The top part of the figure depicts a skin containing a two-dimensional array of sensor nodes. Each sensor node contains (1) a temperature sensor; (2) a combination of force sensors that have different stiffnesses and that, in combination, provide information on both contact force and hardness; and (3) a thermal-flux sensor.

The gaps between the sensor nodes contain strain gauges, which serve as auxiliary sensors for measuring bending of the sensor skin: The strains measured by the strain gauges can be used to estimate the three-dimensional configuration of the skin and, hence, the three-dimensional location of each sensor node. In addition to enabling the assignment of sensory data to specific locations, this three-dimensional information can be useful for measuring and/or controlling the movement of an instrumented object.

A sensor skin like this one is typically fabricated on a 2-mil (≈0.05-mm)-thick polyimide substrate, which affords a combination of flexibility, robustness, and low material cost. Patterned thin metal films are used as piezoresistors, heaters, and temperature transducers, which serve as building blocks of sensors. The sensors and associated circuitry are formed by microfabrication techniques that do not involve high temperatures. Some of these techniques are adapted from fabrication of integrated circuits on rigid substrates, while others have been developed specifically for use on flexible polymeric substrates.

The bottom part of the figure depicts a multimodal sensor node that is one of many such nodes arrayed in a flow-sensing skin. The node contains (1) a pressure sensor comprising a strain gauge on a surface-micromachined parylene diaphragm, (2) a shear-stress sensor comprising a thermoresistor on another surface-micromachined parylene diaphragm, (3) a trio of surface-micromachined hot-wire anemometers for measuring flow velocity in three dimensions, and (4) a pair of surface-micromachined hair-cell sensors for measuring flow velocity in two dimensions along the skin.

The hair-cell sensors are particularly noteworthy inasmuch as they implement an approximation of the same sensory principle as that of flow-sensing cilia of fish. A cilium is bent by an amount proportional to the flow to which it is exposed. In the artificial sensor skin, the bending of an artificial cilium is measured by means of a strain gauge at its base.

This work was done by Chang Liu of the University of Illinois at Urbana-Champaign for **Goddard Space Flight Center**.

In accordance with Public Law 96-517, the contractor has elected to retain title to this invention. Inquiries concerning rights for its commercial use should be addressed to:

University of Illinois at Urbana-Champaign
319 Ceramics Bldg, MC-243
105 South Goodwin Avenue
Urbana, IL 61801

Refer to GSC-14821-1, volume and number of this NASA Tech Briefs *issue, and the page number.*

Artificial Hair Cells for Sensing Flows

Small, robust sensors can be fabricated on a variety of substrates.

Goddard Space Flight Center, Greenbelt, Maryland

The purpose of this article is to present additional information about the flow-velocity sensors described briefly in the immediately preceding article. As noted therein, these sensors can be characterized as artificial hair cells that implement an approximation of the sensory principle of flow-sensing cilia of fish: A cilium is bent by an amount proportional to the flow to which it is exposed. A nerve cell at the base of the cilium senses the flow by sensing the bending of the cilium. In an artificial hair cell, the artificial cilium is a microscopic cantilever beam, and the bending of an artificial cilium is measured by means of a strain gauge at its base (see Figure 1).

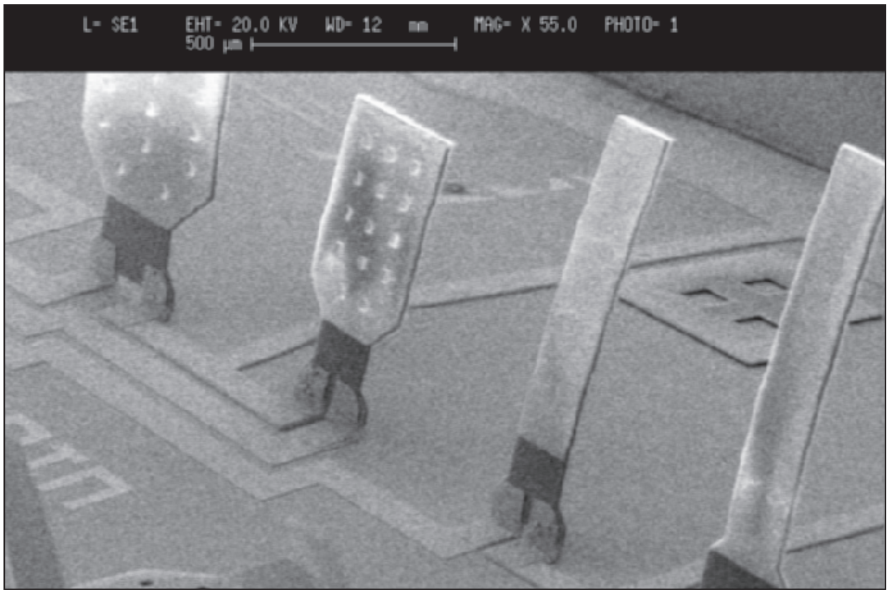

Figure 1. **Artificial-Hair-Cell Flow Sensors** shown in this scanning electron micrograph have several different widths as well as different heights ranging from 0.6 to 1.5 mm.

Figure 2 presents cross sections of a representative sensor of this type at two different stages of its fabrication process. The process consists of relatively-low-temperature metallization, polymer-deposition, microfabrication, and surface-micromachining subprocesses, including plastic-deformation magnetic assembly (PDMA), which is described below. These subprocesses are suitable for a variety of substrate materials, including silicon, some glasses, and some polymers. Moreover, because it incorporates a polymeric supporting structure, this sensor is more robust, relative to its silicon-based counterparts. The fabrication process consists mainly of the following steps:

1. A 0.5-µm-thick sacrificial layer of Al is deposited (by evaporation) and patterned on a substrate.
2. A 5.8-µm-thick layer of a photodefinable polyimide is spun on and patterned photolithographically. The polyimide is

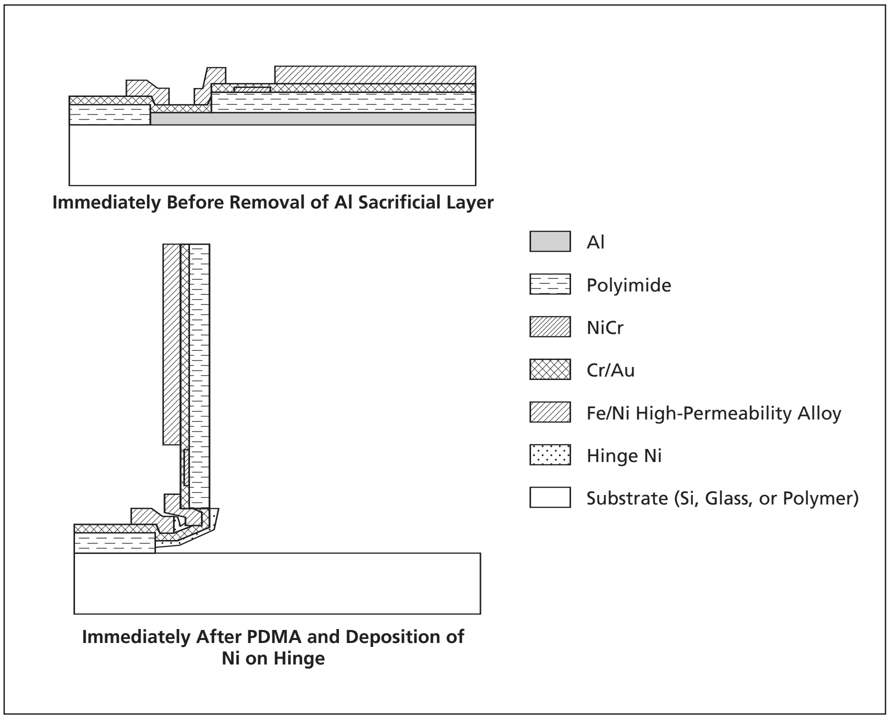

Figure 2. **The Cantilever Remains Horizontal** during most of the fabrication process. It is released by etching away the aluminum sacrificial layer, then raised to its perpendicular orientation by PDMA.

cured in a 1-torr (≈133-Pa) atmosphere of N_2 for 2 hours at a temperature of 350 °C (this is the highest temperature used in the fabrication process).

3. A 750-Å-thick layer of NiCr, intended to serve as the electrically resistive transducer in the strain gauge, is deposited by electron-beam evaporation.
4. A layer of Au/Cr 0.5 µm thick, from which the strain-gauge electrical leads and a bending hinge are to be formed, is deposited by evaporation.
5. A portion of the Au/Cr layer also serves as a seed layer for electrodeposition of a 5-µm-thick layer of a highly magnetically permeable Fe/Ni alloy. Once this alloy has been deposited, the remaining unused Au/Cr is removed by lift-off.
6. A 1.8-µm-thick polyimide film (omitted from the figure) is deposited to form a protective coat on the Fe/Ni alloy layer and the NiCr strain gauge.
7. The workpiece is placed in a basic solution for more than a day to etch away the sacrificial layer of Al.
8. The workpiece is rinsed, then placed in an electroplating bath. A magnetic field is applied to pull up on the Fe/Ni layer, thereby bending the cantilever upward at the hinge. While the magnetic field remains thus applied, Ni is electrodeposited onto the Au/Cr hinge to a thickness of ≈10 µm, thereby reinforcing the hinge and fixing the cantilever perpendicular to the substrate.

This work was done by Chang Liu and Jack Chen of the University of Illinois at Urbana-Champaign for **Goddard Space Flight Center**.

In accordance with Public Law 96-517, the contractor has elected to retain title to this invention. Inquiries concerning rights for its commercial use should be addressed to

University of Illinois at Urbana-Champaign
Office of Technology Management
319 Ceramics Building, MC-243
105 South Goodwin Avenue
Urbana, IL 61801

Refer to GSC-14812-1, volume and number of this NASA Tech Briefs *issue, and the page number.*

Video Guidance Sensor and Time-of-Flight Rangefinder

A prior VGS would be modified to incorporate the rangefinder function.

Marshall Space Flight Center, Alabama

A proposed video guidance sensor (VGS) would be based mostly on the hardware and software of a prior Advanced VGS (AVGS), with some additions to enable it to function as a time-of-flight rangefinder (in contradistinction to a triangulation or image-processing rangefinder). It would typically be used at distances of the order of 2 or 3 kilometers, where a typical target would appear in a video image as a single blob, making it possible to extract the direction to the target (but not the orientation of the target or the distance to the target) from a video image of light reflected from the target.

As described in several previous *NASA Tech Briefs* articles, an AVGS system is an optoelectronic system that provides guidance for automated docking of two vehicles. In the original application, the two vehicles are spacecraft, but the basic principles of design and operation of the system are applicable to aircraft, robots, objects maneuvered by cranes, or other objects that may be required to be aligned and brought together automatically or under remote control. In a prior AVGS system of the type upon which the now-proposed VGS is largely based, the tracked vehicle is equipped with one or more passive targets that reflect light from one or more continuous-wave laser diode(s) on the tracking vehicle, a video camera on the tracking vehicle acquires images of the targets in the reflected laser light, the video images are digitized, and the image data are processed to obtain the direction to the target.

The design concept of the proposed VGS does not call for any memory or processor hardware beyond that already present in the prior AVGS, but does call for some additional hardware and some additional software. It also calls for assignment of some additional tasks to two subsystems that are parts of the prior VGS: a field-programmable gate array (FPGA) that generates timing and control signals, and a digital signal processor (DSP) that processes the digitized video images.

The additional timing and control signals generated by the FPGA would cause the VGS to alternate between an imaging (direction-finding) mode and a time-of-flight (range-finding mode) and would govern operation in the range-finding mode. In the direction-finding mode, the VGS would function as described