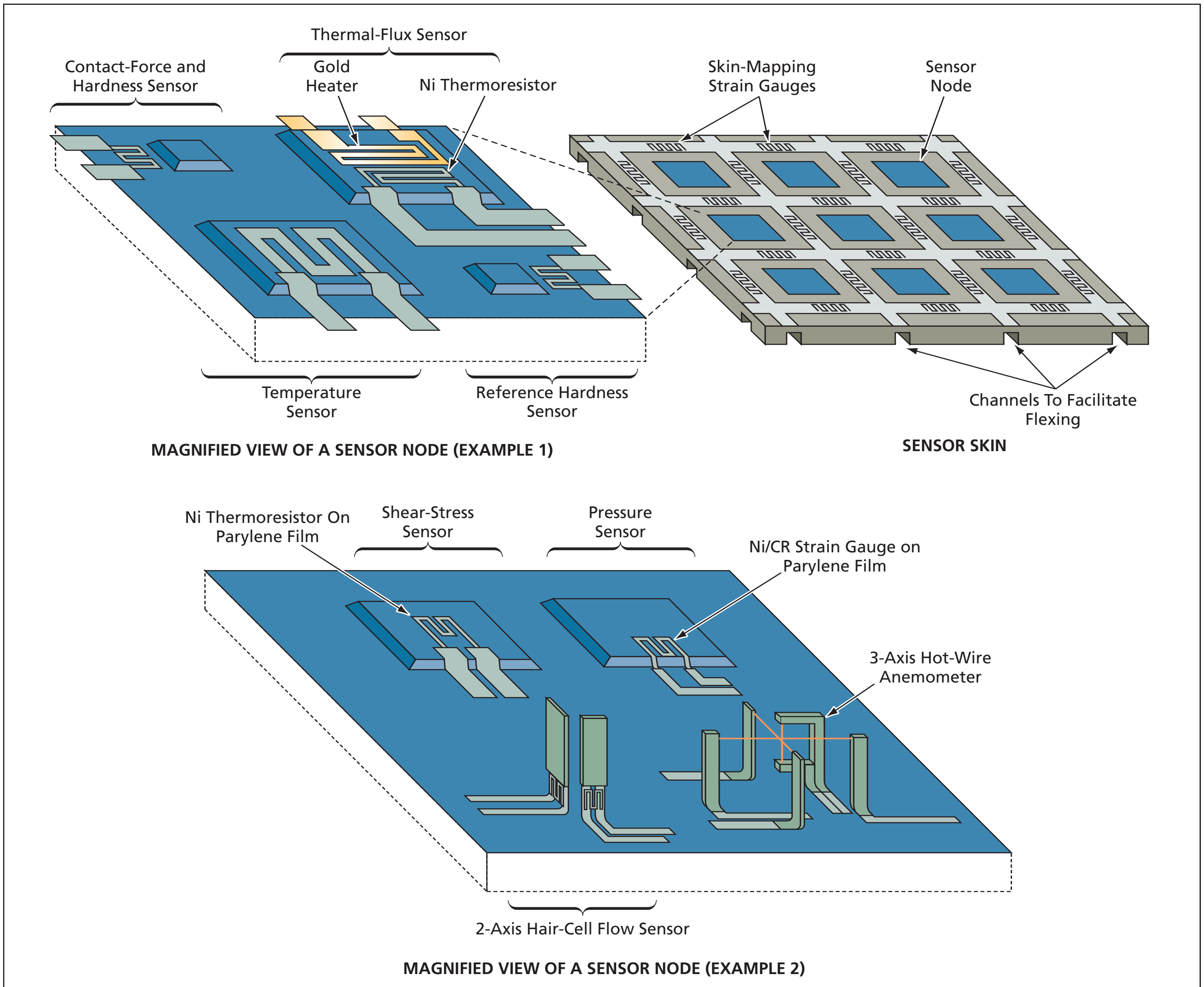
Flexible Skins Containing Integrated Sensors and Circuitry

Densely arrayed tactile sensors measure multiple, spatially registered physical quantities simultaneously.

Goddard Space Flight Center, Greenbelt, Maryland

Artificial sensor skins modeled partly in imitation of biological sensor skins are undergoing development. These sensor skins comprise flexible polymer substrates that contain and/or support dense one- and two-dimensional arrays of microscopic sensors and associated microelectronic circuits. They afford multiple tactile sensing modalities for measuring physical phenomena that can include contact forces; hardnesses, temperatures, and thermal conductivities of objects with which they are in contact; and pressures, shear stresses, and flow velocities in fluids. The sensor skins are mechanically robust, and, because of their flexibility, they can be readily attached to curved and possibly moving and flexing surfaces of robots, wind-tunnel models, and other objects that one might seek to equip for tactile sensing.

Because of the diversity of actual and potential sensor-skin design criteria and designs and the complexity of the fabrication processes needed to realize the designs, it is not possible to describe the sensor-skin concept in detail within this article. Instead, an approximation of the concept is illustrated here by means of the following two examples:



A **Sensor Skin** contains an array of sensor nodes, each node containing multiple sensors that measure different quantities. The sensor nodes shown here are examples only: the variety of potential sensor-node designs is practically unlimited.

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**.

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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).

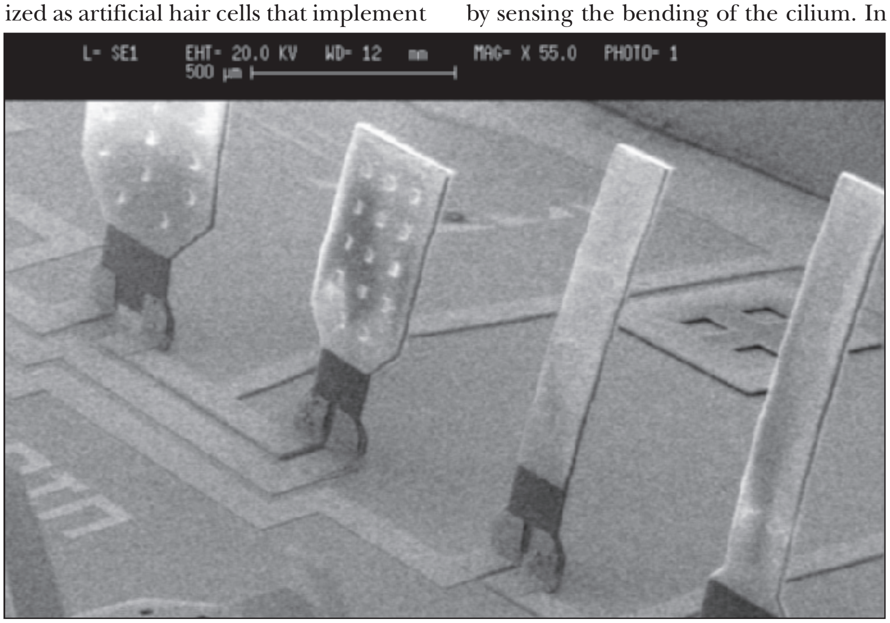

Figure 1. **Artificial-Hair-Cell Flow Sensors** shown in this scanning electron micrograph have several different widths as well as different heights ranging from 0.6 to 1.5 mm.

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