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


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**Weather, winds, thermals, and turbulence pose an ever-present challenge to small Unmanned Aerial Systems (UAS). These challenges become magnified in rough terrain and especially within urban canyons. As the industry moves to Beyond Visual Line of Sight (BVLOS) operations, resilience to weather perturbations will be key. As the human decision-maker is removed both from the in-situ environment and from one-to-one responsibility for the safety of the air vehicles under his or her control, better weather detection and prediction at increasingly small scales becomes vital to preserving the safety of the National Airspace System (NAS).**

**In order to provide decision-quality weather information to the UAS pilot or operator, two critical pieces of the puzzle are required. First, better detection and prediction capabilities at a much smaller scale are required. However, prediciton cannot account for local, dynamic perturbations. The pilot or operator need to understand the effects of weather on the specific UAS for which they are responsible. This area of knowledge – the effect of the disturbance on a UAS and its ability to reject this disturbance - presents some unique concerns, especially for commercial UAS which tend to be designed with Commercial Off the Shelf (COTS) components, and have rapid development, deployment, and disposal cycles.**

**Second, understanding the influence weather has on small UAS is imperative as we start to define the performance requirements for the Unmanned Traffic Management (UTM) system. Indeed, the UTM concept is based on the idea that users of the system will share their intent amongst themselves and thus achieve a type of strategic deconfliction. As the size of the operational volumes reserved shrinks, the flight plan looks more and more like a four-dimensional trajectory (4DT) operation. Multiple vehicle 4DT requires a sufficiently "tight" – or at least quantified – performance from the UAS to guarantee safety. In fact, the current standard for UTM requires that the UAS shared intend or "flight plan" include enough buffer to contain the UAS 95% of the time.**

**This paper presents the work done to date in developing a repeatable technique for quantifying the response to disturbances and the associated ability to maintain course and timeline (i.e. 4DT "flight plan") of a commercially relevant, operationally representative UAS.**



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# 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 drone 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 possible range of technical specifications (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 are experiencing the same 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 Fig. 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).

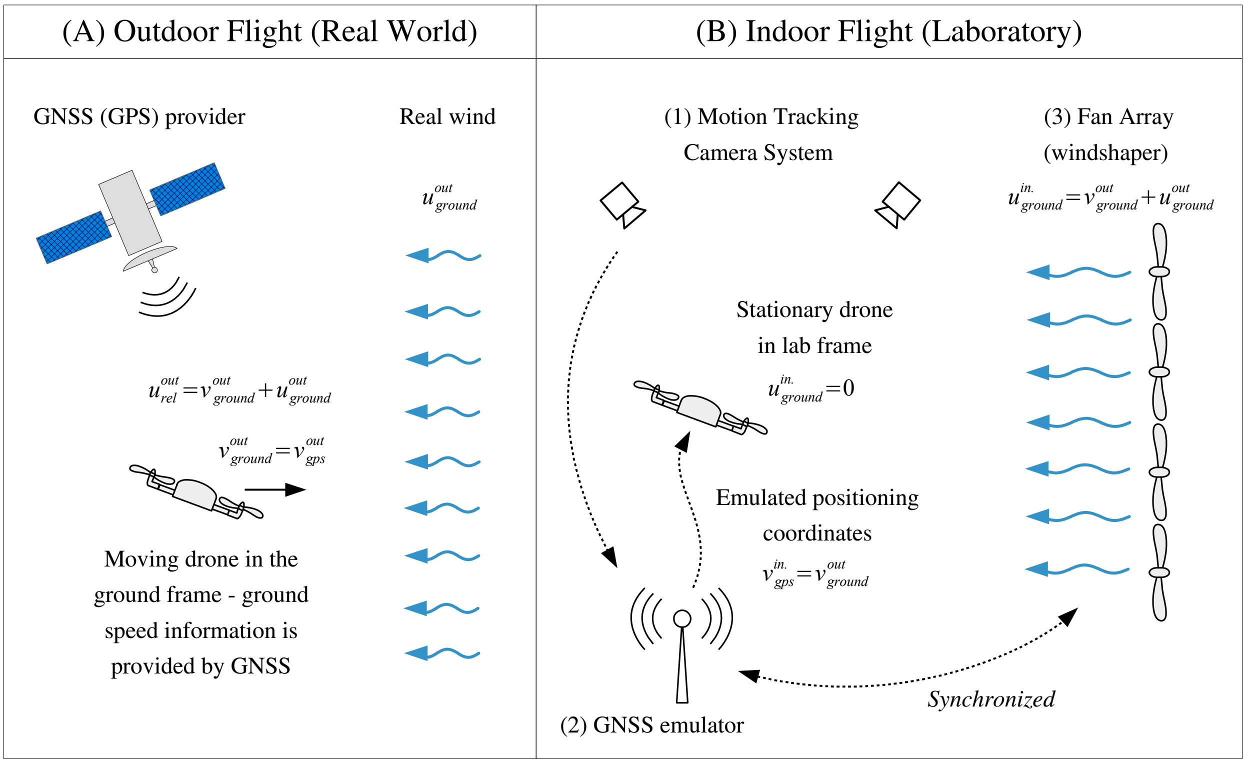


**Fig. 1 Comparison between (A) a real-world test flight and (B) a similar simulated test situation. In both cases the drone is subjected to the same forces and receives the same positioning signal (GNSS).**

| | **(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 be always 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. 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 sensor, 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 (Fig. 3), namely multi-fan facilities or windshapers [1]. Each single fan can be activated independently, thus enabling he 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 $3.6\,\mathrm{m/s^2}$.

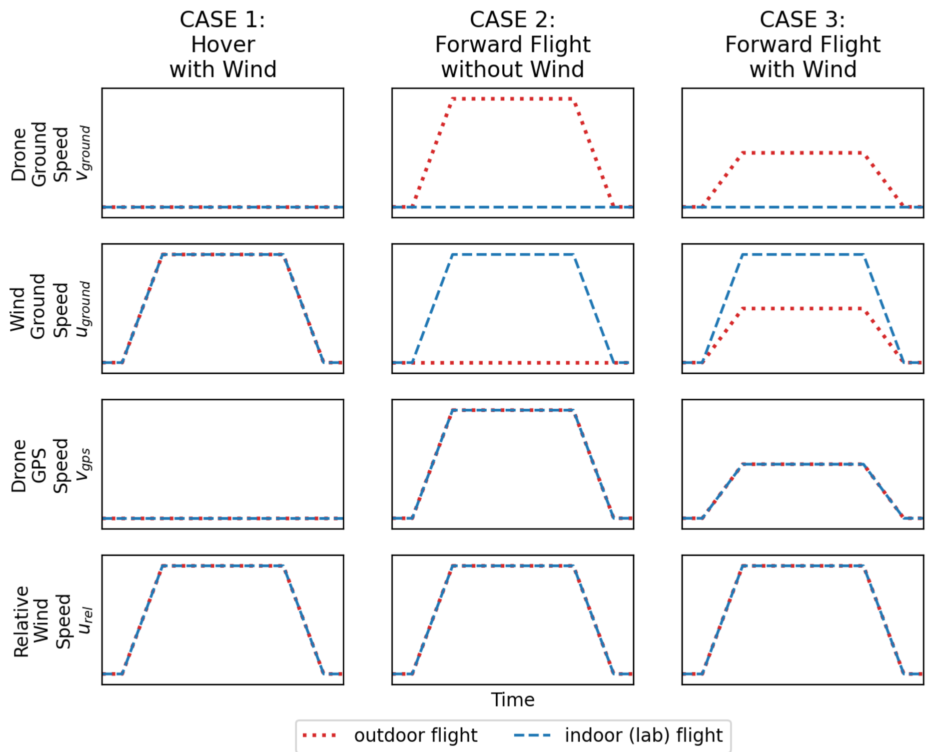


**Fig. 2 Ideal speed plots comparisons between an outdoor flight and an equivalent lab flight for three different use cases.**

### 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°.

### 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)

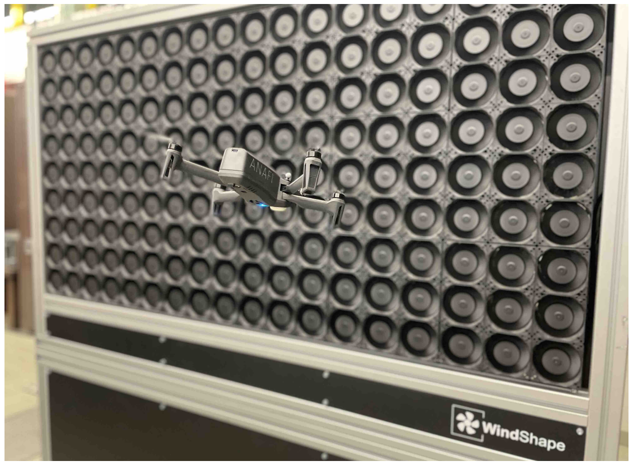


**Fig. 3 Parrot Anafi in free flight test in a WindShape testing facility. WindShape, Switzerland, November 2021.**

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, (downward facing camera, GNSS, IMU) to regulate its speed in order to reach the target position accurately. As stated before, the 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.

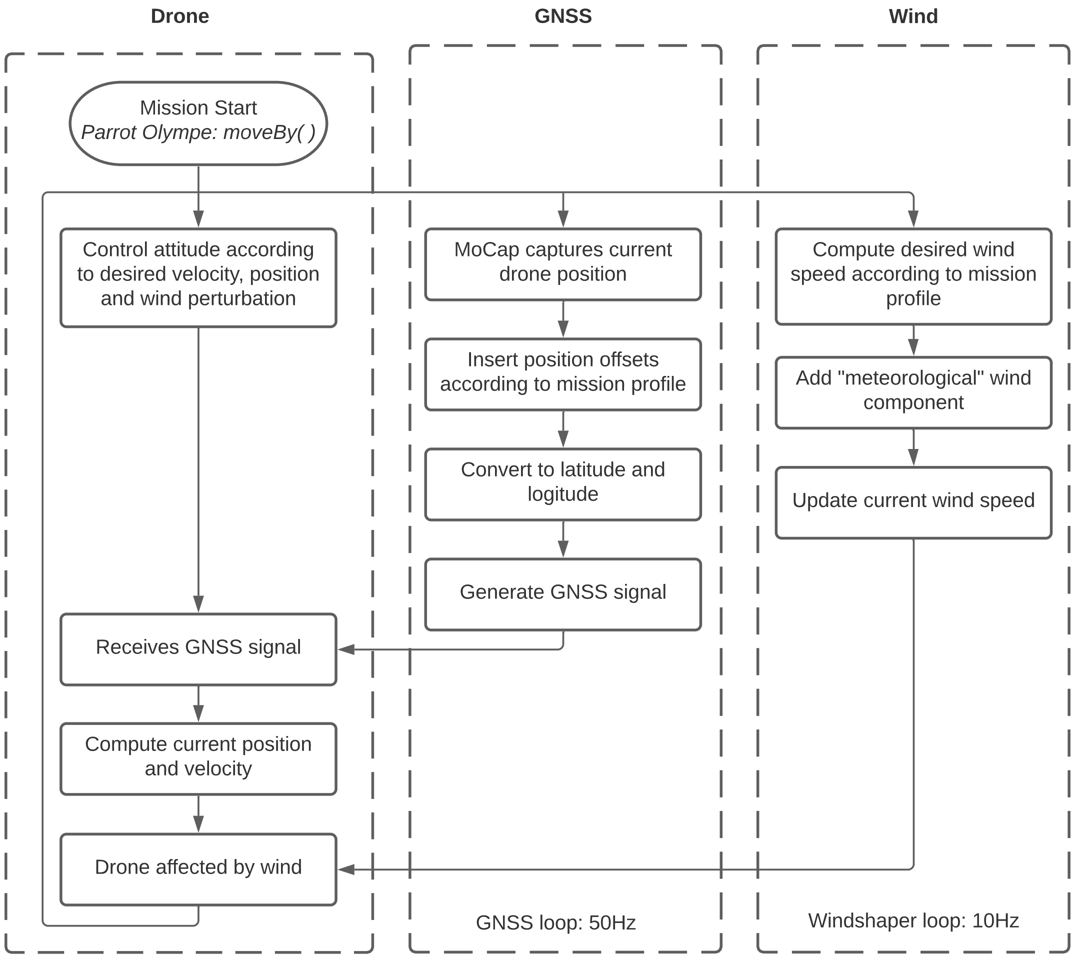


**Fig. 4 Test loop showing the interactions between the different test systems. The drone receives a "mission" (i.e. move by a given distance at a given speed). This triggers the start of the GNSS position offset generation and the relative wind generation. At any moment in time during the mission, the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

## 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. Fig 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 ($v_{\mathrm{gps}}^{\mathrm{in}}$).

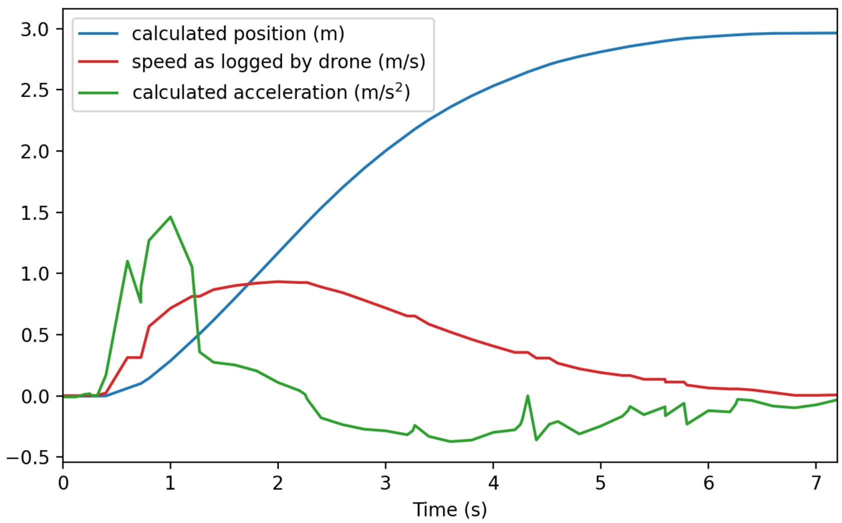


**Fig. 5 Drone kinematics resulting from a `moveBy()` command, which ordered the drone to move by 3 m at a speed of 1 m/s. The drone was able to log its own speed using its down-facing camera. From there, numerical integration and differentiation were used to calculate respectively the position and acceleration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

### 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 Fig 6 shows a situation in which the drone is hovering in a constant ground wind, $u^{out}_{ground} = 2\,\mathrm{m/s}$. In this situation, as the drone is not moving ($v^{out}_{ground} = 0\,\mathrm{m/s}$), the relative wind speed at the drone, $u^{out}_{rel}$, is equal to the wind ground speed $u^{out}_{ground}$. 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 Fig 6) match the outdoor curves.

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

### E. Case 2: Forward flight without wind

The second scenario, for which the resulting velocity profiles are presented in the center column of Fig 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 Fig 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

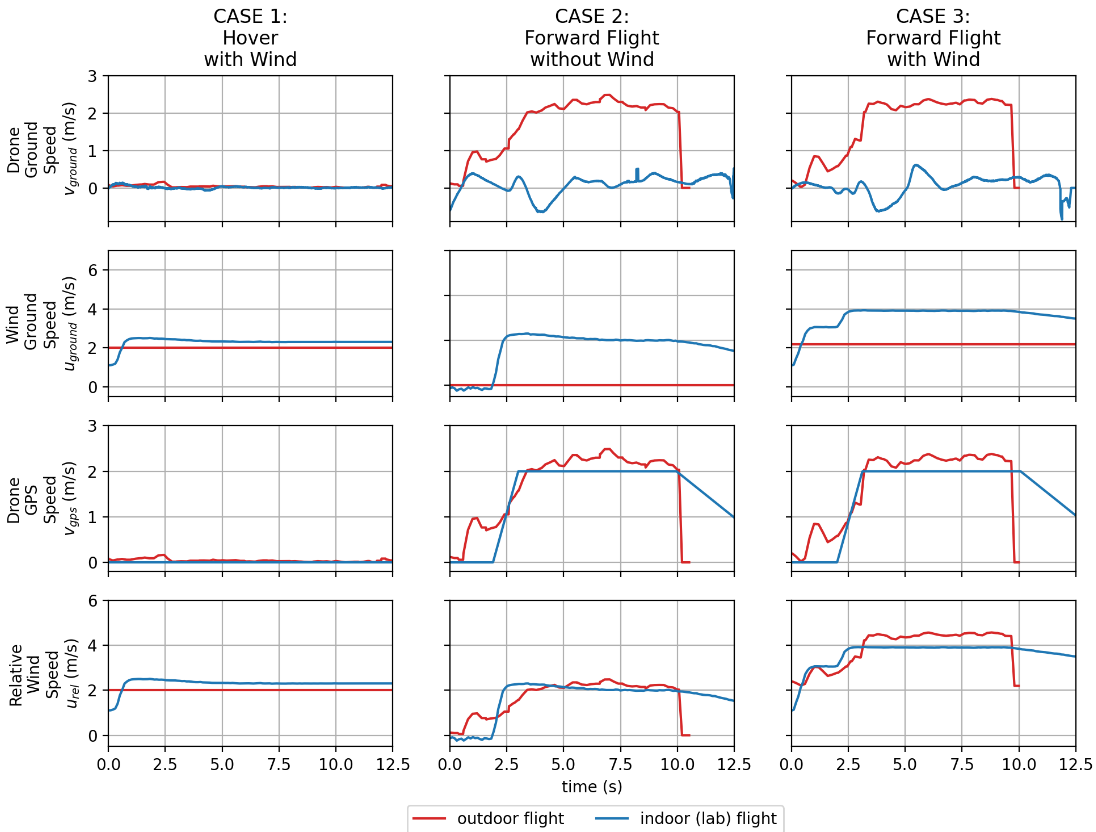


**Fig. 6 Speed profiles for each of the three test cases, showing how the drone's ground speed of an outdoor flight is compensated by a spoofed GNSS signal and a wind to recreate the same apparent conditions for an indoor (laboratory) and steady test flight.**

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 Fig 7 (center graph), one could see that the drone's distance from its origin (take-off location) does not vary much (±0.5 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 Fig 7), is similar to test Case 2.

## VI. Conclusion

Resilience to weather conditions and dynamic perturbations will be a major challenge for the fully autonomous flying systems of the future. Safety requirements and regulations require quantifiable performance metrics to guarantee a safe aerial environment with ever-increasing traffic. Testing drones' flight characteristics in wind remains a challenge.

Currently, drone manufacturers and operators rely on outdoor test flights and onboard data logging to evaluate and improve the flight worthiness, reliability and perturbation rejection capability of their vehicles. This poses majors challenges such as the availability of desired conditions and the capacity to quantify the given test conditions of the day.

We propose an innovative indoor testing methodology where the drone can fly freely whilst being subjected to

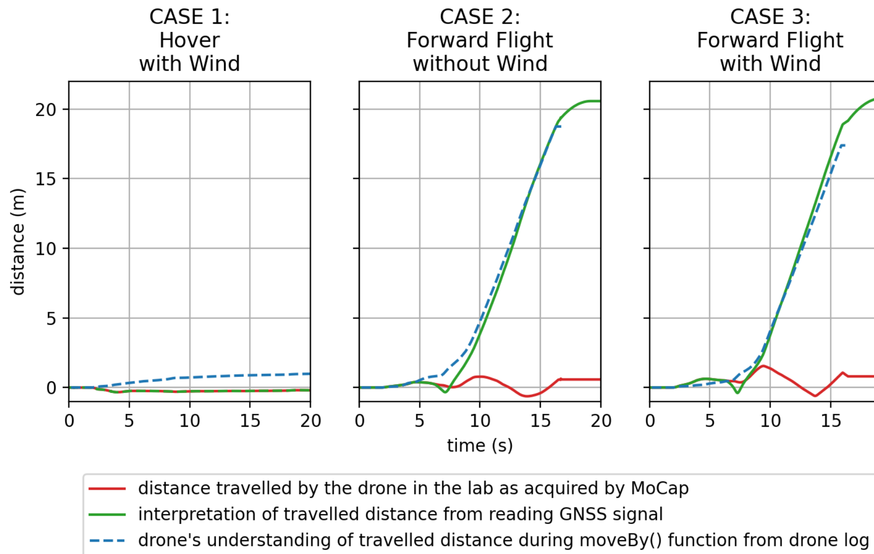


**Fig. 7 Comparison, for each of the three laboratory flight tests, between the drone's actual travelled distance as acquired by the MoCap; the GNSS signal simulating the travelled distance; and the interpretation of the travelled distance by the drone, which is extracted directly from the flight logs.**

steady wind or wind gusts.

To accomplish this, a testing environment comprised of a wind generator (windshaper), motion tracking camera system and GNSS generator has been assembled. By coordinating the windshaper, the GNSS signal and Motion Capture camera feedback with the drone's mission profile, we demonstrated that we can re-create outdoor flight conditions in the lab.

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 all tests, we demonstrated that by using indoor GNSS signal simulation and wind generation, the drone displayed the characteristics of a 20 m move forward, while actually staying stationary in the wind tunnel, within $\pm 1$ 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.

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.

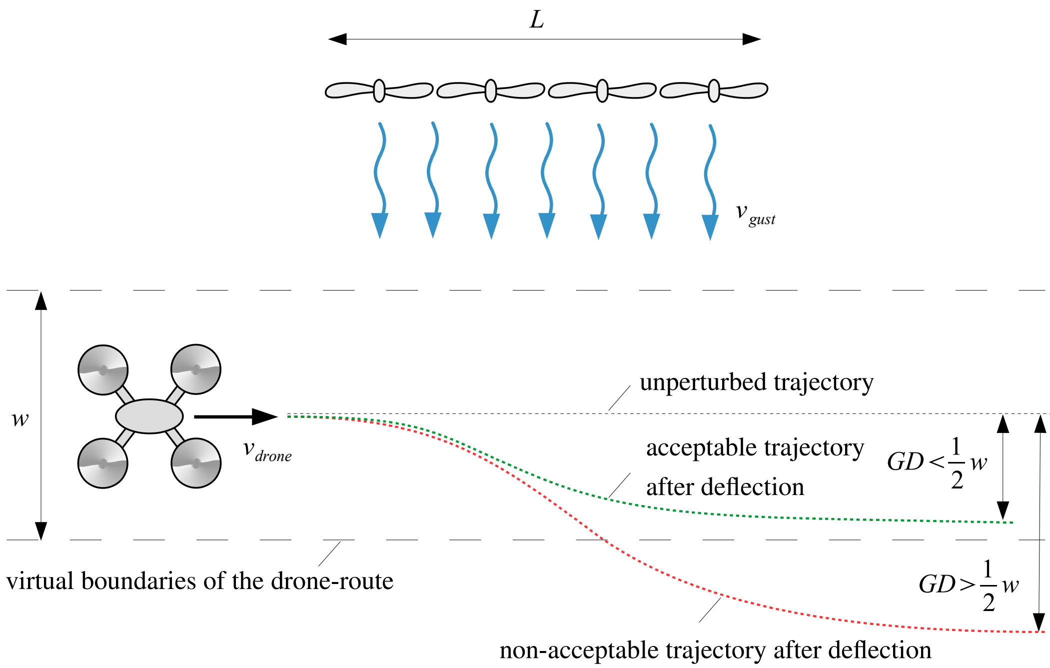


**Fig. 8 The ability of a drone to reject a lateral perturbation can be tested by confronting a forward flying drone to a strong lateral wind.**

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.

# References


[1] Noca, F., Catry, G., Bosson, N., Bardazzi, L., Marquez, S., and Gros, A., "Wind and weather facility for testing free-flying drones," *AIAA Aviation 2019 Forum*, 2019, p. 2861.

[2] Parrot, "Anafi White Paper," , 2020. URL `https://www.parrot.com/assets/s3fs-public/2020-07/white-paper_anafi-v1.4-en.pdf`.

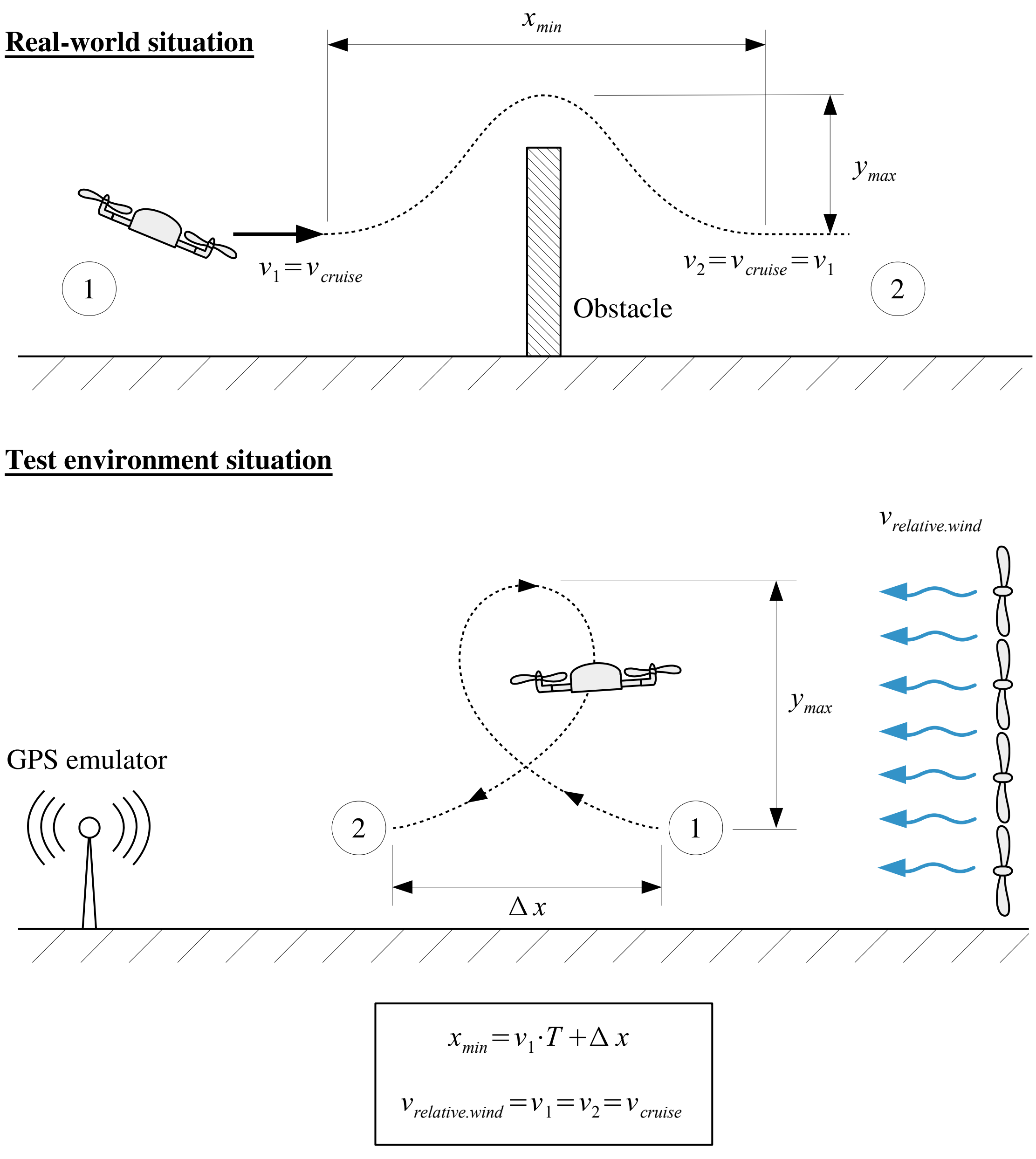


**Fig. 9 Reproduction of a real-world obstacle avoidance scenario in a test environment: the drone feels identical aerodynamic and inertial forces, and receives the same positioning signal.**