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Measurement of the Atmospheric Boundary Layer in an Urban Environment with a Flying Anemometer

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ABSTRACT

This paper investigates the potential application for a novel multi-rotor unmanned aircraft system “flying anemometer” in the urban atmospheric boundary layer. In recent years, advancements in unmanned aircraft system technology have made multi-rotors increasingly commonplace in a wide variety of civilian applications including urban wind measurement. Although the endurance of multi-rotors generally limits their suitability for measurements within the upper regions of the atmosphere, useful sampling times in the lower regions of the atmospheric boundary layer is still possible. It is envisaged that the wind data collected in the lower regions of the atmospheric boundary layer can be used by architects, civil engineers and urban planners to understand and potentially mitigate the effects of high-frequency turbulent fluctuations.

1. Wind Sensing in the Atmospheric Boundary Layer

Characterizing the airflow in an urban environment has several important applications. It can be used to protect buildings against wind damage, investigate gust-related safety and comfort issues for pedestrians and building occupants, track pollutant dispersion and model unique weather patterns that are generated within the urban atmospheric boundary layer (ABL)(Oke 1988). Urban centers have radical impacts on the aerodynamic features of a local environment due to the disruption of flow associated with the proximity of buildings as well as anthropogenic radiative forcing (Menut *et al.* 1999). Velocity distribution within the urban ABL is complex and is predominantly determined by the roughness of the surface both on a meso-scale (tall buildings and street canyons), down to the micro-scale (vegetation and traffic) (Oke 1988).

Traditional Techniques

Traditional measurements in the upper portion of the ABL are typically conducted by tracking weather balloons using doppler radar, meteorological satellites or by high-altitude sounding. While these techniques are suitable for measuring airflow at the high altitudes required to characterize the upper section of urban ABL, they are restricted by the low spatial resolution of the resulting data and the cost of setup and operation (Walterscheid, 2009). At altitudes below 100m, anemometers and LIDARs can be rigidly mounted to vertical masts. The altitude range for these sensors is limited by the maximum height of the mast (Dupont *et al.* 1999)(Eamon & Steven 2011). Ground-based LIDAR can be used to measure the upper portion of the urban ABL with altitudes on the order of 1-2km (Kumer *et al*. 2014)(Lim *et al.* 2016). High-temporal-resolution analysis of the structure of the urban ABL can be achieved using LIDAR but this requires the sensor to have a high signal-to-noise ratio and thus high laser output energy. Low energy LIDAR systems have been developed but these have limited temporal resolution (Menut *et al.* 1999).

Wind Sensing MUAS

Multi-rotor unmanned aircraft systems (MUAS) offer a novel platform for measuring wind flow in an urban environment because they can fly in close-proximity to buildings and collect point-measurements for relatively low-risk and cost (Wallace et al. 2012)(Prudden et al. 2017). MUAS provide hovering capability at precise points in space for extended periods of time as well as maneuverability in all directions. A known limitation of MUAS-based wind measurement is the relatively low flight time compared to fixed-wing systems. This is driven by the available on-board energy storage, which is typically composed of Lithium Polymer (LiPo) batteries and results in a maximum flight time of less than 30 minutes (Mulgaonkar et al. 2014). While this sampling time is significantly shorter than mast-mounted sensors, it is suitable for measuring elements of the higher fluctuating frequencies of the ABL, that have periods of less than one hour (Martin et al. 2011). These higher frequencies often contain considerably more energy compared to lower frequencies and are of considerable interest when investigating wind loading on a building, pedestrian comfort and safety (Stathopoulos 1984) (Visser & Cleijne 1994). Tethered power solutions have been found to be an effective method for increasing the endurance of MUAS by providing continuous power as long as a ground-based power supply is available (Duffy & Samaritano 2015). However, these systems also add considerable mass and complexity to the system and limit the area of operation due to the requirement for direct Line of Sight (LOS) wired connections (Elbanhawi *et al.* 2017).

As demonstrated in Figure 1, the hover capability of MUAS-based wind sensors provides the capability for measuring wind at altitudes higher than typical masts. This creates opportunities for conducting measurements at potential sites for tall buildings in urban areas. Tall buildings are wind sensitive structures, and wind phenomena around buildings and urban environments can be a challenge to predict. It is envisaged that MUAS could aid architects and civil engineers in determining regions with adverse wind conditions in an urban environment. The two major wind-induced concerns for building designers are the lateral deflection and extreme vibration of the structure (Huang *et al.* 2012). It is perceived that data collected from the MUAS, in conjunction with static-sensors (anemometers, LIDAR, etc.) will provide a method of measuring these effects and ensure tall buildings meet their wind-induced serviceability design requirements.

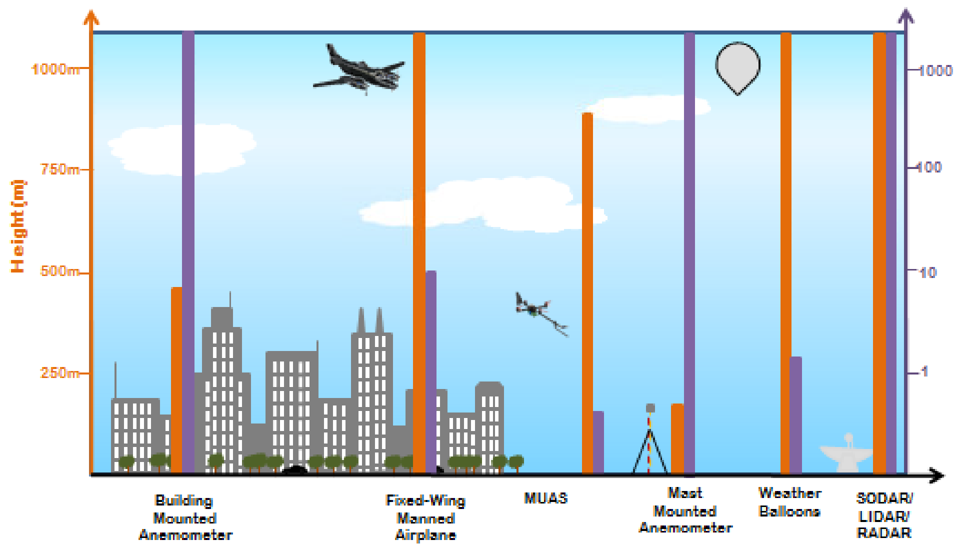

Figure 1: The endurance and measuring range of traditional wind measurement devices in the urban environment compared to a MUAS.

Understanding the micro-meteorological airflow behavior surrounding a building could be used to potentially optimize the location of wind deflectors and reduce aerodynamic high-impact loading by improving wind-resistant façade design (Geurts *et al.* 2004) or altering the geometry of the building to minimize lateral deflection and high-impact gusts (Chuan-Li, Shu-Yan et al. 2013).
The wind data provided by the MUAS could also be used to assess factors that affect human comfort, particularly in high-density urban environments where high-wind velocity and thermal effects can be detrimental to health. In large buildings excessive wind vibrations can lead to habitability concerns. The perception of vibrations related to body sensation is typically in the low frequency range (<2Hz). Perception relating to visual cues is generally dominant in the higher frequency range (>2Hz). High-intensity wind gusts and pollutant dispersion in the air also pose a risk to pedestrians. Wind flow is generally accelerated through a street canyon (Oke 1998) and this highly-disturbed flow can be often difficult to characterize with static instruments. Dynamic flow mapping techniques offered by MUAS have the potential to assist urban planners in designing streetscapes that ameliorate pedestrian comfort (Menut *et al.* 1999).

MUAS also have the capacity to validate Computational Fluid Dynamics (CFD) models. Mohamed *et al.* (2015) demonstrates the effectiveness and reasonable accuracy of mapping airflow around representative urban buildings using the Improved Delayed Detached Eddy Simulation turbulence model. The computational power required to effectively run the simulation across a broad range of altitudes is a significant limiting factor. Additionally, computational models rely on assumptions that may compromise their accuracy and need to be validated. Developments in control systems and swarming techniques provide the possibility of using multiple aircraft to conduct simultaneous measurements of ABL profiles at multiple altitudes, i.e. a “virtual mast” shown in Figure 2. This has the potential to increase the flexibility of the wind measurement locations compared to existing mast-mounted systems and provide a more robust validation for CFD models.

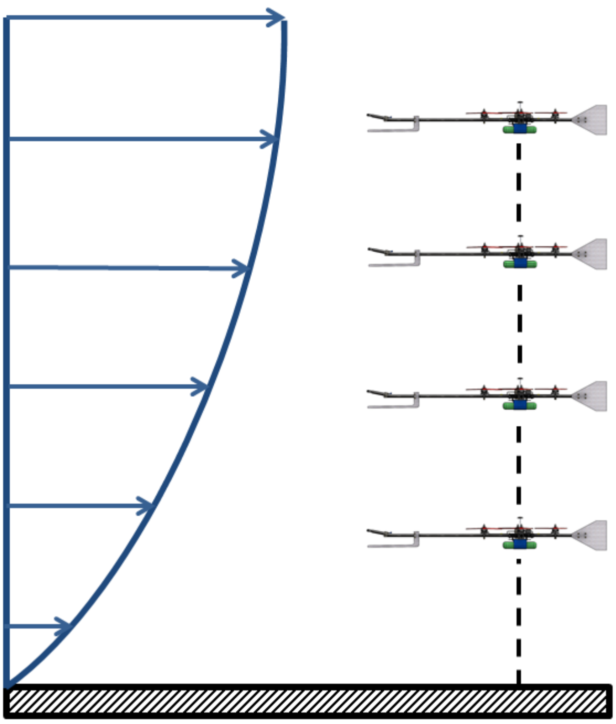

Figure 2: Multiple aircraft swarming together to create a ‘virtual mast’. This ‘mast’ can be used to collect simultaneous measurements at multiple altitudes in close-proximity to tall buildings.

2. Overview of Narwhal 2.0

The MUAS evaluated in this paper is the “Narwhal 2.0” which is an evolution of the previous “Narwhal 1.0” vehicle developed in (Prudden 2018). This “flying anemometer” uses a rapidly prototyped multi-hole pressure probe (MHPP) to collect high-frequency wind fluctuations up to 400Hz. This is deemed sufficient for measurement in an urban environment since a majority of the atmospheric turbulence spectral density occurs at frequencies below 10Hz (Watkins et al. 2010). The pressure probe has a theoretical cone of acceptance of 90°, and can resolve wind direction, velocity and turbulence intensity in a range of flow conditions. As discussed in the previous section, measuring and characterizing high-frequency wind flow in close proximity to buildings has potential application in architecture and building design. An onboard Inertial Measurement Unit (IMU) and field programmable gate array - based data logging system allow for the attitude, angular velocities and linear velocities of the probe to be accounted for in wind vector measurements. Local reference pressure fluctuations, such as those induced by the rotors, are damped using an onboard foam-filled Reference Pressure Cell (RPC). The probe was mounted “3.6” rotor radii in front of the leading rotor. This was done to place the probe far upstream of the rotors to reduce the effects wake-induced interference on the sensor measurements (Prudden 2016). Figure 3 shows how the MHPP is integrated into the airframe along the longitudinal axis.

Component	
Flight Controller	PixRacer Autopilot
ESC	35A 4-in-1 ESC
Motor	T-Motor F40 Pro 1600KV
Battery	6600mAh 4S LiPo
Propeller	HQProps 7045

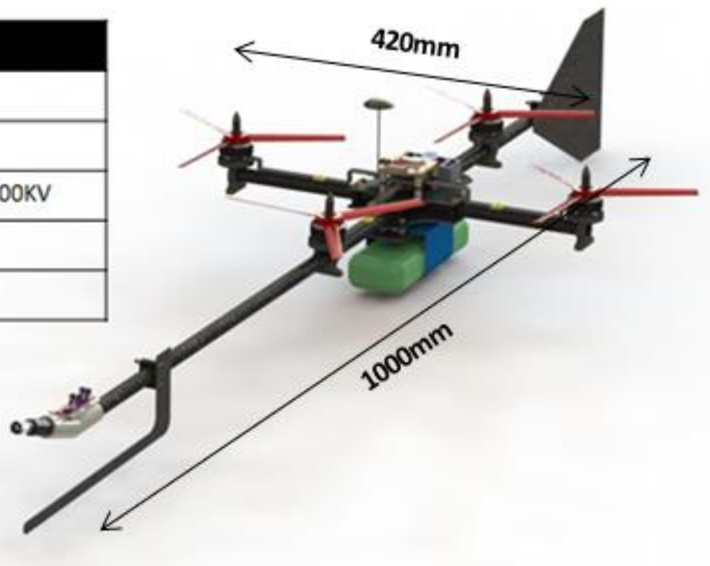

Figure 3: Narwhal 2.0 and associated avionics. The mass of the system is approximately 1.2kg.

For a preliminary evaluation of the vehicle’s energy expenditure during climb, we employed a blade element momentum theory (BEMT) solver in MATLAB. The solver minimizes a squared-error cost function in order to solve for the induced downwash and swirl at each station along the blade, at each time step. Initial analysis indicates an approximate hover time of 20 minutes at 500m, and 17 minutes at 1000m. At ground level the approximate hover time is 25 minutes. This endurance was deemed more than sufficient for sampling from ground level to the top of an urban canopy. Initial calculations should be taken as a conservative estimate only, though they indicate that the aircraft should approach the desired performance of 20 minutes sampling time at 500m above ground level. Future analysis will be undertaken to consider the complex geometry of the airframe and the power consumption for corrections due to wind buffeting.

5. Concluding Remarks

This paper considers the potential application of a novel MUAS 'Narwhal 2.0' in an urban environment. Preliminary investigation indicates that the aircraft should have sufficient endurance to measure high-frequency wind flow from ground level to the top of an urban canopy. The optimization of the vehicle's climb and descent rate shall be explored further with computational models to improve the time available for hovering (and therefore the sampling duration) of the MUAS. In addition, it is envisaged that a future study will use the aircraft in a swarming formation to measure flow structures in close-proximity to buildings and validate the CFD model proposed in Mohamed *et al.* (2015).

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