Wearable Anemometer for 2D Wind Detection

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***Abstract*—This paper presents a small wearable anemometer for detecting two dimensional wind vector by using a micro thermal flow sensor incorporated with a wireless mobile device. The flow sensor consists of three roundabout Pt hot-wires uniformly distributed in a circle fabricated on a flexible polyimide substrate using micromachining technique. The anemometer integrates the thermal flow sensor, a miniaturized conditioning circuit with a low power Bluetooth module packaged in a watch-like case, and a personal mobile device that wirelessly acquires sensor data and extracts wind velocity and direction by using an improved algorithm. The anemometer takes merits of small size, light weight, and low power consumption, aiming at versatile applications on personal electronics, distributed measurements for meteorology and agriculture.**

Keywords—wearable anemometer; flow velocity and direction; flexible flow vector sensor

I. Introduction

Anemometer for detecting two-dimensional flow velocity and direction has wide applications in fields of aviation, meteorology, agriculture and fieldworks. Conventional anemometer is bulky using such as electromechanical self-orienting vanes or pitot tubes, which need hard mechanical ties and intrusive pneumatic links inside. Another method using a cylinder with a channel network connecting the internal pressure sensors with the lateral surface has also been used to detect wind velocity and direction [1]. The miniaturization approach is to use micromachining to fabricate distributed micro heaters and micro thermometers on a substrate to detect flow velocity and direction angle [2-6]. These sensors usually need multiple isolated heaters and thermometers and sometimes thermal isolation structures, thus make the sensor complicated and more power consumption [2, 5]. Another compact sensor proposed previously by our group [7-8] is to use three or four thermal roundabout wires uniformly distributed in a round fabricated on a glass or polyimide substrate. Each thermal wire is served as both Joule heater and thermometer to simplify the sensor structure and reduce its power consumption. The flow velocity and direction are deduced using a neural-network based data fusion technique.

In this paper, we propose a wearable anemometer integrating a compact flexible flow vector sensor using three roundabout Pt hot-wires on a polyimide substrate, a miniaturized conditional circuit, a low power Bluetooth module packaged in a watch-like case, and a personal mobile device where the wind velocity and direction are figured out by using a smart algorithm formulated in a cell phone. Compared with existing anemometer, the proposed device is small, highly-integrated, with wireless transmission, compatible with mobile application. Due to its unique features, the developed device can be extensively used in distributed measurements for weather prediction and environmental monitoring, as well as personal electronics.

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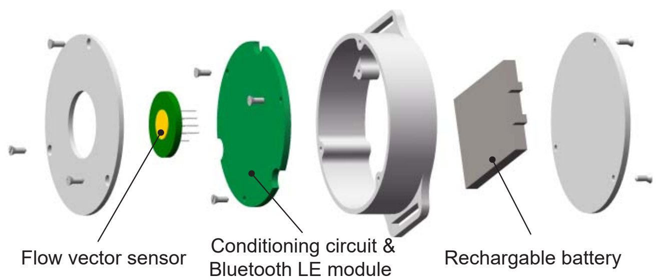
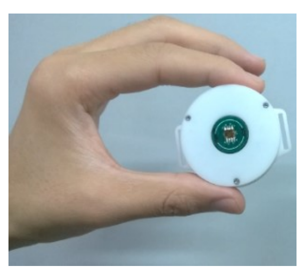
II. Anemometer Design

A. Configuration of Anemometer

Fig.1 shows the anemometer comprised of a micro flexible flow vector sensor, a signal conditioning circuit, a Bluetooth LE module, and rechargeable battery, all of which are packaged in a watch-like plastic case. The anemometer is small, wireless, and low-power configured for a long term usage.



(a) Configuration of anemometer



(b) Prototype of anemometer

(c) Flow vector sensor with I/O interface circuit.

Fig. 1. Configuration and prototype of developed anemometer.

B. Flow Vector Sensor

Fig. 2 shows homemade flexible flow vector sensor, where the roundabout Pt wires is fabricated by using one-step lift-off micromachining process on a 50 μm thick polyimide substrate [8]. A parylene thin-film is coated on the fabricated sensor and served as an encapsulation for waterproofs and dustproofs. The temperature coefficients of resistance of the fabricated Pt thermal elements are tested to be about 1,800 ppm/K, and the resistance of each element wire is about 32 Ω. Three roundabout Pt wires (called thermal elements) constitutes a round. Each element is served as both heater and thermometer. Three elements are heated to a higher temperature than ambient temperature, and construct a round hot zone above the sensor surface. When a wind blows over the sensor surface, the temperature distribution of the hot zone is deflected along the flow direction, which is detected by the distributed thermometers. Each thermal element of the sensor is operated in a constant temperature difference (CTD) mode due to its advantages of high sensitivity and fast response. Detailed operation principle of the sensor can be found in our previously published paper [8].

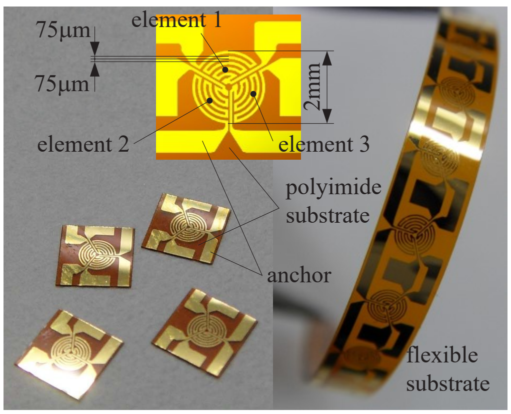


Fig. 2. Flexible flow vector sensor.

C. Signal Flow and Algorithm for Extracting Flow Velocity and Direction

The output signals of three thermal elements of the flow vector sensor are acquired by using a CTD-based conditioning circuit. And then the sensor data are transmitted wirelessly to a smart phone using a Bluetooth module. In order to minimize power consumption, the device combines a Bluetooth4.0 LE module (DA14580) with an MCU to construct a digital data acquisition system. The smart phone receives the data, and executes signal processing and further extracts flow velocity and direction. Fig. 3 shows the signal flow chart of the anemometer. A tailor-designed android app is programed to calculate the flow parameters and display the results on a smart phone as shown in Fig. 4. The whole power consumption of the anemometer is tested to be about 100 mW at the overheat ratio of 0.3% for the thermal flow sensor, and the response time is less than 0.5 s.

In our previous work, the data fusion algorithm used to extract flow velocity and direction was based on 3-layer Back Propagation (BP) neural network. However, for wearable and mobile application, an effective algorithm with simple calculation is necessary so as to reduce the computation load for the device. Here we propose an algebraic method to implement the data fusion. It has been proved that the outputs of three thermal elements follow sine or cosine laws with respect to the wind angle [7-8].

$$
\begin{aligned}
V_1 &= V_0 + V \cdot \sin\alpha \\
V_2 &= V_0 + V \cdot \sin(\alpha + 120^\circ) \\
V_3 &= V_0 + V \cdot \sin(\alpha + 240^\circ)
\end{aligned} \tag{1}
$$

where, V_1, V_2, V_3 are the outputs of three thermal elements of the flow sensor; V_0, V and α are zero output, magnitude and wind angle respectively. Accordingly, an algorithm can be deduced from (1), which can be used to extract flow velocity and direction angle.

$$
\begin{aligned}
V_0 &= \frac{V_1 + V_2 + V_3}{3} \\
V^2 &= \left(\frac{V_2 - V_3}{1.732}\right)^2 + \left(\frac{2V_1 - V_2 - V_3}{3}\right)^2 \\
\alpha &= \tan^{-1}\left(\frac{\sin\alpha}{\cos\alpha}\right) = \tan^{-1}\left(\frac{2V_1 - V_2 - V_3}{1.732\left(V_2 - V_3\right)}\right)
\end{aligned} \tag{2}
$$

By (2) and the outputs of the sensor, the flow velocity proportional to V_0 or V and the flow angle α can be figured out. This algorithm has been well operated in a standard MCU or a smart phone.

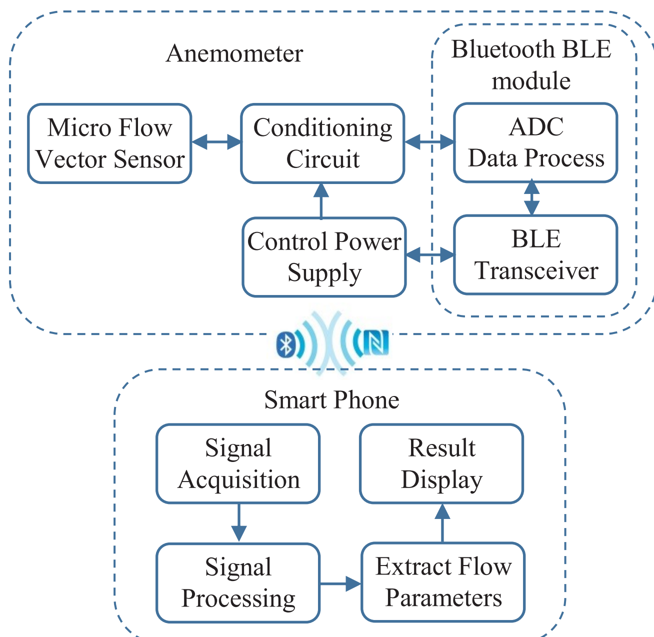


Fig. 3. The block diagram of signal flow.

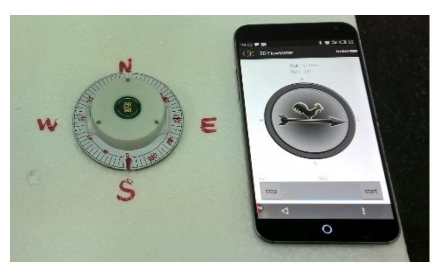


Fig. 4. Data communication between anemometer and phone.

III. Experiments of Anemometer

The characterization of the developed anemometer is conducted by using a wind tunnel experiment. The sensor surface is exposed to an airflow. The flow rate is controlled and modulated by using a mass flow controller (Fluke molbloc-L). The flow angle is modulated by rotating the anemometer around its longitudinal axis. The flow velocity is varied from 2 m/s to 20 m/s (at 2 m/s per step) and the flow direction is rotated from 0 to 360º (at 30° per step) under each constant flow velocity. The experiment is conducted at room temperature around 20ºC. Fig. 5 show the experimental results for the outputs of three thermal elements corresponding to the changes of the flow velocity and angle. From the results, it is convinced that the output of each element follows a sine/cosine law against the wind angle. The zero output and magnitude of sine wave are increased with the flow velocity, which is consistent with the analysis from (1).

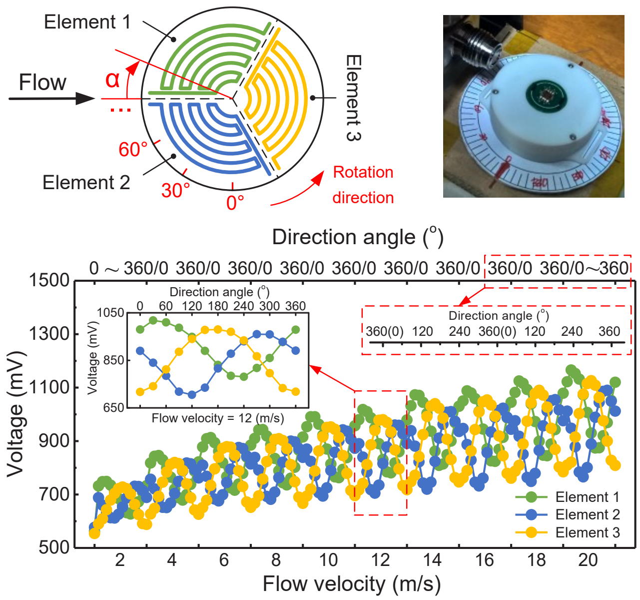
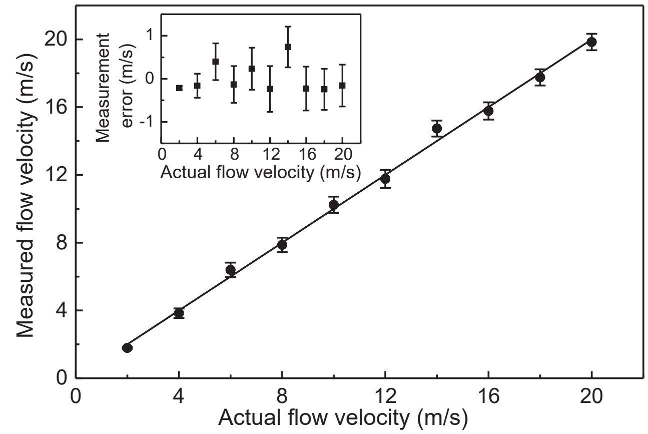


Fig. 5. Experimental setup and results.

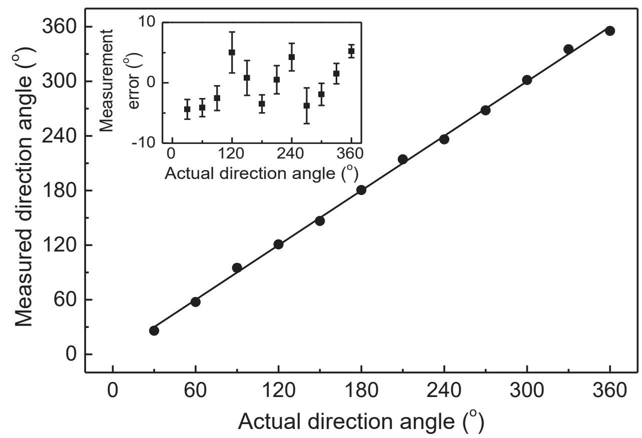
The data shown in Fig. 5 are further employed to extract flow velocity and direction angle by (2). The measured flow vector parameters are shown in Fig. 6. It is seen that the measured flow velocity and angle fit the actual parameters very well. The root mean square error of the flow velocity reaches 0.44 m/s in the range of 2~20 m/s and the error of the flow direction angle reaches 2.15 ° in the range of 0~360°.

IV. Conclusion

We present a miniaturized wearable anemometer to detect wind velocity and 2D direction. The anemometer is small, low-power, wireless, compatible with mobile phone, and thus capable for wearable and personal applications. Besides, easy operation and low-cost make it feasible for distributed measurements in agricultural production and meteorological monitoring. An improved and simplified algorithm for extracting flow parameters is proposed to minimize computation load for the devices, which can be further integrated with applications of other sensors, such as magnetic sensors and accelerometers.



(a) Measurement results of flow velocity



(b) Measurement results of flow direction angle

Fig. 6. Measurement results of flow vector detections. The inserted plots show the measurement errors.

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