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Using MAVs for Atmospheric Wind Measurements: Opportunities and Challenges

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ABSTRACT

MAVs are increasingly being used as flying sensors due to their ability to be positioned in hard to access locations for relatively low risk and cost. The use of fixed wing and multi-rotor MAVs as flying anemometers were investigated by instrumenting one of each with multi-hole pressure probes (simplified versions of the TFI Cobra probes) and obtaining data on windy days. A batch of probe heads were produced by stereolithography (STL) rapid prototyping and it was found that a universal calibration could be used for one batch unless extreme levels of accuracy are required. The craft, on-board sensors and the signal processing techniques are described. The limited endurance of multirotors was found to be a significant limitation when trying to obtain the relatively long samples of data (required for good descriptions of atmospheric turbulence). As wind data are usually required at several spatial locations (e.g. vertically displaced replicating the function of several anemometers on a mast) it is necessary to have several craft flying concurrently. Another challenging aspect was holding a steady position for the multi rotor craft. Automated position holding is part of on-going work and we plan to investigate using the technique of stabilising the craft by upstream flow measurements (proven on the fixed wing MAV) for multi-rotors.

1 INTRODUCTION AND OBJECTIVES

MAVs are increasingly being used as flying sensors due to their ability to be positioned in hard-to-access locations for relatively low risk and cost. One potential application is documenting the atmospheric wind, including its interaction with structures and terrain, using either fixed wing and/or multi-rotor craft. The advantage of multi-rotors is that they can hover (either with respect to the Earth or wind), whereas fixed-wing generally cannot. However fixed-wing MAVs can fly faster which can be an advantage if a long time record of the wind needs to be captured (i.e. wind run). As atmospheric flows vary continuously with time and space it is often required to document the turbulence characteristics, such as intensities, scales and spectra in three orthogonal directions. For meteorological and wind engineering studies sampling times are at least 20 minutes and often over an hour and sampling frequency can be relatively low (O(1 to 10 Hz). Of relevance to wind effects on buildings structures, cars, aircraft etc. is the turbulent energy in the micro meteorological range (generally known as gusts), as opposed to weather map fluctuations driven by larger scale climatic events. The duration of the sample lengths fall in the spectral gap centred about one hour. For more details see [1].

Typically MAVs are less than a metre wingspan and can be of either fixed wing or multi rotor configuration. The advantage of multi rotors over fixed wing craft is that they can hover (either with respect to the Earth or the atmospheric wind), take off and land vertically and are more manoeuvrable (particularly in the lateral and vertical directions and in yaw). Fixed-wing aircraft generally can fly faster and for longer, which can be an advantage if a long time record of the wind needs to be captured (i.e. wind run) and/or when strong winds are to be measured. Flight speeds of micro fixed wing aircraft are from 5 to 30 m/s, with a similar top speed for multi rotor craft.

Traditionally wind data has been obtained from fixed locations, using mast-mounted anemometers, Lidar etc., where the sensor is essentially rigidly mounted. Thus these methods are not significantly affected by motion of the support. This is not the case for airborne measurements unless the aircraft is held steady relative to the ground. When the sensor is moving; either in a steady translation, or perturbed by motion of the aircraft, the ensuing spurious motions can sometimes be removed, thus the resulting data is then in the (Earth) body axis system. However MAVs are small, have low mass and MOI, and fly at relatively low speed thus perturbations from turbulence can be significant. This is particularly noticeable for fixed wing MAVs in the roll axis ([2]). As MAVs generally carry inertial measurement systems (often using the data in feedback control to assist in flight stabilisation) the acceleration data can be integrated to give velocity information about sensor movement which can be then removed from the wind data.

Our objectives are to understand the opportunities and challenges of measuring wind utilising a fixed wing and a

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quad-rotor aircraft. The sensors used were multi-hole probes based on the TFI Cobra probe [1].

2 INSTRUMENTATION: MAVS AND SENSORS

2.1 *Fixed Wing*

A Slick 360 aerobatic aircraft was used which is neutrally stable, has a 0.490 m span NACA0012 aerofoil section wing, a typical flying mass of 130g mass and was fabricated via injection moulding from relatively rigid high-density foam. The wings had no twist or dihedral and the large ailerons (30% x/c) extended over the entire semi-span. The reason for selecting a model with nominally neutral stability was that with suitable active stabilisation systems a relatively straight and level flight path could be held even under turbulent conditions. Initially a standard inertial-based stabilisation was used, but then an improved patented stabilisation system was fitted. This was found to significantly improve the steadiness of flight in the turbulent atmosphere and utilised upstream measurements of pitch angle perturbations about to impinge on the wing to give increased time for the control system to reduce the unwanted roll reactions. The improved stabilisation system utilised two carbon fibre multi-hole pressure probes (described later). The model, with probes fitted, can be seen in Figure 1 and details of the method can be found in [3].

Figure 1: Fixed Wing Aircraft

2.2 *Multi Rotor*

A bespoke racing quadcopter was modified to incorporate multi-hole pressure probes as shown in Figure 3. Under the main probe shaft can be seen a carbon-fibre protection strut which is to provide protection during take-off and landing. The placement of the probes relative to the rotor flow field was part of a separate research program [4, 5] and for the work reported here the probe head was sufficiently far removed from the rotor flow field for the influence to be insignificant.

2.3 *Wind Sensing Instrumentation*

Three-component velocity sensing was via multi-hole pressure probes, which are being increasingly used for turbulent flow documentation as they are less fragile and expensive than hot-wire or laser-Doppler anemometers. An overview of the technique can be found in [6]. Typically such probe systems are individually calibrated; both in terms of angle and frequency response. A dynamic calibration is often applied to correct for the amplitude and phase changes that occur due to the tubing system and pressure transducer response. The data zone of acceptance for the four-hole head design used here (see Figure 3) is a 90 degree cone. Data that lie outsize this zone can be rejected.

For commercially available multi-hole probe systems, data acquisition and processing is normally performed via a personal or laptop computer. For the current applications it was desirable to incorporate on-board data logging, with data downloaded and analysed post-flight. Thus the probes and associated hardware had to be lighter than existing commercial systems. As the risk of ground or building impact was considered high, low cost, easily replaceable probe heads were necessary. A series of heads were manufactured via rapid prototyping, including an assessment of whether a single, (or average calibration) could be used for a batch of probe heads. This work is described in [4]. A bespoke calibration was used for the two flying systems described here. The outputs of the probe were connected to four pressure transducers with temperature compensation and analog-to-digital conversion. The digital pressure data was then transmitted to a central FPGA-based processing unit, which also interfaced with a GPS system and IMU. All data was logged to a microSD card. This setup allowed for very accurate (O(10us)) synchronization between IMU/GPS and pressure data, which is necessary to correct for any movement of the aircraft, and resolve the measured wind velocities into the global frame.

3 WIND MEASUREMENTS

Several flights were undertaken using the fixed wing aircraft including outdoors and in three wind engineering tunnels. The outdoor flight path depended upon the wind speed; when winds of higher magnitude than the flight speed were encountered the aircraft could be held closely stationary (relative to the Earth), whereas for lower winds the aircraft was moving relative to the ground thus obtained a wind run which could (depending upon terrain/fetch) be hundreds of meters long. Figure 4 shows a raw pressure data from the probes with velocity spectra shown in Figures 5 and 6. The typical error in pressure measurements was ±1 Pa and the

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[1] http://www.turbulentflow.com.au/Products/CobraProbe/CobraProbe.php

Figure 2: Rotorcraft

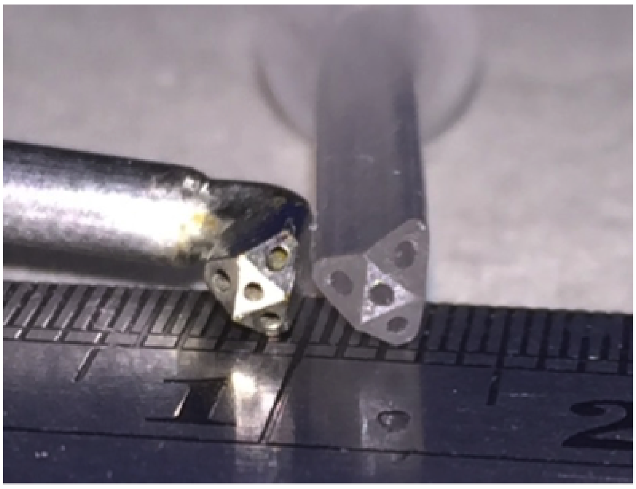

Figure 3: TFI Cobra Probe next to the STL-manufactured Probe

spectra show close alignment with the theorised Von Karman Spectra.

To date only one short trial flight was conducted with the quadrotor. There were issues identified with holding a steady position relative to the Earth but the trial demonstrated the potential of using a quadrotor- mounted system, see Figure 7,8 for a plot of elevation vs time (from GPS) and wind longitudinal velocity vs elevation. Estimated error in elevation measurements was ±2m.

4 CONCLUDING THOUGHTS AND LESSONS LEARNT

The endurance of rotor craft generally means that sample times will be limited to below 20 minutes and in our initial flight trial this was approximately 12 minutes. This is an issue especially if the wind is to be measured at significant elevations (of order of hundreds of metres) as considerable battery energy is utilised to climb and descend to the desired altitude leaving little for the measurement phase. As our trial was limited to one quadrotor we attempted to obtain data at several elevations to document the velocity profile but clearly the sample length was not long enough to be statistically useful for meteorological and wind engineering purposes. However if only the high frequency end of the spectra is required, which will be the case for turbulence studies on MAVs, this should not pose a problem.

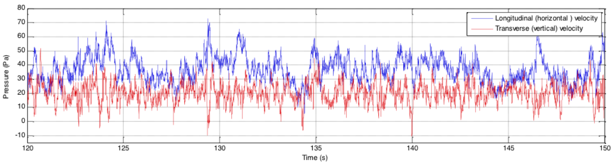

Figure 4: Airborne raw pressure measurements

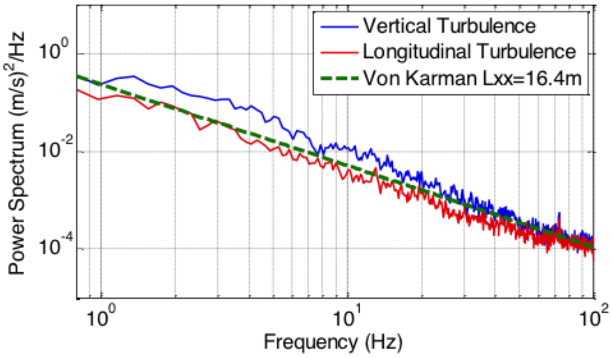

Figure 5: Turbulence velocity spectrum outdoors @ Ti=8%

Flying rapidly through the turbulence field can be advantageous for both types of craft since a long wind run can be obtained, effectively compressing the sampling time.

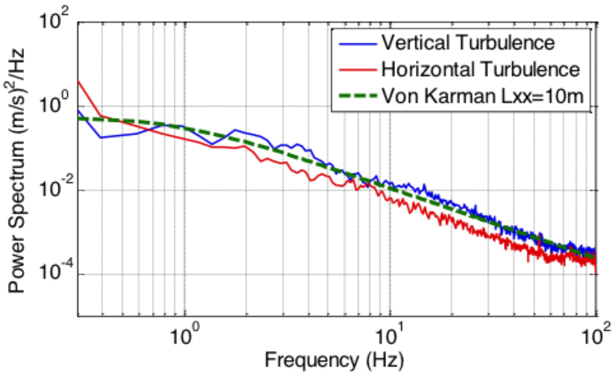

Figure 6: Turbulence velocity spectrum in Wind tunnel @ Ti= 7.5%

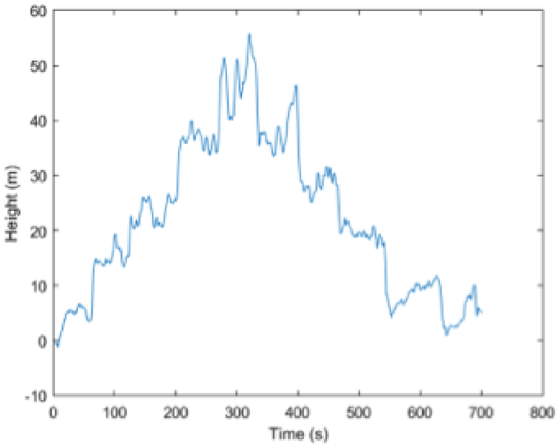

Figure 7: Elevation vs Time from Initial Flight of Quadrotor

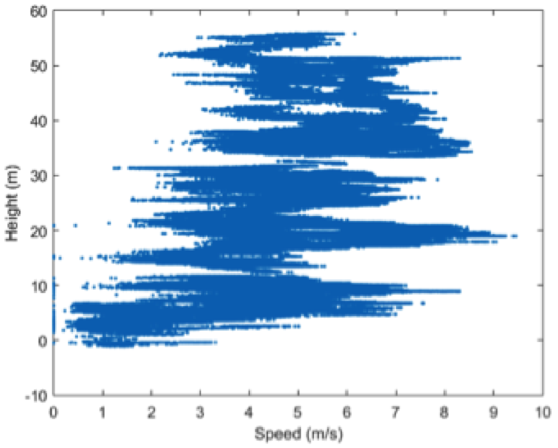

Figure 8: Velocity Profile from Initial Flight of Quadrotor

Clearly this depends upon the terrain/fetch in question, but where this is permissible it is a useful technique. As long as the sampling frequency and system response is sufficiently high, data samples can then be uncompressed (by removing the mean flight speed of the aircraft) which gives a longer effective time record of data. This can technique can be beneficial under low wind conditions when (from a stationary sampling location) very large flow angles are encountered; greater than the 90 degree zone of acceptance for the four hole probes used here. Increased flight speed reduces the magnitude of the fluctuating angles. Data can then be post processed to remove the effect of flight speed in a similar manner to uncompressing the velocity magnitudes. Note that this technique has been applied to hot wires which have been flown through bluff body wakes enabling very large fluctuating angles to be captured. ([8]).

The multi-hole pressure probes were found to be very suited to taking 3-D wind turbulence data and rapid prototyping can mass produce probes reasonable well. With typical STL techniques one universal calibration can be used for a batch, unless extreme levels of accuracy are required. Being a pressure-based velocity measuring system it has a nominally parabolic response of output to velocity. This makes them insensitive at low wind speeds but as data are usually required for high wind speed (¿5m/s) this was not a problem.

The technique of measuring the upstream flow on the fixed wing craft and utilising the information for stabilisation control was found to be very useful; particularly in roll. It enabled flight in very high frequency energetic turbulence including in wind engineering wind tunnels with levels of turbulence of over 20% and of a scale of similar dimension to the craft.

5 WHERE TO FROM HERE?

As wind data are usually required at several spatial locations (e.g. vertically displaced replicating the function of several anemometers on a mast) it is necessary to have several craft flying concurrently. The lack of endurance is problematic but swarming will be useful. We plan to extend to a swarm of four rotor craft.

Another challenging aspect was holding a steady position for the multi rotor craft including at several elevations as shown in Figure 7. Automated position holding is part of on-going work and we plan to investigate using the technique of stabilising the craft by upstream flow measurements (proven on the fixed wing MAV) for multi-rotors.

It is envisaged that the continuing reduction in cost for automated micro planes will lead to them being used increasingly in swarms, with commensurate reduction in the use of mast-mounted anemometers.

6 ACKNOWLEDGMENTS

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