BAA 97-43

SMART DUST

UC Berkeley, “other educational”

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Section IIA. Claims

Smart Dust: *millimeter scale sensing and communication platforms.*

We will develop and demonstrate a family of distributed sensor network systems. Each system will consist of one or more data receivers, and hundreds to thousands of sensor nodes.

Dust mote

Each sensor node (dust mote) will consist of:

- **Power supply** Solar cell array, thick film battery, or commercial hearing aid battery, individually or in combination.
- **Sensor(s)** One or more MEMS sensors chosen from the set including at least: vibration, temperature, barometric pressure, sound, light, magnetic field.
- **Circuits** Analog interface to the sensor, analog to digital conversion, RAM and PROM, plus digital sequencing and control circuitry.
- **Communication** Corner cube reflector (modulated retroreflector) and/or hybrid infrared laser diode for transmitting, photodiode for receiving.

These sensing elements will vary in size from 1 cubic millimeter for a mote with solar cells and thick film battery, down to 100 times thinner for a mote with just solar cell power, and up to as much as a sugar cube for units powered by commercially available batteries.

Sensing element **cost will vary from roughly $0.10 (ten cents) per node** to several dollars per node, mostly depending on the type of power supply (hearing aid batteries are expensive).

Data receiver

The data receiver will consist of a conventional optical system to collect the signals from hundreds or thousands of sensors simultaneously, a custom CMOS imaging chip to process the signals, and a display system to present the data. For communication

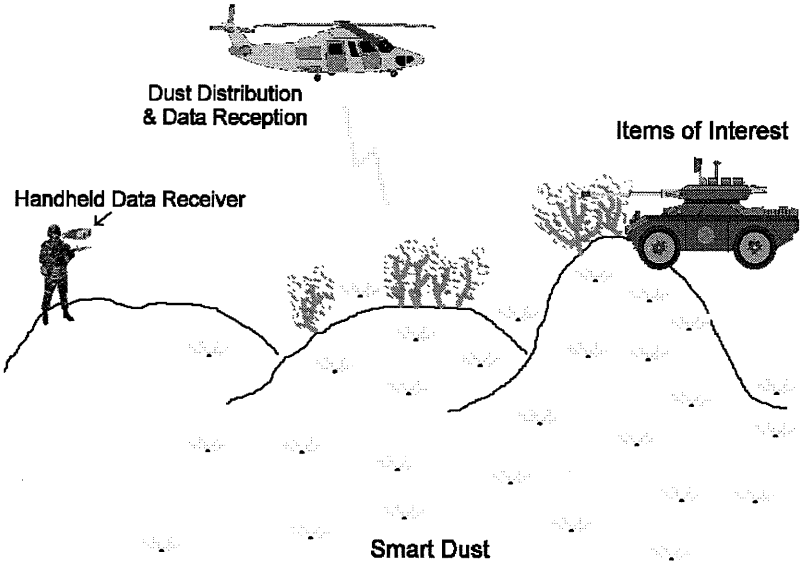

Figure 1: Primary deliverable: a battlefield sensor network. Thousands of sensor nodes covering square kilometers are delivered by autonomous helicopter. They track motion of vehicles for hours/days, and report information superimposed on live video when interrogated by hand-held receiver or helicopter borne receiver.

range up to a few hundred meters, **the entire receiver will be built into something the size of a pair of binoculars, with real-time sensor data from the dust motes superimposed on a real-time video image of the scene.**

For data reception over longer distances receiver systems weighing 10kg will be able to read the sensor data at distances of up to several tens of kilometers, allowing reception from by unmanned aerial vehicles (UAVs).

The heart of the data collection system is the custom CMOS imaging chip. We have already demonstrated parallel data transmission using conventional CCD imaging chips, but these chips are limited to rates of a few thousand frames per second with reasonable resolution. Data transmission rates are limited to at most half the frame rate. With active pixel CMOS imaging, local processing of the image can be done at each pixel, or in pixel neighborhoods, so that extremely high data rate signals from thousands of individual sensors can be collected by a single chip.

Applications

The following applications are suggested to demonstrate the technology. We are open to collaboration with all branches of the military and the commercial sector.

Military applications

With sensor motes containing acoustic, vibration, and magnetic field sensors it will be possible to cover many square miles of territory with a sensor network which will record the passage of any vehicle larger than a motorcycle, and report back a time history of all such vehicular traffic upon interrogation. Sensors could be delivered to the area by UAV, artillery, or broadcast like seed from a moving vehicle or vehicles. The network could be interrogated by MAV or by individual soldiers with modified binoculars. The sensor density required would be roughly 10,000 per square kilometer (ten meter average spacing), or in the range of thousands to tens of thousands of dollars per square kilometer.

Chem and bio sensors are beyond the scope of this work, but MEMS experts agree that these sensors will become increasingly available over the next few years. Once integrated into a Smart Dust system, these sensors will allow distant and early detection of chem and bio agents in combat. They could also be used to monitor pre-cursor chemical usage at and around fabrication facilities in countries such as Iraq. Again, dispersal and interrogation by UAV systems would be possible. Communication to 60km altitudes is possible, allowing interrogation of the system by high-flying spy planes, such as the U2.

Condition based maintenance

The sensors need not be distributed randomly. By careful placement of distributed sensors on critical parts of aircraft, ground vehicles, and manufacturing equipment, the lifetime and maintenance cost of these investments can be dramatically improved. Condition based maintenance has been a hot topic in the military and industry for years - MEMS technology gives us the possibility of implementing it on a grand scale.

We have chosen high cycle fatigue (HCF) of rotating compressor blades as a demonstration vehicle. The ability to instrument high speed rotating parts demonstrates the great potential of wireless microsensors, and HCF is chosen because it is a problem for both military aircraft and commercial compressor equipment. Currently, engine parts must be inspected for fatigue on a regular basis, with the period chosen to minimize the likelihood of failure before inspection. The ability to attach a sensor to a blade and measure the amplitude and number of cycles could be of great use in both reducing the amount of unnecessary maintenance that is performed as well as detecting surprise failures that occur before the next scheduled inspection. A major limitation in using sensing to help mitigate the risks and costs associated with high cycle fatigue is the difficulty of wiring sensors that are located on a rotating fan. In addition, vibration and acceleration levels can be quite high, causing difficulties for conventional electronics hardware and connectors. For this application we are partnering with United Technologies, parent company of Pratt & Whitney and Sikorsky.

Section IIB. Deliverables

Year 1

Dust motes: In year 1 we will demonstrate working prototypes of dust motes powered by hearing aid batteries. These motes will be fully self contained, with a sensor (probably temperature), analog interface, analog to digital converter, and corner cube retroreflector and/or IR diode transmitter. Total volume of the nodes will be less than one cubic centimeter, almost entirely composed of battery. Packaging will consist of a transparent plastic cap.

System: We will demonstrate at least 10 of these motes communicating in parallel their own unique ID and sensor information from a distance of at least 50 meters to a portable receiver. The imaging will be based on a commercial CCD video camera.

Year 2

Dust motes: Demonstrate solar powered dust motes. These will be less than 10 microns thick, fabricated by lifting off the surface layers of a CMOS die. With no battery backup, they will only be active during daylight or while being interrogated with a laser.

These devices will not be packaged! Their terminal velocity in air will be less than 10cm/s, roughly equivalent to dust. Their strength to weight ratio will be so high that thousands of them will be safely carried in a cubic centimeter vial. Their fabrication cost will be just the cost per square millimeter of the CMOS process, which is typically between 5 and 20 cents per square millimeter.

Integrate several other sensor types into dust motes: vibration, magnetic field, and acoustic.

System: Demonstrate a CMOS active pixel camera receiving data from at least 10 parallel sources at 10kbps each.

Application: Demonstrate data transmission from rotating fan blades on a working compressor.

Year 3

Dust motes: Integrate thick-film rechargeable batteries with the solar cell based mote from year 2, in a 1 cubic millimeter package, providing at least 1 day of battery life between solar recharging.

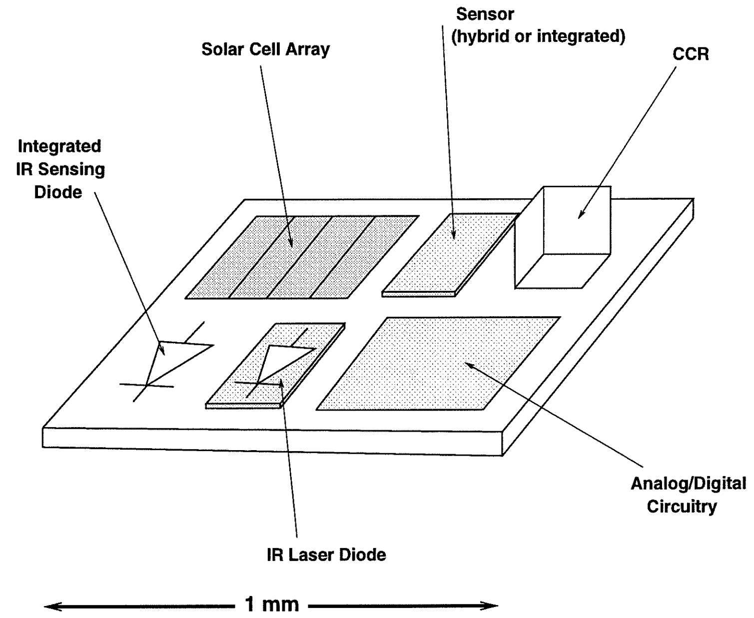

Figure 2: A solar powered dust mote is a completely autonomous sensing and bidirectional communication platform. Other versions will incorporate a cubic millimeter rechargeable thick film battery, and/or a zinc-air hearing aid battery.

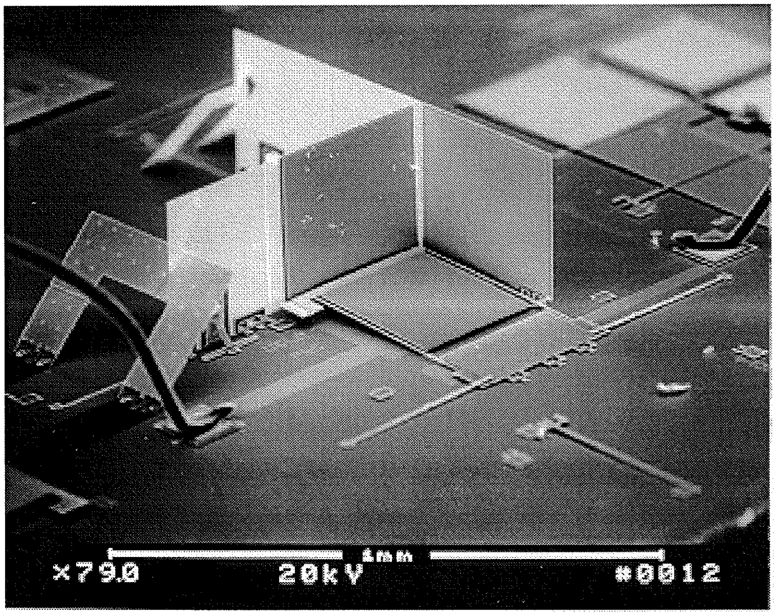

Figure 3: A polysilicon corner cube reflector with integrated electrostatic nano-power modulator.

System: Demonstrate portable system receiving data from at least 1000 dust motes transmitting different types of information at ranges of at least 1 kilometer. Display of data in real-time superimposed on a real-time video image of the terrain.

Application:

An autonomous helicopter UAV made by Photo Emission Technologies will be used to receive data from a distributed sensor array. The array will be sufficiently dense and robust to track the motion of ground vehicles and report this information at a later time to the UAV helicopter.

Section IIC. Cost

Task	Year1	Year 2	Year 3	Total
Dust Motes	300k	300k	300k	900k
CMOS Camera	200k	200k	200k	600k
Thick film batteries	200k	200k	100k	600k
IR laser integration	200k	200k	100k	600k
UAV System	50k	200k	200k	350k
	950k	1100k	900k	2950k

Section IID. Technical approach

Most of the subsystems proposed here are already fairly mature, and a large part of the proposed work is integration of a wide range of disparate technologies and devices.

Corner cube reflectors

Corner cube reflectors work as transmitters by modulating reflected light. A laser beam entering a perfect 90 degree corner will bounce off of the three mirrors and return directly toward the source laser (although with some additional spread in the beam). If you are standing next to the laser, you will see a bright dot where the corner cube is sitting. If one side of the corner is moved out of alignment, even by less than a degree, the reflected light goes off in other directions. From the perspective of the observer near the laser, the spot goes out. This allows the corner cube to communicate digital information to the observer by the laser, merely by making very small motions of one side of the cube. The source of the optical power comes from the observer (interrogator).

With a photodiode on the dust mote, the laser interrogator can communicate *to* to the mote by modulating the laser intensity. In this way, the mote can remain passive unless it receives an appropriate coded signal. This means that an array of thousands or even millions of sensor nodes in a square kilometer area could be completely covert and undetectable. The CCR communication has inherently low probability of interception.

We have demonstrated corner cubes modulating at up to 10 kHz, and data transmission rates of up to one thousand bits per second (1 kbps). The corner cube driver circuitry currently uses an RS232 serial data transmission protocol.

The parallel transmission receiver consists of all off-the-shelf components: a small telescope (Edmund Scientific Celestron with a four inch aperture), CCD video camera, laptop PC, and video frame grabber. A 5 mW Radio Shack laser pointer is attached to the telescope to illuminate/interrogate the corner cubes. The images from successive frames of video are subtracted to remove background light, and whenever a corner cube in the field of view switches from on to off or off to on, this shows up as a bright spot in the image. Tracking the bright spots over time and converting the signal from serial/RS232 yields the data from each corner. Thousands of corners can transmit simultaneously because their signals are spatially separated in the image, so the signal will appear physically separated on the CCD camera and in the resulting frames.

We have demonstrated parallel transmission of data from two corner cubes (transmitting their own unique IDs and data words) to the receiver unit 80 meters away.

Although the bandwidth was only 10 bps (limited by the frame rate of the commercial CCD video camera used), the transmitting corner cubes were burning on the order of a nanoWatt of power.

We have demonstrated working corner cube reflectors in both a polysilicon surface micromachined process (MCNC/MUMPS) and in standard CMOS (2 micron Orbit through MOSIS).

CMOS Imager

To make a high-speed data receiver for Smart Dust, it is absolutely imperative to have local processing at the pixels. As the corner cube modulation increases from today's demonstrated 10kbps, it becomes not just impractical, but impossible to run a CCD array fast enough to keep up.

Active pixel CMOS imagers were first proposed in the late 60s, but until the last decade the technology was not mature enough for them to compete with CCD cameras. Now, however, with linewidths well below a micron, CMOS processes can integrate a substantial amount of analog and digital circuitry physically in parallel with the imaging surface. While some penalty is paid in sensitivity (factor of 2), the advantages of having a low cost standard process and on-chip signal processing make clear economic sense in some applications.

A similar commercial application is the CMOS imaging chips used in some computer track-balls, in which the motion of the spots on the ball is measured directly at the pixel level, and transmitted from the chip to the computer, with no other processing necessary.

Power supply

Solar cells deliver roughly 100 microWatts of power per square millimeter in full sunlight (i.e. with 1 mW/mm^2 incident optical power and 10% efficiency). Under laser illumination higher power output is possible. By placing cells in series or parallel the power can be delivered at any voltage desired, with corresponding reduction in current at higher voltage.

Kovacs' research group at Stanford has demonstrated a technique for fabricating arrays of electrically isolated photodiodes in a standard process. Their first attempt failed due to a circuit design error, but the technique is fundamentally sound. With the move to SOI processes, solar cells become even easier.

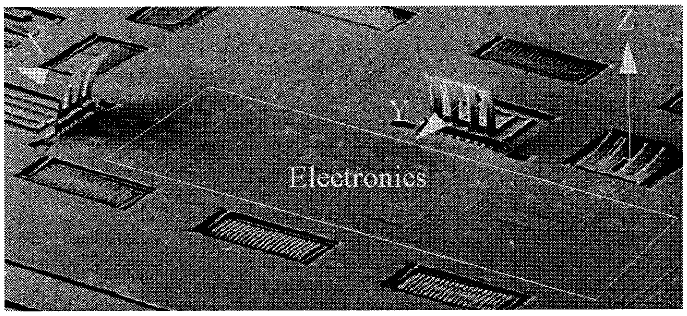

Figure 4: A 3-axis accelerometer fabricated in standard CMOS.

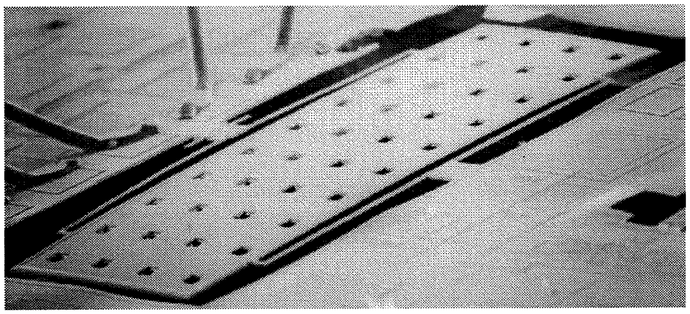

Figure 5: A resonant magnetometer with a noise floor in the nanoTesla per root Hertz range.

Thin and thick film batteries demonstrated by Bates at Oak Ridge and Bruce Dunn at UCLA are based on lithium/vanadia. These batteries have demonstrated energy densities well above 1 Joule per cubic millimeter, and thousands of cycles of rechargeability. Dunn's group at UCLA is already working on integration of these batteries with MEMS devices in smart structures.

Commercially available zinc-air batteries (for hearing aids) store 1000 Joules in a few hundred cubic millimeters, and can deliver peak currents in the tens of milliAmps. Typical power drain for passively listening smart dust would be in the range of 10 μW to 1 mW, giving a battery lifetime of from a several days to a year. Under similar loading, the cubic millimeter thick film batteries will provide from 20 minutes to 24 hours of power.

Sensors

In commercially available CMOS processes we have demonstrated 3-axis accelerometers, 3-axis high frequency magnetometers, and single axis low-frequency high-sensitivity magnetometers.

Integration

Most of the devices discussed above have been demonstrated by simple post-CMOS micromachining of chips with working on-chip electronics. To the extent possible, that is the approach that will be used in this effort. However, we do not intend to beat our heads against the wall inventing new and clever ways to integrate all possible devices in the same process. Certainly the magnetometers, accelerometers, temperature sensors, and solar cell arrays will all be fabricated in a standard, commercially available process, as they have been before. These processes are much cheaper and more reliable than those that can be run by students in a university clean room.

The corner cubes may also be fabricated in the CMOS process, although to date the higher performance corners have been fabricated through MCNC/MUMPS. If MUMPS corners are required, they will be transfered from the MUMPS dice to the CMOS dice by manual assembly at a probe station (possibly motorized and automated). Note that this transfer and assembly operation is *not* being proposed as a major deliverable of the contract - we'll just do it - it's not that big a deal.

A brief anecdote: the first 20,000 accelerometers shipped by Analog Devices required manual assembly by technicians (they were stuck to the substrate during release). The total cost per accelerometer of the technician and probe station time to do this was 17 cents (personal communication, Richie Payne, Analog Devices). For this proposal, anything under a dollar per mote is acceptable.

Similarly, if IR laser diodes are used for communication, they will definitely need to be assembled on the CMOS die (IR lasers are made from III-V semiconductors).

Helicopter interrogation

Photo Emission Technologies has a 2 meter rotor diameter autonomous helicopter platform under development which will be used to carry the interrogation system developed in years 2 and 3. The helicopter payload is 15kg, which will be used for the interrogation system, a high speed data link from the helicopter to the ground, and a Smart Dust dispersal system.

In the final year 3 deliverable, the helicopter will be used to seed an area of many hundreds of square meters with Smart Dust, then return at a later time to interrogate the dust and determine the number, type, time, and direction of the vehicles that have passed through that location. The information will be relayed in real time to the ground controller.

Section IIE. Other research

There is a growing body of MEMS research in the area of free-space micro optics. Groups at UCLA, UC Berkeley, Sandia, and AFIT have produced an impressive array of micro optical components including lasers integrated with micro-lenses [UCLA, UCB], rotating diffraction gratings [AFIT], motorized mirrors [Sandia, UCB], and tunable frequency lasers [UCB]. Our communication work will leverage off of this impressive base of devices, almost all of which are fabricated in the DARPA-supported MCNC/MUMPS process.

Thin film battery technology is also maturing rapidly. This research effort will benefit from the work done by Bates and others at Oak Ridge.

Distributed sensor networks on a much larger scale have been the focus of several DARPA-sponsored projects, including the wrist-watch personal monitors at U. Michigan, and the battlefield and home security sensors developed by UCLA/Rockwell. These projects are demonstrated proof-of-concept for MEMS distributed sensors, although at a linear scale ten to a hundred times larger than that proposed here.

Investigators Pister and Kahn have a contract with Hughes Space and Communications division to develop autonomous microsensor networks for sensing and communication inside of satellite payload compartments, and much of the work proposed here is supported by preliminary work done under that funding.

Pister has NSF money in collaboration with Washington State University to develop the processes necessary to make the solar cell arrays described in this abstract manufactureable.

Dunn has a contract from DARPA to develop the thick film batteries here for application in smart structures. This funding has helped create the infrastructure which will allow the work described in this proposal to be completed and transfered to a manufacturing environment.

Section IIF. Organization

Kris Pister, associate professor, UC Berkeley, will the lead team. He brings experience with distributed sensor networks, low cost microsensor design, ultra-low power communication, and integrated microsystem design. He co-authored the successful LWIM proposal currently being run by Bill Kaiser at UCLA. He has a patent pending on low cost accelerometer design which has been licensed and prototyped by a major analog circuits house. His research group was the first to demonstrate a working micro Corner Cube Reflector, and currently has the highest performance in that area. Much of his research effort is focussed on the development of autonomous micro-systems and micro-robotics.

Joseph Kahn, professor, UC Berkeley, provides expertise on IR communication and optical communication in particular. He is one of the foremost researchers in high speed IR communication today.

Bruce Dunn, professor, UCLA, is the world leader in sol-gel thin film and thick film batteries.

Richard Murray, associate professor, Caltech, is an expert on the control of nonlinear flow and rotating stall and surge in compressor systems, and a regular consultant with United Technologies Corporation.

Photo Emission Technologies has received several SBIR awards in autonomous systems for battlefield surveillance. Autonomous UAV helicopters developed under other contracts will be modified to carry Smart Dust receivers for the year 3 demonstration. PET is also a good candidate for technology transfer for large scale low cost manufacturing of the dust motes.

Tanner Research, Inc. has developed several CMOS camera designs under DARPA sponsorship, including a 2000 frame per second CMOS imaging system. In addition, they are actively developing corner cube communication systems for IFF applications. They are an ideal partner for transfer of the CMOS imaging technology, and will be in an excellent position to manufacture systems using this technology.

United Technologies is a $23 billion corporation that provides a broad range of high-technology products and support services to customers in the aerospace, building and automotive industries worldwide. UTC's best-known products include Pratt & Whitney aircraft engines, Otis elevators and escalators, Carrier heating and air conditioning systems, Sikorsky helicopters, Hamilton Standard aerospace systems and UT Automotive components and systems. The corporation also supplies equipment and services to the U.S. space program.