing, wireless communication, and autonomous power supply within a volume of only a few millimeters. The smart dust mote as illustrated in figure 1 is a single package integration of 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.

As tiny wireless Microelectromechanical sensors (MEMS), Smart Dust can detect everything from light to vibrations. It consists of hundreds to thousands of dust motes networked wirelessly and each containing the ability to sense and monitor environmental conditions and communication with other devices. Sensor nodes are minute electronic components capable of sensing many types of information from the environment including temperature, light, humidity, radiation, the presence or nature of biological organisms, geological features, seismic vibrations, specific types of computer data, and more. These nodes are small in size and have the ability to gather, process, and communicate information to other nodes and the outside world. Smart Dust nodes can be highly mobile, since nodes are small enough to be moved by winds or even to remain suspended in air, buoyed by air currents.

Smart Dust Components

The components of smart dust include:

1. **Sensor**: Depending on the mission to be achieved, a variety of sensors, including light, temperature, vibration, magnetic field, acoustic, and wind shear, can be integrated into the mote. Sensors collect information from the environment such as light, sound, temperature, chemical composition, etc. An integrated circuit will provide sensor signal processing, communication control, data storage, and energy management. A photodiode allows for optical data reception while two transmission schemes, passive transmission using a corner-cube retroreflector (CCR) and active transmission using a laser diode and steerable mirrors are explored.
2. **Corner Cube Retro-reflector (CCR):** A corner cube retroreflector is an optical component with the rare ability to reflect and return an incident beam of light to its originating point regardless of the beams angle of entry, provided that it is incident within a certain range of angles centered about the cube's body diagonal at kilobits per second. It has been designed as an optical passive transmitter in wireless optical communication with low power consumption (Park & Park, 2013). Not having a light source,(that is, does not emit light) the CCR can transmit the data to the source by the digitally modulated reflection of the incident light. This passive optical transmission technique which is the transmission of modulated optical signals without supplying any optical power is carried out by the CCR. The CCR enables mote to base station transmission, that is, to the BTS only when the CCR body diagonal happens to point directly toward the BTS, within a few tens of degrees. It is pertinent to emphasize that the CCR-based passive optical links require an uninterrupted line-of-sight path. The CCR is made up of three mutually perpendicular mirrors of gold-coated polysilicon. If any of the mirrors is misaligned, this retroreflection property is damaged. The microfabricated CCR includes an electrostatic actuator that can deflect one of the mirrors at kilohertz rates.
3. **Laser diode and Steerable mirrors:** If the application requires dust motes to use active optical transmitters, MEMS technology is used to assemble a semiconductor laser, a collimating lens, and a beam-steering micro-mirror, as shown in Figure 1. 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. Active transmitters make peer-to-peer communication between dust motes possible, provided there exists a line-of-sight path between them. Power consumption imposes a trade-off between bandwidth and range. The dust motes can communicate 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.
4. **An optical receiver** (a photodiode) which allows for optical data reception, signal processing, and control circuitry consisting of an analog I/O, Digital Signal Processors (DSPs) to control and process the incoming data and a power source based on thick film batteries and solar cells with a charge integrating capacitor for a period of darkness.

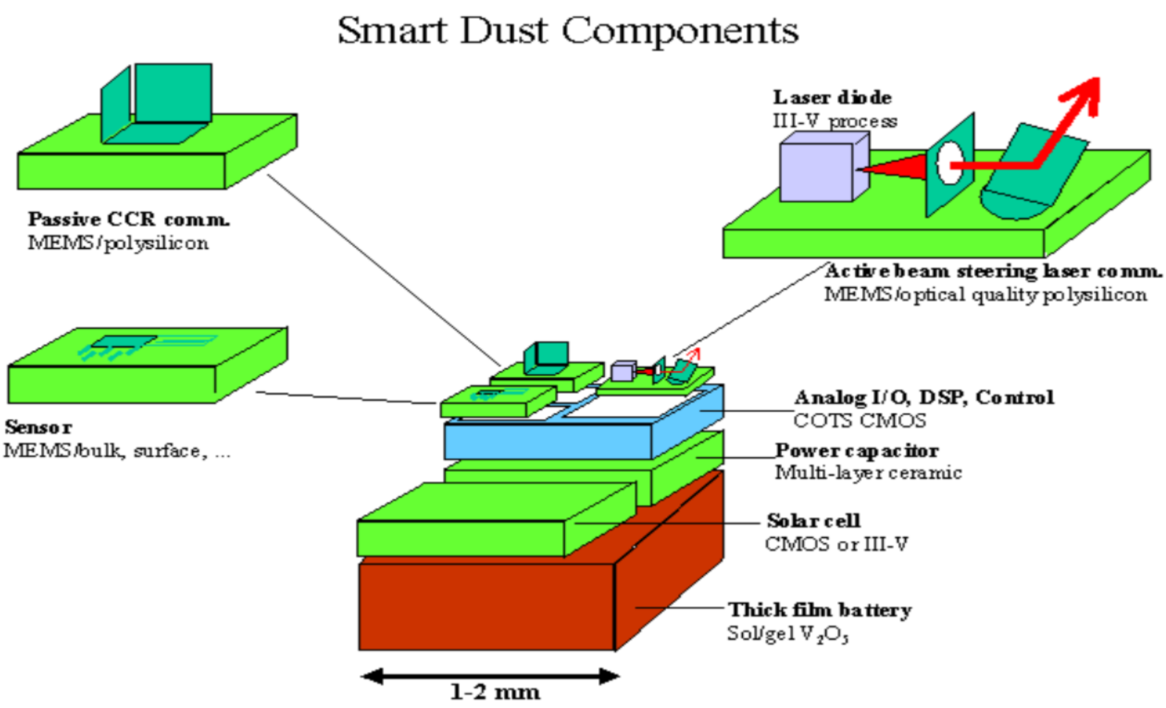

Figure 1: Conceptual Diagram of the Smart Dust Mote [13]

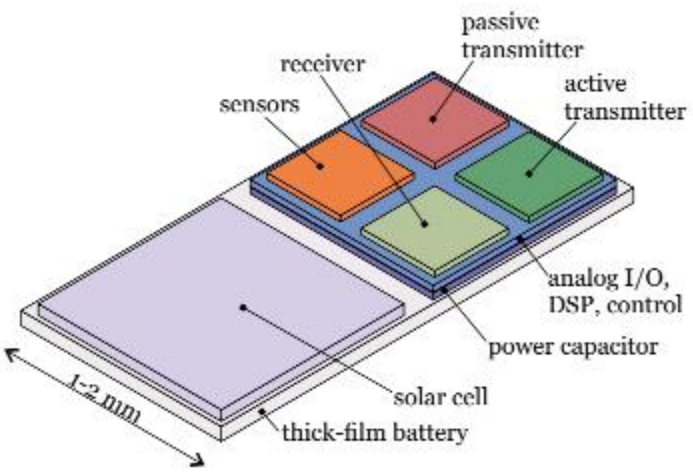

Figure 2: Schematic diagram of Smart dust concept [11]

Figure 3: Dust family [14]

Figure 3 shows the different generations of Smart Dust sensor nodes (Motes). The left picture is a 1st generation smart dust sensor node "Rene Mote". From left to right, the right picture shows the "MICA Mote" (2nd generation), "MICA2 Mote" (3rd generation), and "MICA2-Dot Mote (3rd generation)".

Applications of Smart Dust Technologies

The envisioned dust-grain size of Smart Dust nodes has several important implications concerning their hardware design [15]. As a result of its tiny size, Smart Dust will enable several novel applications. Smart Dust nodes can be moved by winds and suspended in air, thus supporting better monitoring of weather conditions, air quality, and many other phenomena. Some applications of smart dust technology include:

1. It can be used for tracking the location of real-world phenomena using a remote-controlled toy car as a sample target. It can be used for target location estimation, node localization, time synchronization, and message ordering that match the requirements of Smart Dust. Since target location estimation is solely based on detecting the proximity of the target by individual Smart Dust nodes, the presented tracking system should apply to a wide range of possible target types [15].
2. It can be used for vehicle detection and tracking. The Smart Dust is one of the potential sensor nodes which can be used in vehicle detection systems in the future. The essential components of the vehicle detection system in smart dust node include a processor, sensor, and radio, whose integration into minute size through MEMS technology and in addition to its low power design is suitable for implementing the vehicle detection sensor networks [14].
3. Smart-Dust sensor nodes can be potentially used in a wide range of applications such as enemy monitoring on the battlefield, temperature measurement in a building, environmental monitoring, etc. [14].
4. It can be applied in the Intelligent Transportation system (ITS). In the work (Arief et al, [9]), several ITS applications involving smart dust, in collaboration with other sensing technologies used in the TRACKSS project were designed and developed. As the unit cost of motes, which is perceived as the low-cost, ubiquitous sensor of the future continues to go down, it will become financially feasible to deploy them in large numbers. According to the authors, smart dust technology will eventually offer a steep change in how we manage, sense, and operate our transport networks of the future.
5. The addition of gravitational perturbations to the astro-dynamical models of smart dust allows much larger eccentricities in the solutions of equilibrium orbits (when AMR _ 32.6087 m2⁄kg, the maximum eccentricity allowed is 0.732) [6]. Using five representative points in their study of the long-term orbital evolution, it was discovered that there are long-term stable orbits, not only with small eccentricities, but also with large eccentricities, due to the influence of gravitational perturbations, solar radiation pressure, and drag
6. Sun-pointing Smart Dust provides a propulsive acceleration aligned with the Sun-spacecraft direction [10]. The sun-pointing smart dust is used in the scientific exploration of the Earth's magnetic tail [16].
7. Smart Dust satellites represent very low-cost alternatives to more conventional configurations. They can substantially reduce a spacecraft mass by substituting the system with a single integrated circuit and to realize new operational missions, for example with monitoring purposes, for space weather applications, and in support of interplanetary exploration [11]. Smart Dusts are especially attractive for distributed science missions since their architecture guarantees small costs, reasonable development efforts, system redundancy, and fault tolerance [11].
8. Smart dust can be used in varied applications, in addition to the excerpts from the different papers above. Smart dust can remain floating or suspended in the air for hours, can be moved in the direction of flow by air currents, pretty difficult to detect and harder to get rid of after deployment. These features make the smart dust applicable in traffic monitoring and redirecting, health and wellness monitoring (enter human bodies and check for physiological problems), seismic and structural monitoring, process and factory automation, security and tracking, and military applications (monitoring activities in inaccessible areas, accompany soldiers and alert them of any poisons or dangerous biological substances in the air).

Challenges of the Smart Dust Technology

Given the limited computing power of smart dust, smart dust IoT systems are much more vulnerable to security attacks. There is also the issue of the bottleneck phenomena in smart dust Internet of Things (IoT) systems which usually have a very large number of devices often deployed in hard-access areas making it difficult for the normal block chain to be used in a smart dust IoT environment. Park and Park [17-19] proposed a lightweight block chain scheme using Tree transformation that helps device authentication and data security in a secure smart dust IoT environment.

Smart Dust is more susceptible to diverse types of attacks and packet loss in the network due to its uniqueness of mobility in the air. To this end, Rajesh and Kiruba [12] proposed a novel, dynamic energy-efficient cluster-based secure routing system which identifies these challenges of attacks while discovering exact routing and malicious wares in smart dust nodes. The system proposed not only enhances security intensity but also energy, diminishes end-to-end delay, improves the delivery of a packet, reduces packet loss in the network, better secure routing, and intrusion identification. The design was structured as a dynamic hierarchy in which information is broadcasted from source to destination without any loss.

Size has been a major constraint in the design of smart dust motes. This has put a severe limitation on energy and its management. There is a conflict in incorporating the functionalities of smart dust such as sensing, computing, and communication in a miniature unit while maximizing operating life and yet consuming low power. These functionalities are only achievable if the total power consumption is limited to microwatt levels, which again is a challenge. Maintaining unfettered line of sight communication links is also an uphill task.

Conclusion

Innovative research in wireless sensor networks is pushing towards building smaller hardware architecture with enormous functionality at low power and cost. Smart dust presents a unique integrated tiny-sized single package wireless electronic component with the capability of sensing, computing, and communication. Small and light in weight, smart dust can remain suspended in the air like an ordinary dust particle, moved by air in the direction of airflow and deployed ubiquitously. It has numerous applications in space, traffic monitoring and control, health and wellness monitoring, military applications, environmental monitoring, IoT, and so on. Its implementation is however not without challenges. Size has been a major constraint in its design, thus putting a severe limitation on energy storage. More research is encouraged to take care of the challenges identified in this work.

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