ABSTRACT
Boundary layer flow imaging can provide real time information for flight control of air vehicles, and collision avoidance and stealth detection of underwater vehicles. High density, micro-scaled sensor arrays based on microfabrication techniques have made it possible to enable these new applications. We report on the development of such a flow sensor array. It is realized by combining surface micromachining and three-dimensional assembly. It consists of a linear array of 16 integrated hot-wire anemometers (HWA) evenly spaced 1 mm apart. Each sensor uses a 400 µm long thermal element (hot-wire) that is made of a thin film nickel/polyimide composite, and is elevated 600 µm above the substrate. Under constant temperature (CT) mode, the threshold velocity sensitivity to water flow is down to 100 µm/s, and the frequency response to dynamic signals is up to 1000 Hz. The capabilities of the sensor array on boundary flow measurement and hydrodynamic wake imaging are demonstrated via wind tunnel and water channel experiments.

INTRODUCTION
Hot-wire anemometry is a well-established technique for fluid flow sensing [1]. Conventional HWA sensors have been widely employed for aerodynamics and fluid mechanics studies, but their use is limited by several major drawbacks. First, the fabrication and assembly processes are delicate and do not guarantee uniformity of performance. Secondly, it is prohibitively difficult to form large and dense arrays of HWA for flow field imaging. Furthermore, they are mainly used in laboratory research, and the transition to commercial practice and field use is difficult.

In the past decade, efforts have been made on applying a variety of microfabrication processes to realize HWAs [2-5]. However, those micromachined HWAs are almost “flush-mounted” to the surface of the substrate. The sensing elements reside on the substrate surface instead of being out-of-plane. Consequentially, insufficient thermal isolation becomes inevitable, that directly degrades the frequency response to dynamic measurements. Besides, the flush-mounted sensing elements are only capable of measuring shear stress of flow along solid surface (boundary); they lack the ability to provide rich information beyond the surface limits their applications.

To overcome the issues mentioned above, we developed a new type of micromachined HWA sensor array [6]. It was based on surface micromachining technique in conjunction with a unique three-dimensional assembly method. The resulting sensor array is capable of flow field imaging with high spatial-temporal resolution. This differs from laser-Doppler velocimetry (LDV), which permits high temporal resolution for only pointwise flow measurements, and also differs from particle image velocimetry (PIV), which allows flow field measurements but with low temporal resolution. In addition, with integrated on-chip constant-temperature feedback circuits, the sensor array can be easily applied to different platforms, such as to Unmanned Air Vehicles (UAV) for flight control, and to Autonomous Underwater Vehicles (AUV) and submarines for collision avoidance and stealth tracking.
**FABRICATION PROCESS**

Surface micromachining is used to define individual HWAs, including two support prongs, and a hot-wire sensing element. The hot wire consists of a nickel filament that is sandwiched by two layers of polyimide, which serve as passivation and structural support. It exhibits a temperature coefficient of resistance \( (\alpha) \) of 4,100 ppm/°C. The surface micromaching process starts with deposition of an aluminum sacrificial layer followed by a spun-on of photo-definable polyimide. Nickel resistors and gold wiring are then deposited and patterned using lift-off. After that, permalloy flap is electroplated, followed by sacrificial layer etching. The top image in Fig. 1 shows an individual HWA sensor after these surface micromachining steps.

To elevate the hot-wire sensing element out of plane, a magnetically-assisted assembly step is applied [7]. It plastically deforms the gold hinge at the base of a prong, and raises the sensing element to a specified elevation. This process is immediately followed by a selective nickel deposition to reinforce the gold hinge. The bottom image in Fig. 1 shows a HWA sensor after three-dimensional magnetic assembly. After that, individual sensors are monolithically integrated with signal processing electronics. This process is performed under room temperature and does not cause incompatibility with elements of electronics circuits. At the end of the process, the HWA sensor array is encapsulated by a conformally deposited, 2 µm thick Parylene film for water proofing and further structure strengthening.

![Figure 1. Schematic of individual HWA sensor. The top one is before three-dimensional assembly, and the bottom one is after three-dimensional assembly.](image1)

![Figure 2. Schematic (top) and scanning electron micrograph (bottom) of HWA sensor array. It consists of 16 HWA sensors spaced 1 mm apart.](image2)

Because of the use of photolithography process, micromachined HWA sensors can have wire length from as small as 50 µm to as long as 400 µm. For present application, we focused on wire length of 400 µm and elevation of approximately 600 µm. Miniaturizing the hot wire element and increasing its elevation present several advantages, including large electrical resistance and reduced thermal conduction loss to the substrate heat sink. The miniaturization of the sensing element also eliminate unwanted disturbance to the flow field. The yielded sensor array consists of 16 HWA sensors arranged in a linear format with spacing of 1 mm, as shown in Fig. 2. We have designed custom circuits and data acquisition system to perform parallel channel data acquisition.
CHARACTERIZATION AND CALIBRATION

For dynamic measurement of turbulent flow, it is important to characterize the frequency response (bandwidth) of an HWA sensor under test. This has been achieved by exposing a sensor to a steady water flow, applying a small sinusoidal voltage disturbance $v_{in}$ to the constant-temperature feedback circuit of the sensor, and then characterizing the ratio of output response $v_{out}$ to input $v_{in}$ in frequency domain [6]. Fig. 3 shows the frequency response of a HWA sensor, which was operated under constant temperature (CT) mode in water, with overheat ratio of 0.05 and water velocity of 0.3 m/s. It can be seen that the ratio $v_{out}/v_{in}$ increases slowly in a wide frequency range below 1000 Hz; such large bandwidth is necessary to ensure accurate measurements of unsteady and turbulent flow.

The threshold velocity sensitivity of an individual sensor is another important parameter for flow sensing. In order to achieve extremely low flow velocity with high flow quality for this characterization, experiments were conducted in quiescent water by moving a HWA sensor through a precision translation stage (Newport Corporation, model IMS600PP). In each run the translation speed maintains constant during measurement; for different runs the speed varies. From the top plot of Fig. 4, it can be seen that with the speed below 0.2 mm/s, the sensor output remains nearly constant with a very small irregular variation. After this threshold, however, the sensor output monotonously increases with increasing speed. This threshold value defines the threshold velocity sensitivity of the characterized HWA sensor; that is 0.2 mm/s.

For comparison purpose, a conventional HWA sensor (Dantec Dynamics, model 55R11) has also been tested under the same conditions and with the same overheat ratio (0.1). The results are presented in the bottom plot of Fig. 4. It is evident that the sensor output starts to follow translation speed at a threshold of 1 mm/s, which is five times higher than the above micromachined HWA sensor.

The micromachined HWA sensor array is further calibrated in both a wind tunnel (Omega Engineering Inc., model WT-4401) and a water channel (ELD Inc., model 501) to examine its performance in different media. An overheat ratio of 0.1 was used in both cases. The top plot of Fig. 5 shows calibration results from the wind tunnel. It is evident that for all 16 HWA sensors, the calibration curves match well. This indicates that micromachining processes have guaranteed a superior uniformity of the array performance. Also noteworthy is that a typical nonlinear trend of flow velocity versus voltage output, which occurs to conventional HWA sensor, was shown very well by the micromachined HWA sensors.

In contrast, from the bottom plot of Fig. 5, it can be seen that calibration curves of the 16 HWA sensors in water channel scatter in certain range, although the nonlinearity trend remains. This is caused by impurities in water, e.g., minerals, which were coated on the surface of sensing filaments of individual sensors, and thereby undermined the array’s uniform sensitivity. In fact, before this calibration, the same sensor array has been employed for other experiments in water for quite a while without special cleaning treatment. Yet, this degraded sensitivity uniformity does not affect accurate measurements, as long as the sensor array is carefully calibrated beforehand.
BOUNDARY LAYER MEASUREMENTS

Upon characterization and calibration, the micromachined HWA sensor array was employed for flat plate boundary layer measurement in the wind tunnel. Figure 6a shows the experimental setup. The sensor array was mounted to a PC board that generated a boundary layer flow at a inflow velocity of 5 m/s. The sensor array was oriented along the streamwise direction. To avoid flow separation at the leading edge of the PC board, an angle of attack of 3° was applied. According to the boundary layer theory, boundary layer thickness along a flat plate grows at a rate of $x^{0.5}$ for laminar boundary flow and $x^{0.2}$ for turbulent boundary flow, where $x$ is the streamwise distance from the leading edge of the plate to the measuring point [8]. In both cases, at the same elevation inside the boundary layer, velocity decreases with increasing distance $x$, due to the growth of boundary layer thickness. From Fig. 6b it can be seen that the decreasing trend has been achieved by the HWA sensor array. However, the measurement results might have been affected to some extent by two facts – flow disturbances and heat convection originated from upstream sensors and measured by downstream sensors. Employing a sensor array with diagonal arrangement to the inflow can minimize such effects.

WAKE MEASUREMENTS

To further demonstrate the capability of micromachined HWA sensor array on flow imaging, experiments were conducted in the water channel to measure a hydrodynamic wake. As shown in Fig. 7a, the wake was generated by a circular cylinder exposed in uniform flow; it consisted of alternately shed large-scale vortices known as a Kármán Street [9]. The diameter of the cylinder is 25 mm, and the inflow velocity is 0.2 m/s. Thus the corresponding Reynolds number is approximately 5000. The HWA sensor array was exposed in the wake behind the cylinder, and was oriented perpendicular to the inflow and to the axis of the cylinder. The PC board holding the substrate where sensors resided was tilted at an angle of attack of 5° to suppress flow separation from the leading edge on the sensor side. In order to image the wake signature, the HWA sensor array was traversed back and forth across the wake when it was moved downstream (Fig. 7a). Systematic measurements on velocity fluctuation were conducted at stepped longitudinal and transverse positions of the wake, with each measurement providing 16 channel outputs simultaneously in a width of 0.6D (D – diameter of the cylinder) across the wake, and an overall scanning of 3.5D in width and 6D in length.
Based on the measured results along the entire wake, a distribution of rms velocity was extracted, as shown in Fig. 7b. It is evident that the rms velocity pattern contains the main feature of a cylinder wake, as was revealed by experimental and computational fluid dynamics studies [10]. In details, there is a dramatic change when going across one of the dual peaks in the near wake, and moderate change with overall high turbulence level when traversing the wake further downstream. This feature could allow an HWA sensor array to track a hydrodynamic trail using signal processing techniques.

**POTENTIAL APPLICATIONS**

**Ground testing of aerospace vehicles.** As a type of flow sensors, microfabricated hot-wire sensors can be widely used for wind tunnel testing of all kinds of aerospace vehicles, as well as for experimental studies on aerodynamics and fluid mechanics. The dense distribution of individual sensors makes them superior on providing high resolution local flow patterns, spatially and temporally. This capability can effectively advance aerodynamic designs of aerospace vehicles, and studies of boundary layer flows and turbulent flows.

**Flight control of aerospace vehicles.** With integrated on-chip control circuitry, arrayed hot-wire sensors are highly compact and portable, and can be easily applied to the wings of aerospace vehicles for real time flow measurement and monitoring. Such sensor responses can be integrated into an effective and robust control system, which allows more aerodynamic control of aerospace vehicles to achieve nimble maneuvering and reduce power consumption. This is especially important for unmanned air vehicles (UAV) and micro air vehicles (MAV). The instant flow field awareness gained from the sensor array enables UAVs and MAVs to deal with unsteady, turbulent flow fields.

**Navigation of underwater vehicles.** Inspired by biological behavioral studies on fish lateral line – a superior flow sensing organ of fish, a microfabricated hot-wire sensor array can be applied as an artificial lateral line to underwater vehicles for hydrodynamic flow sensing. Such novel sensing capability can give underwater vehicles a third sense in addition to vision and sonar. This is especially important to submarines. By sensing the water disturbances caused by other moving objects, a submarine might be able to locate and track others; by sensing pressure variation, a submarine could avoid collision into still obstacles. This superb “distant touch” capability can significantly improve submarines’ navigation performance, especially in the situation when vision and sonar capabilities are limited.

**CONCLUSIONS**

An out-of-plane hot-wire anemometer array is developed based on surface micromachining process and three-dimensional assembly method. This HWA sensor array is of compact sensor arrangement, fast frequency response, high velocity sensitivity, and out-of-boundary flow imaging capability. With an on-chip integration of temperature feedback circuits, the sensor array can be easily applied to a variety of aeronautical and underwater vehicles and platforms to satisfy diverse flow sensing requirements.

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**REFERENCES**


