ICAS 2020 SHANGHAI
International Council of the Aeronautical Sciences
32nd Congress of the International Council of the Aeronautical Sciences
September 6-10, 2021
Pudong Shangri-La, Shanghai, China

FLIGHT TESTING OF 65KG T-FLEX SUBSCALE DEMONSTRATOR

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Abstract

FLEXOP is a project within the European Union's Horizon 2020 framework which develops methods for aeroelastic wing tailoring and active flutter suppression. The developed methods are integrated within a subscale flight demonstrator named T-FLEX. The demonstrator is a 65kg take-off weight, 7m wingspan unmanned aircraft with a V-Tail and is powered by a jet engine. T-FLEX is also used by the follow-up project, FLiPASED. The paper describes the flight test environment of the demonstrator by providing insight into the setup of the aircraft, its systems and flight surroundings. Special effort is made to explain the operational procedures and preparations required to safely perform the flight tests.

Keywords: Flight Testing, Subscale Demonstrator, UAV, FLEXOP, FLiPASED, T-FLEX

1. Introduction

Downscaled physical models of larger full-scale aircraft (also known as free-flight subscale demonstrators) are becoming increasingly popular for testing new aviation technologies [1, 2, 3]. In relation to manned aviation they have lower operating costs and lower risks [4]. Additionally, the tools currently used in aircraft design are capable of scaling-up the results from subscale demonstrator flights. Therefore, such subscale tests allow to better estimate the efficiency of applying a new technology on a full-scale aircraft without paying the full price of its implementation.

But subscale flight testing does pose challenges of its own. Much of the hands-on knowledge comes from hobby radio-controlled model flying communities where guidelines for design, piloting techniques or equipment-related topics are discussed. However, other aspects required by the scientific community like flight testing techniques, operational procedures for complex models or data analysis workflows are still not sufficiently documented [5]. In this paper we contribute to this research gap by sharing our lessons learned while performing flights tests with a complex 65kg demonstrator T-FLEX, built and used within the projects FLEXOP (Flutter Free FLight Envelope eXpansion for ecOnomic Performance improvement)[6] and FLiPASED (Flight Phase Adaptive Aero-Servo-Elastic Aircraft Design Methods)[7].

FLEXOP was a project within the European Union's Horizon 2020 framework covering the topics of wing aeroelastic tailoring and active flutter suppression (AFS). Launched in 2015, its goals were to develop new advanced methodologies for wing design, modelling of the AFS systems, integrating the developed methods within a subscale flight demonstrator (figure 1) and finally evaluating the real-life potential of the technologies in a scale-up study. FLiPASED, the follow-up project, was launched in 2019 and uses the T-FLEX demonstrator for its purpose.

So far the 65kg, 7m wingspan T-FLEX demonstrator is the biggest air vehicle that was built and tested by the Institute of Aircraft Design at Technical University of Munich (TUM). Even though most of the project team were already familiar with flight testing (either for smaller models or for sailplanes), working with a demonstrator of this complexity and size raised challenges that were not anticipated during the design phase. The implications of these challenges were only realised after the initial flight test campaign. It was agreed that some of these challenges could have been avoided if tackled during the design phase. Therefore, the goal of the current work is to share the methodology and operations

Figure 1 – FLEXOP Subscale flight demonstrator during landing (F. Vogl/TUM).

for flight testing a subscale demonstrator of such size. This should allow the readers to gain more insight of what could be expected when dealing with subscale demonstrator flight test programmes. The paper is structured into 3 main sections: demonstrator description (section 2.), operational procedures of flight-testing (section 3.) and some of the lessons learned (section 4.). Main points are again summarised in a conclusion (section 5.).

2. Demonstrator Environment and Setup

The following subsections describe the demonstrator design, its systems, flight and legal environment and the ground control station.

2.1 Demonstrator Design

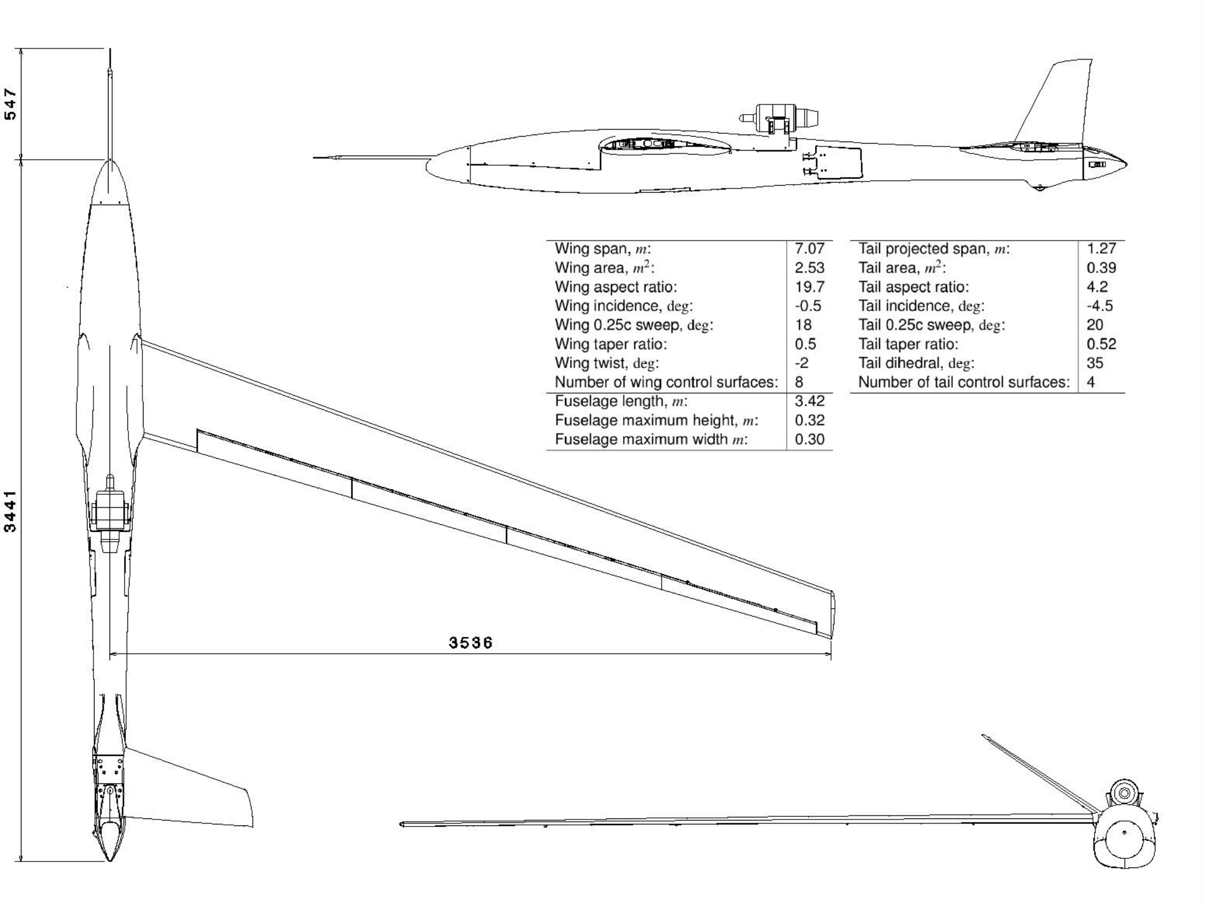
The two goals of the FLEXOP project- aeroelastic tailoring and active flutter suppression- presented very different requirements for flight tests. Testing of the aeroelastic tailoring would require high load factors on the wings and were not expected to pose any operational challenges. On the other hand, flutter testing demands high airspeeds and, therefore, big areas for manoeuvring (acceleration, deceleration, high-speed turns). Additional requirements were placed by the scale-down task (geometry similar to a new generation commercial airliner), sensors required for the measurements (minimum 2kg of payload capacity) and limitations due to logistics (maximum part size of the unrigged aircraft should not exceed 4m).

Based on these requirements a flight test mission was designed and, including the UAV design experience of TUM, a preliminary design of the demonstrator was done. This resulted in a 65kg take-off weight (TOW) demonstrator with a swept, 7m span wing and a V-Tail. The demonstrator received three pairs of wings: the rigid wing for setting the baseline (designated as -0), the wing with active flutter control (-1) and the aeroelastically tailored wing (-2). Risk alleviation by system redundancy was incorporated for aircraft controls. The concept required symmetrical control of the aircraft even if one of the batteries powering the aircraft control surfaces would lose voltage. This requirement resulted in 8 wing flaps (4 per wing) and 4 ruddervators (2 per V-Tail). Additionally as a last measure to protect the infrastructure, parachute with was integrated.

Main characteristics of the demonstrator can be found in figure 2. References are provided for demonstrator aeroservoelastic design([8, 9, 10, 11]), mission design ([12]) and flutter controller design ([13, 14]).

2.2 Ground Testing of the Demonstrator

As a prerequisite for flight-tests, ground tests were performed on the demonstrator. These started with electro-magnetic compatibility testing on a wooden mock-up, followed by static load tests. Static



Wing span, m:	7.07	Tail projected span, m:	1.27
Wing area, m^2:	2.53	Tail area, m^2:	0.39
Wing aspect ratio:	19.7	Tail aspect ratio:	4.2
Wing incidence, deg:	-0.5	Tail incidence, deg:	-4.5
Wing 0.25c sweep, deg:	18	Tail 0.25c sweep, deg:	20
Wing taper ratio:	0.5	Tail taper ratio:	0.52
Wing twist, deg:	-2	Tail dihedral, deg:	35
Number of wing control surfaces:	8	Number of tail control surfaces:	4
Fuselage length, m:	3.42		
Fuselage maximum height, m:	0.32		
Fuselage maximum width m:	0.30		

Figure 2 – T-FLEX Subscale flight demonstrator. Note that the left wing and V-tail are excluded.

load tests were performed for wings only and with two goals in mind: test the maximum operational loads and calibrate the structural model. Ground vibration testing was done at Institute of Aeroelasticity, German Aerospace Centre (DLR), Germany. In parallel, flight control computer was tested within a hardware-in-the-loop simulator at SZTAKI. Most of the operation-related systems (ground control station equipment, intercom and flight management software) were tested in various other projects before being implemented on T-FLEX [15, 16].

More information about the ground testing of the demonstrator can be found in [17].

2.3 Flight and Legal Environment

Early in the design process it was decided that the demonstrator will be flown within Germany. Consequently more requirements on the demonstrator specifications and operations were added as national laws concerning unmanned aerial vehicles applied. For any UAV heavier than 25kg a special permit would need to be requested by a competent authority [18]. Additionally, the aircraft would have to be flown within Visual Line of Sight (VLOS) and in a closed airspace.

An extensive operation risk assessment was done as a first preparation step for flight testing the demonstrator. The assessment was based on guidelines as described by Joint Authorities for Rulemaking of Unmanned Systems (JARUS) [19, 20]. Additional publications regarding the risk assessment for UAVs proved to be useful [21, 22]. Further on, identified risks were taken as a basis for emergency case and procedure planning. Each risk case received a procedure for identifying it and how it should be handled in flight. One of the four emergency procedures was assigned in this case: control takeover, expedited landing, emergency landing (not on the runway), immediate chute release.

All flight test activities took place at Special Airport Oberpfaffenhofen (EDMO) which has a 2286m long concrete runway that is 45m wide. Located around 20km southwest of Munich, Germany, EDMO is considerably more convenient to reach from TUM than any other airport. The airport is a host to

Flight Experiments department of DLR and also has a CTR surrounding it (CTR Oberpfaffenhofen) which allows the airport to maintain the required separation in between manned and unmanned flights. A 30 minute long window would usually be issued by EDMO during which the demonstrator flights can take place within a specified flight-box (figure 3). During the test flight the demonstrator is required to land and leave the runway area within 3 minutes. Note that the pilots have no visual cues for the flight box, therefore they would have to be guided by the Flight Test Operator (section 3.1.3) from within the Ground Control Station (GCS).

After the first phase of demonstrator testing the guidelines for acceptable weather were set. This resulted in maximum wind of 7m/s. Minimum temperature of 5deg Celsius was set, as below that using the transmitter for the pilots becomes uncomfortable. Dry runway would be required for all operations. It was also noted that summer flights in the morning would result in bad visibility conditions due to the position of the sun, as the pilots were always facing south-east.

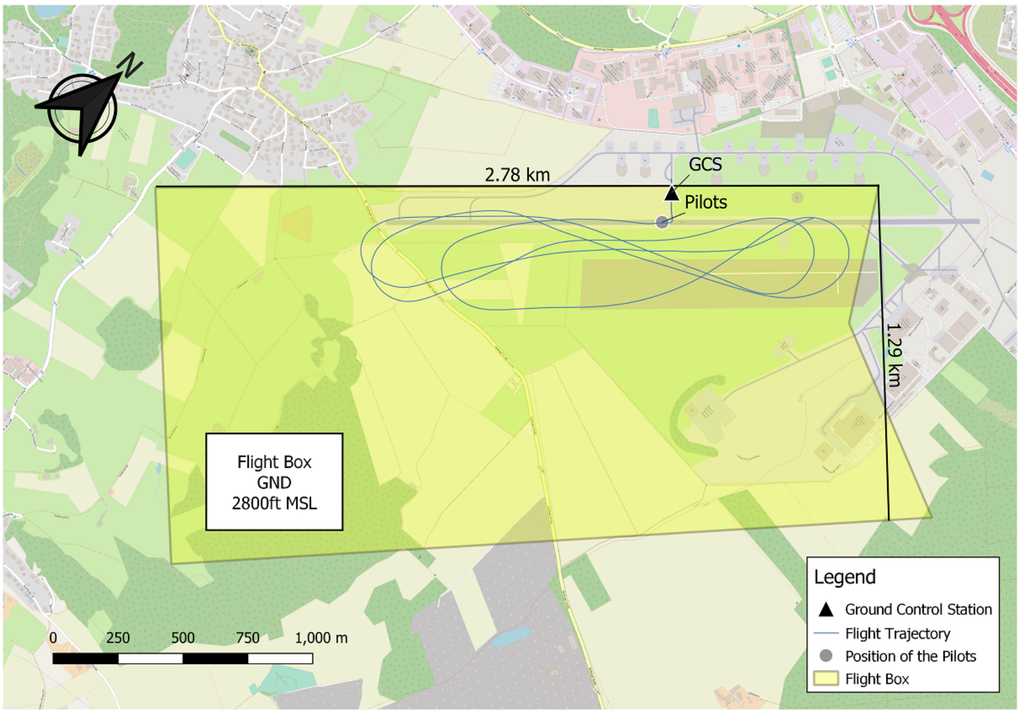


Figure 3 – Allowed airspace for testing at EDMO airport.

2.4 Installed Sensors and Systems

2.4.1 Control Systems

The demonstrator is mostly flown manually by pilot via external vision. Rate control flight mode is used, where in manual mode the surface deflections are directly linked to the joystick positions on the transmitter.

The aircraft has two control links. Control via two different transmitter brands was desired to decrease the risk of both transmitters failing together due to the same issue (either connectivity, electrical or mechanical). The main one is a Jeti DS-24 system which has an additional back-up receiver that is integrated further away from all the other radio links. The secondary, controlled by the backup pilot, is a Graupner mc-28 system. Graupner has only one receiver with four antennas that are pointed in different directions. In comparison, Jeti receivers have only two antennas.

Control signals inside the aircraft are distributed via a custom built Flight Control Computer (FCC) developed by the Institute for Computer Science and Control in Hungary (SZTAKI). The autopilot is used only during some test sequences, but never during take-off or landing.

2.4.2 Propulsion System

The main requirements while designing the propulsion system were high acceleration, low vibration and precise speed tracking [23]. Taking these requirements into account, a jet engine paired with a fast-response airbrake system [24] was selected. The jet engine is a BF B300F turbine with 300N maximum thrust capability [25]. The engine was mounted on a pylon above the fuselage with the fuel tank located directly below it. This was designed with the intent to keep the same centre of gravity throughout the flight.

2.4.3 Telemetry Links

There are three telemetry systems installed within the aircraft: the Unilog link, the Micro Air Vehicle link (MAVLink [26]) and the Engineering Data Link (EDL).

The main purpose of the Unilog link is to have the secondary airspeed reading transmitted directly to the pilot in case the main telemetry link (or the intercom) breaks down.

MAVLink sends telemetry data that can be displayed via the Mission Planner software [27]. The software has been customised to allow autopilot control from the GCS. The Mission Planner software is used by the Operator.

The parameters available via MAVLink connection are:

1. Position coordinates
2. Attitude angles
3. Angle of attack and sideslip
4. Pressure altitude
5. GPS (ground) velocity and indicated airspeed
6. Distance from the GCS

Engineering Data Link (EDL) is used for receiving the measurements mostly related to aircraft's health and status. It transmits data from the Engine Control Unit (ECU), Servo Health Monitoring (SHM) units or status information of internal FCC modules. The data is displayed via a custom-made software built upon the MATLAB [28] GUI Toolbox.

The parameters always visible via the EDL are:

1. Position differences to the reference signals and temperatures of 8 wing, 4 tail and 2 airbrake servo motors
2. Airspeed and load factor of the aircraft
3. Battery voltages
4. Actual and command RPM values for the engine control
5. Remaining fuel
6. Engine temperature
7. Autopilot and flight control module status flags

2.4.4 Other Systems

A 5-hole air-data probe provides the measurements of aerodynamic angles and airspeeds, as well as static and total pressures. The measurements are captured within the Micro Air-Data Computer manufactured by Aeroprobe. The probe is mounted on a boom 55cm in front of the demonstrator nose. The boom length was determined using the airflow data received from the Computational Fluid Dynamics (CFD) simulations. During the simulations, airspeed and flow angle values were compared at different distances away from the nose. The distance which resulted in local flow values within 1 percent of the free-stream values was chosen.

A secondary airspeed reading is measured by a low-cost air-data probe mounted on the right V-Tail of the aircraft. To make sure that the readings on the secondary air-data probe are satisfactory for backup operation, the calibration of the probe was checked in the wind tunnel. Furthermore, the airspeed measurements in between the two probes were compared during the first flight of the demonstrator. Good correlation of both measurements gave confidence that even in the case when the main airspeed sensor is lost, a reliable backup would be available.

The position and attitude of the aircraft is measured by a high-precision Inertial Measurement Unit (IMU) MTi 710 manufactured by xSens. Additionally, multiple IMU units were installed in the wings for capturing structural acceleration data during flutter testing. Additionally, fiber Bragg grating (FBG) system was installed in the wings for accurate deflection measurements [17].

A parachute system, comprising of a drag chute and the main chute, is installed in the aircraft (manufactured by skygraphics AG). In case the chute release is triggered, the magnet, holding the tail cone, is released. The tail cone is then pushed away by the incoming airflow. It has the drag chute attached to it, which, consequently pulls the main parachute out.

Two small cameras (Mobius 1080p HD Action Camera) are integrated within the tail cone. The cameras were placed in a way to overview both wings in-flight and provide visual feedback after test runs. They were not accessible online and would only be used for offline evaluation.

Interior layout of the systems is displayed in figure 4.

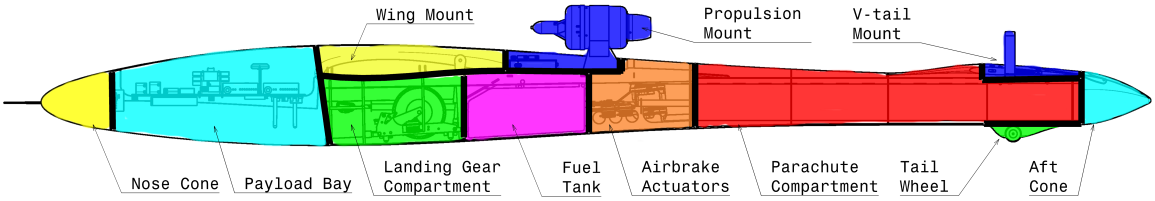


Figure 4 – Interior layout inside the T-FLEX demonstrator.

2.5 Ground Control Station

The Ground Control Station (GCS) is a Mercedes-Benz Sprinter outfitted with storage, tools and workspace specific for flight-testing. It houses mounting for external antenna mast for each of telemetry links and the intercom system. There are two seated workplaces inside with four permanently installed screens (figure 5). It has a separate power supply that can be charged either from the engine or via external power line.

3. Operational Aspects

The operations for T-FLEX flight tests were designed building upon two things: checklists and training. Every part of the operations was put into a checklist or an algorithm. This was necessary in order to handle the complex demonstrator and organise the 5-people flight test crew together. It resulted in 7 separate steps performed in the following order:

1. Flight Preparation
2. Assembly
3. Pre-Flight Briefing
4. Systems Check and Start-Up
5. Flight Test
6. Shutdown
7. Post-Flight Briefing

Figure 5 – Ground Control Station prepared for operations. Flight Test Operator's place on the left and Flight Test Engineer's on the right.

Each step would be described by a set of checkpoints noted in the same format as for the test cards. Following sections describe the roles assigned for flight test activities and presents the operations required to run the T-FLEX flight test programme.

3.1 Flight Test Crew

During the design of the Concept of Operations (ConOPS), 5 flight test crew roles were identified: main pilot, backup pilot, flight test manager, flight test operator and flight test engineer. These roles were defined in relation to the responsibilities that were necessary for safe operation during a flight test. The tasks that required to be done before and after flight were distributed after the flight-time roles were set. Roles and their responsibilities within the flight test crew are described below.

3.1.1 Main and Back-up Pilots

Two pilots were required during flight. Main Pilot would control the main transmitter (Jeti). The Backup Pilot would follow the movement of the aircraft and replicate the inputs with the secondary transmitter (Graupner). In case the main pilot would lose control over the aircraft, the backup pilot could take over the command. This could be initiated either when the main pilot manually triggers the command handover himself, or when the first transmitter loses link to the aircraft.

Additionally, to terminate the flight in an emergency (fail-safe mode of the aircraft and release of the parachute), command from both pilots would be required.

The pilots would be assigned one week before the day of flight. The assignment would usually depend on the availability. All the pilots were required to perform training flights with a smaller jet-powered radio-controlled model to become familiar with control techniques. Additionally, participation in simulator training was compulsory.

Communication in between the two pilots would be necessary even if connection with the GCS is lost. Therefore during the flight tests the pilots would stand close together. This way both of them could communicate without the need of intercom (section 3.1.5) and take decisions together.

3.1.2 Flight Test Manager

Flight Test Manager (Manager) would be responsible for all of the administrative tasks regarding the planning of flight test. He would be well informed about the flight plan and would announce manoeuvre commands during the flight. Additionally, he would take notes during flight and communicate with airport tower. He would usually stay within the GCS and would have access to all the information that is also available to the Operator or Engineer.

As the Flight Test Manager would usually be the person designing the flight plan, he would make the decision regarding any changes of the plan during flight.

Before the flight, Manager would be responsible for confirming the assembly checklist as well as conducting the pre-flight briefing and guiding the system start-up checklists. After flight, he would take notes during the debriefing immediately after landing and system shutdown.

3.1.3 Flight Test Operator

Main responsibility of the Flight Test Operator (Operator) would be to inform the pilots about the aircraft's speed, altitude, attitude and its position in relation to the allowed flight box. He would as well help the pilots align the aircraft for manoeuvres or landing. The Operator would observe the main flight map with the flight box overlayed and would announce when the pilots should turn or adjust aircraft's heading. During turns the Operator would provide feedback regarding the bank angle of the aircraft.

To help with Operator's tasks, an automated airspeed and altitude announcer was employed (section 3.1.5). During take-off or landing, when the automated announcer was switched off, the Operator would announce the airspeed. If a flight test manoeuvre required timing, Operator would give time or command cues for the pilots. For example, during the pushover-pullup manoeuvre the Operator would follow the pitch angle of the aircraft and announce when should the pilot pull-up and when should he level out. In such cases, delay in telemetry data and intercom would be taken into account and the cues would be announced before the target values were achieved.

3.1.4 Flight Test Engineer

Flight Test Engineer (Engineer) would primarily focus on health of aircraft systems via the EDL. This could be status of the autopilot modes, actuator temperatures or battery voltages. He also is the backup for the Operator duties in case the MAVLink telemetry connection is lost. In such case, only airspeed would be reported to the pilots.

Figure 6 shows the typical view inside the GCS during the operations.

Figure 6 – Flight test crew during flight operations inside the Ground Control Station. Flight Test Manager on the left, Flight Test Operator in middle and Flight Test Engineer on the right (F. Vogl/TUM).

3.1.5 Communication

During the operations, four communication channels are available to the crew: live communication in between the two pilots, live communication in between the GCS crew, communication via duplex intercom in between the GCS crew and the pilots and half-duplex radio communication between the Manager and the air traffic control.

In addition, an automated airspeed and altitude announcer is used to inform the pilots. The announcer runs through the main intercom and under normal conditions reports the airspeed only. If the aircraft leaves the pre-defined safe altitude and airspeed envelope, additional warnings are used. The automated announcer is muted during take-off and landing the Operator reports the airspeed himself, decreasing the number of different voices heard by the pilots. This was found to decrease the workload required by the pilots during the more intense tasks.

The schematics of communication can be found in figure 7.

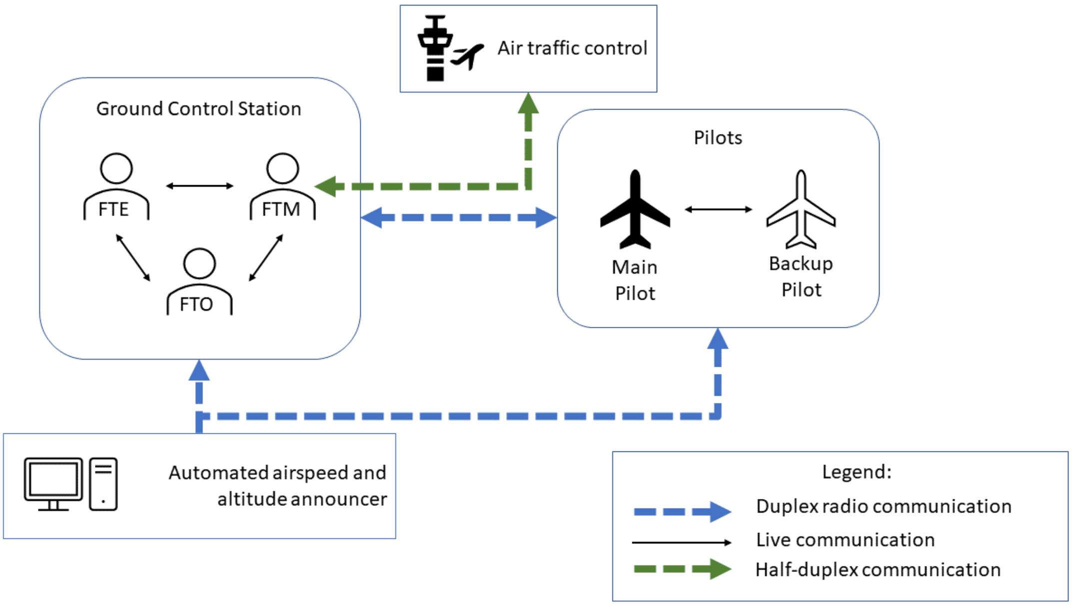


Figure 7 – Communication diagram during the flight test operations.

3.2 Pilot and Operations Training

To prepare for flight testing, pilot and crew training was done. The training used the flight simulator environment SimVis provided by the Institute of System Dynamics and Control, DLR [29]. The flight physics were simulated based on a non-linear flight model. A representative three-dimensional T-FLEX model was used within the simulator and the demonstrator was projected on a 4.3x1.8m screen (3840x1600 pixel resolution) in third-person view as would be seen by the pilots in real life (figure 8).

Even though the high resolution of the screen, the projected aircraft would be almost invisible when the real flight box and altitude requirements were followed. To cope with this, the training flight altitudes within the simulator were decreased. Also, the colour scheme of the aircraft was changed to orange in order to have a higher contrast against the blue sky background. It was furthermore suggested to implement an auto-sizing function in the simulator, where the aircraft would be scaled up when further away from the pilot.

During the simulator training, the actual transmitter was used. This allowed the pilots to get used to the control layout already before the first flight. Additionally, the Operator role could be trained with the actual Mission Planner software.

The simulator training proved to be the most beneficial preparation for the actual flight tests. Simulating the planned flight missions raised awareness to what situations the flight test crew would have to deal with during the test flights. The communication rules were designed during training and only slightly adapted after the actual test campaign started. Training flights were also conducted to keep the currency of the flight test crew after longer periods without flying.

Figure 8 – Pilot and operations training setup using the flight simulator environment SimVis [29].

3.3 Pre-Flight Operations

The Flight Test Manager would usually compile the test plan together with the partner interested in test results a couple of weeks before the planned flight. He would then go through the flight Preparation step which includes packing checklists and coordinate the flight schedule with the airport. After arriving at the airport on the day of the flight the aircraft would be assembled in the hangar and then the systems of the aircraft would be checked. A simple taxi test would often had to be done before the test flight. This would allow for a more realistic system check. If everything works as expected, the pre-flight briefing would follow where the flight plan for the day would be discussed in detail. A more complex flight plan might be additionally reviewed during simulator trainings before.

After the pre-flight briefing the aircraft, the ground control station and the flight test crew would move to the holding point next to the runway and prepare for system start. Start-up would follow.

Throughout most of the project, paper test cards were used. A4 landscape format was chosen and a copy of the whole test plan would be provided to each member of the crew. Even though space for comments was provided next to each step, in the end the Manager's test card set would have notes all over them. After the flight the Manager would collect the notes from each member and usually would only digitize the summary notes taken during the debriefing.

The main advantages of using paper test cards were their simplicity and ease of use. However, such format appeared to be inflexible if small changes were made as complete sets of cards would have to be reprinted. Printing the cards also took effort, as well as digitising them after the test. Therefore methods to use digital test cards are currently being investigated.

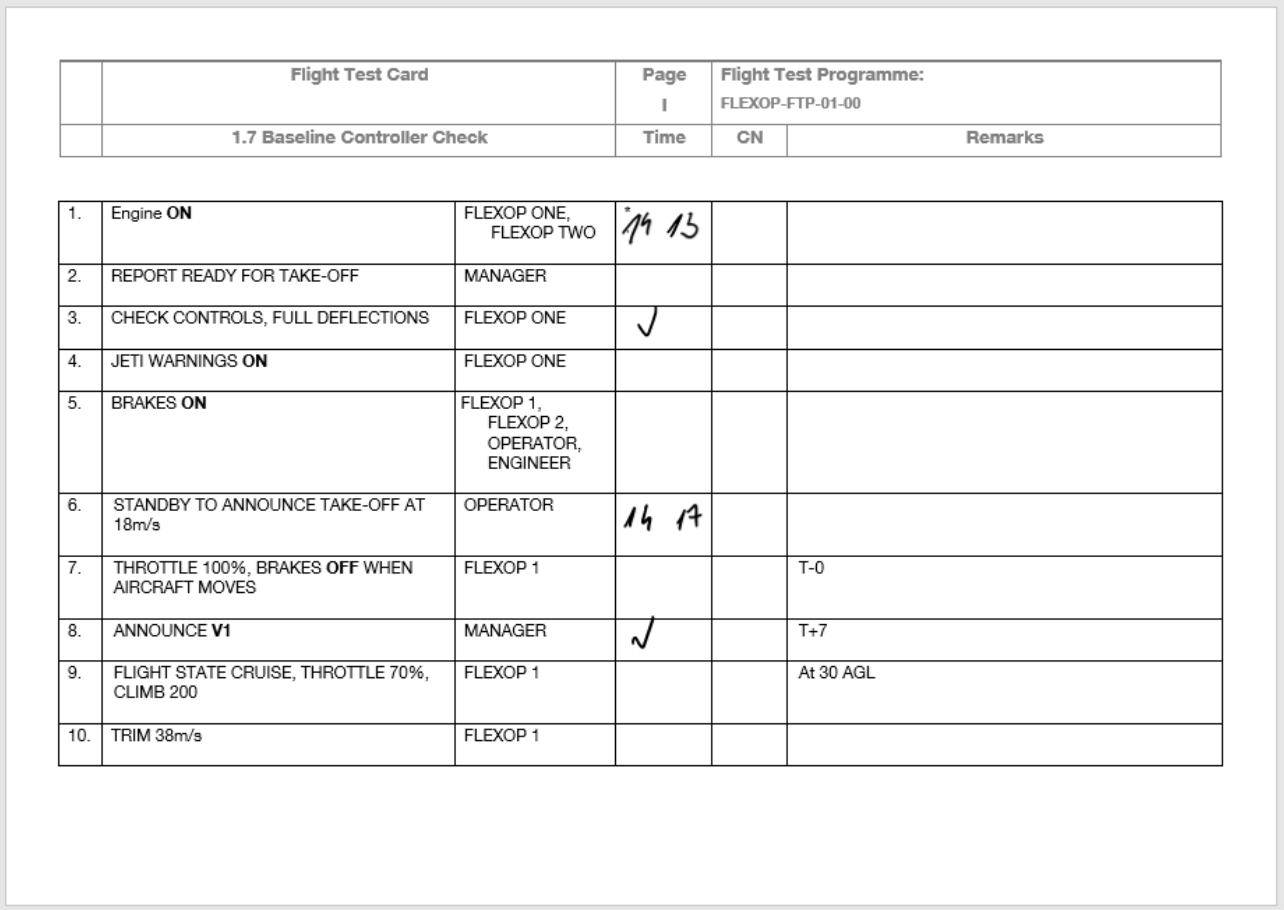
An example of a test card is provided in figure 9.

3.4 Operations During and After Flight

If start-up procedure is successful and clearance for flight has been given, then the aircraft moves on to the runway. This is when the flight is officially started. The aircraft is aligned and the Manager guides the take-off procedure. It was found that reporting the V1 and take-off airspeed helps the pilots, as they have no direct feedback of airspeed.

During the flight, most of the communication happens in between the pilots and the Operator as he guides them within the flight box. This puts a lot of workload on the Operator, which is why the aircraft health related monitoring was assigned for the Engineer. In the meantime, the Manager follows the aircraft on the screen and announces the test manoeuvres to be done next. He would also note down the comments from the crew, if any.

Most of the test points were conducted manually. However, with increasing complexity of the test programme, more use of the autopilot is expected. For example, during the rigid and flexible mode



	Flight Test Card		**Page** I	**Flight Test Programme:** FLEXOP-FTP-01-00	
	1.7 Baseline Controller Check		**Time**	**CN**	**Remarks**
1.	Engine **ON**	FLEXOP ONE, FLEXOP TWO	*14 13		
2.	REPORT READY FOR TAKE-OFF	MANAGER			
3.	CHECK CONTROLS, FULL DEFLECTIONS	FLEXOP ONE	✓		
4.	JETI WARNINGS **ON**	FLEXOP ONE			
5.	BRAKES **ON**	FLEXOP 1, FLEXOP 2, OPERATOR, ENGINEER			
6.	STANDBY TO ANNOUNCE TAKE-OFF AT 18m/s	OPERATOR	14 17		
7.	THROTTLE 100%, BRAKES **OFF** WHEN AIRCRAFT MOVES	FLEXOP 1			T-0
8.	ANNOUNCE **V1**	MANAGER	✓		T+7
9.	FLIGHT STATE CRUISE, THROTTLE 70%, CLIMB 200	FLEXOP 1			At 30 AGL
10.	TRIM 38m/s	FLEXOP 1			

Figure 9 – An example of the test cards used.

identification flights, specific manoeuvres were preprogrammed within the flight control computer (FCC). During such flights, the pilot would trigger the autopilot and one of the preprogrammed manoeuvres would be executed. After the manoeuvre is finished and the control is back to manual, triggering the autopilot would select next manoeuvre in the queue and perform it. This way the pilot would cycle through all the manoeuvres stored within the FCC. Similar flight testing procedure was already described by Sobron [3].

After upgrading the firmware of the FCC, selection of manoeuvres was made possible by the Engineer via MAVLink. In this case a manoeuvre could be repeated if the previous one was considered to be done not according to requirements.

The usual flight time would be around 20 minutes. For landing, the Operator would guide the Pilot towards the landing point just before turning to base leg. After that he would only inform the pilots about the airspeed. After landing, the flight test crew would vacate the runway area. The flight test would then be finished and post-flight debriefing would take place. During the debriefing, important points from the flight test are discussed and noted down. If deemed necessary, telemetry logs and video footage taken from within the ground control station would be analysed on the spot. Notes taken during the debriefing were key in identifying critical situations and implementing mitigation strategies by revision of routines and procedures after the test day.

3.5 Data Pre-processing and Preliminary Analysis

During initial phases of flight testing within the project, no on-field flight test data analysis was done. This was mainly due to high workload while on the test field. Consequently, the probability of immediately spotting problems with the aircraft or sensors was reduced, as data received via telemetry was limited. This was identified as a potential risk when multiple flights would be planned for a single day later on in the test campaign. If sensor problems are not identified during the visual inspection or via the telemetry, the test data recorded during the follow-up flight might become useless. Such risk was also identified by Sobron [3].

To counter this risk, a routine in MATLAB [28] was developed for formatting, correcting and analysing the raw flight test data. The main purpose of the routine was to conduct an automated preliminary flight data analysis right after the test flight with minimum intervention from the crew. The routine comprised of two steps: post-processing and analysis.

The post-processing step requires the raw log file (recorded at 200Hz) and aircraft setup file as inputs. The latter describes the parameters of the aircraft during the flight day, such as the centre of gravity position, take-off weight and sensor calibration values. Next, the post-processing step cleans up the raw log file from variables not related to flight physics, such as debug or sensor status variables. It is followed by trimming the flight log to 5 minutes before and after touchdown in order to reduce the file size. Finally, standard atmosphere variables for the day are assembled. As a result, a single file with a "timetable" variable is created.

The flight data analysis step further inspects the processed log file. Any of the following functionalities can be selected for the automated analysis:

1. Filtering and resampling

   By default, most of the variables are passed through a peak filter and Spencer smoothing filter as recommended by Klein and Morelli [30]. Resampling is done only to speed up some of the functions listed bellow.

2. Sensor position error correction

   The air-data probe and main IMU sensors are corrected for position errors [30].

3. Generating force and moment coefficients

4. Flight segmentation

   The flight test trajectories always comprised of turn and straight legs, during which actual test manoeuvres were done. Therefore it was convenient to have the straight legs automatically extracted. This is done by looking at the smoothed turn rate variable. After the segmentation, a summary of each leg is stored within a table including averages of airspeed, bank angle and other parameters for the segment. Therefore a single leg can easily be chosen for a more detailed analysis without having to look at the complete flight.

5. Flight envelope display

   Flight envelope is displayed together with flight data points marked within. This provides a quick overview about the moments during the flight that might have been outside the allowed flight envelope, but were not noticed live via the available telemetry.

6. Flight test report generation

   After the analysis, a Preliminary Flight Test Report can automatically be generated. The report includes trajectories, altitude and airspeed graphs, sensor error triggers, flight segment descriptions. It provides a quick overview of the flight and ideally can be already used during debriefing.

Similar and more advanced routines to the one described above have already been developed by Sobron ("ALAN Scripts") [31], Seher-Weiss ("FitlabGui") [32] and Bazzocchi [33].

4. Lessons Learned

4.1 Using Simple Flight Models for Testing Complex Systems

During the flight test programme, many updates had to be made to the flight control computer, transmitters or the GCS software. Having only one working vehicle that could test the correct functioning with the updates proved to be a problem. The logistics required to move to the airport and test a new firmware only to find out that something is not working were time consuming.

On the other hand, it was impossible to implement the T-FLEX FCC onto a more simple model without significant modifications to the FCC. The unique control system of T-FLEX required 8 wing flaps and

4 tail surfaces, therefore structure of the FCC would have to be modified to make it applicable on a smaller platform. This problem, however, could have been solved if applicability to a simplified demonstrator version would be stated as a requirement during the design phase. In such case an off-the-shelf radio-controlled (RC) model could have been used for testing the updates to the FCC or GCS software. In case the updates do not work as planned, losing the RC model, or time required to test it, would cost significantly less than when the updates are tested on the main vehicle.

To conclude, authors suggest that projects of similar complexity as T-FLEX should make use of smaller, comparable in geometry and preferably off-the-shelf radio-controlled models which would allow testing the software updates before they get implemented onto the main vehicle.

4.2 Complexity of Operations

The complexity of operations needed to successfully operate a system usually depends on the complexity of the system itself. This is a clear advantage of subscale flight demonstrators in comparison to their manned alternatives. However, the complexity in between different subscale demonstrator programmes varies dramatically as well. This is influenced by national requirements regarding handling of UAVs, cost (or time-to-rebuild) and complexity of the demonstrator.

Before the FLEXOP project, the most complex UAV system operated by TUM was 25kg TOW, winch-launched aircraft powered by an electric motor [16]. Operations of the aircraft required a minimum of two people. In comparison, the T-FLEX demonstrator had many more systems that needed maintenance while on the ground or just before testing. The propulsion system, the flight control computer software, the ground control station and others- all had to be well maintained and checked in order to make sure that during the test day everything worked flawlessly. This resulted in high workload that could only be covered by five people. The high number of people required raised additional planning and organisational issues, and the overall complexity of operations grew further.

After the initial flight test campaign the possibility of reducing the required amount of people was discussed. It was assumed that the aircraft health monitoring could be done by the Manager if some of the monitoring tasks were automated. Additionally, having an augmented reality vision for the pilots was discussed. If aircraft's attitude, airspeed and position in relation to the flight box would be visible to the pilots directly, the Operator's role would be redundant. Additionally, it would be easier for the pilots to assess the data received from the aircraft directly than to act according to Operators instructions. Such augmented reality glasses have already been implemented in other projects [34, 35].

It was concluded that anticipating the complexity of flight test operations during the demonstrator design process could have helped to implement some features that would reduce the workload and therefore the complexity of flight tests themselves. If the operations are not considered during the design process the resulting workload might become too high for the flight testing institution and risk for mishaps might increase.

4.3 Design of Operations

Even though the design process of the subscale demonstrators and manned aircraft is similar, the operations surrounding them are very different. The risk of loss of human life has led to extensive flight test manuals covering all points of testing manned aircraft, such as the Introduction to Flight Test Engineering manual [36]. Additionally, many of the operational concerns and best practises regarding the manned flight testing have been described (and required) by the certifying agencies.

In contrast, flight testing and operations of small- to mid-size UAVs have not yet been systematically described, as also noted by Sobron [5]. There exist relatively few legal requirements for mid-size UAVs and the testing operations are usually designed project by project within the testing organisations. After the test programme is finished, the flight test results are shared with the community. But the methodology and operations surrounding the tests are only sparsely described. This lack of guidelines has led to a challenge and unclarity when designing the flight testing operations for T-FLEX, even though most of the authors did have previous flight test experience with UAVs or sailplanes.

Consequently, the authors believe that further work describing and summarising flight test operations of various UAV projects, sorted according to their complexity, would highly benefit the flight test community. This could be especially important for the ever rising number of new UAV manufacturers or academic institutions who are in initial phases of flight testing subscale demonstrators.

5. Conclusion

The paper described the subscale demonstrator T-FLEX used within the FLEXOP and FLiPASED projects with special emphasis on the operations that surround the flight testing. A few operations-related lessons learned were discussed in the section 4.. The conclusions that were made after the flight test campaigns were:

- Simulator training is the most helpful asset in designing the flight test operations.
- Estimating the complexity of the flight test operations of a demonstrator during the design process could allow reduction of the complexity by implementing some features beforehand.
- Systematic review of various UAV flight test projects and derived guidelines would highly benefit the members of UAV flight test community when preparing their own operational procedures.

6. Acknowledgements

The work presented has been conducted within the framework of projects FLEXOP (grant agreement No. 636307) and FLiPASED (grant agreement No. 815058) funded from the European Union's Horizon 2020 research and innovation program.

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8. Copyright Statement

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