Development of a Free-Flight Wind Test Facility Featuring a GNSS Simulator to Achieve Immersive Drone Testing

Guillaume Catry*, Nicolas Bosson†, and Thierry Bujard
WindShape, Rue de Bourgogne 25, Geneva, CH-1203, Switzerland

Andy Thurling ‡
NUAIR Alliance, 250 Harrison Street, Suite 201, Syracuse, New York 13202, USA

Aleksandar Dzodic, Peter Le Porin, Ningshan Wang, Amit K Sanyal, and Mark Glauser §
Syracuse University, Syracuse, New York 13244, USA

Flavio Noca ¶
University of Applied Sciences (HES-SO), Geneva, CH-1202, Switzerland

Weather, winds, thermals, and turbulence pose an ever-present challenge to small UAS. These challenges become magnified in rough terrain and especially within urban canyons. As the industry moves towards Beyond Visual Line of Sight (BVLOS) and fully autonomous operations, resilience to weather perturbations will be key. As the human decision-maker is removed from the in-situ environment, producing control systems that are robust will be paramount to the preservation of any Airspace System. Safety requirements and regulations require quantifiable performance metrics to guarantee a safe aerial environment with ever-increasing traffic. In this regards, the effect of wind and weather disturbances on a UAS and its ability to reject these disturbances present some unique concerns.

Currently, drone manufacturers and operators rely on outdoor testing during windy days (or in windy locations) and onboard logging to evaluate and improve the flight worthiness, reliability and perturbation rejection capability of their vehicles. Waiting for the desired weather or travelling to a windier location is cost- and time-inefficient. Moreover, the conditions found on outdoor test sites are difficult to quantify and repeatability is non-existent.

To address this situation, a novel testing methodology is proposed, combining artificial wind generation thanks to a multi-fan array wind generator (windshaper), coherent GNSS signal generation and accurate tracking of the test subject thanks to motion capture cameras. In this environment, the drone being tested can fly freely, follow missions and experience wind perturbations whilst staying in a modest indoor volume.

By coordinating the windshaper, the motion tracking feedback and the position emulated by the GNSS signal generator with the drone's mission profile, it was demonstrated that outdoor flight conditions can be reliably recreated in a controlled and repeatable environment. Specifically, thanks to real-time update of the position simulated by the GNSS signal generator, it was possible to demonstrate that the drone's perception of the situation is similar to a corresponding mission being executed outdoor.

In this work, the drone was subjected to three distinct flight cases: (1) hover in $2\,\mathrm{m\,s^{-1}}$ wind, (2) forward flight at $2\,\mathrm{m\,s^{-1}}$ without wind and (3) forward flight at $2\,\mathrm{m\,s^{-1}}$ with $2\,\mathrm{m\,s^{-1}}$ headwind. In each case, it could be demonstrated that by using indoor GNSS signal simulation and wind generation, the drone displays the characteristics of a $20\,\mathrm{m}$ move forward, while actually staying stationary in the test volume, within $\pm 1\,\mathrm{m}$.

Further development of this methodology opens the door for fully integrated hardware-in-the-loop simulation of drone flight operations.

*CEO, `https://www.windshape.com`
†COO, `https://www.windshape.com`
‡CTO, NUAIR Alliance, athurling@nuair.org, `http://www.nuair.org`
§Professor, Mechanical & Aerospace Engineering, mglauser@ecs.syr.edu, `https://eng-cs.syr.edu`
¶Professor, Center for Hydro & Aero, flavio.noca@hesge.ch, `http://www.chachacha.ch`

I. Nomenclature

Acronyms

GNSS	Global Navigation Satellite System
GPS	US Global Positioning System, included in GNSS
UAS	Unmanned Aerial System, or commonly drone
MoCap	Motion Capture Camera System

Variables

$v_{\text{ground}}^{\text{out}}$,	$v_{\text{ground}}^{\text{in}}$	drone forward travelling speed in ground reference frame, both for an outdoor and an indoor (laboratory) flight
$u_{\text{ground}}^{\text{out}}$,	$u_{\text{ground}}^{\text{in}}$	ground horizontal wind speed in the ground reference frame, both for an outdoor and an indoor (laboratory) flight
$v_{\text{gps}}^{\text{out}}$,	$v_{\text{gps}}^{\text{in}}$	GPS forward speed as interpreted by the drone, both for an outdoor and an indoor (laboratory) flight
$u_{\text{rel}}^{\text{out}}$,	$u_{\text{rel}}^{\text{in}}$	relative horizontal wind speed in the drone reference frame, both for an outdoor and an indoor (laboratory) flight

II. Introduction

Demonstrating safe operation of Unmanned Aircraft Systems (UAS) through a thorough performance assessment will become part of the process for getting flight authorizations. The industry will be in demand for cost-efficient, reliable and trusted test methods that can ultimately lead to product/operation certification.

Currently, there is only one commonly available – but not standardized – approach to assess a drone's performance: real-world (outdoor) flight testing. While this appears to be the most straightforward approach, it is actually a significant challenge to get relevant information from an outdoor test flight. Environmental conditions cannot be controlled and can hardly be measured, and the test subject (UAS) and the observer are far apart.

This method imposes UAS manufacturers to either (1) restrain UAS performance specifications to the range of conditions that were found in nature during the test session, or (2) chase down some extreme environmental conditions to run test campaigns and widen the operating range of their products (e.g. flight testing at high or low temperature).

Repeatability of test conditions is another requirement that cannot be satisfied while testing outdoors, as environmental conditions fluctuate quite rapidly and in a unpredictable manner at the drone scale.

Both aforementioned challenges showcase a need for indoor testing and certification capabilities for UAS.

In a joint effort toward developing the most immersive test environment in which a UAS can be tested in various conditions, the authors have combined multiple technologies, namely:

1. Windshaper – open-circuit multi-fan wind generator capable of creating an infinite variety of spatially and time-varying wind profiles by independent activation of each fan [1];
2. Global Navigation Satellite System (GNSS) simulator – device capable of generating and emitting custom GNSS positioning signals indoor;
3. Motion Capture Camera System (MoCap) – system composed of multiple optical cameras capable of capturing accurately the live position and attitude of an object.

Interconnecting and synchronizing these technologies makes it possible to create an alternative reality, similar to Virtual Reality (VR) for humans. Indeed, the UAS is in immersion in the sense that its sensors perceive the same phenomena as during a real outdoor flight whilst flying stationary in a test facility. This opens the door for complete hardware-in-the-loop simulation of drone flight operations.

III. Method

In the proposed methodology, UAS flight tests are performed indoor, within a facility that allows for fully controllable and repeatable flight conditions. The setup associates wind generating capabilities together with a system to measure UAS position during a free-flight test (MoCap), and a GNSS signal generator. As shown in Figure 1, the test facility is equipped with the aforementioned systems to accurately recreate a variety of real outdoor flight scenarios. The difference between the real outdoor flight and the equivalent indoor scenario is a change of reference frame (Table 1).

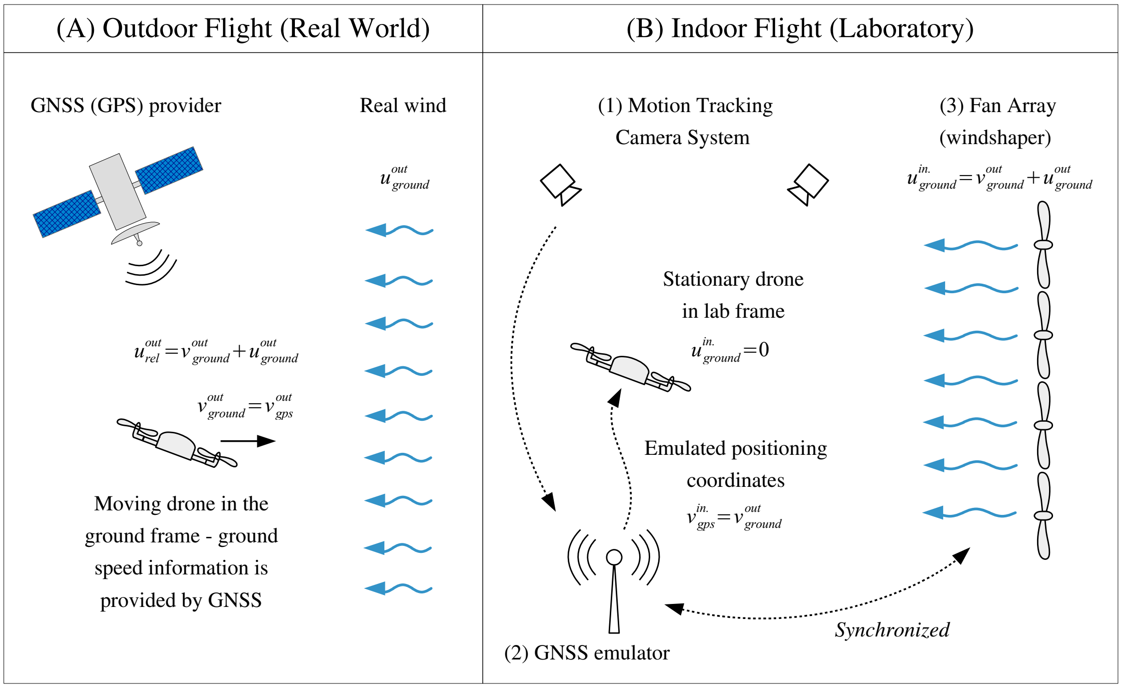

Fig. 1 Comparison between (A) a real-world test flight and (B) a similar simulated test situation. In both cases the drone is subjected to the same forces and receives the same positioning signal (GNSS).

	(A) Outdoor Flight (Real World)	(B) Indoor Flight (Laboratory)
Drone	The drone moves with respect to a ground reference. It receives positioning information from a GNSS provider and derives its ground speed from it. The aerodynamic efforts are proportional to the relative wind speed which is the sum of the wind speed, plus that of the drone.	The drone is stationary with respect to the lab frame. It receives a fabricated positioning information from the GNSS emulator that makes it "believe" it's moving. Thus, it experiences a situation similar to *A*.
Wind	When there is wind, the air moves with respect to a ground reference.	The apparent wind speed is set to be equal to the sum of drone speed, plus that of the wind in *A*.
GNSS	The GNSS provides live position of the drone with respect to a ground reference.	An emulated GNSS signal is emitted so as to let the drone believe that it is moving at the same speed as the drone in *A*.

Table 1 Change in reference frame that is operated to simulate an outdoor flight in the the lab.

In order to demonstrate the feasibility of the proposed test method, three experiments were designed. Each of them is illustrated by a column of graphs in Figure 2, which illustrates the speed regimes for each test case, in a real outdoor flight and an indoor test flight. In particular:

- For a lab flight, **Drone Ground Speed**, v_{ground}, shall always be null as the aim is to have a steady test subject and the flight space available is limited.
- In the lab, the **Wind Ground Speed**, u_{ground}, shall be equal to $v_{ground} + u_{ground}$ taken from an equivalent outdoor flight.
- The **Drone GPS Speed**, v_{gps}, shall always be equal for a lab flight and for an equivalent outdoor flight.
- Lab flight **Relative Wind Speed**, u_{rel}, shall always be equivalent to outdoor flight relative wind speed in order to have similar aerodynamic conditions on the drone.

Case 1 - Hover with wind This test case is the natural starting point for this demonstration as this is the simplest to simulate. In fact, the authors have significant past experience in testing the hovering stability of drones in winds. In past work, drones were able to hover in a stable manner in a wind, essentially by using their on-board optical sensors. In the present study, the drone's vision is voluntarily obstructed, which is identical for the control system as flying by night or at high altitude. In replacement of the optical sensors information, the drone receives a custom positioning signal (GNSS), which enables a stable flight.

Case 2 - Forward flight without wind In this second test case, the drone is in free-flight (in a relative or apparent wind due to its motion only), while it receives moving positioning information. The GNSS positioning advance speed is equal to the (relative) wind speed at the drone. The drone is, thus, made to believe, by its own GNSS receiver, that it is moving at a given speed, while the aerodynamic flow conditions around the drone are identical to the ones of an outdoor flight at the same speed.

Case 3 - Forward flight with wind This last case is more general than the previous one, as the GNSS advance speed and the wind speed do not necessarily match. The drone can either receive a positioning speed that is slower than the wind, which is analogous to an outdoor flight with headwind; or receive a positioning speed that is faster than the wind, which is similar to flying outdoor with tailwind.

IV. Facilities and Setup

A. Test Facility

The development of this test method takes place into two labs in parallel. As explained below, both labs are equipped with similar test systems.

- Autonomous Unmanned Systems Laboratory at Syracuse University, where the test volume is 6m x 6m x 5.4m.
- Center for Hydro & Aero at the University of Applied Sciences (HES-SO) in Geneva, where the test volume is 5m x 3m x 4m.

B. Windshaper

Both laboratories are equipped with similar wind generation capabilities (Figure 3), namely multi-fan facilities or windshapers [1]. Each single fan can be activated independently, thus enabling the generation of an infinite variety of spatially and time-varying wind profiles.

The windshapers used in this project feature 162 counter-rotating fan units (324 controllable fans in total), arranged in an array of 6x3 modules of 9 fan units, that are capable of generating flows speed up to of 16 m/s in the open test section of 1.5m x 0.75m (cross section). The maximum ramp-up acceleration of the air flow is $4\,\mathrm{m/s^2}$ and maximum the ramp-down is $3.6\,\mathrm{m/s^2}$.

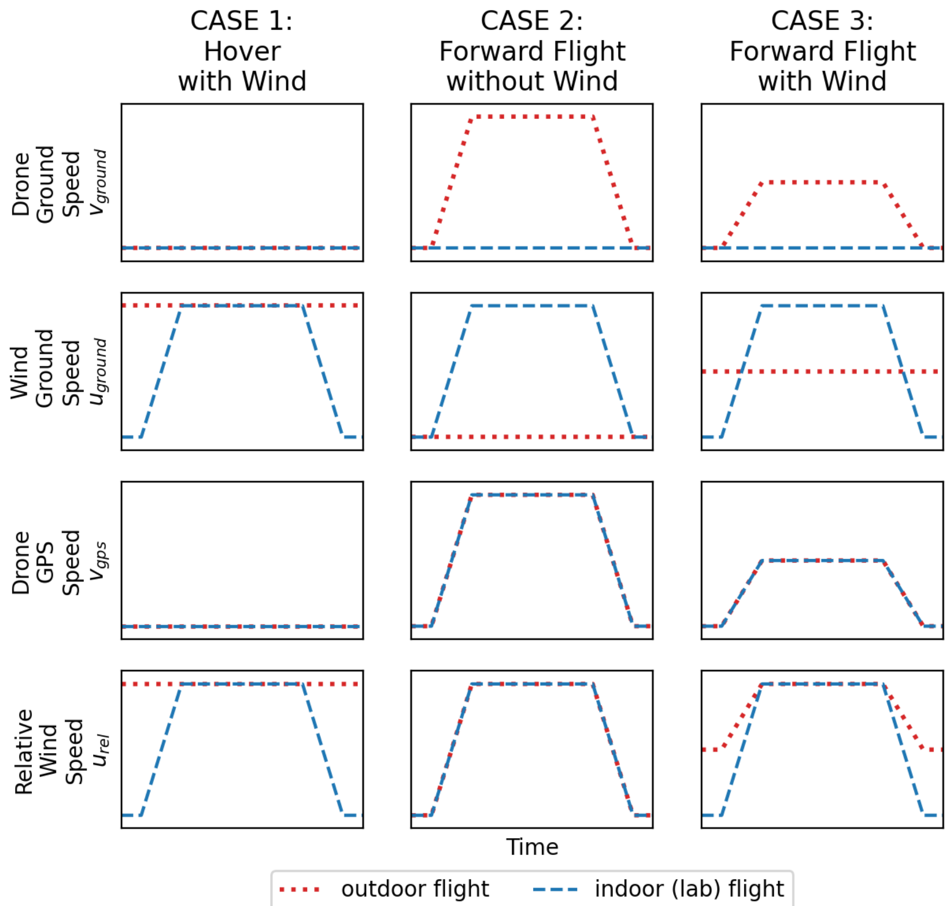

Fig. 2 Ideal speed plots comparisons between an outdoor flight and an equivalent lab flight for three different use cases.

C. GNSS System

For the purpose of generating custom GNSS signals, both labs are equipped with a vector signal generator model SMBV100A from Rohde & Schwarz. This device is essentially a high quality signal generator combined with a GNSS satellite constellation simulator which enables the generation of various positioning signals (GPS, Galileo, ...). For the present study, this device is controlled from its Python API (Application Programming Interface), which makes it possible to synchronize the simulated GNSS signal with the state of the other test instruments (MoCap, windshaper, ...).

D. Motion Capture Camera System (MoCap)

Both labs are equipped with different motion capture camera system (MoCap).

1. Syracuse University is equipped with 8 Vicon Bonita cameras featuring a latency lower than 3ms and and image capture rate of 240 fps.
2. HES-SO in Geneva is equipped with 4 OptiTrack Prime 17W cameras featuring a latency lower than 2.8ms and an image capture rate of 360 fps.

Both system are capable of resolving the position of a rigid body with sub-millimeter accuracy and its orientation (attitude) within 0.1°.

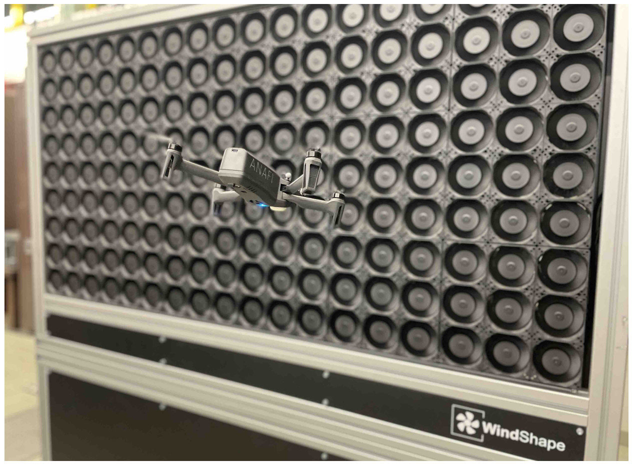

Fig. 3 Parrot Anafi in free flight test in a WindShape testing facility. WindShape, Switzerland, November 2021.

E. Drone

The drone that was selected for the validation of the proposed method is a commercial quad-copter from the company Parrot. An important reason for choosing a commercial drone was to demonstrate that the method works without needing to interfere with the drone's control system. For this study the drone has been considered as a black box to which mission commands can be sent, and from which logs can be read after the mission. The main reason for selecting this particular model, the Parrot Anafi, is the availability of a complete SDK (Software Development Kit) suite, including the Olympe environment from which commands can be issued to the drone using a linux computer. The principal command used for this study is the `moveBy()` function (or `extendedMoveBy()`), which makes it possible to order the drone to achieve a given maneuver (i.e. move by 5m at 2m/s). The drone uses its sensors, (IMU, accelerometer, GNSS receiver) to regulate its speed in order to reach the target position accurately. As stated before, the optical flow downward-facing camera was obstructed using a piece of tape in order to test only the GNSS simulation.

Drone Characteristics	
Model	Parrot Anafi [2]
Size	175x240x65 mm
Weight	320 g
Maximum flight speed	15m/s

Drone's GPS Module	
Model	U-BLOX UBX-M8030
Sensibility at cold start	-148 dBm
Sensibility during navigation	-167 dBm
Time-To-First-Fix	35 seconds
Position	1.2 m standard deviation
Speed	0.5 m/s standard deviation
Gain GPSL1	+0 dB
GalileoE1	+0 dB
GlonassL1	-4 dB
BeiDouB1C	+0 dB

F. Test Loop

In order to accommodate these various systems into a synchronized working environment (as required by the methodology of Figure 1), a communication protocol was developed to coordinate the mission task requirements of each sub-system (drone, MoCap/GNSS, wind), as laid out on Figure 4.

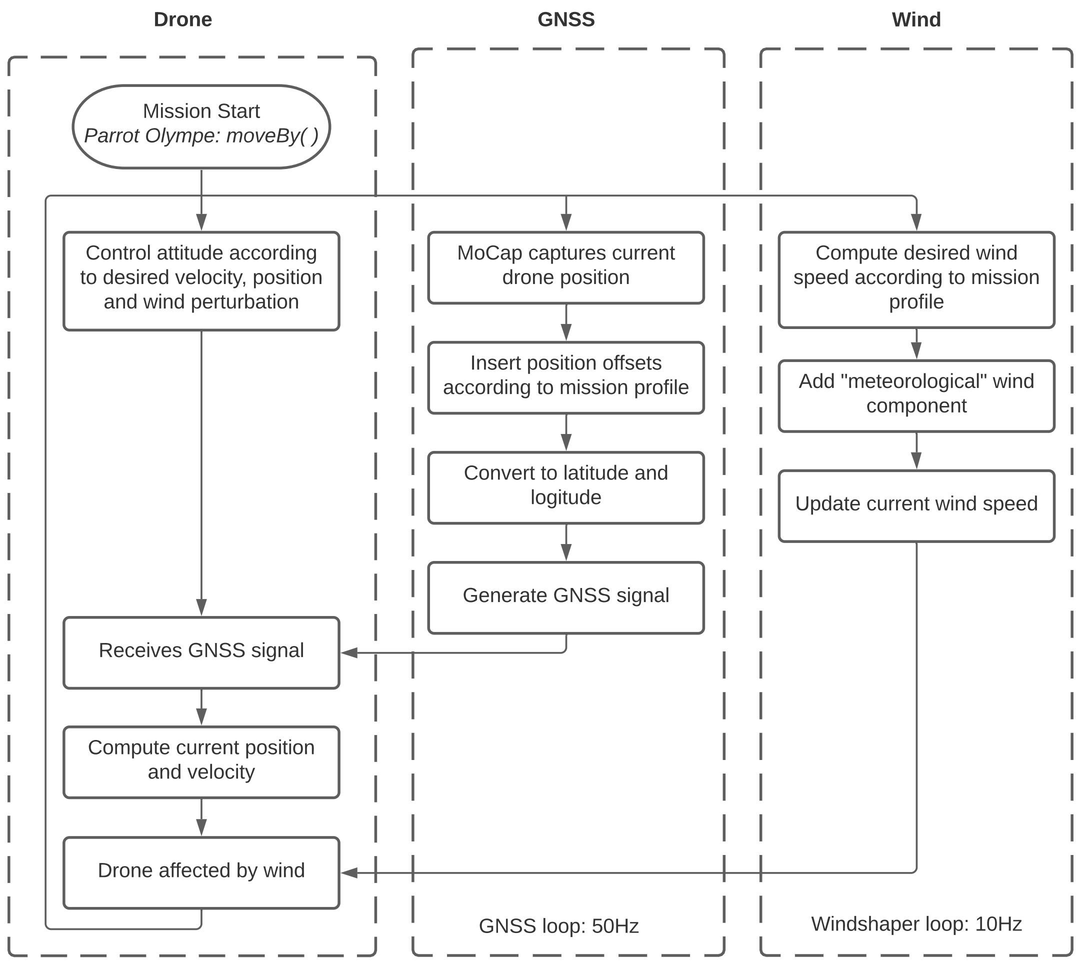

Fig. 4 Test loop showing the interactions between the different test systems. The drone receives a "mission" (i.e. move by a given distance at a given speed). This triggers the start of the GNSS position offset generation and the relative wind generation. At any moment in time during the mission, the GNSS provides the expected speed and position of the drone, while the windshaper generates the correct wind.

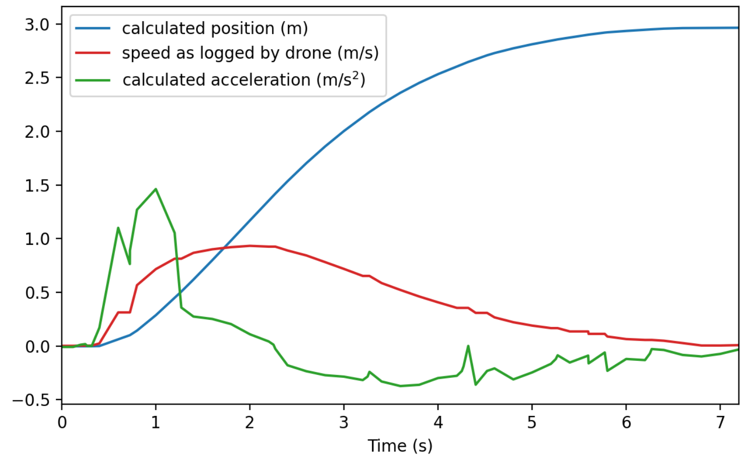

Fig. 5 Drone kinematics resulting from a `moveBy()` command, which ordered the drone to move by 3 m at a speed of 1 m/s. The drone was able to log its own speed using its down-facing camera. From there, numerical integration and differentiation were used to calculate respectively the position and acceleration of the maneuver.

V. Results

A. Characterization of drone trajectory

As a first step, the drone dynamics had to be characterized. The goal of this characterization was essentially to record the drone movement that resulted from a `moveBy()` command issued from Parrot Olympe SDK environment. Figure 5 shows the kinematics of a forward translation of 3 m at a max speed of 1 m/s. One can see that the maximum acceleration is around $1.5\,\mathrm{m/s^2}$ and the maximum deceleration is roughly $-0.4\,\mathrm{m/s^2}$. The figure also shows that the drone is capable of reaching the desired position at the desired speed.

B. GPS spoofing functions

The GPS kinematics were designed according to the drone forward translation maneuver presented above. For simplicity, it has been decided to use a constant acceleration at $1.8\,\mathrm{m/s^2}$ and a constant deceleration of $0.35\,\mathrm{m/s^2}$, which gives a trapezoidal GNSS speed curve ($v^{\mathrm{in}}_{\mathrm{gps}}$).

C. Wind functions

The design of the wind function is similar to the design of the GPS spoofing function. The wind speed reaches the desired value after a constant acceleration of $1.8\,\mathrm{m/s^2}$ and then decelerate at a constant rate of $0.35\,\mathrm{m/s^2}$.

D. Case 1: Hover with wind

The left column of Figure 6 shows a situation in which the drone is hovering in a constant ground wind, $u^{\mathrm{out}}_{\mathrm{ground}} = 2\,\mathrm{m/s}$. In this situation, as the drone is not moving ($v^{\mathrm{out}}_{\mathrm{ground}} = 0\,\mathrm{m/s}$), the relative wind speed at the drone, $u^{\mathrm{out}}_{\mathrm{rel}}$, is equal to the wind ground speed $u^{\mathrm{out}}_{\mathrm{ground}}$. In order to reproduce this scenario in the lab, an accurate GNSS positioning signal was fabricated using the live drone position feedback from the MoCap. As a reminder from section III, the drone's optical stabilization system was voluntarily obstructed in order to force the drone to only rely on the GNSS signal. One can see that all indoor (laboratory) curves for the hovering case (left column of Figure 6) match the outdoor curves.

This result validates the proposed method for keeping the drone in position in the lab ($v^{\mathrm{in}}_{\mathrm{ground}} = 0\,\mathrm{m/s}$ means hovering) even while it is subjected to a constant wind perturbation, here $u^{\mathrm{in}}_{\mathrm{ground}} = u^{\mathrm{in}}_{\mathrm{rel}} = 2\,\mathrm{m/s}$.

E. Case 2: Forward flight without wind

The second scenario, for which the resulting velocity profiles are presented in the center column of Figure 6, present a situation where a drone is flying at a constant speed, $v^{out}_{ground} = 2\,\mathrm{m/s}$, without environmental wind, $u^{out}_{ground} = 0\,\mathrm{m/s}$. During such a forward flight, the drone receives a GNSS positioning signal from which it can infer its speed. In a real outdoor flight, the GNSS-based speed should match the ground speed of the drone, $v^{out}_{gps} = v^{out}_{ground}$. In the laboratory, the goal is to keep the drone stationary ($v^{in}_{ground} = 0\,\mathrm{m/s}$), while maintaining similar aerodynamic conditions around the drone, and ensuring an identical GNSS signal as for an equivalent outdoor flight. Thus, it is necessary to compensate for the outdoor ground speed by generating both an equivalent relative wind speed and GNSS speed in the laboratory. This translates into $u^{in}_{ground} = v^{in}_{gps} = v^{out}_{ground}$.

The results of this test case (center column of Figure 6) provide a validation for the proposed methodology, and confirm that it is possible to replace the drone forward speed by an equivalent wind speed, and a matching GNSS speed. One can notice the delay between the beginning of the drone's maneuver, and the beginning of the GNSS spoofing. This is mainly due to the fact that the timing necessary for Parrot's Olympe SDK `moveBy()` function to be effective (i.e. start the maneuver) cannot be controlled accurately. A more precise result could certainly be achieved with a more accurate control on the drone's maneuver.

A good success criterion could be the measure of the ability for the drone to maintain its position during the indoor (laboratory) flight. By looking at Figure 7 (center graph), one could see that the drone's distance from its origin (take-off location) does not vary much ($\pm 0.5\,\mathrm{m}$), while its interpretation of the travelled distance is 20 m.

F. Case 3: Forward flight with wind

The last test, in which the drone achieves a forward flight in a headwind, is obtained by combining the two former test cases. In other words, it is a forward flight situation where $v^{out}_{ground} = 2\,\mathrm{m/s}$, on top of which a wind ground speed is applied $u^{out}_{ground} = 2\,\mathrm{m/s}$, which leads to a more important apparent wind speed $u^{out}_{rel} = 4\,\mathrm{m/s}$.

This result shows that the drone's ability to maintain a fixed position during the indoor test (which can be seen on the right graph in Figure 7), is similar to test Case 2.

VI. Conclusion

This work proposes an innovative indoor testing methodology where drones can fly freely whilst being subjected to steady wind or wind gusts.

To accomplish this, a testing environment comprising a fan-array wind generator (windshaper), a motion tracking camera system and a GNSS signal generator has been assembled. By coordinating the windshaper, the motion tracking camera feedback and the position emulated by the GNSS signal generator with the drone's mission profile, it was demonstrated that outdoor flight conditions can be reliably recreated in a controlled and repeatable environment. Thanks to the built-in logging functionality of the drone used for this work, it was possible to validate that the drone's perception of the situation is exactly the same as it would be outdoor during the execution of a similar mission, and that its position estimator produces corresponding output.

In these tests, the drone was subjected to three distinct flight cases: (1) hover in $2\,\mathrm{m\,s^{-1}}$ wind, (2) forward flight at $2\,\mathrm{m\,s^{-1}}$ without wind and (3) forward flight at $2\,\mathrm{m\,s^{-1}}$ with $2\,\mathrm{m\,s^{-1}}$ headwind. In each case, it could be demonstrated that by using indoor GNSS signal simulation and wind generation, the drone displays the characteristics of a 20 m move forward, while actually staying stationary in the test volume, within ± 1 m.

VII. Next steps

Based on the presented method, the authors are currently investigating various test scenarios, including the selection that is presented hereafter.

A. Gust Deflection

Airspace sharing between regular aviation and unmanned aviation (UA) is a concern for UTM. Chances are that UA specific routes will be defined in a near future. One of the measurable performance parameters could be the ability of a drone to maintain route when hit by a gust of wind.

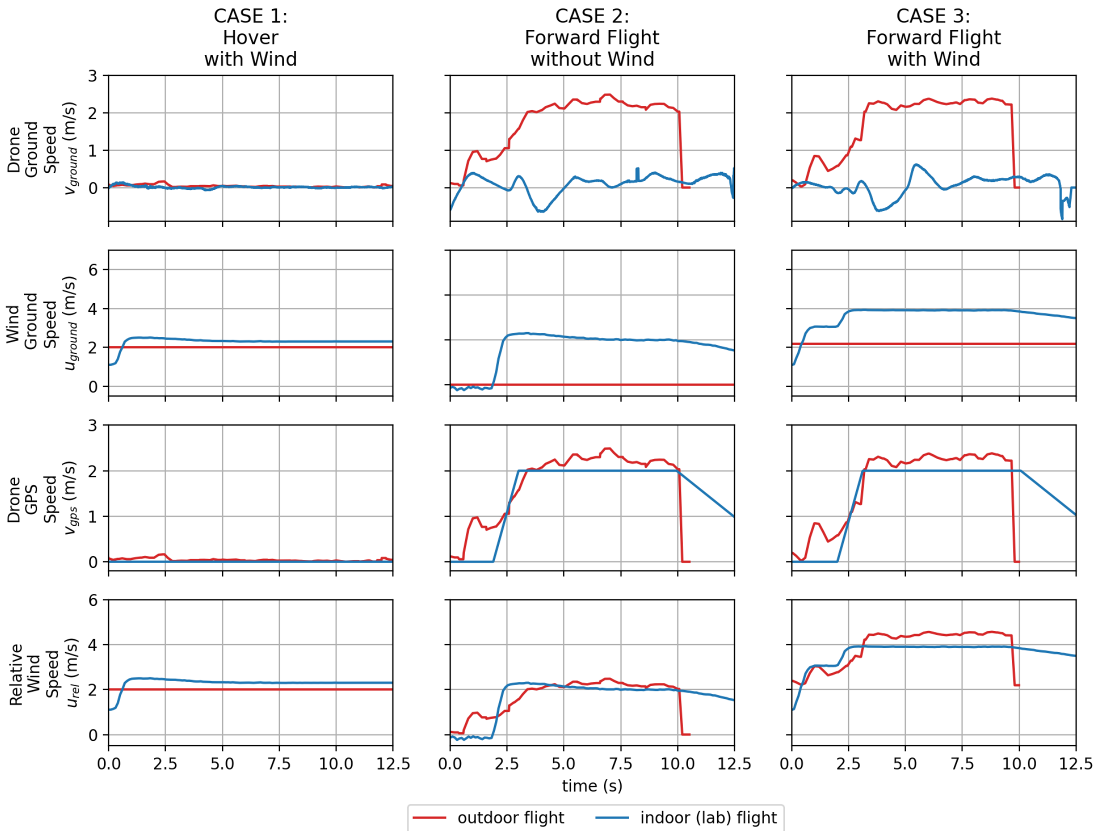

Fig. 6 Speed profiles for each of the three test cases, showing how the drone's ground speed of an outdoor flight is compensated by a spoofed GNSS signal and a wind to recreate the same apparent conditions for an indoor (laboratory) and steady test flight.

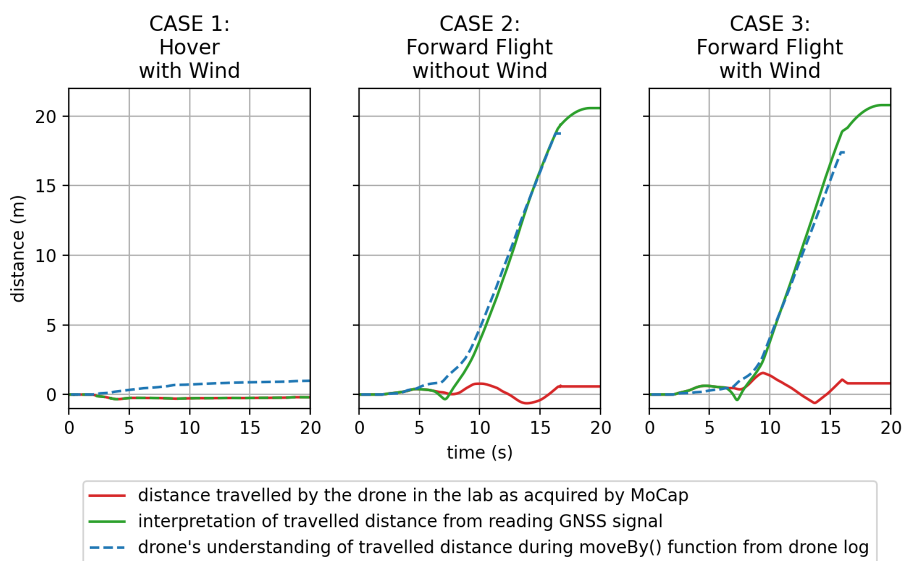

Fig. 7 Comparison, for each of the three laboratory flight tests, between the drone's actual travelled distance as acquired by the MoCap; the GNSS signal simulating the travelled distance; and the interpretation of the travelled distance by the drone, which is extracted directly from the flight logs.

routes.

Before allowing any drone to fly these routes, it will be necessary to investigate their gust deflection. Only drones with good ability to reject gust perturbation will be granted access to such routes in high-wind. It is not safe to fly untested drone on such routes as their behavior is unpredictable, which could lead to collision with manned aviation or crash on the ground.

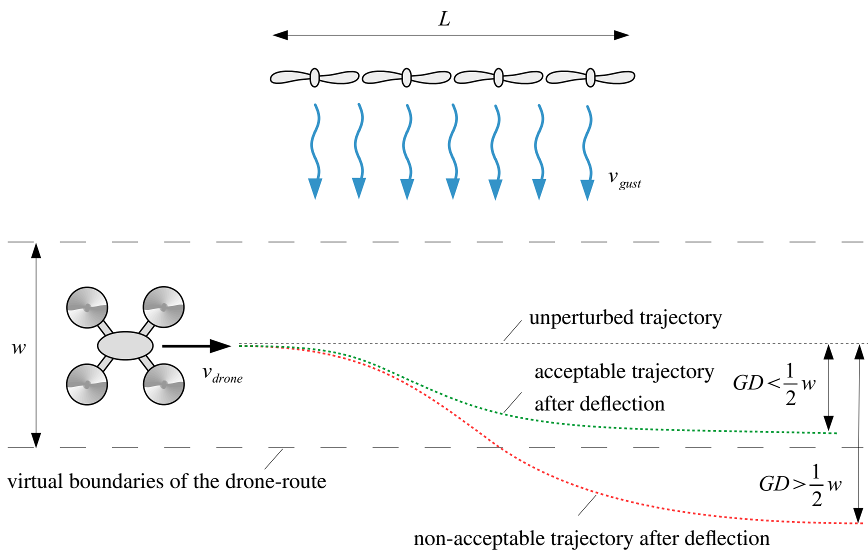

Fig. 8 The ability of a drone to reject a lateral perturbation can be tested by confronting a forward flying drone to a strong lateral wind.

Multiple Test Cases

- Updraft
- Downdraft
- Transverse gust

$GD = f(L, v_{drone}, v_{gust})$

The proposed test (Figure 8) confronts a forward flying drone to a sudden lateral gust. The drone's deflection is measured thanks to the motion tracking camera system. The performance requirement related to this test is simply the deviation distance that must be kept as small as possible.

B. Avoidance Trajectory

Drones will often need to adapt their route in order to go around a static or moving obstacle. In order to avoid potential crashes, it will be necessary to set some safety margins on various performance parameters (e.g. limiting speed to make sure a drone can stop). If those margins are too important, it will drastically reduce the performance and limit the operation of drones. On the contrary, if the margins are too small, the minimal acceptable safety level may not be reached. Fine-tuning these margins, along with testing accurately obstacle avoidance capabilities is challenging.

The following test scenario (Figure 9) presents an approach to evaluate the capability of a drone to safely avoid an obstacle. This approach not only tests flight dynamics capabilities but also decision-making algorithms and control systems.

Some possible test objectives are:

- Minimize x_{min} to ensure the drone recovers its trajectory quickly after the avoidance maneuver.
- Maximize y_{max} to ensure that the drone has a maximum of margins during the maneuver.
- $\Delta x = 0$ to ensure that the drone maintains its original flight time despite the maneuver.

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Obstacle Avoidance Capability – Avoidance Maneuver

Situations where drone will need to adapt route in order to avoid a static or moving obstacle will also happen. The following test scenario presents an approach to evaluate the capability of a drone to safely avoid an obstacle.

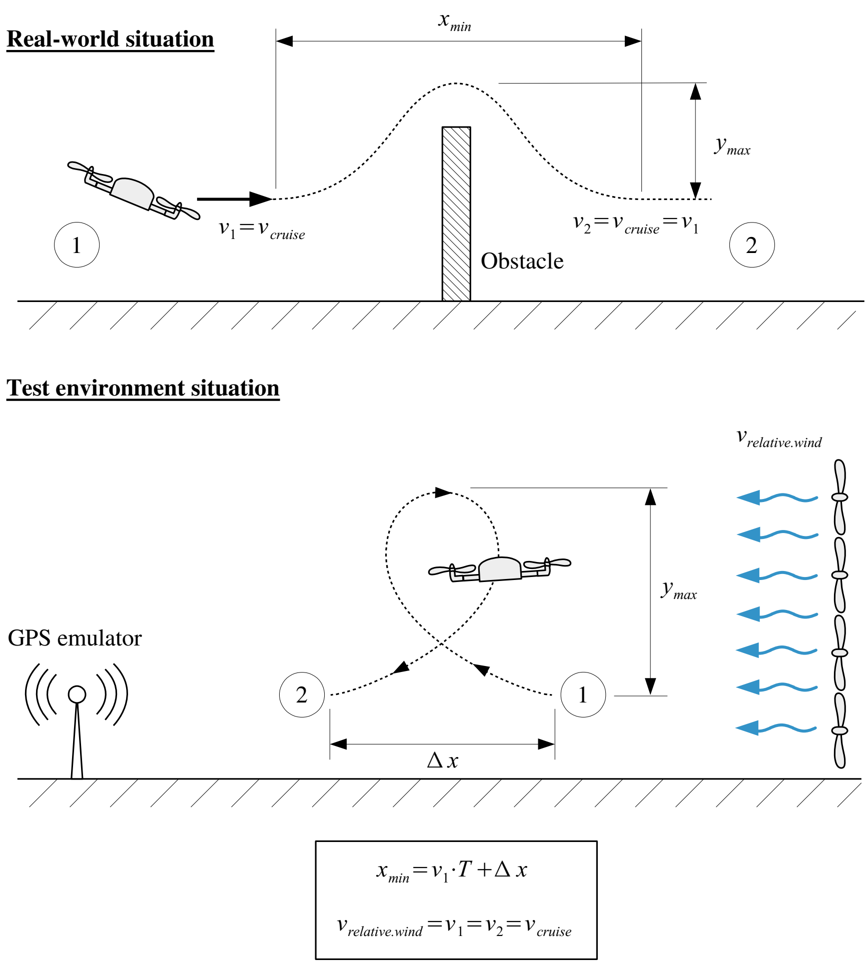

Fig. 9 Reproduction of a real-world obstacle avoidance scenario in a test environment: the drone feels identical aerodynamic and inertial forces, and receives the same positioning signal.

Test Objectives

1) Minimize x_{min} to ensure drone recover its trajectory quickly after the avoidance maneuver.
2) Maximize y_{max} to ensure that the drone has a maximum of margin during the maneuver.
3) $\Delta x = 0$ to ensure that the drone maintain its original flight time even considering the maneuver.