

Integrated quantitative monitoring of structural integrity is urgently needed to determine the actual condition of structures in real time. Such a system would insure rational application of condition-based maintenance, and rapid structural health determination after exposure to seismic events. The widespread damages due to recent earthquakes in Japan and U.S. draw attention to the risk of weakened structures designed using earlier codes. Engineers, public safety officers, and urban planners must know the condition of structures and their needed repairs and retrofits.

Fortunately, powerful advances in emerging technologies such as materials, new sensors, electronic communication, and information processing can be brought to bear on nondestructive evaluation of structural condition. Consider the following scenario:

*Tiny self-contained sensors are installed near critical structural points in a key building. Onboard intelligence discerns normal structural deterioration and meaningful damage. Sensors report the location and kinematics of damage during/after an earthquake, allowing rapid, accurate structural health determination. Public safety is assured as unseen structural damage is identified without costly and dangerous deconstruction.*

This proposal outlines the full scale demonstration of such a system. Our objectives are:

- 1) Large-scale demonstration of wireless MEMS dynamic monitoring system.
- 2) Dense instrumentation of large-scale test structures with 100 2- and 3-component accelerometers to develop detailed understanding of the dynamic structural response.
- 3) Leveraging of currently planned CUREe/Kajima three-story reinforced concrete flat plate, and CUREe/CALTECH multi-story asymmetric wood frame, structural dynamic testing programs.
- 4) System performance assessment using system identification. This is an essential task for performance-based design.
- 5) Teaming of CUREe and Berkeley Sensor and Actuator Center (BSAC), aiming towards future integration of state-of-the-art MEMS technologies into civil infrastructure systems.

Our remote real-time monitoring scheme involves dense instrumentation of large-scale test structures with up to one hundred 2- and 3-component wireless accelerometers. Two current structural testing proposals from UC-Berkeley are keyed towards making full use of advanced instrumentation techniques for complete understanding of dynamic structural response (Mosalam, personal communication). The project leverages the CUREe/Kajima three-story reinforced concrete flat plate structural dynamic testing to determine role of detailing in terms of slab/column connection, and the CUREe/CALTECH multi-story asymmetric wood frame structure program to quantify the effects of retrofitting and finish materials (Mosalam, private communication). Quantification of these details are of utmost importance to characterize the dynamic response, e.g., punching failure in the first and load sharing and damage distribution in the second. The complexity of these systems and their expense mandate the use of intense array of measurements.

Development of analytical tools to capture the evolution of system response in terms of damage initiation, damage propagation, and structural system response, understanding the interaction between the structural system and its components is essential. The dense sensor array will provide close and detailed monitoring of all essential components during the test. From the collected data, evolution of system performance can be assessed, which is an essential task for performance-based

design. The so-called system identification (SI) approach is a powerful and tidy tool to quantify and assess system damage parameters, and has been so applied by many, many, structural researchers (e.g., Udwadia and Shah, 1976; Beck, 1978; Gersch and Brotherton, 1982; Safak, 1988; Werner et al., 1994). The P.I. has extensive experience applying parameter-based SI, both stationary and recursive, to complicated soil structure problems interpreting vertical array data.

### **Advanced Instrumentation**

The centerpiece of our project is the incorporation of advanced micro-electromechanical systems (MEMS) wireless 2- or 3-component accelerometers. These devices, called Macro-Motes, large scale models for smart dust, are devices that incorporate communications, processing, sensors, and batteries into a package about a cubic inch in size. The current design incarnation of the Macro-Mote to be used for seismic structural monitoring is shown in Fig. 1.

The basic structure of the Macro-Motes consists of an atmel microcontroller with multiple sensors and a communication unit, as illustrated by the functional diagram shown in Fig. 2. The accelerometer module is a low cost, low power, complete 2- or 3-axis accelerometer with a measurement range of 2 g, functional over a  $-40^{\circ}\text{C}$  to  $+85^{\circ}\text{C}$  temperature range. The device can measure both dynamic acceleration (e.g., vibration) and static acceleration (e.g., gravity), with bandwidth adjustable from 0.01 Hz to 6 kHz. The typical noise floor is  $500\mu\text{g}/\sqrt{\text{Hz}}$ , allowing signals below 5 mg to be resolved for bandwidths below 60 Hz. Digitization of the analog signal takes place inside the accelerometer module so there are no signal processing costs and problems associated with the unit. At present the Macro-Mote incorporates 4 channels of magnetic field measurement, as well as humidity, light, temperature, and air pressure measurements made by integral sensors. These 8 channels of A/D conversion can be replaced by any set of inputs the user desires, giving a full wireless link controlled by an on-line interactive microprocessor. The Macro-Motes are simple, robust, and can be built from readily available components. The current component costs are about \$250, but they are continually becoming more inexpensive. The tested devices will basically be ready for widespread field deployment

### **Damage Assessment**

The dense acceleration histories will be used by Mosalam for input into detailed constitutive models. In addition, simpler, more tractable methodologies will be applied to data interpretation - a

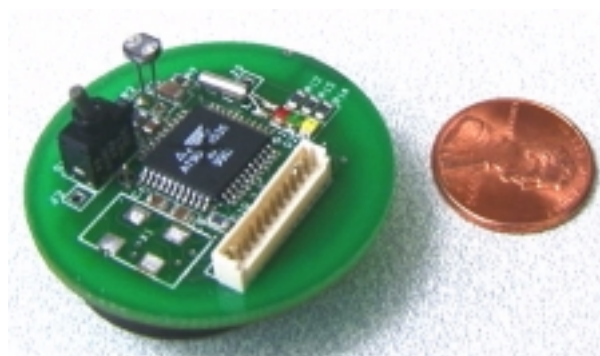


Figure 1. Full scale photograph of the Macro-Mote device.

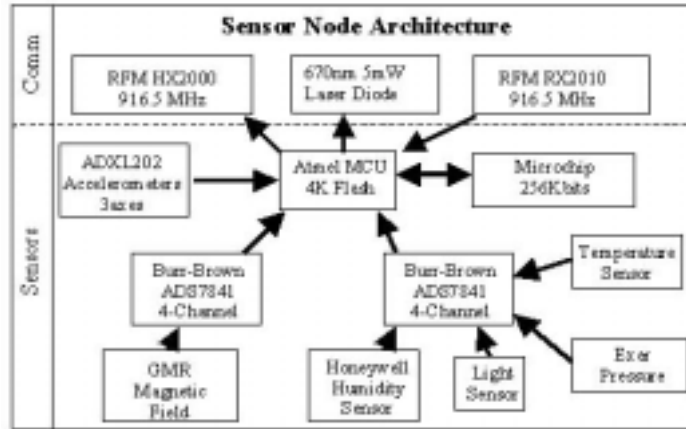


Figure 2. Functional architecture of present-generation Macro-Mote.

methodology which can easily be built into the Macro-Mote microprocessor for real-time damage analysis. The characterization of a system model through inversion, and estimation of useful parameters, is commonly known as system identification (SI). This includes non-stationary (or, non-linear) effects through the use of recursive models and adaptive (Kalman) filters. Note that since SI is a stochastic analysis of time series, our hypotheses can be proven (or disproving) to a well-defined degree of confidence.

Initial system parameters will be estimated for each undamaged structure and test case. As the structure is shaken, damage will initiate and grow, affecting structural stiffness and damping, both locally and globally. Dense instrumentation allows localization of the damage region with greatly increased sensitivity, since on a local scale response can be greatly affected while global behavioral change remains insignificant. This avoids the major complaint about the damage sensitivity as the SI approach. Finally, actual damage can be quantified by inspection after each increment of shaking, for later calibration of the SI analysis.

The autoregressive-moving average (ARMA) model upon which we base the identification is very powerful in that it can easily model sharp drops, sharp peaks, and smooth spectral behavior. It is also the most parsimonious estimator (Robinson, 1982), describing a complex process with very few parameters calculated from a small length of data. SI modeling avoids many of the difficulties inherent in the traditional Fourier methods (e.g., Glaser, 1995; Pandit, 1991). An important property of the ARMA model is that the associated ARMA difference equation is the difference equation of the integral of the equation of motion of a single degree-of-freedom lumped mass oscillator (Ghanem et al., 1991). The damping ratio and resonant frequency of the  $N$ -degree-of-freedom oscillators are contained in the  $2n$  AR parameters. Phase relations are preserved in the MA parameters.

ARMA parameters can be sequentially estimated so that the parameters are adaptive to the changing nature of the process. The ARMA parameters are updated after each data point, tracking slowly non-stationary signals. The so-called extended Kalman filter has been very successfully applied to non-stationary (and non-linear) estimation problems (e.g. Baise and Glaser, 2000; Ljung, 1979; Astrom and Eykhoff, 1971).

## Collaboration, Integration, and Results

The testing program will piggyback on the work Mosalam will perform for the CUREe-based structural testing. Kajima leverages their substantial investments to greatly increase the knowledge output of the testing as well as development and proof of a unique wireless MEMS sensor system. Kajima also leverages the \$400,000 investment by CUREe/CalTech for testing of wood frame structures. We also count on collaborating with the sensor and smart structures group at Kajima.

Our testing program will proceed by the schedules outlined by Mosalam. Evaluation of collected data will proceed throughout the second year, and will also involve close interaction with the physical results generated by Mosalam.

At the end of the project we will have demonstrated an inexpensive wireless real-time structural health monitoring system. We will have demonstrated the ability to densely monitor structural dynamics without wires, to localize and characterize damage through SI evaluation of accelerometer data, and will have expanded the community's understanding of the detailed behavior of earthquake loaded structures.

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