Determination of the Surface Boundary Layer Using a Quadrotor

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I. Abstract

Wind velocity data was taken by a quadrotor UAV using accelerometers, gyroscope, and a barometer. Data was taken at different altitudes over a single position to determine the boundary layer at the surface of the earth. The data taken was compared to the results from numerical methods to determine if this is a practice application for a quadrotor. A few weeks before the test was set to get underway, the quadrotor suffered a very hard crash while testing the GPS and altitude hold function and wasn't able to completely recover from it. Theoretical results and experiment proposal are covered.

II. Nomenclature

k	Von Karman costant
L	Obukhov length
$\bar{V}$	theoretical wind velocity
U_a	wind velocity from experimental data
u_*	friction velocity
z_0	aerodynamic roughness length
Φ_M	normalized wind shear

III. Introduction

The atmospheric boundary layer is the bottom layer of the troposphere, which is in contact with the earth. This layer is directly influenced by the friction on the surface of the earth. The thickness of the layer varies in time and space but is normally ~1 mile thick. The boundary layer has different profiles for temperature, moisture, and wind, which fluctuate during different times of day. This project will deal most closely with the wind profiles seen in the surface boundary layer up to an altitude of about 300 ft. The surface layer has approximately constant shear stress because the flow is not affected by the rotation of the earth and the wind structure is primarily determined by the friction on the earth's surface and the vertical temperature gradient. Above the surface layer, the wind velocity is determined similar to the surface boundary layer but is also influenced by the rotation of the earth. Above these two layers is the free atmosphere where the flow is no longer influenced by surface friction and is in geo-strophic balance. While measurements would be helpful in better understanding, it is often hard to collect measurements of wind speed, at different altitudes, and at a constant latitude and longitude.

Weather balloons have been used to acquire some of this data but are unable to maintain a constant altitude. The balloons are easily disturbed by any wind, which throws off the latitude and longitude, creating mixed readings at a specific GPS location. Research has been underway, in the Artic Basin, developing a tethered weather balloon system[4]. A tethered weather balloon would allow for high resolution profiles of temperature, humidity, wind speed, and wind direction through the atmospheric boundary layer. Tethered balloons are much more accurate than untethered but are still subject to changes in positioning since they are very large and are still moved by wind or weather. The weather balloons also have wind speed, temperature and altitude operating range limitations. In addition to weather balloons there are other methods of collecting atmospheric profiles, these include ground-based and satellite-based remote sensing instruments. These methods are expensive and do not provide as precise resolutions.

A device with the ability to gather an average wind speed over a longer period of time, at each altitude point, would clarify wind patterns and winds aloft data. This information would be helpful for weather data and aviation calculations. A quadrotor that collects wind speeds and can be GPS controlled would be an innovative way to accurately collect this data. In this project, a quadrotor will be used based off the *Arducopter*[6] platform from *diydrones.com*[5]. The quadrotor uses an inertial measurement unit (IMU) that measures and reports on its orientation and attitude using a 3-axis gyroscope, 3-axis accelerometer, barometer, magnetometer and GPS. With the help of the IMU, the quadrotor will be able to maintain position holds at different altitudes over specified GPS coordinates. In position hold during windy conditions, the IMU will compensate for drift and tilt by sending pulses to the brushless motors, which will correct its orientation, making the quadrotor self-stabilizing. These pulses, along with accelerometer and gyroscope readings, will be sent back to a ground station using Xbee modules. The instantaneous data collection at the modules results in real time telemetry and is then converted into equivalent wind speeds.

Data collection of wind speeds may be an innovative use of quadrotors, but they have been used in different areas for years. One of the initial uses of quadrotors was as a camera platform in the movie industry. Instead of paying to hire helicopters to achieve overhead and landscape shots, a large quadrotor was used as a stable camera platform. Since being used in the movie industry, quadrotors have been used in everything from point of view radio controlled flight, using a video downlink, to demonstrating obstacle avoidance using sonar. Quadrotors have also evolved into a practical project for hobby enthusiasts interested in radio controlled flight. While quadrotors have been popular for these recreational uses they are an ideal vehicle for attaching sensors and collecting serious data.

IV. Experimental Apparatus

Data taken from the quadrotor will be compared to both anemometer readings and theoretical calculations of wind speed in the surface boundary layer. The quadrotor uses the Adrino Pilot Mega IMU from DIYdrones.com[5] with the addition of the DIYdrones HMC5843 magnetometer, MediaTek GPS module, and two 900 Mhz Xbee modules for telemetry data. This setup will provide for both altitude and GPS hold while flying, allowing for data collection at specified altitudes. Figure (1) shows the quadrotor next to a laptop that will be used for the ground station and the Xbee module that will be used for real time telemetry.

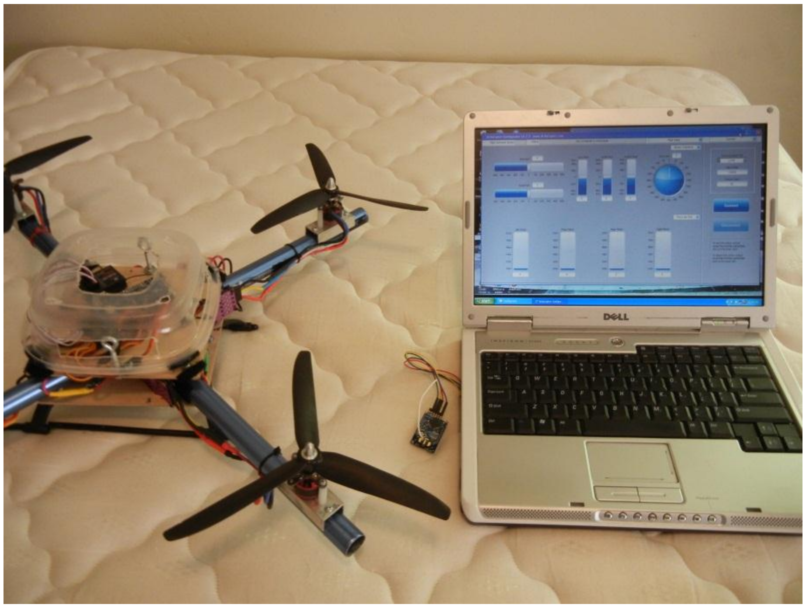


Figure 1. Schematic of the quadrotor with laptop test setup showing the Arducopter's Configurator.

A few weeks before the test was set to get underway, the quadrotor suffered a very hard crash while testing the GPS and altitude hold function and wasn't able to completely recover from it. Therefore experimental data was not able to be collected and all following assumptions are based off theoretical data.

V. Procedure

The quadrotor would have been taken out to Cal Poly's model aircraft runway a few miles northwest of the University's campus. The surrounding airspace would be checked to make sure other aircraft would not compromise the testing equipment. Before the test is conducted, a check out flight of the quadrotor and equipment would take place to make sure everything is in working condition. This would verify that the IMU had properly loaded the control algorithms, all the sensors were working, the GPS had satellite lock, and the Xbee's were communicating with the ground station. The quadrotor would then be set in a centralized location and altitudes for several points would be assigned. Altitude would be determined from a hand held laser range finder on the ground. Gyroscope and accelerometer rates would be sent back to the ground station and then used to determine wind speed. Figure (2) shows an example of how the experiment would have been performed. Telemetry data would be viewed in real time using Arducopter's configurator software. This would enable gyroscope and accelerometer data to be seen and recorded based on the tilt in the quadrotor and the shift in its position. The configurator would also show the pulse width modulation values that are sent to each motor based on the sensor inputs interpreted by the control loop.

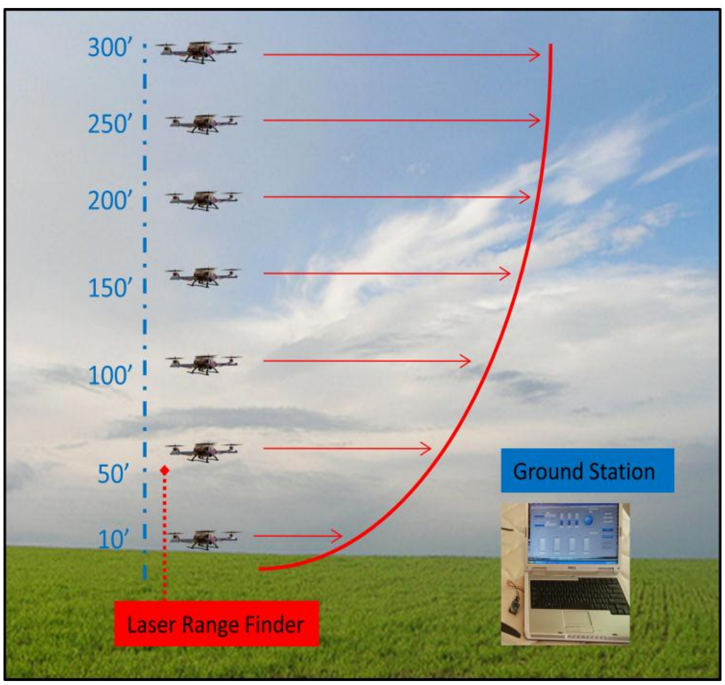


Figure 2. Example test procedure.

Data would be collected at altitudes from the minimum flight altitude of about 10 feet, up to 300 feet, where the surface boundary layer starts to diminish.

VI. Analysis

Winds in the boundary layer are caused by several different factors. Drag on the ground causes the wind speed to be reduced to zero at the surface of the earth, while aloft, the winds are stronger.

Table 1. Aerodynamic roughness length based on location[5].

Z_0 (m)	Classification	Landscape	C_{DN}
0.0002	Sea	Calm sea, paved areas, snow-covered flat plain, tide flat, smooth desert.	0.0014
0.005	Smooth	Beaches, park ice, morass, snow-covered fields.	0.0028
0.03	Open	Grass prairie or farm fields, tundra, airports, heather.	0.0047
0.1	Roughly open	Cultivated area with low crops and occasional obstacles (single bushes).	0.0075
0.25	Rough	High crops, crops of varied heights, scattered obstacles such as trees or hedgerows, vineyards.	0.012
0.5	Very rough	Mixed farm fields, forest clumps, orchards, scattered buildings.	0.018
1.0	Closed	Regular coverage with large sized obstacles with open spaces roughly equal to obstacle heights, suburban houses, villages, mature forests.	0.030
>2	Chaotic	Centers of large towns or cities, irregular forests with large clearings.	0.062

In general, wind speed in the surface layer, exhibits a logarithmic profile approximated by,

$$\bar{V} = \frac{u_*}{k} \ln\left(\frac{z}{z_0}\right)$$

where k, the Von Karman Constant is 0.4 and Z_0 is the aerodynamic roughness length. The roughness length is defined as the height of zero wind speed, as extrapolated down logarithmically from the stronger winds in the surface layer. These values can be seen in table (1) as shown from *Atmospheric Science*[5]. A value of 0.1 was used for the aerodynamic roughness length based on the terrain at the airport. This provides a general approximation but in reality, wind-profile shape varies slightly with static stability. When the boundary layer is statically stable under turbulent conditions the wind shear is well defined as,

$$\Phi_M = 1 + 8.1\frac{z}{L}$$

where L is the Obukhov length. Statically unstable conditions are also able to be approximated using surface-layer similarity theory from the equation,

$$\Phi_M = 1 - 15\left(\frac{z}{L}\right)^{-1/4}$$

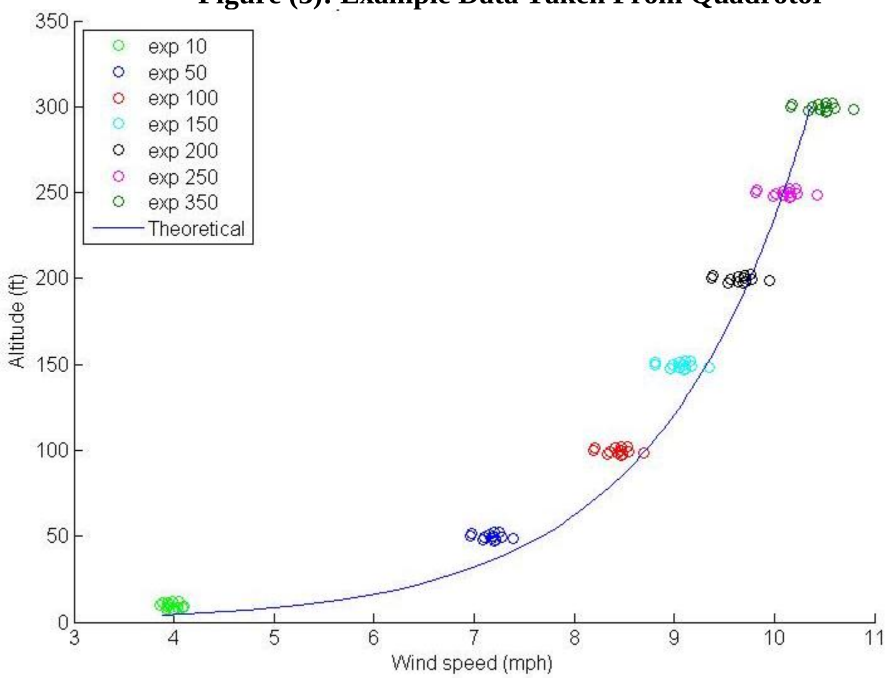
These three conditions are important approximations for the surface boundary layer but only the general profile will be compared to the experimental data. Example quadrotor data is plotted next to the theoretical results in figure (3).

Data taken from the quadrotor would have been recorded as gyroscope data in the x,y,z directions, accelerometer data in x,y,z directions, and the pulses sent to each motor by the IMU. This data will be used to find the wind shear for the surface boundary layer. First the pulse width modulation data sent to each motor from the IMU will be used to find wind velocity by,

$$U_a = \frac{(\Delta PWM_f + \Delta PWM_b)\sin(\Theta)}{L}$$

where ΔPWM is the difference in pulse width modulation from steady level flight and Θ is the gyro roll angle. The harder the wind blows, the stronger the pulses will need to be in order to stabilize the quadrotor. At each of the elevations tested, these pulse width modulation values will be averaged to ultimately determine the wind speed at each elevation point. Equally spaced increments from the lowest available station keeping position, of about 8 to 10 feet, up to 300 feet, will be tested. A sample of expected results is shown in figure (3). The quadrotor will position itself perpendicular to the wind so that two motors, in the front and back, will affected by the wind velocity at the same time. The pulse width modulation values from the front and back motors will also be averaged to get PWM_f and PWM_b. Altitude values are also averaged because the station keeping abilities are not exact and the quadrotor may drift around in a 3 to 4 foot circle. Averaging the pulse width values and the altitude values over a 3 minute span will give a better estimate at a single altitude.

Figure (3): Example Data Taken From Quadrotor



VII. Conclusion

Collecting data pertaining to wind velocity in the surface layer is easily obtained using a quadrotor but many specific calculations are required. Data could be taken from almost any point, at any location, with just the R/C controller, a laptop and of course a quadrotor. People have built quadrotors capable of super stable position hold, with less than 1.5 feet of position divergence in strong winds. This accuracy makes quadrotor data collection a very appealing method of collecting information over specific coordinates. Given more time and funding, I would be able to repair the damage suffered to the quadrotor during testing and a complete collection of data would have been conducted. Even without the actual experimental data, I was able to infer from theoretical data that this method would be viable for collecting wind velocity data. Currently, other methods such as weather balloons and remote sensing from the ground and space are used to collect data about the atmospheric boundary layer. Of the existing methods, tethered weather balloons compare closest to a quadrotor for accurate data collection. They have the ability to adjust the length of the tether to obtain data at specific altitudes and use a pitot-static system to get wind speeds. Data from the quadrotor could be improved by using the quadrotor platform only for station keeping and implementing a pitot-static system, similar to the weather balloons, for gathering wind speed data. Both of these techniques would prove extremely helpful to weather reporting and to airport controllers who both need winds aloft data for daily functions.

References

[1]Crasto, Girogio. *Numerical Simulations of the Atmospheric Boundary Layer.* Universita degli Studi di Cagliari. Cagliari, Febbraio 2007.

[2]Finnigan, J.J., Kaimal, J.C. *Atmospheric Boundary Layer Flows, Their Structure and Measurement.* Oxford University Press, Inc. 1994

[3]Garratt, J.R. *The Atmospheric Boundary Layer.* University of Cambridge. 1992.

[4]R. Storvold, H. A. Eide, P. Utley, K. Stamnes, and G. Adalsgeirsdotti. *Boundary-Layer Structure Obtained with a Tethered Balloon System and Large-Scale Observations of the Arctic Basin Obtained with a Satellite Data Acquisition System at the SHEBA Ice Cam*. University of Alaska Fairbanks.

[5]Wallace, John. Hobbs, Peter. *Atmospheric Science, An Introductory Survey*. 2nd edition. University of Washington. 2006. Elsevier Inc.

Online Resources

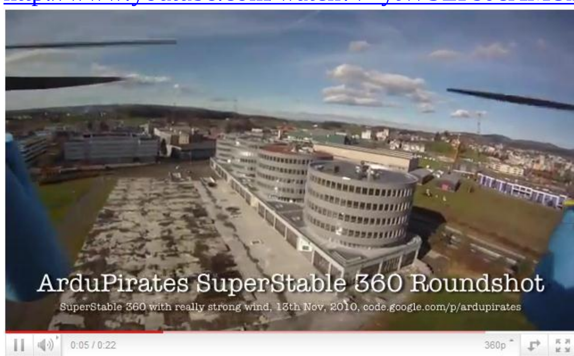
[6]Anderson, Chris. DIYdrones.com. 2011 (May 5, 2011)

[7]Arducopter Project Home. Code.google.com/p/arducopter/. 2011. (May 5, 2011)

Appendix A: Videos showing very stable quadrotor

http://www.youtube.com/watch?v=-7Tr8hqnqGQ

http://www.youtube.com/watch?v=ytWSZPs0cAM&feature=player_embedded



http://www.youtube.com/watch?v=Wit4tqS9c2k&feature=player_embedded#at=23

http://www.youtube.com/watch?v=RvsAE7tW_Kk&feature=player_embedded