

thin-film sensor is meant for detection of low concentrations of NO gas, mainly in the ppb or lower range, and is being developed concurrently with other sensor technology for multi-species detection.

This development demonstrates that ITO is a sensitive sensing material for NO detection. It also provides crucial

information for future selection of nanostructured and nanosized NO sensing materials, which are expected to be more sensitive and to consume less power.

*This work was done by Jennifer C. Xu and Gary W. Hunter of NASA Glenn Research Center, José M. Gonzalez III of Gilcrest at NASA GRC, and Chung-Chiun*

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*Inquiries concerning rights for the commercial use of this invention should be addressed to NASA Glenn Research Center, Innovative Partnerships Office, Attn: Steven Fedor, Mail Stop 4-8, 21000 Brookpark Road, Cleveland, Ohio 44135. Refer to LEW-18782-1.*

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## Gas Composition Sensing Using Carbon Nanotube Arrays

**Lightweight sensor provides measurements as accurate as conventional methods.**

*Ames Research Center, Moffett Field, California*

This innovation is a lightweight, small sensor for inert gases that consumes a relatively small amount of power and provides measurements that are as accurate as conventional approaches. The sensing approach is based on generating an electrical discharge and measuring the specific gas breakdown voltage associated with each gas present in a sample.

An array of carbon nanotubes (CNTs) in a substrate is connected to a variable-pulse voltage source. The CNT tips are spaced appropriately from the second electrode maintained at a constant voltage. A sequence of voltage pulses is applied and a pulse discharge breakdown threshold voltage is estimated for one or more gas components, from an analysis of the current-voltage characteristics.

Each estimated pulse discharge breakdown threshold voltage is compared with known threshold voltages for candidate gas components to estimate whether at least one candidate gas component is present in the gas. The procedure can be repeated at higher pulse voltages to estimate a pulse discharge breakdown threshold voltage for a second component present in the gas.

The CNTs in the gas sensor have a sharp (low radius of curvature) tip; they are preferably multiwall carbon nanotubes (MWCNTs) or carbon nanofibers (CNFs), to generate high-strength electrical fields adjacent to the tips for breakdown of the gas components with lower voltage application and generation of high current. The sensor system

can provide a high-sensitivity, low-power-consumption tool that is very specific for identification of one or more gas components. The sensor can be multiplexed to measure current from multiple CNT arrays for simultaneous detection of several gas components.

*This work was done by Jing Li and Meyya Meyyappan of Ames Research Center. Further information is contained in a TSP (see page 1).*

*This invention has been patented by NASA (U.S. Patent No. 7,426,848). Inquiries concerning rights for the commercial use of this invention should be addressed to the Ames Technology Partnerships Division at (650) 604-5238. Refer to ARC-15460-1.*

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## Sensor for Boundary Shear Stress in Fluid Flow

**These sensors can be used in automobiles, airplanes, and ocean engineering.**

*NASA's Jet Propulsion Laboratory, Pasadena, California*

The formation of scour patterns at bridge piers is driven by the forces at the boundary of the water flow. In most experimental scour studies, indirect processes have been applied to estimate the shear stress using measured velocity profiles. The estimations are based on theoretical models and associated assumptions. However, the turbulence flow fields and boundary layer in the pier-scour region are very complex and lead to low-fidelity results. In addition, available turbulence models cannot account accurately for the bed roughness effect.

Direct measurement of the boundary shear stress, normal stress, and their fluctuations are attractive alternatives.

However, most direct-measurement shear sensors are bulky in size or not compatible to fluid flow.

A sensor has been developed that consists of a floating plate with folded beam support and an optical grid on the back, combined with a high-resolution optical position probe. The folded beam support makes the floating plate more flexible in the sensing direction within a small footprint, while maintaining high stiffness in the other directions. The floating plate converts the shear force to displacement, and the optical probe detects the plate's position with nanometer resolution by sensing the pattern of the diffraction field of the grid through a glass window. This con-

figuration makes the sensor compatible with liquid flow applications.

Most shear boundary fluid sensors using a direct measurement method include a floating plate and a position sensor. The plate moves under the shear force. To obtain high sensitivity, the floating part of the plate is supported with a structure flexible in the sensing direction and stiff in other directions. The structure could be in plane with the plate or out of plane. The in-plane support structure has an advantage to be fabricated by micromachining technology. The flexible support requires long beams and results in a large footprint. This approach applied a folded beam support to the floating plate design. The

folded beams allow a much smaller footprint to achieve the same flexibility as the conventional configuration.

The breadboard sensor was tested in a water tank testbed. The testbed includes a “false bottom” plate and a running conveyor belt. The false bottom plate simulates the riverbed, and provides an opening for attaching the sensor mounting plate and an air pocket for separating the encoder from the water. The running belt is placed parallel to the direction of measurement, and is placed on a structure different than the false bottom for vibration isolation. The belt was running at controlled speed of up to 2 m/s in both forward

and opposite directions, about 38 mm above the false bottom plate where the sensor was mounted. An average position change is about 620 nm, corresponding to a change in direction of the boundary shear stress. The fluctuation is believed to be caused by the turbulence of the flow.

Another flexure with a 3D configuration was proposed as well. The 3D version was designed to allow for a plate to rotate about an axis defined by three sets of flexures. The plate is mounted on a beam that passes through this axis and extends on the other side of the axis where it has a free end. An optical or capacitive sensor would read the displacement of the free

end of the beam, which would be used with the flexure’s stiffness to calculate the shear force on the sensor plate. This configuration could use the horizontal blade to separate the test media, such as water, from the optical or capacitive sensor, but would present more manufacturing and packaging challenges.

*This work was done by Xiaoqi Bao, Mircea Badescu, Stewart Sherrit, Yoseph Bar-Cohen, Shyh-Shiuh Lih, Zensheu Chang, and Brian P. Trease of Caltech; Kornel Kerenyi of the Federal Highway Administration; and Scott E. Widholm and Patrick N. Ostlund of Cal Poly Pomona for NASA’s Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1). NPO-47812*

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## Model-Based Method for Sensor Validation

*NASA’s Jet Propulsion Laboratory, Pasadena, California*

Fault detection, diagnosis, and prognosis are essential tasks in the operation of autonomous spacecraft, instruments, and *in situ* platforms. One of NASA’s key mission requirements is robust state estimation. Sensing, using a wide range of sensors and sensor fusion approaches, plays a central role in robust state estimation, and there is a need to diagnose sensor failure as well as component failure. Sensor validation can be considered to be part of the larger effort of improving reliability and safety.

The standard methods for solving the sensor validation problem are based on

probabilistic analysis of the system, from which the method based on Bayesian networks is most popular. Therefore, these methods can only predict the most probable faulty sensors, which are subject to the initial probabilities defined for the failures.

The method developed in this work is based on a model-based approach and provides the faulty sensors (if any), which can be logically inferred from the model of the system and the sensor readings (observations). The method is also more suitable for the systems when it is hard, or even impossible, to find the probability functions

of the system. The method starts by a new mathematical description of the problem and develops a very efficient and systematic algorithm for its solution. The method builds on the concepts of analytical redundant relations (ARRs).

*This work was done by Farrokh Vatan of Caltech for NASA’s Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1).*

*The software used in this innovation is available for commercial licensing. Please contact Daniel Broderick of the California Institute of Technology at [danielb@caltech.edu](mailto:danielb@caltech.edu). Refer to NPO-47574.*