Wind Data Collection Techniques on a Multi-Rotor Platform

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Abstract - **Meteorologists require reliable methods of obtaining high-quality atmospheric data, such as temperature, humidity, pressure, and wind velocity, to better understand and predict weather phenomena. Tethered weather balloons and ground towers are the current standards for research-grade atmospheric profiling. However, weather balloons and ground towers suffer from several disadvantages including high cost, low mobility, and labor intensive setups. Due to their dynamic nature, unmanned aerial vehicles (UAVs) do not suffer from those disadvantages.**

Previous efforts at the University of Virginia have demonstrated the feasibility of collecting temperature and humidity data using low-cost sensors mounted on a multirotor UAV. Those efforts also explored a variety of ways to measure wind speed and direction, both of which continue to be a challenge. This paper investigates additional methods for obtaining wind data, including the use of low cost anemometers (wind sensors) mounted on a UAV, and using the flight response of the UAV itself to determine the wind velocity. A challenge in using anemometers is that disturbances caused by the rotors affect the wind in the near-field of the UAV.

Testing has verified the feasibility of using the low-cost Modern Device Wind Sensor Rev. P for accurate wind speed measurements. Additional testing identified sensor configurations that compensate for wind noise introduced by rotor downwash. To measure wind direction, testing will determine the feasibility of both using an array of sensors as well as integrating sensor data with pitch and roll information from the UAV itself.

Index Terms - Anemometer, Atmospheric profiling, Unmanned aerial vehicles

INTRODUCTION

Meteorologists need a reliable method of obtaining various weather data such as air pressure, temperature, humidity, wind speed, and wind direction. Tethered weather balloons and stationary towers are current standards for low-altitude, research-grade atmospheric profiling (data collection over a range of specific elevations) [1]. These platforms are equipped with thermometers, hygrometers, and anemometers. However, these experiments are time-consuming, requiring hours of human involvement for setup and retrieval. Balloons and towers are also relatively immobile once deployed, as towers are in a fixed position and balloons cannot be adjusted mid-flight. Furthermore, balloons are occasionally unrecoverable, incurring a significant financial risk for each deployment.

To address these concerns, a design was made utilizing an unmanned aerial vehicle as a platform upon which sensors were mounted. The use of a UAV offers increased flexibility and ease of use over towers and balloons, as UAVs are able to be programmed to act autonomously. In addition, a quadrotor UAV can be flown with mounted sensors comparable in quality to those used on balloons and towers, and is at lower risk of being unrecoverable compared to balloons. This project's client, Professor de Wekker in the Department of Environmental Sciences at the University of Virginia, has a particular interest in the use of UAVs to collect atmospheric profiles. Previous projects have proven the feasibility of using rotor-based UAVs to collect temperature and humidity measurements [1] [2], but there is still concern that interference from the rotors affected wind measurements. The majority of this project was devoted to assessing the possibility of using flight feedback to obtain wind direction and external anemometers to obtain wind speed while accounting for noise introduced by the vehicle dynamics.

PROBLEM FORMULATION

System requirements were obtained from client interviews. For high-level functionality, it is important that a final design is 1) Able to collect atmospheric data measurements of comparable or better quality to balloons and towers 2) Able to operate in the lower atmosphere in fair weather conditions long enough to collect meaningful data and 3) Maneuverable to specific locations in the lower atmosphere. These were focused into the following specific requirements.

TABLE I
RANGE AND ACCURACY REQUIREMENTS

Measurement	Minimum	Maximum	Tolerance (+/-)
Wind Speed (m/s)	0	15	0.3
Wind Direction (°)	0	360	10
Temperature (°C)	-20	49	0.2
Relative Humidity (%)	0	100	2
Air Pressure (hPa)	500	1100	0.01

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- Flight times with payload shall exceed 10 minutes,
- The system shall be operable up to 100 m above ground level,
- The system shall maintain position or return to the ground upon loss of connection,
- The system shall be usable without a computer science or engineering background, and
- Users shall be able to program flight plans including the locations and elevations for data collection

Many of the range and accuracy requirements can be addressed using sensors from earlier research, specifically concerning temperature and humidity readings [1]. The primary challenge is collecting accurate measurements for wind speed and direction. Research conducted by deBloisblanc et al. [1] utilized an Airmar 200WX sonic anemometer mounted directly above a UAV, and they were unable to collect measurements within their required specifications. This may have occurred for a few reasons, chiefly the choice of anemometer and the mounting location. Rotary wing UAVs create thrust by drawing air from above the rotors and expelling it downwards at a higher velocity, which has the potential to interfere with measurement taken by nearby anemometers. Any mounted sensors must therefore be placed in a location to minimize this interference.

Previous research noted that some anemometers tend to be inaccurate for low wind speeds, which likely reflects on the choice of the anemometer itself [1]. Many sensors have difficulty reporting information at lower speeds, which is often a function of the type and quality of the sensor. Although the previous design used a sonic anemometer, choosing a different model may produce better results at lower wind speeds.

The use of a UAV itself also affords novel ways of determining wind speed and direction. When a UAV encounters wind, its control algorithms attempt to compensate by tilting the aircraft. This tilt may be analyzable to determine the magnitude of the wind speed. Additionally, the UAV's rotation and internal compass could be used to determine wind direction. These measurements could serve to either supplement or replace the use of anemometers when collecting wind-related measurements.

DESIGN METHODOLOGY

The focus of the research was on determining an accurate and effective mechanism for measuring wind speed and direction. The team explored two avenues for obtaining reliable measurements. The first involves an analysis of various lightweight anemometers to determine which are most suitable for UAV use. It also involves characterizing the flow field around a UAV to determine where anemometers can be mounted to avoid interference. The second involves analyzing feedback from a UAV's flight parameters to determine wind speed and direction from the movement of the UAV.

I. Anemometer Characterization

The anemometers considered for mounting on a UAV include the Applied Technologies TriSonica Mini [3], Modern Device Rev. C, Modern Device Rev. P [4], and the Kestrel 5000 [5]. The team compared price, weight, and power requirements for each sensor, and assessed sensor accuracy through testing.

The Rev. C and Rev. P are thermal anemometers: Wind cools a heated element, changes its resistance, and causes a voltage drop to be recorded by a sensor. This voltage drop correlates to wind speed. The Kestrel is a vane anemometer: Incoming wind causes a impellor to spin, which allows the sensor to report the wind speed. The TriSonica is a sonic anemometer. It emits ultrasonic sound pulses, which are then affected by any present wind. The sensor reads these pulses to determine wind speed and direction. Of these anemometers, only the TriSonica can record both wind speed and direction; the others are only able to determine speed.

Price and weight are important factors to consider when comparing anemometers. Weight is of crucial importance, as each added gram places more strain on the UAV's battery, limiting flight time. The results of these comparisons are shown in Table II. The Kestrel was immediately dismissed as an option due to weight concerns.

TABLE II
COMPARISON OF ANEMOMETER PRICES AND WEIGHTS

Name	Type	Price (USD)	Weight (g)
Modern Device Rev. C	Hot Wire	17	2
Modern Device Rev. P	Hot Wire	24	2.6
Kestrel Handheld 5000	Vane	250	121
TriSonica Mini	Ultrasonic	1,600	38

A variety of tests were performed to determine sensor accuracies. The first involved mounting the Rev. P and Rev. C sensors to a Clearpath Robotics Jackal ground vehicle. The Jackal traveled down a hallway at 2 m/s to simulate wind. This test's results can be seen in Figure I, where the Rev. P provided more accurate and less noisy readings. From this, it was concluded that the Rev. P was superior to the Rev. C.

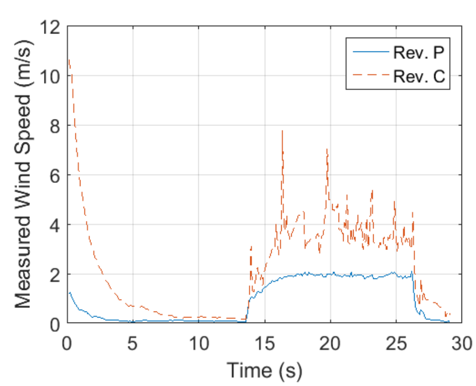

FIGURE I
TESTING OF REV. P AND REV. C ANEMOMETERS AT 2 M/S USING JACKAL GROUND VEHICLE

The next set of sensor tests concerned the Rev. P through two outdoor trials. A Rev. P mounted on a weather tower collected data outdoors over the course of 22 hours for the first test, and 16 hours for the second. An RM Young 85000 sonic anemometer [6] was used to provide a baseline wind speed and direction. It was selected due to its use as a standard in the University of Virginia's Department of Environmental Science. The RM Young is too heavy to be mounted on most UAVs. In general, the Rev. P responded to changes in wind speed but often reported numbers lower than the RM Young.

We hypothesized a combination of factors that could have caused this discrepancy, including directionality, wind speed, and temperature. The board on which the hot element of the Rev. P is mounted disrupts wind flow approaching the sensor from certain angles, resulting in poor readings of wind approaching from the rear. Wind speed measurements from the Rev. P and RM Young sensors were sorted into 1 degree wide bins from 0 degrees to 360 degrees. Average wind speed bias for each bin was then calculated. Figure II is a plot of analysis, with the angle of wind incident relative to the Rev. P on the x-axis and the wind speed bias relative to the RM Young wind speed reading on the y-axis. This confirmed the effect of direction on the accuracy of the Rev. P. The lines represent polynomial fits for different direction ranges, which were later used to correct the Rev. P data during a post processing step.

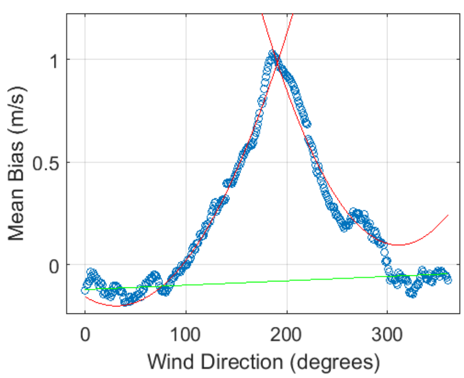

FIGURE II
CHARACTERIZATION OF WIND SPEED BIAS OF REV. P IN RESPONSE TO WIND ANGLE

In addition to directionality, temperature and wind speed biases were analyzed. Figure III plots the relationship between temperature and bias, and Figure IV shows the relationship between wind speed measured by the Rev. P and bias.

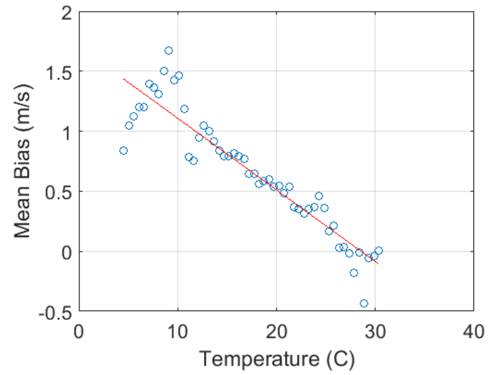

FIGURE III
REV. P WIND SPEED MEASUREMENT BIAS IN RESPONSE TO TEMPERATURE

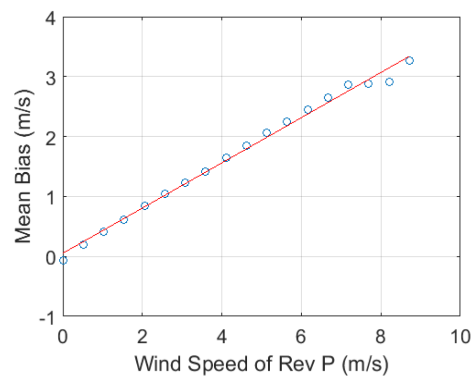

FIGURE IV
REV. P WIND SPEED MEASUREMENT BIAS IN RESPONSE TO MEASURED SPEED

The temperature and wind speed bias plots can be approximated well by a linear fit. Directionality is more complicated, requiring three curve fits. One polynomial accounts for the -60 - +60 degree range relative to the front of the Rev. P sensor that is unaffected by wind direction. The second polynomial accounts for the 60 to 180 degree range in which bias increases with increasing angle. The third polynomial accounts for the 180 to 300 degree range in which bias decreases with increasing angle. This analysis allowed the team to create an adjustment protocol to apply to every reading of the Rev. P sensor, if temperature and wind direction relative to the sensor are known. The adjustment protocol reduced the standard deviation of the bias of all measurements, and centered the mean bias on 0 +/- 0.2m/s, as seen in Figure V.

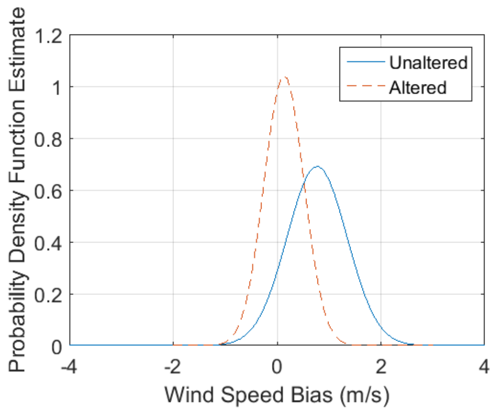

FIGURE V
COMPARISON OF PROBABILITY DENSITY FUNCTION OF BIAS FOR UNALTERED REV. P DATA AND ADJUSTED REV. P DATA

From this, the team envisioned a potential design using multiple Rev. P sensors in different orientations to compensate for the directionality. The discovered functions could then correct the data to obtain more accurate measurements

The team also investigated the TriSonica Mini ultrasonic sensor. Future testing plans include creating a system of the TriSonica, the RM Young, and an array of four Rev. Ps to collect data on a weather tower over the course of several hours. This test will allow for not only an analysis of the TriSonica sensor, but also of the feasibility of using a network of Rev. Ps in different orientations to compensate for their directionality.

II. Rotor Airflow Analysis

The second aspect of analyzing the sensors involved characterizing the flow field around a UAV. Any anemometers mounted on a UAV have the potential to erroneously report the airflow created by the UAV as wind. It was therefore important to locate zones of low interference—where there was minimal wind induced by the UAV. The team acquired a Cheerson CX-20 quadrotor UAV for the final design, so it was selected for analysis. A tripod mounting system restricted the UAV's movement while the Cheerson operated at full throttle to simulate the maximum possible disturbance. An image of this system can be seen in Figure VI. A Rev. P anemometer measured wind speed around the UAV to find zones of low interference. A Vicon motion capture system recorded the position of both the UAV and the sensor. All data was stored in the same file during testing. Measurements were taken at various distances from each of the 8 cardinal and primary intercardinal directions relative to the Cheerson. Figure VII identifies the 8 directions from which measurements were taken and the dimensions of the Cheerson.

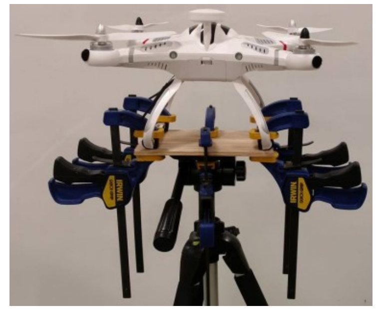

FIGURE VI
TRIPOD MOUNT FOR FLOW TESTING

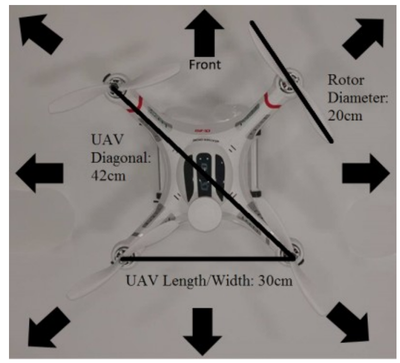

FIGURE VII
ORIENTATION AND DIMENSIONS OF CHEERSON CX-20 UAV

Figure IX shows the results of this testing, where it was determined that a low-interference zone exists roughly 0.7m from the UAV's center. For each of the 8 directions, the reported wind speed was under the 0.3 m/s threshold. This influenced the system design, providing a minimum distance for the booms that extended the anemometers from the UAV. Placing at this minimum distance should ensure that any mounted sensors are minimally influenced by the downdraft from the UAV. It should be noted that air could be felt reflecting off the floor and the test rig, which may have interfered with measurements as the Cheerson was only mounted 1.5 m off the ground. In an outdoor, real-world environment this effect should be minimized.

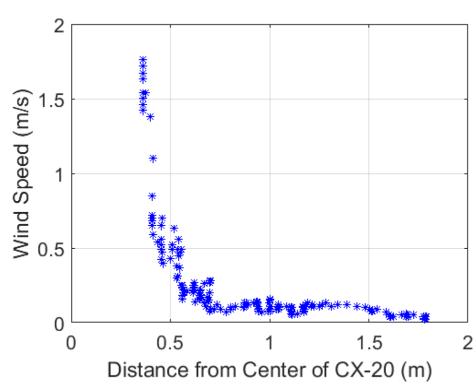

FIGURE IX
WIND DISTURBANCE FROM THE BACK RIGHT OF THE CX-20

III. Correlation of Flight Behavior to Wind Speed and Direction

The method of determining wind speed and direction through UAV flight dynamics involved extensive analysis of UAV mechanics and of testing with the Vicon system. The Parrot Bebop 2 provided a UAV platform for testing. The Bebop is a quadrotor UAV equipped with optical sensors and computer systems allowing it to maintain its position without user input. It was used to measure the impact of wind on the UAV's tilt; as it encounters wind, the Bebop rotates itself in a way to hold its position.

The first test utilizing the Bebop involved setting it to maintain its position while in the flow of a box fan. From this, analyzing the pitch and roll of the UAV could provide a proof of concept showing that the magnitude of changes in pitch or roll could be used to determine wind speed. The results of this test can be seen in Figure X.

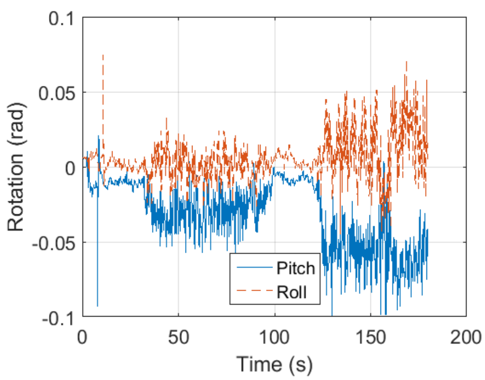

FIGURE X
EFFECT OF WIND SPEED ON UAV PITCH AND ROLL

When the fan was on low (40s-80s) the pitch increased. When the fan was set on high (125s-170s), the pitch doubled. This confirmed that the UAV does tilt to compensate for wind. Other researchers are further testing this relationship [7] [8].

The next test for the Bebop sought to determine the direction of incoming wind by analyzing the relationship between the pitch and roll. A similar test was run as before, but the fan was moved to eight different locations equidistant around the UAV (0, 45, 90, 135, 180, 225, 270, and 315 degrees). The fan was run on high speed, and data on the location of both the Bebop and the fan was collected using the Vicon motion capture system. The Bebop also self-reported its pitch and roll. The results of this test were visualized in Figure XI.

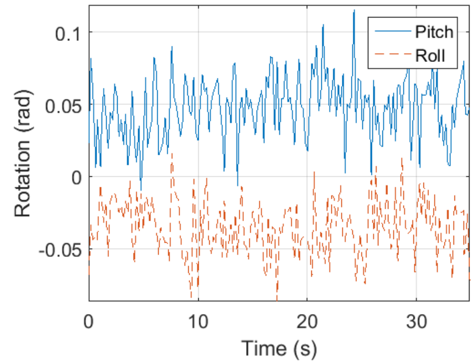

FIGURE XI
EFFECT OF WIND DIRECTION (225 DEGREES) ON UAV PITCH AND ROLL

The test was confounded as it was not possible to keep the Bebop at a precise angle. However, it did prove the concept of pitch and roll adjusting in wind approaching from different directions. Pitch was mostly affected in tests where the Bebop faced the wind or faced away from the wind. Roll was mostly affected in tests with the wind approaching from the left and right. Both pitch and roll were affected in tests where the wind arrived in between axes. This experiment was limited in that it only utilized 45 degree increments; obtaining different increments may reveal a trigonometric relationship. Additionally, further testing could utilize a control algorithm allowing the Bebop to use Vicon data to maintain an exact position relative to the fan.

DESIGN REVIEW AND EVALUATION

A final design is envisioned with multiple Rev. P and/or TriSonica anemometers mounted off the arms of the Cheerson UAV. The Rev P. sensors will utilize custom foam booms extending from the arms of the UAV, and the TriSonica will utilize a custom 3D printed plastic mount extending from the center of the UAV. An Arduino Mega and prototyping board will be mounted to the underside of the Cheerson CX-20 using velcro, with circuits soldered to prevent wire slippage. The prototyping board will include an SD card for data storage and a GPS for time synchronization. The Cheerson will provide power to the sensor package, eliminating the need for an additional power source. The Cheerson CX-20 can be programmed to fly to specific points autonomously, allowing it to collect atmospheric profiles without significant human interaction.

The first prototype tested will include four Rev. P sensors mounted off the arms of the Cheerson. An image of this prototype is provided in Figure XII. The UAV will hover in place next to a ground tower mounted with the RM Young anemometer, and measurements from the two systems will be compared. Both systems will face north to ease data analysis. This testing will determine the viability of the mounting system as well as the effectiveness of the Rev. P placement concerning minimizing interference. Later field tests will utilize mounting the TriSonica sensor and collecting flight dynamics information from the Cheerson.

FIGURE XII
PROTOTYPE WITH FOUR MOUNTED REV. P SENSORS

RECOMMENDATIONS AND FUTURE WORK

While anemometers were compared based on accuracy, the TriSonica remained the only mountable anemometer able to record wind direction by itself. The team hypothesizes using arrays of the low-cost Rev. P sensor to determine wind direction, but this research is still ongoing. It would be economically advantageous to be implement a system only with low cost sensors.

Furthermore, while work was done to analyze the effects of wind on a UAV's flight behavior, no work was done on analyzing the effect that mounted sensors had on the UAV. By shifting the UAV's weight distribution, the flight dynamics were likely altered. Tuning the UAV's control parameters to address this effect may improve system performance.

CONCLUSIONS

Specific anemometer models were identified that are strong candidates for mounting on unmanned aerial vehicles, and researched the feasibility of using feedback from UAVs to determine wind speed and direction. The resulting system, especially when utilizing the low-cost Rev. P anemometer, has the potential to be less expensive and easier to use compared to the existing technologies of weather towers and balloons. Further testing will be conducted to analyze the accuracy of the TriSonica sensor as an alternative to the Rev. P as well as the feasibility of the system in real-world conditions. More research will also be conducted into correlating pitch, roll, and yaw to wind speed and direction. Once this is accomplished, existing humidity and pressure sensors can be attached to the UAV and the performance of the resulting design can be evaluated with regards to system requirements.

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