Flight Test Design for Remotely-Piloted Aircraft in Confined Airspace

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ABSTRACT

This paper presents various techniques and procedures that aim to simplify flight testing of fixed-wing, remotely-piloted aircraft with the purposes of performance evaluation and system identification. These methods have been specifically developed for flight within visual line-of-sight, a type of operation that limits the available airspace severely but offers major cost advantages considering the current regulations for unmanned flight in most Western countries.

KEYWORDS: *flight testing, visual line-of-sight, UAS, data acquisition, flight dynamics*

1 INTRODUCTION

According to the current regulatory frameworks for unmanned aircraft systems (UAS) in most European countries, there is in most cases a considerable economic and logistical step between certified operations within visual line-of-sight (VLOS) and beyond visual line-of-sight (BVLOS). Low-cost equipment for BVLOS operations is nowadays available in the market and it is often used even by hobbyists for recreational purposes according to model flying regulations. However, for certified commercial or research operations of remotely-piloted aircraft (RPA), most aviation authorities still require the use of a segregated airspace. The cost of such airspace plus the eventual certification of the relevant aircraft systems often motivates the choice of a much more affordable VLOS certification.

Flight testing fixed-wing RPA in general, and under VLOS rules in particular, requires different approaches than those traditionally followed by manned aircraft. The reduced testing time, the need for constant manoeuvring and the difficulty of executing precise excitation manoeuvres are just some of the factors that complicate the process severely.

1.1 Typical Regulatory Scenario

At this time there is no international or European standard regulating the operations of civil UAS, although work in this direction is progressing quickly [1]. According to the European Aviation Safety Agency (EASA), the regulation of UAS with a maximum take-off mass (MTOM) of less than 150 kg currently falls within the competence of each state. However, for the kind of operations and limitations that concern this paper, there seems to be a comparable framework within most Western countries. In this case, the current Swedish regulation of civil UAS [2] is taken as reference.

Conforming to this regulation, any civil UAS operation that is not carried out solely for recreational purposes needs a platform-specific authorization and a different set of safety elements in consonance with the corresponding category. There are currently four different categories which take into account both the proximity of operation (VLOS or BVLOS) and system characteristics such as mass and maximum kinetic energy. Fig. 1 shows qualitatively the tremendous operating cost increase associated with BVLOS operations, mainly caused by two safety factors: the requirement of some sort of type certification, and the necessity of booking a segregated airspace. The significant cost difference often motivates the choice of VLOS operation, at least during the phases of development and flight testing.

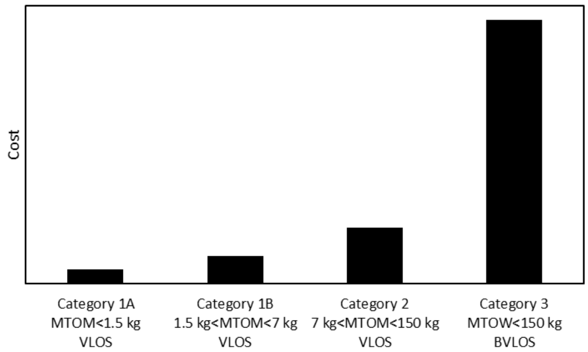

Figure 1: Qualitative comparison of operating cost between the four civil UAS categories according to the current Swedish regulation. The description of the categories has been simplified and the cost figures are based on estimations.

1.2 Purposes of Flight Testing RPA

As usual in manned aircraft, flight testing is an unavoidable stage of UAS development. Besides a qualitative assessment of the flying qualities, quantitative measurements are possible by means of sensor data acquisition and processing. Flight tests can be designed to evaluate the performance of the platform and its systems, but also to obtain its flight-mechanical characteristics through system identification. This information is critical to validate or to improve simulation models and flight control systems. Testing autonomous navigation and communication systems is in many cases only relevant during flight BVLOS. Autonomous flight is therefore disregarded here since no real advantage can be expected from testing these within VLOS.

There is also an increasing use of remotely-piloted subscale demonstrators for research and development; see reference [3] for a good overview. This method, often referred to as *subscale flight testing*, is based on studying the performance and dynamics of a scaled model in order to increase the knowledge and confidence over an eventual full-scale design. The final purpose of the platform is, therefore, the flight testing itself. As a complementary design tool, the short development time and cost savings associated with VLOS operation become even more relevant. However, flight testing in a very confined airspace can become challenging when the test objects are heavy and large dynamically-scaled models such as in [4], [5] and [6]. The latter, shown in Fig. 2, is with 20 kg of MTOM one of the heaviest fixed-wing platforms used for research at Linköping University. Its high flying speed makes it a challenging case for flight testing within VLOS, and therefore it is used as an application example throughout this paper.

Figure 2: The *GFF* demonstrator: a 2-meter, jet-powered platform used for research at Linköping University [6].

2 METHODOLOGY

The ideas, techniques or procedures proposed here do not originate from a particular methodology. Some of them have been adapted from existing "full-scale" industry practices and more traditional techniques found in the literature. Others are based on the authors' experience in UAS operation or inspired by radio-controlled model flying techniques. However, the ideas presented here have proven, in the authors' opinion, to be of practical use for this kind of flight testing using different platforms. All these techniques have been either systematically evaluated through experimentation, or are currently being tested and refined.

3 FINDINGS

For the sake of clarity, the results are grouped and discussed into separated topics.

3.1 Essential Flight Test Instrumentation

In the case that the test object is a platform designed for autonomous or semi-autonomous flight, measurements can be acquired directly from the installed sensors and/or existing flight controller. If the platform is not aimed towards autonomous flight, it has to be equipped with an additional data acquisition system. Low-cost data acquisition systems are nowadays able to provide reliable flight data thanks to relatively advanced sensor-fusion and flight path reconstruction algorithms, some of which are included even in open-source distributions such as [7]. In fact, algorithms used in open-source autopilot projects can be sometimes useful for data acquisition during tests within VLOS since they are already well tuned for small platforms with very fast dynamics and turbulent environments. See reference [8] for a previous development at Linköping University.

An accurate GPS (or equivalent) positioning system is strongly recommended for flight tests within VLOS. This kind of flight involves constant manoeuvring and quick changes of trajectory and speed. Precise position measurements at a rate of at least 5 Hz facilitate considerably flight path reconstruction. GPS augmentation methods such as Real Time Kinematic (RTK) systems are ideal for this purpose.

In addition, the authors recommend to include flow angle transducers in the data acquisition system. Although there are relatively accurate flow-angle estimation techniques such as [9], it has been observed that direct measurements of the flow properties ease and improve considerably the data analysis, especially in the case of the highly-dynamic flight testing within VLOS. The *Insituto Tecnológico de Aeronáutica* has experience with 5-hole pressure probes, while Linköping University typically uses custom-made flow angle vanes such as in [6], Fig. 3.

Another consideration is to provide means to increase the awareness of the actual aircraft airspeed to the pilot. Initial (or entrance) airspeed is often an important parameter that has to be set appropriately before each manoeuvre execution. This can be sometimes difficult to assess by a remote pilot due to the lack of visual clues and the energy losses during the tight turns. To avoid loss of visual contact with the platform, the most straightforward solution is to read out loud the incoming airspeed values from the ground station. The authors are also testing a new system that transforms airspeed values received via telemetry into beeping sounds of variable pitch, in a similar way to the electronic variometers typically found in gliders.

Regarding communication links between air and ground, these can be kept uncomplicated since the platform is continuously within VLOS: high-power transmitters or tracking antennas are usually not needed. Again, this is a significant advantage in terms of cost and simplicity.

Figure 3: Direct measurement of the flow conditions improves significantly the flight reconstruction. Image shows a custom-made airdata nose-boom with alpha and beta transducers installed on the *GFF* platform.

3.2 Flight Test Crew

In some cases, the minimum personnel and roles to be covered are specified by the respective regulation. Besides this, the minimum crew required is often determined by the platform characteristics and specific logistical needs. However, even with the smallest and simplest of the platforms, the authors have identified that to carry out a flight test in VLOS it is needed an absolute minimum of three people: test conductor, pilot, and safety manager. An additional ground station operator must be added in the case that this exists. Although the chain of persons carrying out the test should be kept as straightforward and direct as possible, additional crew members can facilitate significantly tasks like test documentation and surveillance of the test area.

3.3 Facilities

Since no segregated airspace is required, flight testing within VLOS can take place in a much broader range of airfields and suitable areas. Model-flying clubs are often a convenient and affordable choice. Ultimately, the characteristics of the platform and team logistics will determine the most appropriate option. However, the local regulation might set specific guidelines or eventual restrictions, as it will be discussed later in 3.5.

3.4 Flight Test Planning

Although for organizations used to operating larger platforms or familiarised with aircraft certification this point could seem obvious, the authors would like to mention the importance of defining a precise flight test plan with specific step-by-step instructions. This practice is often forgotten to some extent during test campaigns with small platforms mainly due to the very low cost-per-flight-hour. However, it remains as one of the easiest and most effective ways of improving the efficacy, safety, and documentation of flight tests, especially with hard constraints in airspace and time frame.

In a nutshell, the authors recommend the following procedure: according to the project's general flight test programme (if this exists) or logistical considerations, it usually possible to define a feasible number of flights per session. Once the available test-time per flight is known or estimated, the intended manoeuvres have to be translated into individual test points or "positions". For each flight, it is convenient to write down the sequence of test points in a one-page document, together with other relevant information such as aircraft configuration and desired flight conditions. The order of the test points must be chosen carefully to balance the flight, save time, and account for eventual variable factors such as fuel weight. Finally, a flight test card containing all the relevant information has to be prepared for each one of the test points, as the example shown in Fig. 4. Experience has shown that it is convenient to prepare also alternative "b" test sequences in case that necessary parts of a previous sequence cannot be completed.

Standardised flight test cards streamline considerably the communication between the pilot and the test conductor. During the flight, the test conductor reads out the respective test card to the pilot, mentioning clearly the desired initial conditions at the beginning of the manoeuvre. In this way, mistakes are minimised and the pilot does not lose visual contact with the aircraft at any time. In addition, the test conductor can write down on the test card any eventual observation that needs to be documented.

These procedures are nevertheless very similar to traditional practices used in "full-scale" flight testing. See for example references [10] and [11] for more ideas and further information.

Position 1	**Altitude** 100 m	**Speed** 40 m/s	**Header** ...	**Config.** ...	**Fuel** 50 %	**Test type** Sys. Identification
Manoeuvre description Relevant configuration ...				Notes ...		

Figure 4: Example of a generic flight test card.

3.5 Management of the Available Airspace

The airspace available in flight within VLOS is extremely limited. While the maximum allowed distance between the aircraft and the pilot is ultimately determined by the definition of VLOS, the most common presumption is 500 meters. The maximum allowed flight altitude is usually 120 meters above ground level (AGL), although this might vary according to local airspace rules or eventual temporary clearances by the air traffic control services. These results in a cylindrical airspace of very limited dimensions, in which is often difficult to deal with fast-flying platforms with high wing-loadings such as the mentioned GFF demonstrator. Another important disadvantage is that the flight takes place close to the ground, i.e. in the most turbulent atmospheric layer. Hence, flight within VLOS often requires calm wind conditions for successful test results.

According to the regulations, this airspace cannot cover any populated area at the time of the test. Consequently, the ground covered by this airspace – plus a defined safety margin – must be kept free of any persons outside the test crew. The responsibility of keeping this area clear lies on the safety manager. Since it could be difficult to monitor the entire area, the authors recommend using only half of the cylindrical airspace, as it is usually done in model flying clubs. This decision should be agreed during the pre-flight planning according to practical criteria such as visibility, sun position, and wind direction.

Once the testing team location and active runway have been decided, it is important to agree on visual references for external the safety area, the intended manoeuvring area, and the test window. For the latter, the runway itself is often a convenient reference. Fig. 5 shows these areas over the trajectory of a flight test in VLOS performed with the *GFF* demonstrator.

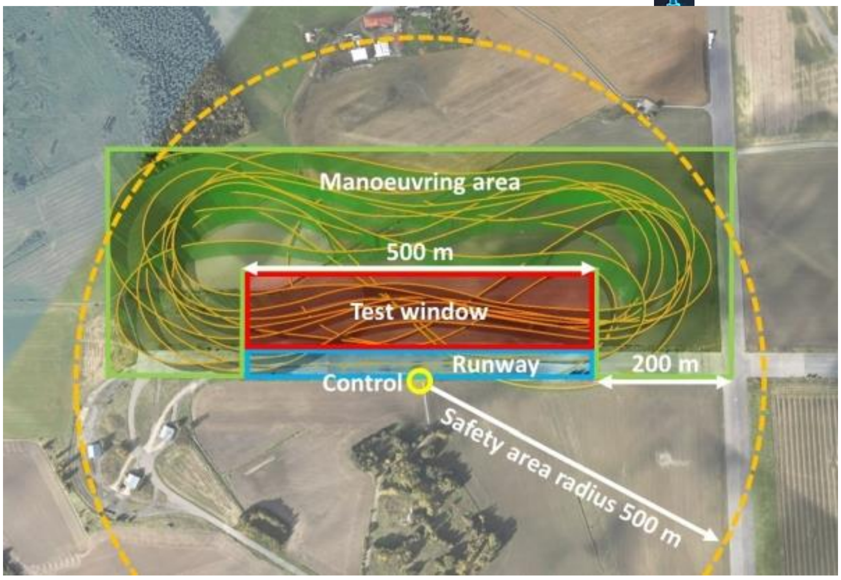

Figure 5: Trajectory followed during a real flight test under VLOS rules carried out with the *GFF* platform. The coloured polygons help to visualize the precise management of the very limited airspace.

3.6 Automation of the Excitation Manoeuvres

Probably the most significant contribution of this work is a novel method for commanding pre-programmed excitation manoeuvres automatically, without the need of any closed-loop flight controller or any ground station. This means that only a minimum equipment – a radio control system and a data logger – is needed to take full advantage of precisely-executed input signals on any of the control surfaces. On one hand, this benefits the smallest, low-cost platforms by saving further costs and simplifying their development. On the other, it allows more complex platforms to perform automated flight test manoeuvres even before the automatic flight control system is correctly tuned.

In fact, it is possible to program full sequences of test points covering the entire flight test plan. As a result, the pilot can focus on the challenging task of flying the aircraft through the manoeuvring area and entering the test window at the required speed, altitude and attitude.
This "magic" is possible thank to the latest software developments in computerized radio-control transmitters: motivated by the hobby market demands, some manufacturers have equipped their transmitters with the possibility of interpreting and executing custom scripts written in *Lua* programming language [12]. Although these scripts are mainly used by the public to visualize in sophisticated ways information from the sensors on board the model aircraft, the authors explored the possibilities of using them to actuate the controls following complex signals.

The result is a *Lua* application that allows the testing team to assemble easily an entire sequence of testing points, both using a computer or directly on the transmitter screen. The application uses an external library of input signals that can be updated independently at any moment. Both analytically-described functions and discrete point-defined signals can be loaded. During the flight, the pilot selects the corresponding test point and triggers the manoeuvre by flipping a switch. The corresponding signals will be then executed on the intended control surfaces according to the specified timing and recurrence. An information window can also be displayed on the transmitter's main screen, showing the test point status and any eventual errors, Fig. 6. In addition, audible signals and commands are played out through the transmitter's speakers so the pilot does not need to lose visual contact with the aircraft.

Several safety measures have been incorporated during the development of the application in order to avoid any sort of malfunction to affect the platform. Ultimately, the pilot can always regain manual control of the aircraft at any time by releasing the trigger switch.

Due to hardware limitations, the signals can be transmitted at a maximum frequency of 50 Hz at the moment. However, this is the same order of magnitude than the typical refresh rate of the radio-control link (from 50 Hz to 100 Hz) and the servo-actuators (about 50 Hz).

This application is still under continuous development at Linköping University, but so far it has been tested on real flight tests with excellent results. Ideally, the authors would recommend configuring the application settings during the development of the flight test plan. This specific copy of the code can be kept as part of the electronic documentation of each flight.

Figure 6: Information window of the custom *Lua* application for flight test, displaying the automatic execution of a test point. The screenshots are extracted from the main screen of the pilot's transmitter, in this case a *Jeti Model* DC-24 [13].

3.7 Use of Highly Efficient Input Signals

The following Fig. 7 shows the maximum time that an aircraft remains in a 500 m test window in straight flight. Manoeuvres with very long exposure time, such as the measure of the phugoid motion, are usually not possible under VLOS rules. On the contrary, given the reduced dimensions of the test window, the manoeuvres need to produce as much information as possible in a very short time.

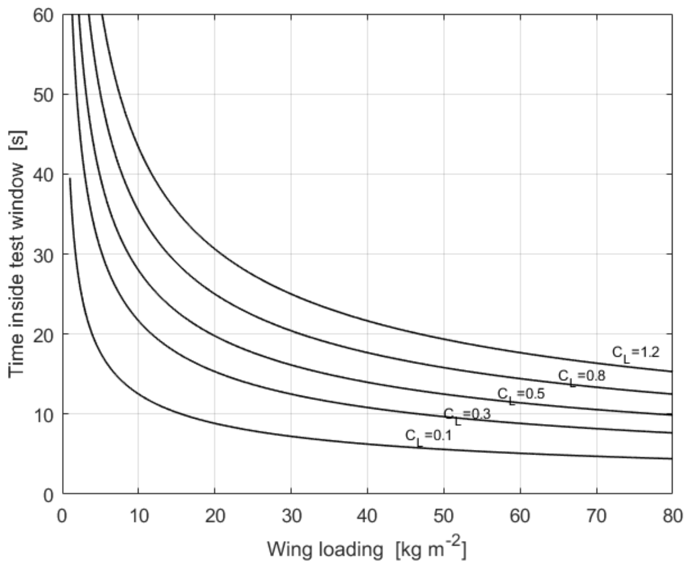

Figure 7: Estimated time to cross a 500 m test window in straight flight.

Focusing on flight testing for system identification, it is beneficial to optimize the excitation inputs from the beginning. An estimation of the expected responses should be obtained from previous flights or from analytical analysis as in [14]. It is also important to further optimize the excitation inputs as soon as new estimations are available.

In fact, there are many different theories on efficient inputs for system identification in the literature. Although these are usually designed for manned aircraft, in most cases it is possible to adapt the techniques to smaller RPA by scaling the dynamic responses accordingly. So far the authors have obtained successful results in the time domain using somewhat-conventional manoeuvres such as pulses, doublets, and "3211" [14]. In the frequency domain, promising experiments are being performed following literature like [15] and [16]. These include inputs such as frequency sweeps along a wide frequency band.

The authors have also started to experiment with novel techniques for optimal input design, multi-sine signals, and simultaneous excitations. As an example, reference [17] describes the procedure to generate orthogonal optimised multi-sine inputs that combine the time efficiency of multi-axis excitation with optimised (minimum) input amplitudes, wideband frequency content, and multiple-input orthogonality in both the time domain and the frequency domain. Even though these techniques are mainly aimed towards shortening the costly flight-test of manned platforms, they could also become a good solution for highly-condensed flight testing within VLOS. However, at the time of writing this paper, it is still too early to offer solid results.

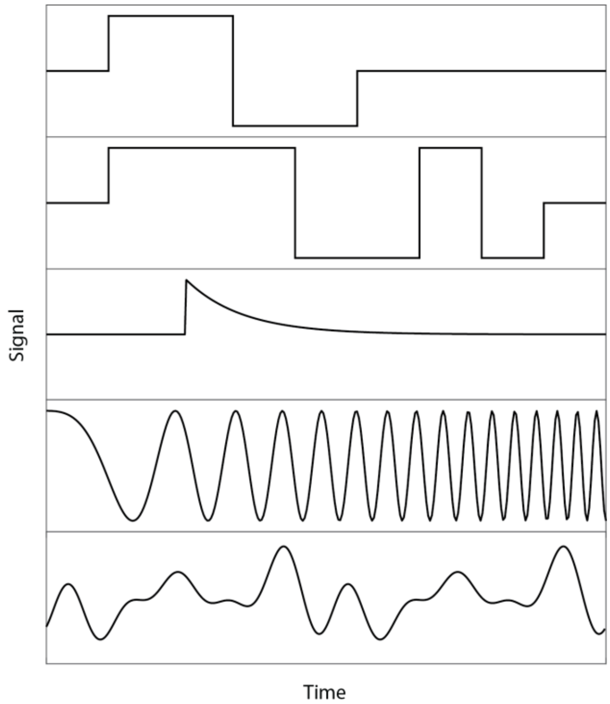

Figure 8: Various input signals generated directly by the radio transmitter using the *Lua* flight test application. From top to bottom: doublet, 3211, pulse with exponential decay, sinusoidal frequency sweep, and random-phase multi-sine.

3.8 Immediate Data Analysis and Feedback

Although this point is shared with any other kind of flight testing, increasing the awareness of the measurements' quality is a key factor for successful results. Ideally, the assessment of the incoming flight data quality and even the estimated aircraft parameters should be done in real time. This would allow, for example, taking corrective measures during flight and saving a significant amount of testing time [18]. Due to the usually-short duration of flights within VLOS and their relatively low cost-per-flight-hour, this does not seem a critical factor here. However, in the author's opinion, it is extremely useful to have the necessary resources to be able to download and analyse the logged data briefly at least between each flight. This provision has proven very useful preventing hardware failures, configuration mistakes, and unnecessary repetitions.

In the case of Linköping University, relevant parameters and system health are usually monitored in real time from a simple ground station: a light laptop running a modified version of the open-source software Mission Planner [19], linked with the platform through a variable-rate telemetry connection. In addition, a set of MATLAB scripts denominated ALAN have been developed in order to analyse, display, and export the flight data within seconds after the platform is shut-down. Nevertheless, both methods continue under constant development and evaluation.

4 CONCLUSIONS

The paper presents some of the most relevant "lessons learnt" from the authors' experience flight testing multiple platforms under the challenging VLOS rules.

Ideas for an efficient planning and execution are given. Specific equipment and procedures are recommended in order to improve the test efficacy and data collection. The authors also present a novel method for commanding automatically complex excitation manoeuvres directly from the radio-control transmitter, i.e. without the need of a closed-loop flight controller. The benefits of platform-specific, optimized excitation manoeuvres are briefly discussed.

In general, these recommendations are useful for economical flight testing of subscale demonstrators for research purposes, as well as for the evaluation and development of UAS under safe conditions. Some of the proposed methods, such as the remote manoeuvre automation, are also suitable for other types of flight testing BVLOS.

In conclusion, flight testing RPA within VLOS entails additional complications over conventional operations. The need for constant manoeuvring and the reduced testing time can become challenging limitations, especially with heavier platforms. However, there is a clear economic benefit that can motivate this choice. The authors continue working towards improving these and other techniques aiming to simplify this process.

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