A new facility for UAV testing in climate-controlled environments*

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Abstract— **Environmental conditions have a great influence on aircraft performance. Thrust reduction with altitude and temperature increase is a well known problem in the aviation industry. For commercial multirotor (UAVs) a systematic approach on performance varying environmental conditions is still an open research field. Many of the existing applications designed for UAVs (e.g. precision agriculture, delivery of instruments or medical supplies) have not been fully exploited by the market so far. This is due to the lack of existing knowledge about flight under variable weather conditions. A bias in the existing tests has been the non-reproducibility of the same climatic conditions. In this paper a dedicated test facility for a systematic study on UAV performance in a climate-controlled laboratory is presented: use cases as well as technical challenges related to the particular environment are discussed. Preliminary tests on thrust performance at different temperatures are reported to provide insight and highlight measurement complexities involved in harsh environmental conditions. Ultimately, this work will facilitate the development of UAV design and safety accounting for weather influence to improve flight stability and controllability.**

I. INTRODUCTION

Since last decade Unmanned Aerial Vehicles (UAVs), known also as *drones*, have become popular for commercial operations thanks to their flexibility and technology improvements. New advanced autopilot flight modes have allowed thousand of applications and extended market opportunities. Environmental monitoring [1], surveillance [2], cinematography [3], search and rescue [4], urban monitoring [5] as well as emergency missions are just few examples in which UAVs are involved: the list of practical applications is wide, well beyond the boundaries of conventional remote sensing scenarios.

To set-up and perform an automatic or full autonomous flight mission, a smart-phone, working as ground station and receiver, and the UAV itself are the only hardware required. *Commercial Off The Shelf* (COTS) components are heavily used by drone industry for the on-board avionics. As a consequence of price reduction, people having access to UAV technology is rapidly increasing and potential air accidents or incidents are more frequent. As reported in [6], technology issues are the key contributor in UAV events, contrary to commercial air transportation industry, where human factors are more relevant. COTS parts usually have higher failure rate than aeronautical products as they are not created equally and following a set of standards. The analysis of one hundred and fifty two drone events [6] showed that UAVs are more likely to experience: i) in flight loss of control, ii) events during takeoff and cruise, and iii) equipment problems.
To improve UAV controllability, stability and safety in wind conditions, a lot of researches have been performed in the past years. As an example, a wind tunnel propeller characterization is reported in [7], providing a complete database of propeller performance usually installed on small UAVs and model aircraft. Another cornerstone is the work performed at Nasa Ames Research Centre [8]: wind tunnel tests were made to measure force and moments as well as electrical power consumption as a function of wind speed and UAV attitude. Autopilot control laws and UAV stability are definitely affected by wind but other weather conditions could lead to an in flight loss of control. For this reason, the impact of environmental parameters on drone flights is a major topic in UAV science and will be the focus of *DronEx* project [9] by Eurac Research. Many of the existing applications designed for UAVs have not been fully exploited by the market so far. This is due to the lack of existing knowledge about flight under variable weather conditions. A bias in the existing tests has been the non-reproducibility of the same climatic conditions.

This paper presents a new test facility to study UAV performance in a dedicated climate-controlled laboratory, improving vehicle design and safety. This paper is structured as follows. Section II provides an overview of the world climatic facilities for industrial tests, presenting characteristics and main limitations for UAV testing. The new *terraXcube* facility is presented in section III, discussing use cases for UAV testing, the experimental set-up as well as the atmosphere considered. Preliminary temperature test at constant pressure are presented in section IV while brief conclusions and future works are summarized in section V.

II. ENVIRONMENTAL FACILITIES

Environmental tests on industrial components allow manufacturers to make sure their products will endure the coldest winter and harshest sun. The automotive industry is a leading sector for environmental testing as many resources are spent to perform detailed thermal analysis. Table I summarises word-wide environmental laboratories and points out research applications: automotive and aerospace sectors as well as medical testing are the main reasons that justify the construction of such facilities.

The UAV industry has recently started to perform environmental test and provide information to the end users. As

*This work is supported by *Eurac Research*

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Test Facility	Country	Applications
FCA climatic wind tunnel	Italy	Road vehicle design and development
Mars Simulation Laboratory	Denmark	Martian atmospheric and UV condition simulations. Sand transport studies
Indoor Climate and Building Physics	Denmark	Influence of indoor climate on public health
TNO Climatic Altitude Chamber	Netherlands	Road vehicle design and deveolpment
MIRA Climatic Wind Tunnels	United Kingdom	Road vehicle design
Lindoe Component and Structure Testing	Denmark	Large components, structures and functional systems test
Artificial Climate Experimental Facility	Japan	Environmental transfert simulation and modelling
WindEEE	Canada	Wind engineering, energy and environment
ACE Climatic Wind Tunnel	Canada	Industrial climatic test
General Motors Wind Tunnel	United States	Road vehicle design and development
Boeing Icing Wind Tunnel	United States	Airplane design and development
Modine Wind Tunnel	United States	Climatic wind tunnel large trucks and automotive

TABLE I: Environmental test facilities

an example, in the Alta 8 flight manual [10], by Freefly System, a table reporting the maximum take-off weight as a function of temperature and altitude is given. Data are based on predictions, simple real test and successful user operation feedback beyond conventional weather conditions. In 2016 PrecisionHawk performed climate-controlled flight test to analyse fixed wing performance for design purposes [11]. These first steps reveal interest in a more systematic approach to quantify performance according to weather conditions. Flight tests in a climate-controlled facility would give potential to improve UAV operations.

In the past automotive facilities were exploited giving potential to perform flight test inside a wide-temperature-controlled area. No standards for UAV testing were defined and activities were limited to the effect of wind and temperature. Pressure influence on rotor and overall UAV performance still remain unexplored due to lacks of dedicated hypobaric infrastructures. Automotive climatic wind tunnels are not suitable for these purposes as not designed for low pressure conditions; hypobaric medical facilities do not provide a wide area for flight tests. In the next few years, dedicated environmental facilities will play a key role for UAV industry development.

A. *WindEEE Research Institute*

The Wind Engineering, Energy and Evironment Research Institute (Ontario, Canada) was establish in 2011 and offers a unique testing chamber for wind studies and innovation. Research topics are related to the impact of wind system (such as tornadoes and downbursts) on buildings and structures; optimisation of wind turbines and air quality studies (outdoor and indoor) are other research fields. The *WindEEE Dome* is an hexagonal wind tunnel (25 m is the inner diameter) that allows the manipulation of inflow and boundary conditions to reproduce wind dynamics.

In April 2015 WindEEE Dome was involved to test UAV flights in severe wind conditions, even tough a systematic study was not launched by the research institute. The effects of vortexes on flight stability were considered in the context of cities, as complex environments for drones in windy days. During the tests UAVs were manually controlled in hover conditions (*pilot-in-the-loop* tests). Up to 6 fans allowed to create a destabilizing flow and a safety cable prevent the multi-copter loss of control to damage the chamber.

WindEEE Dome facility meets the need to perform UAV tests in controlled wind conditions; the inability to consider pressure, temperature and other environmental parameters is the main limitation of this laboratory.

B. *ACE Climatic Wind Tunnel*

The Automotive Centre of Excellence (ACE) by University of Ontario Institute of Technology (UOIT) is a research centre for automotive industrial tests in Canada. ACE Research Centre consists of four test chambers:

- a climatic wind tunnel, for large vehicles;
- a climatic chamber, for small vehicles;
- a climatic four-poster shaker, to simulate drive surfaces and validate suspension and body durability;
- a multi-axis shaker table, for structural durability, detection of noise and vibration tests.

Table II summarizes the characteristics of ACE Climatic Wind Tunnel: this laboratory is suitable for automotive tests in extreme environment, with particular regard to alternative fuel, hybrid and electric vehicles.

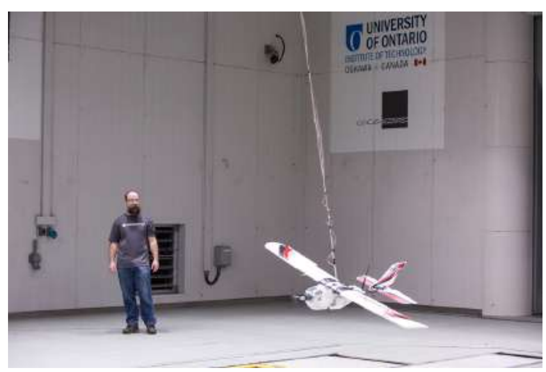

Fig. 1: PrecisionHawk test inside ACE

In 2016, UAV tests (figure 1) were performed by PrecisionHawk at low temperature (i.e. icing of quadcopters), in snow conditions and with multi-axis shaker table. Free flight tests were made inside the climatic chamber using a fixed wing tethered plane with a safety cable and manual control by a pilot engineer.

ACE Research Centre is an interesting reference facility that takes into account wind tunnel, temperature and shaker tests; the effect of low pressure (flight at high altitude) still remains an open question, not covered by this industrial laboratory.

ACE Climatic WInd Tunnel	
Overall dimensions (L x W x H)	20.1 m x 13.5 m x 7.5 m
Temperature	from −40°C to +60°C
Relative Humidity	from 10% to 95%
Wind Speed	up to 260 km/h
Rain Simulation System	available, frontal layout
Snow Simulation System	available, frontal and overhead layout
Solar Simulation System	full diurnal function with azimuth and altitude

TABLE II: ACE Climatic Wind Tunnel specifications

III. TERRAXCUBE SIMULATOR

terraXcube [12] is a new research infrastructure opened in November 2018 in Bolzano, Italy. The facility allows simulation of the Earth's most extreme climatic conditions to study their influence on human beings, ecological processes and new technologies. terraXcube consists of two climatic chambers: i) the *Large Cube* and ii) the *Small Cube*. Table III summarizes the characteristics of the Large Cube. This laboratory is suitable for industrial test: a wide test section is available and suitable for free flight UAV purposes. The Small Cube consists of four independent simulation chambers that can independently replicate different atmospheres at the same time.

terraXcube was built for medical research however, a dedicated UAV programme (DronEx [9]) was launched to study in a systematic way how weather conditions affect drone flight.

terraXCube - Large Cube	
Dimensions (LxWxH)	12 m x 6 m x 5 m
Temperature	from −40 °C to 60 °C
Pressure	from sea level up to 9000 m
Relative Humidity	from 10% to 95%
Wind Speed	available, up to 100 km/h
Rain	available, $0 - 60 \text{l/m}^2$
Snow	overhead layout, 5 cm in 1 hour
Solar Simulation System	day/night simulation at 1000 lux

TABLE III: terraXcube large simulator features

Fig. 2: terraXcube laboratory

A. Use cases

To exploit the capabilities of terraXcube simulator in UAV science, four use cases were defined to understand weather influence on drones.

In the first scenario the propulsion system will be characterized varying environmental parameters. A propeller, a brushless motor and its related electronics (Electronic Speed Controller) will be installed inside the Large Cube in a dedicated test bench. The sensor suite will include a six-axes load cell, a speed sensor and a power-meter to measure thrust, torque, motor speed and power consumption respectively. A dedicated power supply, installed in the control room, will provide electric power to the motor highlighting the environmental effects on the propulsion system only. Test on the single rotor will allow investigation of secondary effects related to the motor heat exchange and power losses if heat is not shed properly. Thermal studies of electric motors are usually performed with finite element methods [29] or lumped-parameter network analysis [30]. Two difficulties arise: i) motor geometrical data are often not available from the manufacturer to the end user (i.e. stator tooth and joke dimensions) and, ii) thermal coefficient, related to material properties, are difficult to estimate (i.e. high turbulent airflow inside the motor case). Accurate modelling is challenging and experimental measurements will be exploited to understand how motor performance will be affected by the environmental conditions.

In the second scenario, an overall UAV will be mounted in the test bench. While in the first use case attention will be given to the thrust produced by the single rotor, this scenario focuses on the complete UAV performance. Thrust, torque, motor speed and power will be measured and analysed. Electric power will be provided using a dedicated power supply to avoid environmental effect on batteries. The total thrust generated by the overall UAV platform will be measured without any oversimplification related to single rotor thrust generation as suggested in [13] and [14].

The third use case will be dedicated to battery tests. Discharge battery performance will be evaluated at different temperature and humidity conditions. Useful information on chemical to electrical power conversion of common batteries will be studied and compared with available data [15].

In the last scenario, free flight test inside terraXcube will be scheduled to check stability, controllability and autopilot behaviour in harsh environments. This is the most interesting and challenging test as UAVs will operate as in real conditions. Technical issues related to autonomous free flight tests will be discussed in the next paragraph.

B. Experimental set-up and technical challenges

For use cases 1 and 2, the same set-up will be exploited and it will consist of: i) a test bench designed to reduce mechanical vibrations, ii) a six-axes load cell, for thrust and torque measurements, iii) motor speed sensors, iv) a power-meter (inclunding current sensors), and v) temperature sensors for the motor and the electronic speed controller. A thermal camera will be used to measure motor winding temperature. Figure 3 schematically shows the data acquisition and control system, in accordance to the work performed by Nasa Langley research centre [8]. Attention will be given to avoid ground, wall and ceiling effect while performing measurements. The results reported in [13] and [14] show that ceiling effect is limited to value of z/R lower than 2; ground effect occurs even for higher z/R when considering the UAV as a whole. A test bench support will allow the alignment of the rotor axis with the test chamber length in order to perform test with high value of z/R.

For use case 3, the Small Cube simulator will be used. The battery will be placed inside the small test section while a discharge device will be installed in the control room to manage the maximum flow current during the discharging process. Voltage and current sensors will be employed to measure the desired data (figure 4).

The main problem related to use case 4 is to allow autonomous flight inside the Large Cube simulator, desirable to avoid pilot control and provide a standard test procedure. As reported in [16] and in [17], the biggest challenge in UAV indoor applications is the attenuation of Global Navigation Satellite System (GNSS) signal induced by walls and furniture (20-30 dB compared to outdoor). Severe multi-path effects and signal reflections must be considered due to metallic panels used in the simulator housing. Different solutions have been investigated: i) optical systems, ii) ultra-wide-band sensors iii) ultrasonic systems, and iv) extension of outdoor GPS signal.

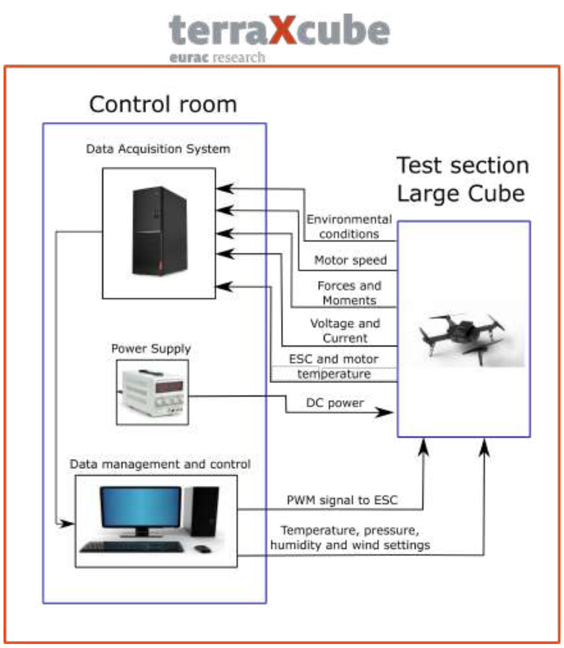

Fig. 3: Set-up for use cases 1 and 2

Optical systems (i.e. Vicon [18] or Optitrack [19]) provide sub-millimetre precision for indoor GPS purposes. They require the installation of a reflective marker and a dedicated on-board computer to convert geometrical position data into conventional GPS data (i.e. NMEA). The system flexibility is

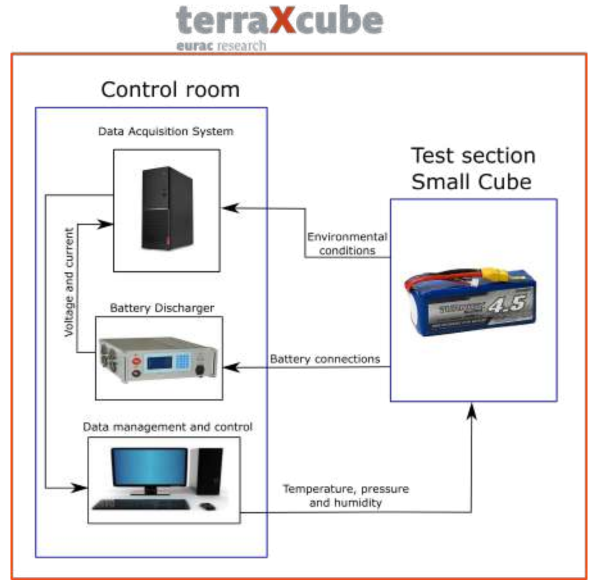

Fig. 4: Set-up for use case 3

limited by the need of fixed cameras looking at the onboard marker. The fly-able area is restricted by the field of view of the cameras (both in range and altitude). A ground computer is mandatory to perform all the computation and provide high frequency data rates. Considering terraXcube, the camera mount system would be affect by temperature changes and the optical system calibration would be mandatory each time a new temperature is set. The high cost of optical tracking systems make them suitable only for control law tuning and development in indoor environment, out of the scope of DronEx project.

Ultra-wide-band (UWB) is the main technology based on radio frequency sensors. The absolute position of a mobile emitter is estimated by measuring the Received Signal Strenght Indication (RSSI) and implementing triangulation algorithms. Thanks to short time pulse duration (10 ns typical), centimetre level accuracy can be reached. An example of UWB indoor GPS is provided by *Race Logic* for the automotive industry [20]. The main drawback of RF sensor family is multi-path signal reflections that could cause severe GPS glitches resulting in dangerous unexpected movements.

Ultrasonic sensors are another feasible solution to generate an indoor GPS signal. The overall system consists of a mobile emitter and several stationary anchors. The on-board beacon generates ultrasound pulses to stationary detectors: a central router collects all Time Of Flight (TOF) data and compute the position of the mobile beacon based on triangulation algorithms. A typical solution is provided by Marvelmind Robotics [21]. A deep investigation and testing activities were carried out on Marvelmind sensor [22]. Results didn't show good position accuracy and stable flight for quad-copter autonomous navigation. The main problem of ultrasonic sensors is they are affected by environmental conditions (temperature and humidity especially). TOF requires a precise knowledge of the speed of sounds, that would be influenced by the simulated environment.

Extending the outdoor GPS signal inside terraXcube would a suitable option as it prevent changes in the navigation system and would allow testing as in real outdoor scenario. An example is reported in [24]: a set of GPS repeaters are placed on the roof of the building and provide signal inside the infrastructure. By knowing the GPS pseudorange and the absolute position of the repeaters, the computation of the absolute mobile receiver inside the building can be done. The GPS repeater consist of a Low Noise Amplifier (LNA) to re-irradiate the GPS signal inside the building. Problems related to this solution are: i) multi-path reflections, ii) time synchronization and iii) extremely low accuracy (the same for outdoor application, not suitable for indoor flight).

Other industrial solutions will be investigated before free flight test execution. A vision based solution could be a good balance between complexity, cost and navigation system integrity.

C. Simulated atmospheres

Four atmospheres will be simulated for use cases 1,2 and 4: i) temperature changes at constant pressure and humidity (from -40°C to $+60$°C, 20°C step), ii) pressure changes at constant temperature and humidity (from sea level up to 4000 m, 500 m step, and from 4000 m to 9000 m, 1000 m step), iii) combined effect of temperature and humidity and iv) combined effect of temperature and pressure based on the International Standard Atmosphere (ISA) model (from sea level to 3000 m, 500 m step). While the first two atmospheres focus on the isolated effect of temperature and pressure (altitude), the last two highlight the combined effect of weather variables to study real scenario. The ISA model is needed to provide a standard test condition, even though seasonal effect and local specific atmospheres are not considered.

As temperature is the main responsible for battery performance degradation [25], for use case 3 the atmosphere simulated will be limited to the effect of temperature and its combination with relative humidity.

Seasonal effects: The ISA model provides a standard atmosphere for vehicle performance testing at various altitude. Considering the troposphere, the assumptions made by ISA model are: i) perfect gas, ii) constant air chemical composition iii) dry air and, iv) constant temperature rate with altitude [23]. The following simplified model results:

$$T(h) = T_0 - \nabla T h \tag{1}$$

where $\nabla T = 0.0065$ [°C/m] and $T_0 = 15$°C. This model is based on average conditions at mid latitudes, providing a good *standard day* for engineering computations.

An analysis was made to highlight seasonal effect and investigate ISA error exploiting historical meteorological data (temperature and relative humidity) from weather stations in Piemonte, Italy, at different altitude [26].

The mean temperature values between 2014 and 2016 during Winter, Spirng, Summer and Autumn were calculated, as reported in table IV. Summer and winter are the two seasons that mostly differ from ISA model as shown in figure 5, especially at low altitude. Autumn and Spring data best fit the temperature predicted by ISA. To take in mind seasonal temperature effects with respect to ISA model, the following corrections will be applied: i) a constant offset of 9.5°C will be added to ISA temperature for Summer and, ii) a linear altitude correction will be applied to simulate Winter according to eq. 2. Spring and Autumn will be approximated using ISA model as the difference between real data ISA temperatures is within 5°C.

Weather station	Altitude [m]	Tempetature [°C]				
		Winter	Spring	Summer	Autumn	ISA
Torino	249	4.72	13.91	23.33	13.77	13.38
Borgone	400	3.21	12.11	21.64	11.94	12.40
Salbertrand	1010	1.07	8.33	16.92	8.84	8.44
Forno Alpi Graie	1215	0.80	7.11	15.43	8.31	7.10
Chiaves	1617	0.91	5.73	14.34	7.52	4.49
Malciaussia	1805	-0.30	4.34	13.14	6.38	3.27
Sestriere	2020	-2.04	2.31	11.99	4.86	1.87
Lago Agnel	2304	-3.20	0.91	10.28	3.88	0.02
Sommeiller	2981	-6.75	-3.48	5.63	-0.23	-4.38
Gran Vaudala	3272	-9.28	-6.11	3.00	-2.67	-6.27

TABLE IV: Measured and ISA estimated temperatures at various altitude [26]

$$T_{winter}(h) = T_{ISA} - (T_0 + ah) \tag{2}$$

where $a = -0.0025$°C/m and $T_0 = 9.19$°C.

The same approach was used to obtain relative humidity data at different altitude as reported in figure 6. It can be noted a parabolic trend for Winter and Autumn seasons, while a quasi-constant behaviour during Spring and Summer. Based on the historical data, a linear equation model will be considered for humidity estimation with altitude for Winter and Autumn seasons (eq. 3 and 4); constant humidity values of 67.4% and 70.5% will be used for Spring and Summer respectively.

$$RH_{winter}(h) = b_2 h^2 + b_1 h + b_0 \tag{3}$$

$$RH_{autumn}(h) = c_2 h^2 + c_1 h + c_0 \tag{4}$$

where $b_2 = 3.01E-6$, $b_1 = -17.15E-3$, $b_0 = 85.31$, $c_2 = 1.31E-6$, $c_1 = -8.63E-3$, $c_0 = 84.27$.

Compared to the international standard atmosphere, this is a first attempt for a detailed atmospheric model able to predict temperature, humidity and pressure closed to real data taking in mind seasonal weather conditions.

IV. TEST PERFORMED

terraXcube simulator will be available in May 2019 for research activities. Preliminary tests were performed to analyse the effect of temperature on single rotor thrust generation inside a smaller climatic chamber. Even tough tests were performed in a smaller test cell, these data provide a trend on rotor performance as well as the order of magnitude of expected quantities. The T-Motor 15 x 5 carbon fibre propeller with T-Motor T60A Electronic Speed Controller and U5 kv400 brushless motor were used to perform all

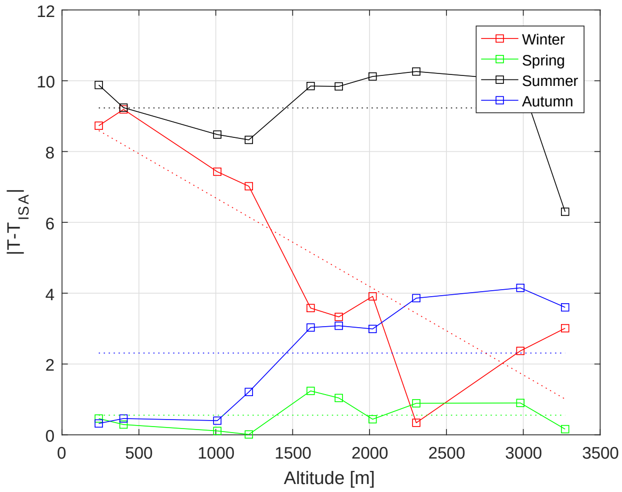

Fig. 5: Difference between experimental data and predicited ISA temperatures at various altitude. Experimental data (square markers) and interpolation models (dashed lines)

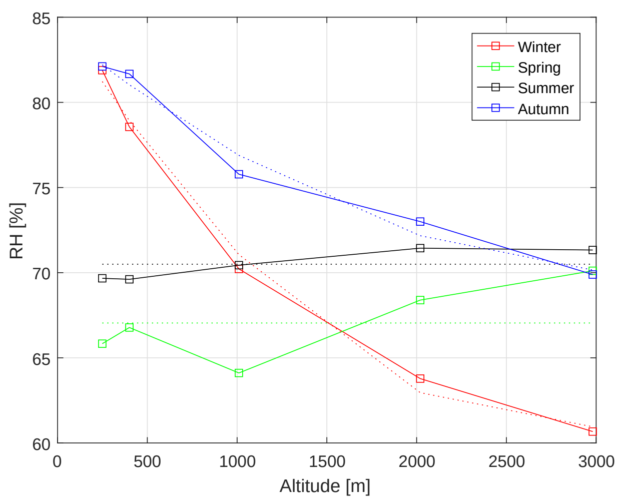

Fig. 6: Humidity experimental data (square markers) and interpolation models (dashed lines)

the measurements inside the Angelantoni PV4500 facility. The rotor assembly was mounted on a test bench platform (RCBenchmark 1520 [27]) inside the chamber as in figure 9. The motor was powered by a dedicated power supplier placed outside the test section. Thrust, motor speed, current and voltage were recorded using a computer in the control room. Figures 7 and 8 show the experimental set-up used for the test and the overall dimensions. The climatic chamber is quite small compared to terraXcube but the tests were made to provide first insight on single rotor performance. The tests were performed in the following way: the operator set the temperature inside the chamber and wait for stationary conditions. As a PWM signal was sent to the electronic speed controller (ESC) the motor started spinning. When the motor reached stationary conditions, measurements were taken for 60 seconds by the data acquisition system. The procedure was repeated for temperatures in the range $-33.5°C$ to $+40°C$; the same PWM signal for motor control was used for all the tests.

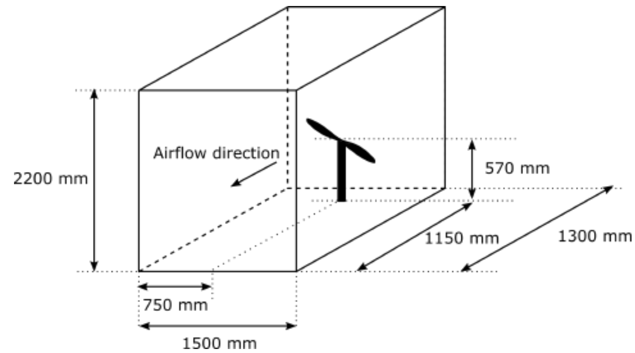

Fig. 7: Climatic chamber dimensions

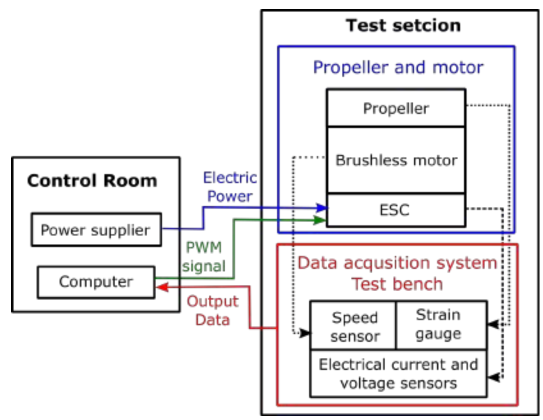

Fig. 8: Experimental set-up

Results at different temperatures are shown in figures 10, 11 and 12 as percentage change with respect to $+15°C$ considered as a reference standard condition.

Figure 10 shows that as temperature decreases the propeller thrust increases. This behaviour is related to the air density changes due to temperature reduction at constant pressure. The electrical power shows the same behaviour of the thrust: as a consequence of thrust increase, more power is needed. The electric current behaves as power and was not reported in the paper. A different trend is experienced by the motor speed (figure 11) which decreases as lower temperature are set. Even though the overall percentage changes are quite small, the speed reduction is related to air density increase as well. The electronic speed controller (ESC) generates three alternating voltages from a constant DC voltage source. As any motor speed feedback is provided, the ESC works in an open loop configuration: the motor speed is not adjusted as the motor load changes. As lower temperatures are set, the air density increases as well as the propeller torque. Given the same PWM input signal to the ESC, the motor speed decreases in response to higher motor load.

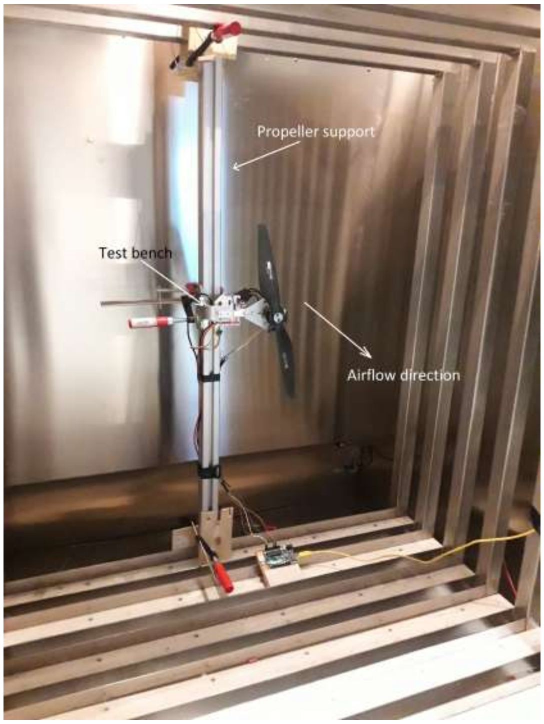

Fig. 9: Climatic chamber during temperature test session

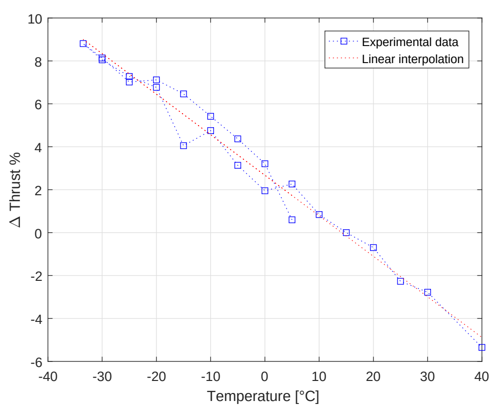

Fig. 10: Percentage change in thrust

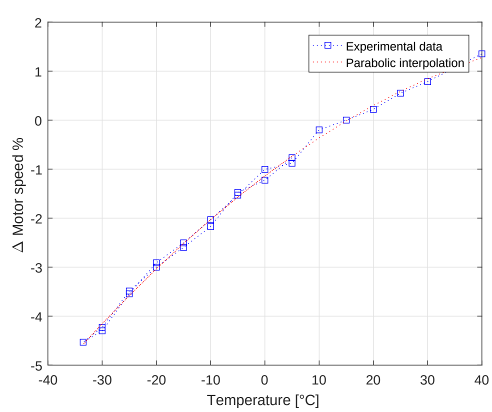

Fig. 11: Percentage change in motor speed

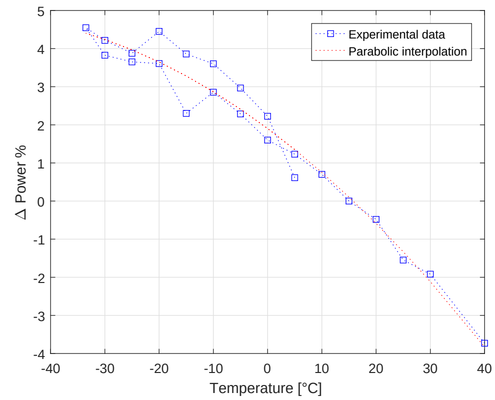

Fig. 12: Percentage change in power

Comparing figures 10, 11 and 12 it can be noted that while a linear interpolation is sufficient for thrust data, a second order polynomial regression model is needed to fit speed and power measurements. Moreover, given the same temperature change, the thrust increase is higher than the power. As an example, at 0°C, thrust has experienced a mean increase of 2.58% while the electric power increase is only 1.91%. This is related to the motor speed that shows a reduction of 1.12%. The overall power increases is dominated by torque increase due to higher air density values, despite lower motor speed.

Because of the small dimensions of the climatic chamber, measurements were influenced by wall effect even though efforts during the installation were made to prevent it. Ground and ceiling effects are combined due to the small chamber dimension. Considering the distances between the main door and the wall surface upstream the propeller, the following ratios can be evaluated: $(z/R)_G = 6.04$ and $(z/R)_C = 0.78$ for ground and ceiling effect respectively. Propeller tip to wall distance ratio is $(y/R) = 2.9$. Despite thrust increase reported in [13] and [14] for ground and ceiling effect respectively, lower thrust was experienced inside the test section probably due to high turbulence. The set-up used in test is different to those reported in [13] and [14] as ground, ceiling and wall effect act simultaneously. A quasi-linear behaviour of combined ground and ceiling rotor performance is reported [28]: the propeller works as an impermeable structure so that the downstream flow (dominated by ground effect) is independent of the upstream conditions (dominated by ceiling effect) and vice versa. Measurements for wall effect, showing a negligible aerodynamic influence, are reported in [28] but in this case the airflow is not affected by ground and ceiling. The comparison with the experimental set-up in figure 8 is not direct: the authors in [28] do not consider the interaction between wall, ground and ceiling effects that would results in high turbulence inside a test section. The high turbulence could leads to thrust reduction, as a consequence of vortex dimension increase. Despite conventional ground and ceiling effect, inside the climatic chamber the downward flow is slowed and tries to disperse radially. The presence of the test section provides additional obstacles for the flow, enforcing the turbulence and resulting in lower thrust. Figure 13 schematically shows the complex aerodynamic field in the chamber.

According to the *Momentum Theory*, the propeller thrust in hover conditions (eq. 5) is proportional to the air density ρ as well as the square inducted velocity v_i^2. The thrust changes should be directly related to air density variations with temperature.

$$T = \rho A v_i^2 \tag{5}$$

Comparing air density (computed by temperature and pressure data) and thrust percentage changes (figure 14), rotor thrust increase is lower than air density change. Thrust measurements are affected by: i) thermal effect on load cell (non linearities and temperature changes on span; during the tests, a drift in thrust sensor zero was observed and calibration was performed each time a new temperature was set), ii) motor speed reduction, and iii) turbulence inside the climatic chamber.

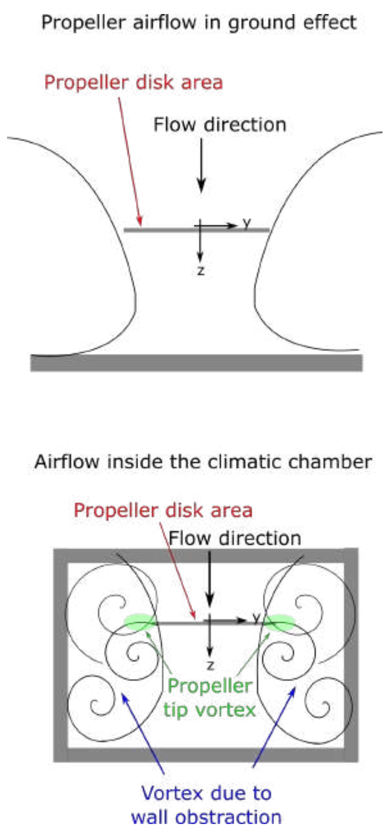

Fig. 13: Schematic airflow conditions in ground effect and inside the climatic chamber

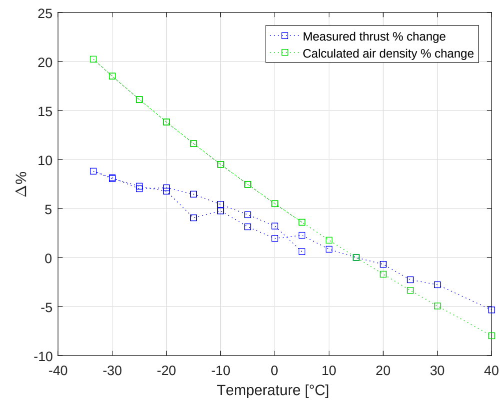

Fig. 14: Comparison between air density and thrust percentage changes

V. CONCLUSIONS & FUTURE WORK

This paper aims to present a dedicated facility for UAV performance test in a climate-controlled environment. The experimental set-up and the related technical challenges due to harsh weather conditions are discussed. Several use cases are defined in terms of equipments under tests and simulated atmosphere. A suitable tracking system to perform flight test inside the Large Cube will be defined while the first tests will be performed on isolated rotors and complete UAV in a dedicated test bench.

The preliminary rotor tests performed inside a small climatic chamber provides insight on temperature effect on thrust and power consumptions. Results are affected by turbulence and sensor accuracies but are in accordance with expected trends on thrust and power while temperature is changing. More realistic data will be collected as soon as terraXcube will be full operational. Pressure (altitude) influence multi-rotor performance as well as combined effect such as temperature and pressure or temperature and humidity will be considered. This comprehensive study is specific to multi-rotors and will eventually lead to more advanced simulation models for propulsion system and UAV performance in harsh environmental conditions. Insight and suggestions for UAV manufacturers and aviation agency for non standard flight approval (e.g. search and rescue missions in avalanche or mountains) will be the main results of DronEx project.

ACKNOWLEDGMENT

The authors would like to thank Eurac Research Institute for Renewable Energy for the access to the facility Accelerated life testing lab, support and collaboration during test activities.

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