ANDroMeDA - A Novel Flying Wind Measurement System

Christian Molter¹, Po Wen Cheng¹
¹ Stuttgart Wind Energy (SWE) at Institute of Aircraft Design, University of Stuttgart
Allmandring 5B, 70569 Stuttgart, Germany
E-mail: molter@ifb.uni-stuttgart.de

Abstract. A novel multirotor aircraft was developed at the University of Stuttgart, designed especially for wind speed measurements. Currently the aircraft is equipped with a combined Prandtl / triple hot wire probe but in general the design is modular. The measurement performance of the overall system is validated and compared to conventional measurement techniques. Methods of validation are a free flight in calm air, wind tunnel tests and a hovering flight next to a met mast. It could be shown that the measurements show a good agreement between 4 m/s and 13 m/s. The maximum wind speed that can be measured could be determined to 25 m/s by extrapolation of the flight envelope but has to be confirmed in the future.

1. Introduction
In the past years several research groups and companies started to use multirotor aircrafts (commonly referred to as drone) to measure the wind speed while hovering at a fixed location in space (compare for example [6], [5]). For a successful wind measurement with a multirotor aircraft, or with a rotary wing aircraft in general, several challenges have to be mastered. First of all it has to be ensured that the rotor inflow of the aircraft does not influence the free-stream measurement. Consequently, a fundamental knowledge about the rotor flow field is necessary.

Another factor is the varying pitch angle of the aircraft, which has to lean against the wind. Most flow measurement probes have a limited inflow angle range. For a five hole probe (FHP) from Aeroprobe, for example, this range is ±20° [2]. The resulting pitch angle of the aircraft can be expressed as a function of wind speed ($v_\infty$), air density ($\rho$), drag coefficient of the aircraft ($c_D$), aircraft weight ($W$) and aircraft reference area ($A$):

$$\tan(\theta) = \frac{\rho \cdot v_\infty^2 \cdot c_D \cdot A}{2W}$$  \hspace{1cm} (1)

Fig. 1 illustrates the relation between wind speed, thrust and pitch angle for a conventional multirotor aircraft with a value of $c_D \cdot A = 0.3 \text{ m}^2$ and a weight of $W = 5 \text{ kg}$. It can be seen that with a probe limited to an inflow angle of 20° a maximum wind speed of only $v_{\text{max}} = 10 \text{ m/s}$ can be measured.

When a sudden change of wind speed occurs, the pitch angle has to change to reach a new state of equilibrium. The rotation necessary to acquire this new pitch angle induces an additional speed on the flow measurement probe as shown in Fig. 2. The induced velocities
can be calculated with the global coordinates of the aircraft’s CG \((x_{\text{CG}}, y_{\text{CG}}, z_{\text{CG}})\), the local coordinates of the probe \((x_p, y_p, z_p)\) and the rotational rates \((p, q, r)\):

\[
\dot{x}_p = \dot{x}_{\text{CG}} - z_p \cdot q - y_p \cdot r \tag{2}
\]

\[
\dot{y}_p = \dot{y}_{\text{CG}} + x_p \cdot r + z_p \cdot p \tag{3}
\]

\[
\dot{z}_p = \dot{z}_{\text{CG}} + x_p \cdot q - y_p \cdot p \tag{4}
\]

The rotor(s) of a rotary wing aircraft in forward flight or in a hovering flight with headwind experience different velocities at the advancing and retreating blade. At the advancing blade the wind speed adds up to the rotational speed, \(\Omega \cdot r\), and at the retreating blade it subtracts from the rotational speed. Consequently, different dynamic pressures and different forces exist and present an unavoidable source of vibration. These vibrations can influence the flow measurement probe and it has to be ensured that either the probe is decoupled from the vibrations or its performance is not affected by them.

Most rotary wing aircraft and especially multirotor aircraft are designed to hover at low wind speeds. To measure wind speeds in the operating range of a wind turbine an aircraft capable of handling higher wind speeds has to be designed.

All those challenges have been addressed in one aircraft, purpose-designed to measure wind speeds in the research field of wind energy. This aircraft is called ANDroMeDA ANWIND Drone for Measurement and Data Acquisition and is presented here. In section 2 after an introduction of the general aircraft design concept and the encountered challenges, the used custom triple hot wire probe is briefly presented. Section 3 shows the different validation procedures with the corresponding results.

2. The ANDroMeDA Concept

To avoid a rotor influence on the measurement probe ANDroMeDA is equipped with a one meter long measurement boom. Intensive simulations and wind tunnel tests have been conducted to develop a fundamental knowledge of the flow in the vicinity of a rotor. Some of the results have been presented in [4].

It could be shown that the inflow field in front of a rotor is much easier to predict than the wake behind it. This inflow field (Fig. 4) has an appearance similar to a dipol singularity in potential flow theory. The size of this inflow field and thereby the region of influence depends purely on the disc loading of the rotor and the free-stream velocity.
Consequently, a rotor with a high disc loading, operated in a very low free-stream velocity will disturb the probe the most. In case of ANDroMeDa, when hovering in a windless environment the probe shows a resulting flow speed of approx. 1 m/s. Hence, it does not make sense to measure very low wind speeds with a rotary wing aircraft.

Tilting rotors play an important role in the ANDroMeDa concept (compare Fig. 3). Three essential challenges could be overcome by the use of tilting rotors. First of all, they are used to stabilize the entire aircraft and the measurement boom, rigidly attached to it, in the longitudinal axis. Thus, the pitch angle of the aircraft does not change anymore with varying wind speeds and the full angle measurement range of the probe is available.

The tilting rotors and the stabilized airframe also lead to minimal induced velocities due to aircraft movements. Only a roll rate (rate p in Fig. 2) can be present during wind gusts, which will not induce any velocity on the probe.

The slender design of ANDroMeDa with its small frontal area in combination with the tilting rotors also leads to an increased flight time at higher wind speeds and a faster alleviation of wind gusts. During the development it was estimated that tilting the rotors is almost three times faster than tilting the entire aircraft to achieve a new equilibrium state after a sudden wind speed increase from 10 m/s to 15 m/s.
The tilting rotors also offer two more advantages. By differential tilting of the left and right rotors a large yawing moment can be developed, which is almost one magnitude larger than the yawing moment that can be reached with a conventional multirotor aircraft, where yawing is realized by differential rotational speeds of the rotors. This larger yawing moment is used to counteract the weather vane effect of the long measurement boom in front of the aircraft.

The last advantage of the tilting rotors is an additional degree of freedom about the longitudinal axis. Other than a conventional multirotor aircraft, ANDroMeDA can hover with a nose-up or nose-down attitude. This feature is used for take-off and landing as shown in Fig. 5. A nose-up attitude results in a large distance between the boom tip and the ground and helps to protect the probe from grass and debris. Also some weight could be saved for the retractable landing gear which consists of only a single strut as shown in Fig. 6. The modular design allows a fast replacement of the landing gear in the field with only six screws.

![ANDroMeDA after Takeoff.](image1)

![Modular landing gear unit.](image2)

Vibrations at the probe are low because the natural frequencies of the measurement boom have been adjusted to avoid the rotational frequency of the rotors and their multiples as shown in Fig. 7. To achieve Fig. 7 a shaker table was built and the measurement boom, as shown on the right side of Fig. 9, was attached to this shaker. Two measurements have been taken simultaneously, one at the shaker table and one at the probe location at the tip of the boom. The transmissibility function expresses the ratio between the two amplitudes of these vibrations. A value of 1 indicates the same amplitude at the shaker, hence the base of the measurement boom, and the tip of the boom.

At the rotational frequency of the rotors in hover the transmissibility function is smaller than 0.5, which means that the vibration amplitude at the tip of the measurement boom is smaller than half of the amplitude at the airframe.

During first test flights it could be observed, however, that the flight controller is sensitive to the natural frequency of the measurement boom. This results in strong oscillations because the controller moves the tilt actuators at the natural frequency of the boom and thereby excites the boom to oscillate. These oscillations could be successfully avoided by the use of a notch filter for the flight control outputs.

In addition the triple hot wire probe, currently used for ANDroMeDA, has been proven to be quite insensitive to vibrations. But of course, vibrations of the boom will induce additional velocities at the probe. To monitor the movements of the boom tip an additional IMU has been installed close to the probe (see right side of Fig. 8).
ANDroMeDA was designed in a modular way and different probes can be used as shown in Fig. 9. Currently, a combined probe including a Prandtl tube, three hot wires and a temperature sensor is used. The temperature measurement is essential to calculate a velocity information from the hot wires. This combined probe has been designed especially for flying wind measurements in cooperation with SVMtec GmbH. SVMtec also provides pre-calibrated hot wires, spare hot wires, the CTA bridges and developed a mainboard to sample all measurement values and send them to the autopilot and data acquisition system. While the Prandtl tube serves as a robust reference measurement, the triple hot wire probe offers an additional information about the inflow direction and a high temporal resolution of up to $f = 2\, \text{kHz}$ (limited by a low pass filter in the CTA bridges). The used tube from ESA Berlin has been proven to be insensitive to variations of the inflow angle up to $\pm 20^\circ$.

Usually a triple hot wire probe, as it is used for lab applications, is a tiny device with all three wires and their prongs mounted to one common shaft. This, however, means that in case of a broken wire the entire unit has to be replaced.

Since the turbulent structures in the atmosphere are expected to be significantly larger than the ones in a wind tunnel the three hot wires can be mounted further apart. Consequently, a special mount has been designed to hold three independent shafts (Fig. 8). The volume enclosed
by the three hot wires is approx. 40 mm × 40 mm × 12 mm. This design offers two important advantages for field measurements. SVMtec provides the three hot wires pre-calibrated. Because ANDroMeDA and its current probe have been designed for swarm measurements with several aircraft, the effort for an individual calibration of every particular probe is too high.

In addition, if a wire breaks, it can be replaced in the field. Every hot wire is calibrated together with the corresponding connections and the CTA bridge. As illustrated in Fig. 10 two connectors are implemented for each position X of the triple hot wire probe, CONN XA and CONN XB. For each position of the probe a hot wire and spare hot wires have been pre-calibrated together with all cables and the CTA bridge. Hence, it is possible to disconnect only CONN XA and replace a broken wire in the field. The calibration data for the replacement wire is then uploaded to the EEPROM of the hot wire electronics via USB.

![Figure 10: Topology of the hot wire measurement equipment.](image)

To use the above mentioned differential tilting for yaw control and the notch filter, to avoid vibrations at the measurement boom, some changes in the flight control software had to be implemented. The position control algorithm also had to be modified to keep the airframe and measurement boom always level. The open source firmware PX4 together with QGroundControl [3] was used as a baseline controller and slightly modified to meet the requirements of flying wind measurements. Fig. 11 shows the control scheme of a conventional multirotor aircraft compared to the ANDroMeDA position controller.

3. Validation of the Measurement Range and Measurement Performance
During the first outdoor test flights the maximum tilt angle was limited to $\sigma = 30^\circ$. With this tilt angle a maximum flight speed of $v = 16$ m/s could be reached in calm air. This means that at wind speeds higher than $v_{\text{wind}} = 16$ m/s ANDroMeDA will fly backwards. However, a higher tilt angle up to $\sigma = 55^\circ$ is mechanically possible and will be tested carefully in the future. Fig. 12 presents an extrapolation of the current flight test data according to Eq. 1. Accordingly, a maximum flight speed of $v_{\text{max}} = 25$ m/s should be possible. This has to be validated in future test flights.

The probe itself has been tested in a small wind tunnel. The angle measurement range of the triple hot wire unit could be identified as $\alpha = -40^\circ .. +20^\circ$ and $\beta = \pm30^\circ$ with an accuracy of $\pm3^\circ$. The Prandtl tube is insensitive to inflow angle changes up to $\pm20^\circ$ and is in this angle range measuring the magnitude of the inflow velocity.

As a first inflight test of the measurement system ANDroMeDA was flown in calm air. Fig. 13 shows the comparison of the flow speed measured with the triple hot wire probe and the GPS ground speed. In general there is a good agreement. Outliers can be explained by curves flown too tight for the measurement range of the probe or wind during the flight. From Fig. 13 it can also be seen that during a hovering flight condition (e.g. at $t = 200$ s) the probe shows an inflow speed of approx. $v_\infty = 1$ m/s which emphasizes the low influence of the rotors on the measurement.
To fully investigate this influence and to demonstrate that at higher free stream velocities there is practically no influence of the rotors on the probe, untethered, radio controlled flights in a wind tunnel have been conducted. As a reference measurement a sonic anemometer was placed inside the tunnel on a stand (Fig. 14). Because of the GPS denied environment inside the steel wind tunnel the aircraft had to be controlled manually. This means that the position is not maintained as accurate as during an outdoor measurement with GPS aided position control. However, an untethered radio controlled flight, compared to the operation of the aircraft on a fixture, means that there is no doubt about the trim condition and realistic thrust of the aircraft.

Fig. 15 shows a comparison between the flow speed measured with the sonic anemometer and ANDroMeDA. The measurements show a constant offset of $\Delta v = 0.4 \text{m/s}$. It is assumed that this results from the fact that the sonic anemometer was always closer to the tunnel wall. In addition to the flight with the measurement boom, other flights have been conducted inside the wind tunnel with a dummy measurement boom. This dummy boom has the same weight
Figure 13: Comparison of GPS ground speed and flow speed measured with ANDroMeDA-1 in calm air.

and inertia as the real measurement boom but no probe. During those tests ANDroMeDA was flown with the tip of the dummy boom close to the sonic anemometer for 20 seconds and then far behind the sonic for the next 20 seconds for several times. No influence of the rotors can be seen at speeds above 4 m/s.

Figure 14: Flight of ANDroMeDA-1 in a wind tunnel.

Figure 15: Comparison of sonic and ANDroMeDA in the wind tunnel.

If the wind vector in an earth frame of reference has to be determined, the local wind vector, measured in the aircraft’s body frame of reference, has to be transformed first. The most simple solution is the transformation with a single rotation matrix. However, this method does not account for movements and rotations of the aircraft itself. The full solution is:

\[
v_{\text{global}} = R^T (u \ v \ w)^T - (v_x \ v_y \ v_z)^T - (q \ p \ r)^T \times (L \ 0 \ 0)^T
\]  

(5)
In Eq. 5 $R$ is a rotation matrix calculated from the attitude quaternion, which is logged by the Autopilot. The vector $(u \ v \ w)^T$ is the inflow vector, measured by the triple hot wire probe. The aircraft’s translational speeds are $v_x$, $v_y$, $v_z$ and the roll-, pitch- and yaw rates are $q$, $p$ and $r$. The distance from the probe to the CG is denoted as $L$.

Because of the actively stabilized measurement boom, the second and third term of Eq. (5) do not alter the results significantly. For most cases it is sufficient to use only the rotation matrix. The rotation matrix, however, is absolutely mandatory to account for the current heading of the aircraft.

As a final “real life test” ANDroMeDA was flown next to a met mast. The mast is equipped with sonic anemometers. With the help of the UTC GPS time of the data acquisition system of the met mast and ANDroMeDA the measurements could be synchronized and compared to each other. The sampling frequency of the sonic anemometer was $f = 20 \text{ Hz}$ while the measurement of the triple hot wire probe was sampled at $f = 100 \text{ Hz}$. During post-processing the measurements of the sonic anemometer were upsampled to the same rate.

The aircraft was piloted and positioned manually with the help of a live altitude reading. The altitude reading is important, because it is very difficult to see if the aircraft is flying exactly at the height of the sonic anemometer at 98 m. During the measurement the position was kept automatically by the autopilot with the help of GPS. In the GPS aided flight mode manual corrections are still possible to change the aircraft’s position, altitude and heading. A live preview of the wind measurement (shown in Fig. 16) was used to adjust the heading manually so that the measurement range of the triple hot wire probe was not exceeded. It is planned to implement an automatic heading adjustment to the position controller in the future. The measurements from the sonic anemometer and ANDroMeDA agree very well, as shown in Fig. 17 to Fig. 19. Furthermore, this experiment has shown that ANDroMeDA can handle wind speeds up to 13 m/s without any problems and the live data is sufficient to supervise a flight and adjust the aircraft’s heading manually.

Figure 16: Live preview of wind measurements with QGroundControl.
Figure 17: Comparison of the measured wind speed measured with a sonic anemometer at the met mast and ANDroMeDA.

Figure 18: Wind direction measured by the sonic anemometer (black) and ANDroMeDA (red).

Figure 19: Vertical wind speed measured by the sonic anemometer (black) and ANDroMeDA (red).

4. Conclusions and Outlook

It could be shown that the multirotor aircraft ANDroMeDA, purpose-designed for wind speed measurements, performs well at wind speeds above 4 m/s and up to 13 m/s. According to the flight performance of the vehicle it can be expected that also higher wind speeds up to 25 m/s can be measured.

With the experience gained from building and operating ANDroMeDA-1 slight improvements
have been implemented in the design. This improvements mostly concern a small series production and wiring of the aircraft.

At the moment several more ANDroMeDA aircraft are being build. In the future multiple vehicles will be used for swarm measurements to investigate the nature of all kinds of flow phenomena, which can be explored by short duration measurements at a high spatial and temporal resolution as for example the wake after a forest in complex terrain, turbine blade tip vortices, shape of the induction zone, etc.

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