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TURBULENCE ESTIMATION BY EDDY DISSIPATION RATE AT LOW-ALTITUDES USING UAV IN-SITU DATA

Balážová R.[*], Ferrari S.[**], Hlinka J.[***], Santus A.[†]

Abstract: *Deploying Unmanned Aerial Vehicles (UAVs) into routine operation requires accurate hyperlocal data. The requirements are set with a significant difference compared to the meteorological information and forecasts that have been sufficient until now. Several challenges need to be solved for the safe operation of UAVs. One of the most significant weaknesses of current meteorological information is turbulence and its detection. This article is focused on the low-altitudes turbulence detection using multicopters and their estimate processed by eddy dissipation rate. A low-cost low-weight method has been identified and will be tested on the field. Eventually, a first attempt to define a minimum safety distance from buildings for the UAVs, depending on building size and wind speed, is investigated via numerical simulations.*

Keywords: Turbulence, Eddy dissipation rate, UAV, sonic anemometer, low altitudes.

1. Introduction

Unmanned Aircraft System (UAS) operations in civilian airspace are growing rapidly, and many analyses and forecasts (Ahmed et al., 2022) predict that trend will continue rapidly over the next decade as regulations are adjusted to allow for greater access to airspace. It is essential that the system maintains a high level of safety and security during its growth so that the potential of UAS (performed by UAVs – Unmanned Aerial Vehicles, also named drones) can be fully realized (Alarcón et al., 2020, Shakhatreh et al., 2019). UAVs are quite sensitive to wind gusts and turbulence; hence, unexpected wind changes and turbulences are a major complication. The unique characteristics of UAS require current aviation meteorological information to be improved and provide drone users with the necessary real-time information to ensure a high safety level.

The review of meteorological information gap for unmanned (low-altitudes) operations in middle Europe was the first part of this dissertation research. In the first phase, a detailed summary of all previous research focused on hyperlocal meteorological information gap for low altitudes was conducted. Subsequently, extensive survey analysis (Voice of the Customer) was performed, that identified gaps between existing aviation information and data requirements from drone operators and their users. Both, results of the survey of existing research works and own Voice of the Customer survey (VOC), identified gaps in information services for future drone operations as critical to achieving safe drone operations in Very Low Level (VLL) airspace. This analysis outlined a potential topic for research, namely, how to fill this lack of information regarding low-altitude turbulence, which is addressed in the second phase of research in 2024. Most respondents of the VOC questionnaire observe frequent "unexpected" turbulence during flights around buildings/bridges/pillars. While conducting a survey of meteorological information and service providers,

[*] Ing. Renáta Balážová, MSc: Brno University of Technology, Faculty of Mechanical Engineering, Institute of Aerospace Engineering; Technická 2896/2; Brno 616 69; CZ, renata.balazova@vut.cz

[**] Assoc. Prof. Simone Ferrari, PhD.: University of Cagliari; Dept. of Civil, Environmental Engineering and Architecture; via Marengo 2; 09123, Cagliari; IT, ferraris@unica.it

[***] Assoc. Prof. Jiří Hlinka, PhD.: Brno University of Technology, Faculty of Mechanical Engineering, Institute of Aerospace Engineering; Technická 2896/2; Brno 616 69; CZ, hlinka@fme.vutbr.cz

[†] Ing. Alessandro Santus, MSc: University of Cagliari; Dept. of Civil, Environmental Engineering and Architecture; via Marengo 2; 09123, Cagliari; IT, alessandro.santus@unica.it

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it was found that information about turbulence is a missing meteorological parameter that no one provides for hyperlocal conditions at low altitudes. The topic of turbulence detection at low altitudes using high-quality anemometers has been addressed by several previous studies (Shelekhov et al., 2022, Luce et al., 2019). This paper is focused on the detection of turbulence at low altitudes with low-cost sensor (the limit for this research is 150 m Above Ground Level).

In the aviation in general, information about the occurrence of turbulence is shared based on two sources. The first form of information is Pilot reports (PIREP), which are routine pilot observation reports. This type of reporting is highly imprecise due to time and positional inaccuracy, pilot subjectivity and aircraft dependency. Due to the inaccuracy of PIREP reports, the detection and prediction of turbulence for commercial aircraft is currently based on the use of In-Situ data, from which it is possible to estimate 3 turbulence indicators: Vertical acceleration, Derived Equivalent Vertical Gust Velocity (Derived Equivalent Vertical Gust - DEVG) and Eddy Dissipation Rate (EDR). The International Civil Aviation Organization (ICAO) has designated EDR as the preferred and standard metric for turbulence reporting (ICAO, 2001). However, the current version of the EDR algorithm created by National Center for Atmospheric Research (NCAR), is not applicable for multicopters. The list of required parameters contains parameters (e.g., Angle of attack) that cannot be measured on a multicopter. Consequently, the first aim of this article (and, in general, of the dissertation) is the operational identification of an EDR measurement system that is easily and feasibly applicable to multicopters. This must be a low-cost and light solution for turbulence detection, mountable on a wide range of multicopters to provide In-situ data. The inspiration is the current deployment of the NCAR algorithm across the world fleet of commercial aircraft and their mutual information sharing. It should be emphasized that the sought solution must be inexpensive. The second aim is a first attempt to define minimum safety limits from buildings depending on building size and wind speed; in fact, UAVs often fly in the Urban Boundary Layer (UBL), where the buildings strongly modify the wind patterns, causing recirculation zones and turbulent wakes which can be dangerous for the UAV flight.

In Chapt. 2., the authors describe 4 important information of the research: the first is the calculation formula; the second is the selection of the measurement sensor; the third is devoted to numerical simulations and their importance, especially in determining the minimum safety limits from buildings depending on the size of the building and wind speed; the last part describes the prepared demonstration mission, which will be carried out in the spring of 2024. The conclusion summarizes the findings so far and explains the next stages of research with a clearly defined goal.

2. Methods

2.1. EDR Calculation possibilities

The eddy dissipation rate (EDR) is the cube root of the dissipation rate of turbulent kinetic energy (TKE) ε, and hence has units of $m^{2/3}\,s^{-1}$. Summarizing, the most relevant velocity processing methods for ε evaluation (Guichao et al., 2022) are: Fluctuating velocity gradients; Smagorinsky closure method; Dimensional analysis; Structure function; Energy spectrum; and Forced balance of the TKE equation. After thorough analysis of previous research activities and taking into an account the specifics of the multicopter, the "Inertial Dissipation Method Using Structure Function" alternative (Kim et al., 2021) was selected as the EDR formula. The anemometers generate a sequence of wind velocities at a set position. To apply the mathematical turbulence models established in the spatial dimension, it becomes essential to utilize Taylor's frozen hypothesis, which links the connection between the physical variables in the spatial domain and those in the time domain. As per Kolmogorov's turbulence hypothesis (Kolmogorov, 1991), the EDR adheres to a particular spatial separation pattern within the Inertial Range (IR) for isotropic turbulence. Following Taylor's frozen hypothesis, EDR is then formulated in relation to temporal separation (τ) and structure function (SF), as:

$$EDR = \left(\frac{1}{U}\right)^{1/3} \left[\frac{\overline{D_U(\tau)\tau^{-2/3}}}{C_K}\right]^{1/2} \tag{1}$$

where the overbar notation is the arithmetic average within the IR, U is the mean velocity, and C_K is Kolmogorov constant ($C_K = 0.52$) and $D_U(\tau)$ is the SF.

In previous studies (using anemometer with sample rate of 10 Hz), the range of τ was set between 0.1 s and 2.0 s and time window around 120 s to calculate SF. Considering the limits of our low-cost concept (sample rate of 1 Hz), the range of τ is set between 1.0 s & 2.0 s and the time window is extended.

2.2. Sensor selection

Summarizing all previous research activities (e.g. Palomaki et al., 2017 and Adkins, 2019), it seems that use of ultrasonic anemometer is an ideal solution for drone-based wind measurement. The main disadvantage of this measurement technique is price that has a range from 1 500 € to 20 000 €. This price range is associated with high-quality anemometers (sample rate of 10 Hz and more). Considering our primary goal, which is to provide a low-cost solution that can be implemented by a wide range of users, high-quality anemometers are not an alternative for use in this research.

A very important and key step was to summarize the specifications of the ultrasonic devices used and the accuracy that was achieved. This information was used as the basic specifications in the search for an ultrasonic anemometer within affordable sensors. One of the main selection criteria was the purchase price, which must not be higher than 300 €. Another parameter is the weight of the sensor, because with quadcopter platforms the user is limited by a maximum payload of 0.5 kg. And the third important factor is to find a sensor that does not need an external power-battery, data logger, etc. and everything will be integrated within the sensor. After a thorough analysis of the market, the model "Ultrasonic Portable Mini" from the manufacturer CALYPSO instruments was selected. This is a wireless, Bluetooth (BLE) and battery-powered, pocket-sized ultrasonic anemometer with sample rate of 1 Hz. Weight of the sensor is 78 g and the purchase price is within the set budget. Sonic anemometers will be integrated in the number of two pieces, one in the horizontal direction and the other in the vertical direction, in order to obtain a 3D wind characteristic.

2.3. Numerical simulations

In the first phase, two different numerical simulation models are processed. One is the AdMaS campus, where a demonstration mission will take place in the spring of 2024 (see Sect. 2.4.) and the results of the numerical simulation will be compared with directly measured In-Situ data using a multicopter (Fig. 1). All numerical simulations were processed using ENVI-met software (license provided by the University of Cagliari).

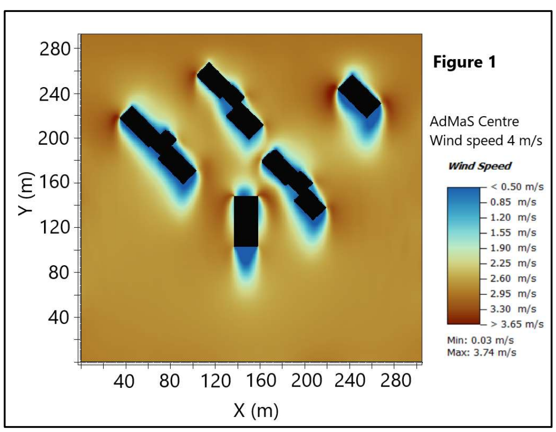

Fig. 1: Numerical simulation "AdMaS Campus".

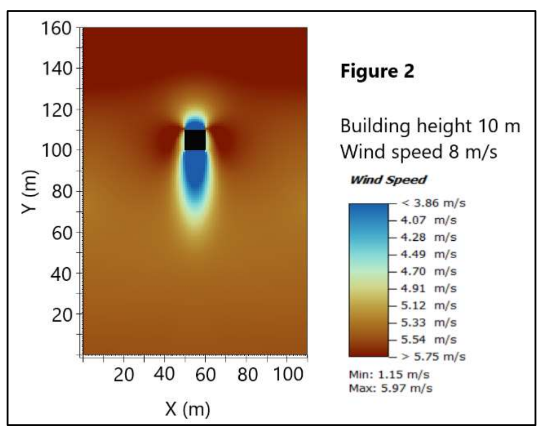

Fig. 2: Numerical simulation "Single building".

Second set of processed numerical simulations are simple scenarios with stand-alone buildings with different heights and under different meteorological conditions. In this set of simulations, the focus is on eddies around buildings and especially on their size. The result of this analysis will be the dependence between 3 key factors, which are the size of the building, the speed of the prevailing wind and the size of the turbulent eddy around the building. Fig. 2 shows an example output of a numerical simulation with a "cube" building size of 10 x 10 x 10 m and a wind speed of 6 m/s. The numerical simulations consist of multiple scenarios with different building heights up to 30 m and wind speeds up to 10 m/s.

2.4. Demonstration Mission

Key test flights, which are considered the most important phase of this research, are planned for spring 2024, (i.e. April – May). This demonstration mission will be performed in Brno, in the AdMaS area (near building H). The unmanned aerial vehicle will be a multicopter, specifically a quadcopter (probably a DJI Phantom 3 Advanced) with an integrated two Calypso sonic anemometers. Test days will be chosen based on weather forecasts. The most important meteorological parameter is wind speed, and the ideal conditions for detecting turbulent eddies are at least 5 m/s and higher.

3. Conclusions

As part of the research, all the weaknesses that need to be overcome to ensure safe UAV operation from the meteorological point of view have been summarized in previous work. Among all the challenges, the main problem was selected with focus on turbulence estimation. The solution is inspired by classic manned aviation, ICAO standard and NCAR algorithm. Since UAVs have significant differences in the concept of the vehicle, maximum payload, different sensor equipment and measured in-situ data, a major modification of EDR algorithm for UAV use is required. The main criterion and goal of this research is not to have the most accurate data possible using a sophisticated sensor, but applicability in a wide spectrum. As part of the research, all possibilities of the EDR formula for estimating turbulence were summarized and the final selection is presented in Sect. 2.1. For the given calculation, it is necessary to have real-time data, which unfortunately the basic DJI platform does not contain, and that is why the integration of an additional sensor is essential. Based on a detailed and comprehensive survey of the market, the final selection was processed with regard to maximum payload, purchase price, power supply and data storage. Selected product is model "Ultrasonic Portable Mini" manufactured by Calypso with a sample rate of 1 Hz. Two pieces of the given sensor will be integrated to ensure 3D wind characteristics. The demonstration mission will be carried out in the spring of 2024 in the premises of the AdMaS center. For this demonstration mission, numerical simulations have been processed using the ENVI-met software, and the results will be compared with directly measured UAV data. Another set of numerical simulations is a domain with single building, where it is monitored the dependence between the height of the building (up to 30 m high), the wind speed (up to 10 m/s) and the size of the vortex behind the building. Based on the dependence between these 3 parameters, minimum safety limits from buildings will be determined. The results of numerical simulations as well as test flights will be published in the summer of 2024.

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