Biomimetic Hair Sensors: Utilizing the Third Dimension

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Abstract—**Nature and biology utilize a myriad of structures, materials, and schemes to achieve superb sensing performance with extreme reliability and robustness. One structure used more commonly in nature is the "hair". Hair-like sensors are used for acoustic, chemical, flow, pressure, and gas sensing, among others. Hair-like actuators and passive structures are also used for thermal management, filtering, fluid flow control, etc. This paper discusses opportunities and approaches for developing hair-like biomimetic structures for sensing. It discusses fabrication technologies for formation of 3-dimensional structures and creation of transduction functions on these hair structures, and proposes how electronics can be utilized to further improve the functionality of these sensors. A micro hair sensor for measuring air flow speed and direction based on hydraulic amplification is presented as an example of a biomimetic hair sensor.**

I. Introduction

With significant advances in fabrication technology, integrated electronics, packaging, and design/analysis techniques, the sensor community has continued to explore new approaches to develop sensors with improved performance, smaller size, lower-cost, and enhanced functionality. One of these approaches has been based on nature and biology, which utilize a myriad of structures, materials, and schemes to achieve superb performance with extreme reliability and robustness [1]. One structure used more commonly in nature is the "hair". Hair-like structures have taken many forms in nature and are used extensively to achieve a variety of functions including: sensing of flow, temperature, vibration, sound, etc., actuation for liquid manipulation and motion control among others, and many passive structures used for thermal control (cooling, heating, insulation) or environmental protection. Hair offers a number of attractive features that make it a desirable and generic platform for many applications: 1) large surface-volume ratio, allowing it to interact with the external environment efficiently, and also enabling more efficient insulation when flat, or heat removal when raised; 2) ability to be raised or retracted to accentuate/minimize its function; 3) easily modifiable mechanical structure and shape, thus providing a wide range of mechanical properties; 4) high aspect ratio, thus producing a very small foot print while providing a large mass and surface area, among others. These and other features potentially enable new functionality and improved sensor performance.

Several papers have reported sensors/actuators based on biomimetic hairs or hair cells. Using a polymer hair-like structure, Liu et al. [2] demonstrated a flow sensor that deflects in response to fluid flow with 4x4 array of cylindrical hairs of 500µm diameter and 3000 µm tall with sensitivities of about 0.1mm/sec. Different versions of artificial hairs have been made from PDMS and a polyurethane rubber. Krijnen et al. have developed capacitive hair-sensor arrays for air flow and acoustic sensing and utilized a variety of techniques to improve spatial and temporal sensitivity and performance [3]. Najafi et al. have used arrays of hair-like structures for mechanical and electrical interconnects for packaging and assembly applications [4]. Cilia and a variety of nanorods and nanofabrication technologies have been used for liquid motion, mimicking what is routinely done in biology [5,6]. As nanotechnology and nanofabrication techniques have expanded, researchers have further utilized large arrays of nanorods for some applications. In these cases, the hair-like structures are shorter (a few microns) than what is typically used in MEMS and microsensor applications, but they nonetheless offer the promise for improved performance. In this work, we propose and present new device structures and fabrication technologies for building hair-based biomimetic sensors and arrays.

II. Features of Biomimetic Hair Sensors

Biologic hair sensors provide excellent performance primarily because they utilize a combination of mechanical and neural structures to offer excellent sensitivity and wide dynamic range. For example, arrays of hair cilia used in the vestibular auditory system deflect in response to inertial forces. Although the deflection might be very small, the cilia provide excellent sensitivity because these small motions are

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detected through electrochemical synapses, which generate electrical signals that are transmitted to the central nervous system for further processing. The synaptic response is very sensitive, and extremely selective. Thus by utilizing a combination of mechanical sensing, local chemo-electric transduction, and sophisticated signal processing, hair sensors provide unique capabilities that are unmatched by any other sensor structure. Figure 1 shows the basic elements of what we propose to be critical components of highly functional, sensitive and selective hair sensors. The structure consists of: A) a core hair-like structure, which is characterized by its height being similar to or larger than its footprint; B) transducing elements that could be embedded within or formed outside of the hair structure to convert the non-electrical measurand of interest to an electrical signal (the transducer element might also be located on the substrate instead of the hair); C) electronic circuits located underneath/adjacent the hair structure to condition the transducer output signal and enable improved sensitivity and selectivity; D) signal processing and control electronics to process the output of an array of hair sensors and extract useful information. It is also important to note that biology utilizes feedback in very effective ways to further enhance sensitivity and selectivity to external parameters. Hair structures are also widely used as actuators [5,6]. Each of these components has specific features that when put together could provide unprecedented performance and functionality.

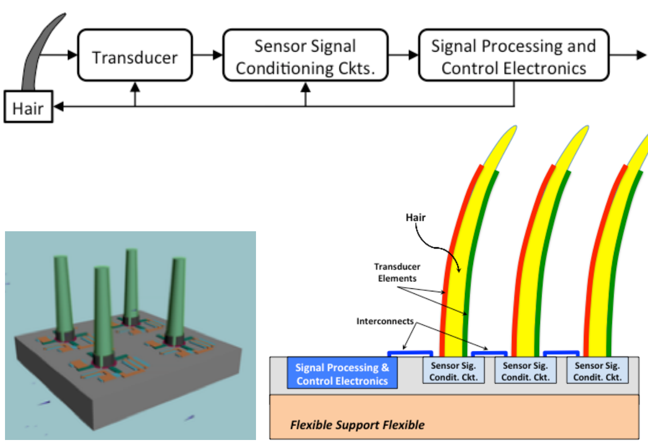

Figure 1: Biomimetic hair sensor structure.

A. Hair Structure:

The hair structure offers a number of advantages for sensing applications. First, the structure is tall, enabling it to interact with its environment because it provides a large surface area, and it uses the third dimension thus providing a very small footprint and excellent spatial resolution. The tall hair structure can also be used to mechanically amplify the signal of interest. Second, the hair's geometry can be tailored to a given application by changing its size, shape, cross-sectional geometry, and material properties. Third, arrays of hair sensors, each with different characteristics, can be used to enhance sensitivity and selectivity to different parameters, robustness and fault tolerance, and provide large area coverage. Fourth, individual, hair structures can be mechanically coupled together to further provide added features and functionality.

B. Transducers:

The hair structure serves as a mechanical substrate for interacting with its external environment. The response of the hair to the external parameter has to be converted to an electrical signal. For example, biology often performs this transduction function through chemical and neurotransmitter species that modulate the rate of firing of action potential in hair cells. This is achieved using different transducers. It is for example possible to incorporate transducer elements like thermocouples, piezoresistors or other conductive materials on either the hair structure itself, or underneath the hair structure on the substrate that supports it. It is also possible that the material of the hair element itself can perform the transduction function, for example using a piezoelectric or thermoelectric process.

C. Local Sense Circuits:

The electrical output from the hair-transducer combination is often very small and needs to be conditioned. All of the biomimetic hair sensors reported so far utilize remotely located electronic circuits, which often causes significant degradation in the overall performance. It is important that the sense and conditioning circuitry be located at the site of each hair sensor element. This will help reduce the effects of parasitics and enable improved sensitivity. This local circuitry can also perform many functions, such as improved selectivity through differential and common-mode signal processing, compensation for effects such as temperature, humidity, and vibration, and signal processing such as analog-digital conversion. Many sensor arrays, such as today's CMOS imagers, utilize this local circuitry to great advantage. Without the circuitry the function of these imaging arrays would not be possible due to both the very faint sensor signal and the large element numbers of these arrays. In biomimetic hair sensors, each of these sensing elements that combine the hair, the transducers, and the local circuitry can be referred to as "hexel", similar to the pixel, or the "picture element" in image sensors.

D. Signal Processing and Control Electronics

Because of their small footprint and 3D structure, hair structures can be formed in large arrays whose outputs can be monitored for specific response patterns that can provide very useful information. The electronics can also be used to provide feedback and other information back to the hair sensor or the array to optimize performance in specific ways. In addition, the control electronics can be used to control the operation of actuators. These actuators could be part of the sensing elements and activated to enhance the output of each sensor, or used for directly interfacing with the external environment, such as in locomotion.

E. Substrate:

The substrate that supports the hairs and the electronics can be made to be thin, or made of compliant materials so that the entire substrate can have mechanical flexibility and be able to conform to different form factors. Note that the sensing and processing circuitry could be located only under each hexel in its own substrate material, or housed inside a continuous semiconducting substrate, including polymers, that is thin enough for mechanical flexibility.

III. Fabrication Technologies

Biomimetic hair sensors can now be fabricated using a variety of technologies and materials. These technologies include DRIE silicon etching, polymer molding, metal electroforming, selective growth, inkjet printing, laser assisted polymerization and deposition, stamping, extrusion, and many other technologies that were traditionally used for forming macro scale structures. The hair structures can be either fabricated on a separate substrate and then transferred to a substrate containing the needed electronics through bonding or self-assembly, or can be directly formed on top of a circuit substrate. They can be formed vertically extending above the substrate, or horizontally on the plane of the substrate and then raised either mechanically or through a variety of actuating technologies. In the latter case, the hairs can be selectively actuated to stand on their ends or controlled to reach a specific vertical position to enhance their response. Examples of different fabrication technologies are provided in the cited references and in the final presentation.

IV. Example Hair Sensors for Air Flow Measurement

Hair structures are very effective in measuring air flow speed and direction. We have reported two different approaches for measuring air flow, one utilizes a very simple technology based on bond wires and thermal sensing [7], and the other on a new microhydraulic structure for hydraulic amplification of the signal and capacitive transduction [8].

A. Thermal Hair Air Flow Sensor:

A low-cost and high-performance hot-wire air flow sensor which utilizes a bond-wire as the sensing element has been demonstrated and shown in Figure 2 [7]. The bond wire, aluminum or platinum, can be attached to a substrate using standard wirebond techniques commonly used in the IC industry. The bond-wire extends above the surface of the substrate, is heated by passing a current through it, and changes its resistance in response to air flow. This hair-like hot-wire anemometer offers high accuracy, high sensitivity and wide dynamic range. Aluminum and platinum wire flow sensors have been successfully fabricated and achieved a measurement range from 2.5 $cm.s^{-1}$ to 17.5 $m.s^{-1}$, with an accuracy of 2 $mm.s^{-1}$ at low flow regime (<50 $cm.s^{-1}$) and 5 $cm.s^{-1}$ at high flow regime (>2 $m.s^{-1}$). Circuits for processing the output signal are fabricated for each sensor and provide improved performance. Future sensors could integrate the electronics right underneath the hair sensor and provide a much higher spatial and temporal resolution.

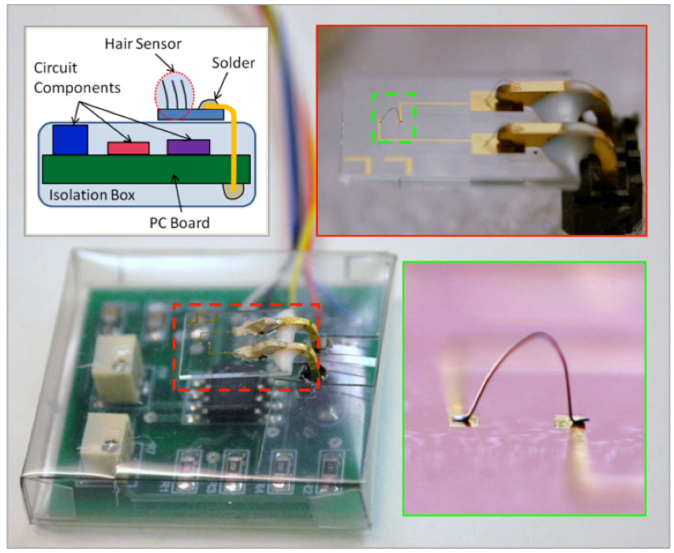

Figure 2: Hot-wire hair air flow sensor: right photos show the aluminum bond wire used as an anemometer, the right photos show the sensor and local hybrid electronics. Arrays of such sensors can also be fabricated [7].

B. Microhydraulic Hair Air Flow Sensor:

The sensitivity of the hair sensor can be significantly improved by using different transduction techniques, including piezoresistive, capacitive, and piezoelectric transduction. Of these, capacitive techniques often provide the highest sensitivity, smaller area, and lower power dissipation. Krijnen et al. have utilized capacitive sensing to achieve excellent performance for acoustic and air flow sensing [3]. In their structure, however, the sensitive capacitive transducer is exposed to the environment and could potentially pose problems in the presence of humidity. In addition, the dynamic and full-scale range of the sensor could be limited when high sensitivity is desired. In our approach, we have developed a new device structure that combines capacitive sensing and hydraulic amplification to achieve wide dynamic range and robustness. Hydraulic systems are frequently used in the macro scale for both actuation and mechanical amplification. We have developed technologies to form miniature hydraulic systems that utilize fluid amplification to enhance the sensitivity of the air flow sensor [9].

The basic structure of a micro-hydraulic capacitive air flow hair sensor is shown in Figure 3 [8]. It consists of two chambers on the front and backside of a silicon wafer connected by a channel. Both chambers and the channel are filled with a silicone fluid; the chambers are capped by a 1-2 μm layer of Parylene to enclose the micro-hydraulic system. Either chamber can be compressed by applying pressure to the flexible Parylene membrane on one side, thus forcing the liquid into the other chamber, causing its membrane to deflect. With a proper choice of the area ratio between the chambers, amplification of either force or displacement is achievable. This amplification, which is characteristic of the micro-hydraulic system, plays an essential role in improving sensor performance. A pair of electrodes on the backside can be used for electrostatic actuation or capacitive sensing.

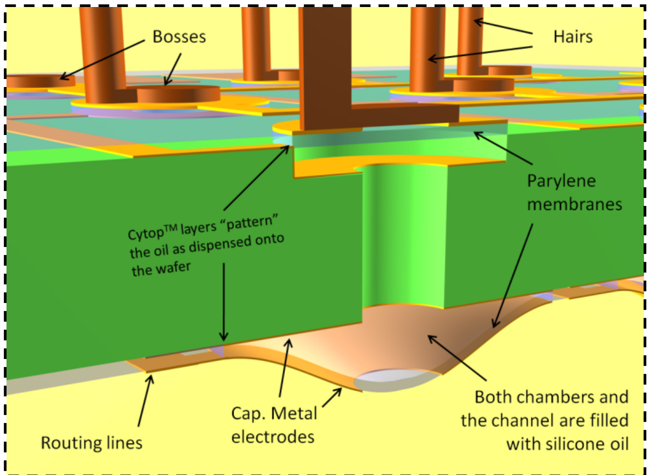

Figure 3. Micro-hydraulic structure with hairs attached on bossed membrane. The base structure consists of top and bottom chambers and a pair of electrodes on the bottom membrane for either electrostatic actuation or capacitive sensing. After integration of the boss, a silicone elastomer epoxy is used to attach the tall hair over the boss [9].

In order to make a hair flow sensor, a hair-like post is needed to convert drag force caused by flow into pressure that is applied on the membrane. We have used prefabricated pins attached to the front-side Parylene membrane with silicone elastomer epoxy. Figure 4 shows an array of four hairs used for sensing flow speed and direction. The microhydraulic chamber connecting the front to the back of the substrate is transparent and visible under each pin. These sensors offer a large air flow speed measurement range, high sensitivity and high bandwidth of about 30 Hz. The sensor responds linearly to increasing flow speed from 0 to 15 m/s, the sensitivity is estimated to be slightly over 2 cm/s. Further improvements can be made with integrated electronics, batch fabrication hair arrays, and device optimization.

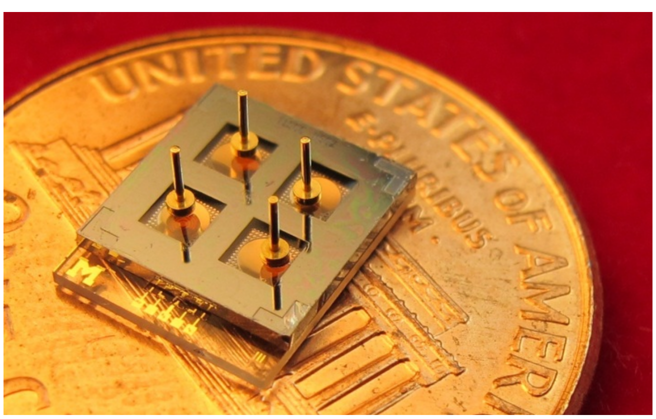

Figure 4. Hairs attached on top of a 4-cell micro-hydraulic system, shown on a US penny [8].

V. Conclusions

MEMS sensors can be improved by utilizing techniques used in nature. One structure used extensively is the hair. Hair-based sensors and actuators have 3-dimensional features that make them suitable for many emerging applications. The tall and small-footprint hair still provides a large mass and large surface to volume ratio, and has ability to incorporate different materials to fit a particular application. Today's micro and nano-fabrication technologies make possible a myriad of geometries, materials and integration options. Large arrays of hair structures can be utilized to improve sensitivity, enhance selectivity, offer redundancy and robustness, increase dynamic range, and enhance functionality. The combination of the hair structure, efficient transduction techniques, and integrated electronics provides many desirable features. Large arrays of sensors can be fabricated in either extremely small areas, thus lowering cost, or on large distributed surfaces, thus increasing coverage. The hair structure can be used as a sensor, an actuator, and or passively used for achieving functions such as thermal management or filtering. Future MEMS will certainly incorporate many features that hair structures have to offer.

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