Deliverable 3.2

WP3: Definizione dei protocolli di test

Analisi dello stato dell'arte

Edizione n. 1
Revisione n. 0

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Data 12/02/2021

Stato di aggiornamento

Edizione / Revisione	**Data**	**Note**
Ed. 1/ Rev. 0	12/02/2021	

Numero di pagine valide

Questo documento è costituito complessivamente da **10** pagine.

Sommario

State of the art on UAV testing

Unmanned Aerial Vehicles (UAVs) have become popular for many applications, thanks to the improvements in electronics and cost reduction. Today, UAV science is focusing on the impact of extreme environmental conditions on drone flight. Many reasons encourage research on this topic: UAV companies are trying to make progress on drone performance; research centres are focusing on stronger control law in complex flight conditions; certifying authorities are proposing regulations to establish rules without compromise technology and market grow. The aim of the present work is to describe the state of the art on drone testing, with interest in extreme environmental conditions. The document is organized as follows: Section 1 outlines environmental test facilities in literature and presents drone test performed inside them; Section 2 dwells on systematic studies on isolated rotor and complete UAVs; conclusions and suggestions for the future works are reported in Section 3.

Environmental tests

Need of experimental test in UAV science

At present, UAV companies perform outdoor test to understand how low temperatures and pressures affect drone performances. In the literature, there are no systematic studies that analyzed the success or failure of a drone flight, based on the variability of climatic conditions. Moreover, a bias in the existing tests has been the non-reproducibility of the same climatic conditions. Flight tests in a climate-controlled facility would give potential to improve drone performance: in the near future, the need of environmental facilities for drone tests will play a key role.

Test facilities

Around the world, many environmental facilities are currently available for different test purposes. Table 1 summarizes these laboratories and points out the research applications: industrial testing, especially for road vehicles in harsh environment, is the main reason that justify the construction of such challenging buildings. However, inside WindEEE and ACE Climatic Wind Tunnel drone flight test have been performed, as it will be presented in the next paragraphs.

Test Facility	Country	Research Center / University	Applications
Mars Simulation Laboratory	Denmark	Department Geoscience Aarhus University	Martian atmospheric and UV condition simulations. Sand transport studies
Artificial Climate Experimental Facility	Japan	Institute for Environmental Sciences	Environmental transfer simulation and modelling
Indoor Climate and Building Physics	Denmark	Technical University of Denmark	Influence of indoor climate on public health
TNO Climatic Altitude Chamber	Netherlands	Netherlands Organisation for Applied Scientific Research (TNO)	Road vehicle design and development

MIRA Climatic Wind Tunnels	United Kingdom	Research Institute	Road vehicle design
Lindoe Component and Structure Testing	Denmark	Force Technology Company	Large components, structures and functional systems test
WindEEE	Canada	WindEEE Research Institute	Wind engineering, energy and environment
ACE Climatic Wind Tunnel	Canada	University of Ontario Institute of Technology	Industrial climatic test

Table 1: Environmental test facilities

WindEEE Research Institute: The Wind Engineering, Energy and Environment Research Institute (Ontario, Canada) was establish in 2011 and it offers the first three-dimensional testing chamber for wind research and innovation. The research topics are related to the impact of wind system (such as tornadoes and downbursts) on buildings and structures, optimization of wind turbines and air quality (outdoor and indoor). The WindEEE Dome is a hexagonal wind tunnel (25 m is the inner diameter) that allow the manipulation of airflow and boundary conditions to reproduce the dynamics of wind. In April 2015 WindEEE Dome has been exploited to test drone flights in extreme wind conditions, although a systematic study on UAV has not been launched by WindEEE Research Institute. The effect of vortexes on flight stability has been considered in the context of cities, as complex environments for drones in strong windy days. During the tests performed, UAVs have been placed inside WindEEE Dome in hover conditions: up to 6 fans allowed to create destabilizing flows and a safety cable ensured that uncontrolled multi-copters could damage themselves or the chamber. Tests have been performed with pilot-in-the-loop, to keep control during flights. Even though WindEEE Dome has been established to focus on wind research, this facility meets the need to perform UAV tests in controlled strong wind environment; the main limitation is the inability to consider pressure, temperature and other environmental parameters.

ACE Climatic Wind Tunnel: The Automotive Centre of Excellence (ACE) by University of Ontario Institute of Technology (UOIT) is a research centre for 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 2 summarizes the characteristics of ACE Climatic Wind Tunnel: this facility is suitable for industrial test in extreme environment, with particular regard to alternative fuel, hybrid and electric vehicles.

Figure 1: ACE Research Centre UAV tests

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	Frontal
Snow Simulation System	Frontal and overhead
Solar Simulation System	Full diurnal function with azimuth and altitude

Table 2: ACE Climatic Wind Tunnel

UAV tests have been performed at low temperature (icing of quadcopters, Fig.1a), in snow conditions (Fig.1.b) and in multi-axis shaker table, although a scientific study on UAV science was not carried out by ACE Research Centre. To perform flight test inside the climatic chamber a safety cable for both rotary and fixed wings has been used, as Fig.1c shows. ACE Research Centre is an interesting reference facility that takes into account wind tunnel and climatic tests; however, the effect of low pressure (flight at high altitude) still remains an open question, not considered in this laboratory.

Systematic UAV tests

The examples in previous paragraphs are first cautious step toward a scientific approach on UAV studies in extreme environmental conditions: details on the experimental setup, on the specific test performed and the results obtained are not yet available. The lack of existing knowledge about drone flight under variable weather conditions still remains a challenging issue. In UAV science systematic studies have been carried out in the following topics:

1. propeller characterization;
2. system identification;
3. aerodynamic characterization in wind tunnel.

The main limitation of current works is the inability to consider environmental conditions when performing the tests.

Propeller characterization

Thrust and torque estimations are key elements for flying vehicle design: in literature, many articles deal with propeller characterization. In the most straightforward case [1], the rotor (propeller and motor) is mounted on a rod connected to a pivot point. A force transducer is used to measure the thrust while a data acquisition system records electric current, voltage and generates pulse-width modulation signals for the motor control. Thrust and torque measurements are not the only quantities of interest: in [2] propeller test at low Reynolds number (from 50; 000 to 100; 000) have been performed to quantify the aerodynamic efficiency (Fig.2). Up to 79 propellers were tested in the 9� to 11�in diameter range: while propeller speed was fixed, the wind tunnel ow changed over a range of advanced ratios. The influence of propellers on propulsion system efficiency is analyzed in [3]. Pusher or puller configuration, as well as the number of blades and the shape of the arms are considered.

System identification

The mathematical description of complex systems such as UAVs requires the estimation of aerodynamic, inertial and structural properties. As the physical modelling approach is complicated and strong approximations are often needed, an input-output black box model relation is used. This is an important step for the design of attitude and position control law. Different solutions are available in literature: the common one ([4],[5] and [6]) consists of a spherical joint that constrains translational motions while it allows three degree of freedom in attitude, as shown in Fig.3. In [7] a test procedure for pitch attitude identification is presented: the multi-copter is mounted over a test bed that constrains the translational motion and the rotational degree of freedom except for the pitch. Moreover, the UAV mounting plate is far away from the floor to avoid ground effect.

Figure 2: Propeller test. Photograph taken from [2]

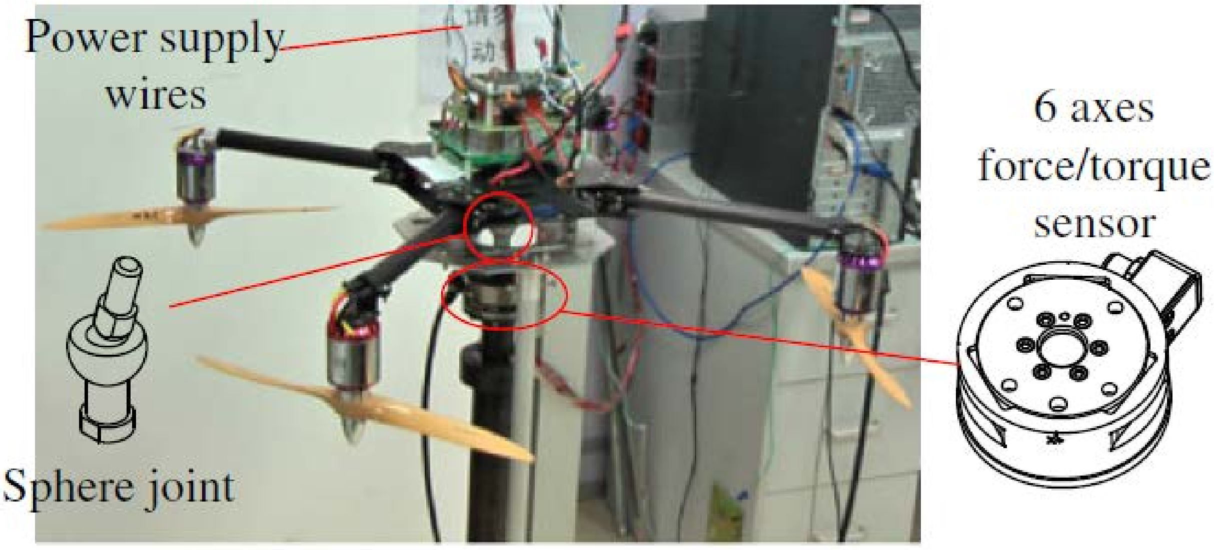

Figure 3: UAV test bed for identification. Photograph taken from [4]

Aerodynamic characterization in wind tunnel

While propeller characterization provides useful data for the design process, wind tunnel tests offer details on the aerodynamics of the complete UAV system: unfortunately, few works are available in literature. In [8] aerodynamic and performance characteristics for a full-scale model of a fixed wing unmanned aerial vehicle are analyzed in the low speed wind tunnel of Korea Aerospace Research Institute (KARI). Various model configurations were considered to collect measurements and evaluates the effect of model components (such as tail, landing gear and booms) on the drag-polar and lift curves. The aerodynamics of small UAVs is studied in [9]: Reynolds number and aspect ratio (AR) effects on the design and performance of fixed-wing vehicles are discussed. Moreover, experimental boundary layer studies, related to the influence of laminar separation bubbles, are shown. The most interesting work on UAV wind tunnel tests is presented in [10], as discussed in the next paragraph.

Figure 4: NASA Ames Multicopter Wind Tunnel Test. Photographs taken from [10]

NASA Ames Multicopter Tests Due to the lack of published data on the performance of multi-copter unmanned aircraft system (UAS), in 2016 NASA planned aerodynamic performance tests for model development and validation. The tests took place in the U.S. Army 7’ by 10’ ft wind tunnel at NASA Ames Research Centre and focused on full vehicles and isolated rotors measurements (Fig.4). Five UAVs were installed on a 6axes load cell placed over a wind tunnel sting support. Full airframe, bare airframe and propeller only were considered as reference test conditions to describe the aerodynamics of drones. The sting arm allowed changing in the ow angle of attack and UAV yaw angle. The collected data include forces, moments and electrical power as a function of rotor speed, airspeed and vehicle attitude. Comparison between full vehicle and isolated rotor tests were useful to evaluate the rotor influence on total lift generation. In addition, the authors not only present drag and lift curves but focus also on vibration level analysis with different running motor configurations.

Conclusions

In the present document the state of the art in UAV test have been presented. At present, no systematic studies related to the environmental effects on drone flight performance are available, even if the market is evolving in the direction of facilities for testing in climate-controlled laboratories. Although climatic chambers for industrial test and wind tunnel facilities have been used for drone testing, the effects of humidity, low temperature and pressure on unmanned aerial systems should be investigated in deeper way, with a scientific approach. The tests should take into account the characterization of the propulsion systems and the complete UAVs to evaluate mechanical and electrical performances, in order to support research groups and manufacturers in the design process. Furthermore, thrust, torque and attitude measurements should be integrated with real flight test to understand how harsh environmental conditions could affect the autopilot and the on-board electronics.

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