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Wind speed and direction detection by means of solid-state anemometers embedded on small quadcopters

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Abstract

This work describes the application of a compact, MEMS-based, 2D anemometer to the estimation of a quadrotor's airspeed. Correcting for the vehicle's ground speed provided by internal GPS and inertial units allows this low cost, mobile platform to provide local wind speed estimates. A series of initial, bench-top tests were performed to characterize and calibrate the sensor, which is an improved version of a recently proposed and novel device. Additional full-scale wind tunnel experiments were performed with the sensor mounted on a fixed quadrotor to test the effect of the propellers on the sensor's performance.

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Keywords: wind sensor, quadcopter, MEMS, UAV

1. Introduction

As quadrotors become increasingly common, capable, and affordable, their utility as a mobile sensor platform continues to grow. Accordingly, this platform has potential applications in wind field estimation for urban planning and climatology, dispersion studies, atmospheric measurement, wind turbine site analysis, and structure design. Recent work demonstrated accurate wind velocity estimation on-board a quadrotor by modelling vehicle pitch as a function of airspeed [1, 2] and correcting for the ground speed using GPS. However, direction accuracy is low and an accurate

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dynamic model must be developed and maintained. This limitation can be mitigated by adding an airflow sensor to the Inertial Measurement Unit (IMU) of the vehicle and using the additional data in a sensor fusion scenario. Pitot tubes, universally used for fixed wing UAVs (Unmanned Aerial Vehicles), can also be used for direct airspeed measurement in quadrotors [3]. However, these devices should be closely aligned along the air velocity vector, which in a quadrotor is unpredictable due to ability of these UAVs to travel in all directions. Multi-directional airspeed detection requires a large number of Pitot tubes to be placed on the vehicle [4], increasing weight and complexity.

In this work, we describe experiments performed by equipping a quadrotor with an innovative 2D wind sensor. The device, which is a variant of a recently proposed anemometer [5, 6], combines small size, acceptable accuracy and low power consumption. These qualities make the sensor particularly promising for use on small UAVs. Measurements include wind tunnel tests performed simulating real flight conditions.

2. Wind sensor description

2.1. Anemometer operating principle and fabrication details

The operating principle of the anemometer consists of probing the pressure distribution induced by the wind on the outer surface of a cylinder. Fig. 1 shows a photograph of the wind-sensor including the electronic interface. The main element is a Poly-methyl-methacrylate (PMMA) cylinder including two micro-channel structures, indicated with X and Y, whose cross-section is shown in the box on the left. It can be shown [5] that the pressure in cavities C_1 and C_2 is a weighted average of the pressure present at the channel inlets. With a particular choice of the inlet positions and corresponding weights (proportional to the inverse of the channel lengths), the pressure difference between C_1 and C_2 cavities shows a sinusoidal dependence on the wind direction. Using two orthogonal structures, it is then possible to derive two differential pressures proportional to the sine and cosine of the wind direction, allowing the latter value to be determined. The channel length was uniform in previous versions [5, 6], while channels with gradually increasing lengths were used in this work in order to increase the range of applicable wind speeds.

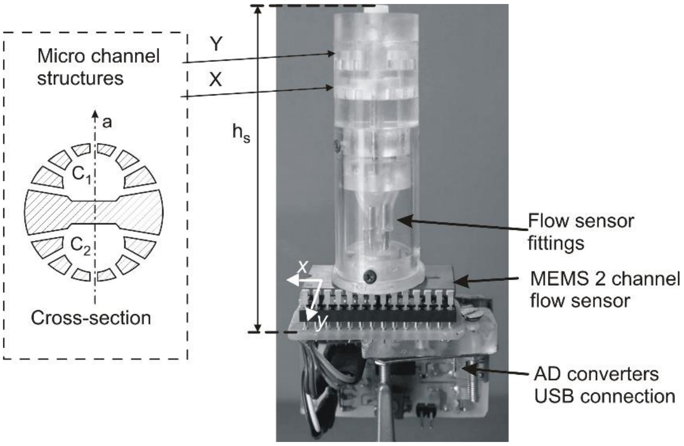

Fig. 1: Photograph of the wind sensor including the PCB used to sample, convert, and transmit the analog sensor measurements over USB. The sensor reference axes, x and y, are indicated. The cross section of the micro-channel structures is shown in the box on the left. The sensor height (h_s) excluding the electronic interface is 6.5 cm, while the cylinder diameter is 2 cm.

2.2. MEMS dual channel differential pressure sensors

In order to keep sensor dimensions to a minimum, a single chip, double channel differential pressure gauge was used to detect the very small pressure differences developed by the channel microstructures. This device, described in [7], detects the pressure difference by measuring the flow induced by the pressure itself through a micro-channel of known hydraulic conductance. The flow is measured using thermal micro-calorimeters formed by two heaters placed between two thermopiles. A gas flow produces a temperature difference that is converted into a voltage. The sensing chip, designed using the BCD6s microelectronic process of STMicroelectronics, includes two micro-flow meters and a programmable electronic interface. Fabrication of the sensor involves micromachining of the sensing chips and application of a PMMA gas conveyor.

3. Results and discussion

3.1. Anemometer calibration

The anemometer was calibrated using a small wind tunnel, consisting of a pipe of 10 cm diameter equipped with a fan and a reference wind-velocity sensor. The anemometer was placed at the outlet of the wind tunnel and was manually rotated to investigate the response to the wind direction.

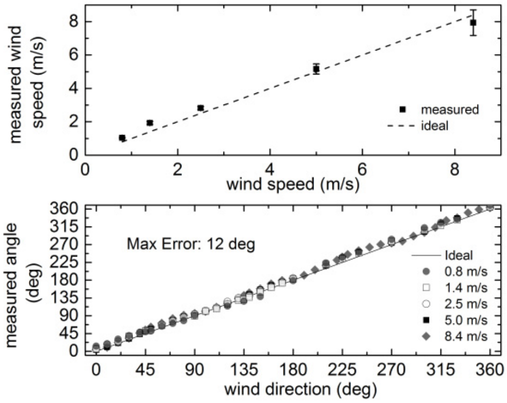

Fig. 2. Results of tests performed in a 10 cm calibration pipe. Top: measured wind speed with error bars showing the total variation of the reading caused by sweeping the wind direction over the full 360° range. Bottom: Measured angle as a function of the actual angle formed by the wind direction with the sensor reference axis.

The sensor output voltages were converted into the respective differential pressures, p_x and p_y, using spline interpolation of the experimental calibration table. The wind speed (u) and direction (θ) were derived from the pressures using the following formulas:

$$u = A\left(p_x^2 + p_y^2\right)^{\alpha}; \quad \theta = \arctan\left(p_y, p_x\right) \tag{1}$$

where A and α are empirical constants estimated from the calibration data. The power law dependence used to fit the velocity-to-pressure data was suggested by the fact that pressure differences across a bluff body are approximately proportional to the quantity $\rho u^2/2$, where ρ is air density. The sensor capability of detecting the wind speed and direction is shown in Fig. 2.

3.2. Tests performed with the anemometer on the quadrotor

The sensor was mounted on the quadcopter in a symmetrical position with respect to the rotor locations and was elevated above the rotor plane to reduce turbulent effects. A schematic view of the sensor / quadcopter assembly is shown in Fig. 3. The sensor communicates with the quadrotor computer through a USB connection. The quadrotor was mounted on a tripod allowing precise setting of the yaw and pitch angles. Yaw angles are measured according to the convention shown in Fig. 3. Tests have been performed inside the Wright Brothers wind tunnel at MIT. This set of tests was aimed at investigating the effect of the downwash flow produced by the quadcopter propellers on the anemometer response. Wind tunnel measurements consisted of recording the sensor output voltages as a function of the wind speed for several yaw / propeller settings. Estimates of the wind speed and direction have been extracted from the sensor output data by means of Eqn. (1).

Fig. 4 shows results obtained with the two specific yaw settings of 0 and 45 degrees, corresponding to the wind directions indicated in Fig. 3. Tests were repeated with propellers on and off.

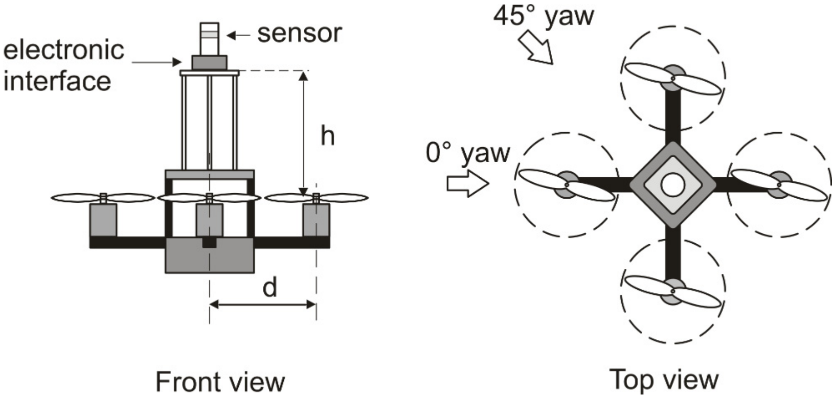

Fig. 3: Simplified front and top views showing the sensor mounted on the quadcopter (not to scale). The 0° and 45° wind direction referred in the text are indicated. Given dimensions are: h=22 cm, d=20 cm, propeller diameter=25.5 cm.

The resulting wind speed and direction measurements suggest that the propellers only have a significant effect on the estimated speed data below 10 m/s, while angle data are practically unaffected in the whole velocity range.

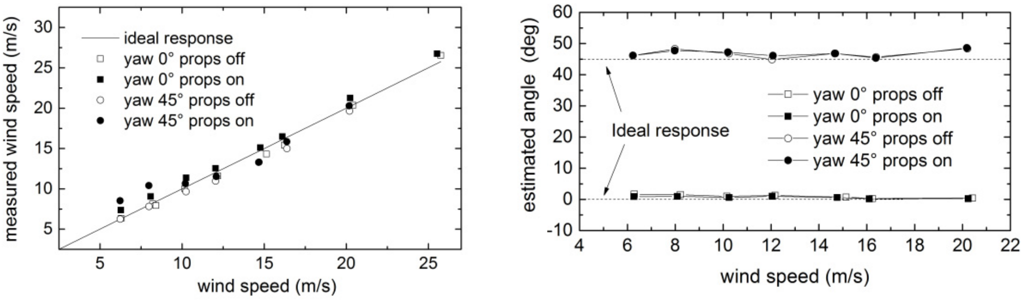

Fig. 4: Measured wind velocity (left) and direction (right) as a function of the ground truth wind speed with the sensor mounted on the quadcopter. Results from two orientations with the propellers both on and off are compared. (b)

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