

## **Advanced Sensors for Monitoring Our Environment**

Professor Steven D. Glaser

Center for Information Technology Research in the Interest of Society

University of California, Berkeley, CA 94720-1764

glaser@ce.berkeley.edu

Let us define the environment as the world that surrounds us, whether at work or at home. This paper addresses the measuring of many of the features of our surrounding environment, emphasizing new approaches and technologies that allow us to make measurements less costly, better, and faster. In particular we will look at arising paradigms in information technologies that not only facilitate the generation of data, but facilitate the generation of information rather than mere data. New approaches in information technologies, microsensor fabrication (MEMS), and data transmission (low power radio) change the functional definition of the sensor - we can now define a “sensor” as a device that combines transduction, signal processing, data distillation, storage, and communication - at a low price. We call this device a Mote.

Motes, or smart dust, are devices that incorporate wireless communications, processing, sensors, sensor fusion, and power source into a package currently about 100 cc in size - networked autonomous sensor nodes. They are designed to be embeddable throughout the environment - low cost (\$200 each now, \$25 each in the future), non-obtrusive, unattended or unmanaged, and dynamically reprogrammable. The promise of the Mote is a self-organizing and adaptive information utility. Embedded operating systems allow multiple applications to be running while providing services such as messaging protocols, periodic timer events, static, persistent data storage, and swapping of system components to create necessary functionality on the fly.

Let us examine several application areas important to sustaining and improving the quality of life for the planet’s population. The MEMS revolution provides a wide variety of acceleration sensors at all price points and sensitivities. We will look at incorporating such devices, combined with advances in information technologies, to improving use of water resources in agriculture, monitoring structural integrity, and reducing natural and man-made hazards - both on the surface and beneath (E-Defense). The usage of acoustic emission for industrial monitoring will be revisited. Our high fidelity quantitative AE sensor opens a new world of interpretation, in particular when combined with more traditional velocity sensors. Micro strain gages for

embedment into machinery bearings are becoming a reality, and laser scanners and interferometers are also becoming more affordable. Finally, new sensors allowing us to monitor the air we breathe will be examined.

## **Agriculture**

Recent advancement in microsensor and network technology allows us to propose a scheme to continually monitor soil moisture at different depths, across a wide range of spatial scales and over multiple years. Accurate knowledge on the amount of moisture in the soil profile, its horizontal variation, and temporal dynamics are important information for issues relating to the management of our planet's natural resource base and environment and for the assessment of our national economic and social health. Soil moisture influences a range of hydrological processes, such as flooding, erosion, groundwater recharge, solute transport, and land-atmosphere interactions. Water resource managers, for example, need knowledge of soil moisture in the upper and lower reaches of a watershed because it affects the supply of water to reservoirs and the demand for irrigation water. On a regional and global basis, information on soil moisture plays a key role in the forecasting weather, predicting droughts and floods and the future climate. Soil moisture has great economic importance through its impact on such ecological and agronomic processes such as evaporation and primary production. For many dry-land farmers a small change in moisture content can spell the difference between losing their crop or having a successful year of exports.

This will be done by intelligent instrumentation processors that allow seamless management of virtually any micro-sensor (e.g. soil moisture, pH, temperature, barometric pressure, relative humidity, wind speed and direction, sun light in a variety of pertinent frequency ranges, atmospheric gasses) and output device (e.g. any of the hundreds of commercial wireless modules). These integrated sensing devices, or Motes, are relatively inexpensive and can be integrated into a multi-layer heterogeneous network. While our current work is focusing on applying the wireless technology to study spatial variation of soil moisture of a grazed savanna woodland, the technology we are developing has potential to be applied to study the soil water balance of irrigated crops, orchards and vineyards.

## **Structural Integrity**

The greatest public safety risk associated with natural hazards comes from the built environment. Knowledge of the integrity of structures can significantly reduce the risk of users by providing information about the collapse potential. To achieve this goal, we propose a densepak™ structural health monitor which enables structures and bridges to monitor themselves using inexpensive Motes that locally sense and determine structural condition (Glaser, 2004). Coupled

with computational models residing in the Mote itself, and on-line through peer-to-peer networks, the System will measure, e.g., ground motion, estimate damage and losses, and provide users with emergency information. The key to this approach are the sensor Motes - such systems must be inexpensive to install and maintain during original construction, and after construction.

Development of analytical tools to capture the evolution of system response in terms of damage initiation and damage propagation - synthesizing the interaction between the structural system and its components - is essential for performance-based design. For the proposed scenario of perhaps thousands of Motes monitoring a large structure, it is not feasible to merely send back all the recorded signals from all the multi-sensored nodes to a common hub. We propose the most powerful and elegant approach to identifying a locally evolving system by pushing the solution of the problem down to the local dense-pak™ Motes surrounding the damage. The most promising parameterization of an evolving system is a unified methodology based on Bayesian/State-Space identification and adaptive estimation. Our Motes have the computational power to solve a system identification inversion through use of parsimonious algorithms such as the LMS (stochastic gradient method).

Devices just described are being commercially developed by Shinkawa Sensor Technology, Co., Tokyo, Japan. Several challenging industrial applications have been instrumented by the Shinkawa engineers in the development process, the first working with Toshiba engineers for periodic monitoring of piping vibration of a nuclear power plant boiler feed pump. The human safety zone at the plant is separated from the pumps to avoid contamination. The wireless units allow monitoring without subjecting the operators to risk. Another application is continuous bearing condition monitoring on a large coal fuel sifter machine at a steelworks outside Tokyo. Impact acceleration data at the bearing is sent to an environment safety zone, allowing workers to avoid an extremely dirty and dangerous area. At the same facility, the crossbeam of a traveling crane, approximately 30 m above the work floor, is monitored by Motes for abnormal vibration. For the constantly moving crane, a wired solution to provide the vibration analyses to the safety of the ground would be very difficult to incorporate.

### **Natural and Man-Made Hazard Reduction**

We contend that radically new information technologies can be used to protect lives and speed the economic recovery of a city after a large earthquake. Buildings equipped with densely distributed intelligent sensor systems and new diagnosis/prognosis facilities will be able monitor themselves and provide owners and occupants information about safety and egress in an emergency. Owners of large manufacturing facilities, transportation networks, and lifeline networks will have accurate information to assess the structural condition of their networks and real-time information to make decisions on restoration after an event. Finally, emergency

response planning in most cities is poorly planned, and experience has shown emergency response is often chaotic and ineffective because of lack, or poor quality, of information on where emergency response services are needed and how to deploy personnel, equipment, and material.

Following an earthquake or terrorist act, a structure will self-diagnose its ability to withstand loads and aftershocks in a safe manner, and provide managers with customized information about the optimal emergency response through internally and externally distributed networks and alarms. The alarms will be integrated into a variety of other emergency scenarios (fire, medical, and security). Instead of the current time-consuming and chaotic manual procedure of inspectors "tagging" a structure, waveforms monitored during the event will be quantified in real time to locally determining safety and integrity - local structural parameters that can be compared to numerical models and base-state measurements of safe structural behavior, alerting users of unsafe conditions in a process of self-tagging (Glaser, 2004). Individual monitoring systems are linked through heterogeneous wide-area network to distributed regional emergency response centers which prioritize the response of emergency personnel.

Moving up one level from individual buildings, owners of many buildings, such as a corporation or a university campus, are concerned with the effect of a disaster on the operation of their enterprise. In a similar manner, utility networks (electricity, gas, water) and transportation networks (highways, railways, ports and harbors, airports) must synthesize damage information to determine how to restore service. Owners of multiple facilities require assessment of damage, estimate of repairs, prioritization of repair, and acquiring and deploying resources for repair. As practiced today this may take weeks or even months. The availability of real-time information on condition and damage will allow owners to make much more rapid and rational decisions on the safety of their facilities and begin recovery.

### **Seismic Monitoring**

The increasing availability of vertical seismic array data from around the world has broadened our ability to analyze wave propagation and site response in the near surface. With accelerometers at depth, we can trace the actual effects of the near surface materials on the propagating seismic waves. So-called vertical arrays have come online in several sites in California, Taiwan, and Japan. By comparing multiple downhole recordings and a related surface recording, one can observe how the waves change as they progress through the ground, encountering the materials in the soil profile. These arrays are changing the way we understand seismic ground motion by allowing the 3-D evaluation of seismic wave propagation (Baise et al., 2001; Stidham et al., 1999; Elgamal et al., 1996; Abrahamson et al, 1991). Vertical arrays have traditionally been very expensive to install and maintain (Steidl and Nigbor, 2001), much like traditional structural seismic instrumentation. We envision a field-deployable array that can be installed in a variety of

manners. Initially the arrays will be installed into uncased (or cased) boreholes. By the end of the project, the arrays will be inserted into the ground by ubiquitous cone penetrometer equipment, and the array elements being commercial available to the entire community.

The Terra-Scope™ system is an affordable 4-D down-hole seismic monitoring system based on independent, microprocessor-controlled sensor Pods (Glaser et al., 2005). The pods are nominally 50 mm in diameter, and about 120 mm long. They are expected to cost approximately \$6000 each. An internal 16-bit, extremely low power MCU controls all aspects of instrumentation, eight programmable gain amplifiers, and local signal storage. Each pod measures 3-D acceleration, tilt, azimuth, temperature, and other parametric variables such as pore water pressure and pH. The following parameters are independently controllable at each pod: pre-trigger length, post-trigger length, trigger time stamp, sampling rate, trigger level, trigger parameters, non-volatile storage, and calibration and self-evaluation. Each Pod communicates over a standard digital bus (e.g. RS-485) through a complete web-based GUI interface, and has a power consumption of less than 400mW. Three-dimensional acceleration is measured by pure digital force-balance MEMS-based accelerometers. These accelerometers have a dynamic range of more than 115 dB and a frequency response from DC to 1000 Hz. The accelerometer chip uses a 5th order delta-sigma feedback loop to yield a noise floor of less than  $(80ng_{rms})/\sqrt{Hz}$ . Accelerations above 0.2 g are measured by a second set of MEMS-based accelerometers, giving a full 160 dB dynamic range. The prototype of the device is currently undergoing evaluation. The first array will be installed in the fall of 2005.

### **Acoustic Emission**

Acoustic emission (AE) monitoring involves instrumenting the chosen structure and listening for characteristic signals. AE are the elastic strain waves generated by rapid release of energy during crack propagation, internal deformations, and externally applied dynamic loads in materials. This release of energy is manifested as transient stress waves which propagate outward from the locus of a structural change brought on by changes in the local stress field. The wave motion transmitted by AE contains information about the location and characteristics of the defect and the host material itself, therefore accurate transduction of the transmitted kinematics is necessary to fully evaluate AE waveforms. High-fidelity sensor arrays are needed so recorded signals can be compared to the theoretical waveforms expected for various types of damage. Much of the past failures of the AE method are directly attributable to the use of resonant-type sensors that yield more information about the sensor response than about the actual internal dislocation itself.

The kinematics of a dislocation in a solid can in theory be estimated by inverting recorded AE signals generated by the dislocation. The microseismic signals are deconvolved from the

calculated theoretical Green's functions to obtain the kinematics of the dislocation (e.g. Stump and Johnson, 1977). This method can be used to invert for sources of any nature and location, but requires extremely accurate boundary conditions. Very few works to date have applied this method successfully to microseismic data. Kim and Sachse (1986) presented a full waveform inversion of indentation cracks and thermal cracks in glass, respectively. In Enoki and Kishi (1986), recorded signals due to cracks were inverted to give the source time function for a fracture toughness testing in steel. In these works, the material is assumed to be elastic, isotropic, and homogeneous while the dislocation is assumed to be a point source.

Glaser's research (Glaser et al., 1998), based on the NBS research in the early 1970's (e.g. Eitzen et. al., 1981; Proctor, 1986; Hamstad and Fortunko, 1995), has resulted in a very accurate and sensitive sensor with a sensitivity of 2.8 V/nm, and a virtually flat frequency response from approximately 10 kHz to 1 MHz, as calibrated by NIST (Fick 1996). We have now extended the frequency response to over 2 MHz. This sensor also has the capability of being fully embedded within the structure being monitored. Rather than ringing like a bell when stirred by an incoming signal, these devices report the actual transient displacements. This allows a novel form of bearing condition monitor. The Glaser sensor is being integrated into the more traditional eddy-current sensor used by Shinkawa Sensor Technology, Co. When a microscopic pit begins to form on a bearing race, a very short and small transient is emitted, which often cannot be noticed by Fourier analysis techniques. The Glaser sensor, however, is optimal for picking out such transients without losing it in the ringing of traditional sensors.

### **Laser Distance Measurement**

One of the best methods of measuring sound and vibration in the audio range is by laser devices. One fundamental advantage of optical techniques is that their frequency response is flat and can be calculated absolutely. traditionally these devices have been referred to as laser vibrometers and have cost up to \$100,000. A new family of devices, referred to as laser distance measurement (LDM) sensors are now on the market for much more affordable prices. These devices use a triangulation principle to measure the travel time from a pulsed laser to a reflector and back to a photo-sensitive diode (PSD) or charge coupled device (CCD). Internal optics and adaptive algorithms account for the changing angle between source and the position of the returning light beam on the PSD. the devices operate with as little as 10% diffuse reflection, and return an analog voltage proportional to distance from the sensor. These devices typically have a frequency bandwidth of up to 25 kHz.

What is new about this class of sensors is a price of \$2000 from some manufacturers. As LDM sensors become more commonplace, it is expected that the costs will fall to the \$500 range for precision devices. For instance, a typical device available for \$2000 will have a bandwidth of 17

kHz, 0.2  $\mu\text{m}$  resolution for a 0.5 mm range, and 0.5 mm resolution for a 400 mm range. Other models yield 100  $\mu\text{m}$  resolution over an 8 mm range but with a bandwidth of 250 kHz. Also available are devices that use a phase comparison method to measure over a 30 ~ 100 m range with 1 mm resolution.

### MEMS Strain Gages

Currently the MEMS revolution is being taken to the automotive market by mechanical engineers at the University of California, Berkeley. They are finding solutions to monitor the roller/hub interaction in automotive wheel bearings, which create a strain field about 100  $\mu\text{m}$  wide at each stressed roller. This small but intense stress field dictates fatigue life of the bearing. The local stresses also relate directly to the force on the bearing, allowing for improvements in traction control applications. The bearing manufacturer requires a 0.1 microstrain resolution and a 10kHz operational bandwidth. Traditional foil gauges are limited in application and size, require complicated and time consuming bonding, and small length foil gauges degrade quickly due to fatigue and overheating. Inherently small MEMS gauges can be integrated directly into the bearing races. Because CMOS micro-circuitry is directly integrated into the MEMS device, the gauges can incorporate local data reduction and analysis, and can be directly integrated into suspension and traction control loops.

The device works on the principle of the gauge's resonant frequency modulating as the distance between anchor points changes with local strain. The prototype devices were fabricated at the Robert Bosch GmbH MEMS foundry service on a two layer polysilicon micro-machined surface, and were packaged in air. The structural layer is about 10.6 mm thick with about 3 mm gaps between the resonating tines. One of the most critical developments is the process of directly bonding the silicon MEMS gauge directly to the bearing steel. The protocol involves cleaning the steel parallels with sandpaper, plating with 40  $\mu\text{m}$  Pb/Sn solder, and a 30~60 s reflow using infrared heating. A summary of the prototype device is given in table 1.

**Table 1: Properties of the UCB MEMS strain gauge**

Gage Length = Anchor spacing 250 mm	Sensor Area ~ 0.5 mm x 0.5 mm
Gage Factor = $(\Delta f/f)(1/\epsilon) = 180$	Sensitivity = 39 Hz/ $\mu\epsilon$
Resolution – 0.1 $\mu\epsilon$ in 20 kHz bandwidth	Center Frequency = 219 kHz
Rated Strain – + 5000 $\mu\epsilon$	Max Strain – + 1000 $\mu\epsilon$
Lifetime Goal – 10 years	Temperature drift - -6.8 Hz/ $^{\circ}\text{C}$ , -0.17 $\mu\epsilon/^{\circ}\text{C}$

## Conclusions

The paper has presented an overview of a variety of new sensors that have become possible because of advances in information technology, MEMS fabrication, and communications. These advances are melded together in the new family of information processors called Motes. The manuscript presented how these devices can be used to solve a variety of problems common to modern society. These areas include agricultural field conditions and monitoring and prognostication of structural health using the dense-pak approach. These same advances can be used to help mitigate natural and man-made hazards such as earthquake and terrorist activities. A solution for E-Defence, the Terra-Scope down-hole seismographic station, was discussed in detail. A new application of quantitative acoustic emission sensors for bearing monitoring was discussed, as was a new MEMS-based strain gauge for automotive bearing monitoring.

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