A New Microtelesensor Chip for Meteorology

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Introduction

A new technology exploiting commercial microsensors developed for atomic force microscopy offers breakthrough capability in ultra-small, low-power, high-accuracy wireless sensors for meteorological measurements. Historically, sensors used in airborne and buoy-based platforms required compromises in performance to achieve the low weight and low power requirements of the mobile platforms. Recent innovations in microelectromechanical systems (MEMS) have provided opportunities to reduce size, weight, and power requirements, but each sensor still required a specially fabricated device with the usual inherent calibration, repeatability, and traceability problems.

The new approach allows hundreds of identical sensors to be inexpensively fabricated on the same semiconductor substrate as the conditioning electronics and the telemetry components. Exploiting semiconductor fabrication technology offers the potential to reduce fabrication costs to a few dollars per component. Sensing humidity, temperature, and pressure have been demonstrated in the lab, with plans (and funds) for meteorological deployment scheduled for later in 1997. Figure 1 illustrates the relative size of currently available microcantilever arrays.

Cost, reliability, size, power consumption, and accuracy are key factors in the deployment of advanced meteorological sensor arrays. Recent advances in microsensor technology at Oak Ridge National Laboratory (ORNL) now permit very significant reductions in sensor cost, size, and power usage, while adding integral local radio-frequency telemetry.

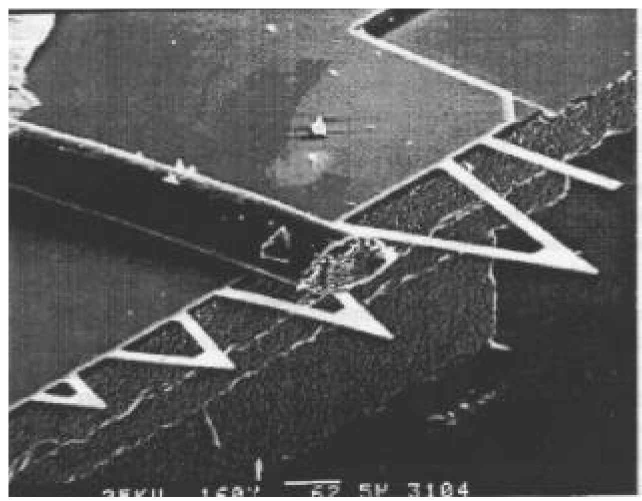

Figure 1. Microcantilever array with human hair.

Integrated MEMS fabrication technology combined with on-chip signal processing and frequency-agile telemetry allows the low-cost fabrication of compact, low-power sensor modules. These devices could facilitate meteorological studies by the rapid acquisition of extensive, multiparametric data sets for monitoring rapid climatic changes over selectable areas. For example, arrays of these modules transmitting via wireless links to a central-area receiver could report changes in local conditions with high precision and timeliness. Even small self-inflating balloons could transport radiosondes based upon this lightweight technology.

ORNL is integrating the sensing technologies, electronic processing, and telemetry to build a family of sensors with multiple-input capabilities (see Figure 2). One

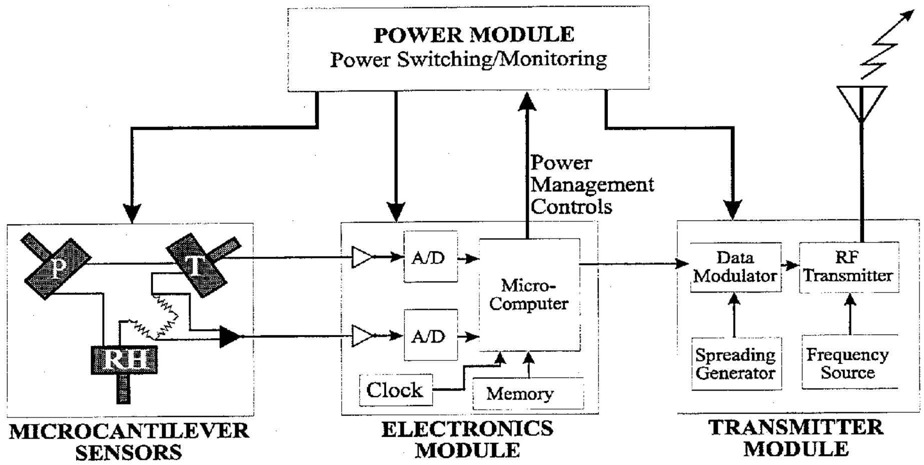

Figure 2. Integrated Microtelesensor.

of the key elements in ORNL's sensor technology is coated microcantilever arrays, which form a powerful universal platform for multiple physical and chemical measurements. Telemetry is also being developed to add robust spread-spectrum data transmission capabilities to the necessary signal-processing electronics. In collaboration with the National Oceanic and Atmospheric Administration's (NOAA) Atmospheric Turbulence and Diffusion Lab, ORNL is slated to demonstrate a chip-level temperature/humidity module later in 1997. Future additions would include sensors for atmospheric pressure, wind velocity, turbulence measurement, and radiometry.

Relevance to the Atmospheric Radiation Measurement Program

As the ARM Program focus shifts from development and deployment to operation and maintenance, the costs of routine measurements begin to swamp all other costs of the site operation. Continued success of the program could hinge on finding ways to reduce these costs without compromising the quality of the data provided. Technologies described here could be used to reduce the cost of sondes, sensor calibration, and other routine operations, while actually improving the coverage of the sites. The ARM concept recognizes the importance of widely distributed, low-cost instruments that can be used to validate the projections extrapolated from the higher performance instruments located at the central facility.

One area of potential significance to the ARM Program is a new generation of radiosondes based on these new microtelesensors. Current sonde packages use reasonably accurate temperature sensors (although their time constants could generally be improved), but the humidity sensors are typically accurate to only a few percent relative humidity, especially in very wet or very dry atmospheric layers. The power requirements of the current sonde package (including telemetry) are such that a moderately large battery is needed; this battery increases the overall size and weight of the package and thereby requires a fairly large balloon to achieve high altitudes. All these factors combine to raise the cost of a launch to $200 or more, for the sonde, balloon, helium, and labor.

With the microtelesensor chips, it should be feasible to significantly reduce the size, weight, and cost of the sonde system, while simultaneously improving the accuracy of the data, especially the humidity measurements. It may also be possible to simplify system preparations and inflation to the point of automating the process, further reducing launch costs and introducing the possibility of more frequent and more accurate atmospheric soundings at the same or lower cost than is currently budgeted.

Another interesting possibility is the development of a low-cost spectrometer, making use of the high temperature accuracy of these sensors. This could allow the deployment of a much larger network of compact solar radiation sensors across a region than is now economically feasible, along with the built-in means to transmit the data to a central site by telemetry. This would provide a means for assessing spatial variability due to cloudiness or, if deployed within a vegetative canopy, due to the highly variable interception of radiation by canopy foliage.

Airplane Application

One item of meteorological interest is the horizontal and vertical variability of temperature and humidity over a landscape, especially a heterogeneous one where land-use types change or bodies of water are present or vegetation is patchy. Currently, there is no satisfactory way to map out such temperature and humidity fields with any detail; data from balloons and/or towers are too sparse. Such mapping can be accomplished at considerable expense with an instrumented aircraft. However, a detailed mapping is extremely tiresome for the pilot, and may require the aircraft to operate at heights below those regarded as safe. An inexpensive remotely piloted vehicle (RPV) would provide the means to conduct such a mapping and, with the addition of differential Global Positioning System (GPS) equipment and an accurate pressure altimeter, could provide a way to program the flight path for optimal coverage with minimal operator intervention. The microtelesensor chip would provide an inexpensive, accurate, small, and low-power sensor for the measurements.

ORNL and NOAA's Atmospheric Turbulence and Diffusion Division plan to collaborate on a prototype version of such an RPV using a commercially available large model airplane, powerplant, and radio control equipment as the basis for the test platform.

Approach

ORNL is integrating the sensing technologies, electronic processing, and telemetry to build a family of sensors with multiple-input capabilities. Initial testing and evaluation of the new instruments will be conducted in ORNL's existing laboratories.

Microcantilevered Sensors

ORNL has developed and patented a novel class of micromechanical sensors as a result of its atomic force microscope cantilever experience. These springboards are sensitive to physical changes in mass, stress, or temperature and can be readily formulated to selectively augment these changes. They are an ideal universal platform for stand-alone microsensor development. For example, a silicon nitride springboard with a gold coating on one face is sensitive to mercury absorption at the picogram level. An aluminum-coated springboard is sensitive to temperature changes of a microdegree or less. Radiation dosimetry has been demonstrated by recording stress changes in coated cantilevers. Springboards themselves are sensitive to viscosity and pressure changes. Because these sensors are readily fabricated in silicon, miniature low-power, monolithic devices can be inexpensively constructed.

Two readout methods that are compatible with highly sensitive monolithic devices have been used: piezoresistive and capacitive. Both allow on-chip circuitry for signal conditioning for low-power operation and very economical fabrication. Detection of dc (static deflection) is accomplished using bridge circuitry, and ac (vibration at resonant frequency) detection can be done by simple oscillator techniques.

Pressure Measurement

Atmospheric pressure is measured by observing the resonance characteristics of balanced cantilevers. Dramatic changes in the resonant frequency, amplitude, and width can be readily measured. For example, using resonant frequency, we have observed air pressure changes of 0.02 inches (Hg). This level of precision is more than three times better than that stated for commercial deployable devices (ENV-50-HUM, Sensor Metrics, Inc., Lakeville, Massachusetts).

Relative Humidity

Cantilevers coated with humidity-sensitive films make exquisite sensors. The sensitivity is primarily due to stress loading in the thin-film coating and can be accurately read out with changes in resonant frequency. Although not optimized in preliminary studies, the sensors had response times of less than a second and were able to work over a 5% to 90% relative humidity range.

Temperature Measurement

The proposed temperature sensor for meteorological measurements is based upon the bending of a micro-cantilever with ambient temperature. Coating the sides of a silicon cantilever with different materials, such as two metal films, makes it very sensitive to temperature variations because of the bimetallic effect. (Subsequent hermetic coating on both sides renders the cantilever insensitive to humidity or other chemical vapors). Remote temperature measurements are even possible using infrared radiation impinging on such a cantilever. A sensor demonstrating this method received the 1996 R&D-100 award.

Although a micromachined bimetallic springboard has a sensitivity far exceeding that required for ambient meteorology, its nanogram mass responds to temperature changes in a millisecond timescale. Furthermore, the addition of a temperature sensor on an integrated chip with humidity and pressure sensing can be accomplished for negligible cost. The cantilever would be coated with a thin organic polymer to seal it against changes induced by humidity or chemicals.

Sensor Optimization

Inexpensive commercial cantilevers have been used for demonstration purposes and have been very successful. Theoretical calculations have shown that performance can be improved by tailoring sensor geometries and materials for specific measurements. Inexpensive, custom-fabricated cantilevers will be obtained in a timely fashion from the Micromachining Center of North Carolina (Research Triangle) using the MUMPs process. When these sensor cantilevers are combined with on-board or on-chip construction, their performance will far surpass that of early demonstration sensors, which have already shown remarkable promise.

Integrated Electronics

ORNL has unique expertise in the areas of low-power, high-performance analog CMOS electronics; digital CMOS, bipolar, and GaAs systems; and battery and RF technology, as well as microcantilever sensors. Virtually all of the electronic subsystems required to support the types of sensor applications proposed have been successfully designed and fabricated as custom application-specific integrated circuit (ASIC) chips by researchers at ORNL and the University of Tennessee-Knoxville. For example, microcantilevered-type sensors generally require low-noise front-end amplifiers and filters to provide high-quality output signals and often need additional circuitry to drive bridge-style sensing structures. Further, the sensor signals may well require adaptive-gain or other conditioning methods to provide wide dynamic-range measurement capabilities. Analog CMOS technology is ideal for this task because of its high speed and low power consumption. Also, the vast majority of competing solutions require digitization of the sensor outputs and downstream compression, averaging, or other manipulations. We propose mixed-signal (analog/digital) ASICs as a solution.

Again, ORNL has successfully implemented several of these types of functions (A/D and D/A converters, micro-computers, memory, general logic, I/O devices) in silicon and GaAs ASICs. For example, numerous systems previously developed for the Navy and other agencies have incorporated both low-power circuitry and specific power-management hardware and software algorithms to accommodate very stringent average power constraints. The RF transmitter block would probably include some standard digital circuitry for generating the spread-spectrum signaling code (to improve data security and robustness), but would consist primarily of high-speed bipolar or CMOS devices to implement the oscillator, mixer, and RF amplifier circuits. Thus, at least initially, three distinct types of chips will be required to realize a practical sensor/telemetry package.

The development team also possesses a strong background in RF communications systems, including direct experience with numerous satellite-linked data collection systems of the National Aeronautics and Space Administration (NASA). A current internal ORNL R&D program is developing specialized RF ASICs to support a wide range of remote data-collection tasks for scientific, industrial, and military applications.

Oak Ridge also has leading-edge programs in high-energy thin-film batteries and in other novel energy sources, including techniques for extracting power from the local environment. Finally, the deployment of systems to measure wind, current, and temperature profiles and atmospheric EM/EO propagation characteristics will necessitate the use of wide-spaced arrays of sensors. In the most likely scenario, these devices would be networked via local RF (wireless) links to a central data concentrator platform, which would then combine the data from the individual sensors, process it, and forward it, as necessary to its final destination.

Validation, Testing, and Calibration

Initial test and evaluation of the new instruments will be accomplished at ORNL in an existing temperature and humidity chamber laboratory. Accuracy and precision will be explored by comparisons between existing sondes and laboratory-grade instruments across the range of simulated atmospheric conditions and altitudes. In addition, potential interferences, both environmental (e.g., water droplets) and electromagnetic, will be examined. When the prototype sensors are judged ready for field testing, the NOAA/ATDD, also based in Oak Ridge, Tennessee, will collaborate with ORNL to compare system performance with existing instruments. Collaboration with NOAA's new National Weather Service office in Morristown, Tennessee, is likely. The instruments can also be mounted on an existing instrumented light airplane operated by ATDD and tested at altitudes up to 5.5 km (18,000 ft) for extended periods.

Wireless Networks

A major requirement for the successful implementation of large-scale sensor arrays is to develop a robust, cost-efficient architecture to support the intelligent wireless networking of advanced sensors and controllers in environmental monitoring, waste management, site remediation, and ecoscientific R&D for the next decade and beyond. Reliable, affordable communications is an essential component in any distributed sensing system.

Spread-spectrum systems offer the flexibility of license-free operation in four distinct frequency bands (902-928 MHZ, 2400-2483.5 MHZ, 5150-5350 MHZ, and 5725-5825 MHZ) and can be deployed to accommodate high data rates concurrently with high link integrity (low error rates), even in the presence of moderate multipath effects and interfering signals. We are also beginning to develop additional advanced signal-processing methods that support improved multipath-rejection capabilities for “difficult” applications (e.g., boreholes, wells, and non-line-of-sight links), “smart” (auto-reconfiguring) RF network operation, and wireless linking of sensor arrays of diverse types. The links could also concurrently handle a wide range of sensor/control data rates and can be programmed to provide a user-controllable hierarchy to support various control- and sensor-signal priorities, degraded-mode control in the event of equipment failures, and continuous communication-system status analysis. The RF transceivers employed would be configured to operate over a wide range of power levels (e.g., milliwatts to watts), as dictated by the application, site layouts, terrain, etc. Intelligent control of the transmitter/receiver pairs (transceivers) would be handled by an integral microprocessor, which would provide automatic message queing, error-handling, traffic control, power management, and data compression/encryption. Individual “smart” sensors under this architecture could be remotely activated, polled, calibrated, reconfigured, and deactivated as dictated by the application. Commercially produced hardware, while not inexpensive, is beginning to be available for the two lower-frequency bands, in either *direct-sequence* or *frequency-hopping* formats; in addition, we are prepared to launch a concerted effort to develop specialized systems for government applications in the uppermost (>5 GHz) bands to exploit the higher security and data rates afforded by the larger frequency span allocated for that block of spectrum.

ORNL has considerable expertise in designing and implementing communication systems in the VHF, UHF, and microwave regions of the RF spectrum (both high and low power) and in analyzing related systems issues such as spectral management, interference avoidance, RF and electromagnetic effects on existing instrumentation and computer-based systems, and network and link reliability engineering.

Recent estimates of total capital costs (including system design engineering, procurement, installation, certification, and documentation) have placed the expense of standard instrumentation cabling for a typical DOE facility at roughly $500/foot, and future wiring costs are bound to increase. On the other hand, RF system prices are already falling as the overall industrial market for wireless data transmission begins to accelerate.

In addition, RF links enjoy unparalleled flexibility of deployment in field data-acquisition tasks (such as environmental monitoring in remote locations or in temporary setups); further, RF signals can often penetrate concrete building walls and floors when necessary to establish short-range communications paths. Use of RF-based technologies can circumvent the need to install cabling, conduits, junction boxes, and related hardware in hazardous, radiation, and/or contamination areas, thus drastically lowering potential personnel exposures, processing of work permits and other documentation, and overall project costs and durations. Real-time RF networking of key facility information to central monitoring and control points can also provide marked improvements in data quality, personnel safety and accountability, environmental compliance, and facility management efficiency, as well as obvious benefits in emergency situations of all types.

The development of advanced RF ASIC devices has the potential of reducing per-point measurement costs into the under-$100 range and should be easily commercializable, which would additionally reduce long-term research and environmental-related costs for U.S. Department of Energy sites.

Conclusion

A $2M investment at ORNL is expected to produce a new class of sensors capable of being adapted to making meteorological measurements for very low cost. The light weight, high performance and low power requirements offer unique advantages that could significantly reduce the cost of operating ARM sites around the world. Integrating the telemetry stage with the sensor provides instantaneous upgrades to existing systems and simplified operation, maintenance, and calibration. The Oak Ridge team is committed to the deployment of this new class of sensor technology for industrial and government mission-related applications.

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