A REMOTE TEST PILOT CONTROL STATION FOR UNMANNED RESEARCH AIRCRAFT

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Abstract

First-person-view ground control stations are an alternative to overcome the drawbacks of an external remote pilot with direct visual line of sight during flight-testing of unmanned aircraft systems. In this paper, a remote test pilot control station with first-person-view for advanced flight-testing is presented. The remote test pilot control station is developed for the German Aerospace Center's ALAADy (Automated Low Altitude Air Delivery) demonstrator aircraft, a gyroplane with a maximum take-off mass of 450 kg. The paper focusses on the system design of the remote test pilot control station, which has to overcome three major challenges: fault tolerance and reliability of the system, the pilot's situational and spatial awareness and latency. The remote test pilot control station is evaluated by pilot-in-the-loop simulations within a dedicated simulation environment. Objective performance criteria as well as subjective pilot ratings based on the Cooper-Harper rating scale are used to assess the control station for the ALAADy-demonstrator in direct mode and flight controller assisted mode. The simulation results show that pilots with experience in manned gyroplanes can consistently control the ALAADy demonstrator with the remote test pilot control station in ideal windless conditions. However, in more challenging crosswind conditions, pilot induced oscillations can be observed in direct mode.

1. INTRODUCTION

The strategy to develop highly automated or autonomous unmanned aircraft systems (UAS) is often supported by the use of a remotely piloted aircraft system (RPAS) in the prototype phase, because a remote pilot can be used very flexible in conducting complex flight-testing tasks. Since no machine has yet achieved the adaptivity or creativity of a human being, a remote pilot is especially capable in situations where some of the behavior of the system is unknown, like e. g. emergency situations. In the initial flight-testing phase of new UAS configurations often no flight controller is available or the flight controller parameter tuning still needs to be validated, so manual flight is the safest option. Most flight-testing tasks, where a remote pilot with manual flying capabilities is needed, have the purpose of data acquisition. This can be, for example, system identification, which is a method commonly used to identify a flight dynamics model [1] [2], or flight envelope expansion, which is the process of increasing the performance of an aircraft while getting closer to its flight envelope limits [3].

For most smaller RPAS usually a remote pilot with direct visual line of sight (VLOS) to the aircraft is used [1] [2]. This comes with the drawback of a limited flight area due to the limited visual range, which can be solved only under special circumstances and with high effort, like e. g. with a remote pilot on a moving vehicle [3], but is generally a hard limitation. On the other hand, first-person-view (FPV) methods enable the remote pilot to virtually take the onboard perspective of the RPAS. While large and expensive military drones have used FPV ground control stations (GCS) for a long time [4], such control stations are still uncommon for civil UAS. However, with the rise of the Specific Category of the European Union UAS Regulation [5] the way is clear for larger civil drones, for which VLOS piloting is not feasible anymore. For these types of UAS, simple, inexpensive and reliable FPV-GCS will be needed, which allow safe and efficient flight testing.

Fig. 1: DLR's Unmanned Research Gyroplane ALAADy Demonstrator

Since 2018, the German Aerospace Center (DLR) is operating a medium sized 450 kg gyroplane, called ALAADy (Automated Low Altitude Air Delivery) demonstrator (figure 1) as a technology demonstrator for unmanned freight transportation under EASAs Specific Category [6]. The first flights were conducted by using a VLOS remote pilot. This has allowed gaining flight experience as early as possible but it has also shown the limits of what can be achieved with VLOS based control. Controllability problems related to visibility as well as crosswind landings and rejected takeoffs were encountered. For the further operations and development towards beyond visual line of sight (BVLOS), DLR is developing a new remote test pilot control station. The remote test pilot control station enables a remote test pilot to safely control the aircraft during all phases of test flights,

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including take-off, landing and experiments such as e. g. detect and avoid procedures or assessing the spiral autorotation for flight termination. Three main challenges have been identified:

- fault tolerance and reliability of the system,
- the pilot's situational and spatial awareness,
- latency in the control- and instrument/video feedback system.

This paper focusses on these three challenges and should give an overview about the developed remote test pilot control station and its design considerations.

2. DESIGN CONSIDERATIONS

In the following sections, the main challenges and design considerations for the remote test pilot control station development are described.

2.1. Requirements and literature review

At the beginning of the development process some high-level requirements were defined to identify the challenges and knowledge gaps. In general, the goal was to develop a system, that is not to complex but flexible to use for different UAS and intuitive enough, so that an experienced pilot of manned aircraft has little difficulty in learning its use. The remote test pilot should be able to accomplish all normal flying tasks, especially the more challenging phases, such as takeoff and landing, without high effort and workload. To achieve this, no excessive training should be necessary. For all the normal tasks, usually a flight controller assisted mode, which enhances the handling qualities of the aircraft, can be used. In case of a failure of the flight controller, fully manual direct mode control should be possible. Despite a higher tolerable pilot workload in such situations, a safe landing should always be possible. Additional to these basic tasks, the remote test pilot control station should also enable advanced flight-testing tasks such as system identification or other highly dynamic maneuvers.

Literature was reviewed to find already existing knowledge and examples of remote pilot control stations. From the military experience it is evident, that RPAS in general have a much higher accident rate than manned aircraft. A control station for an RPAS is per definition a human-machine-interface (HMI), as it enables a human to control an unmanned aircraft, a machine. Therefore, it is clear, that human factors play an important role in designing it. As shown in [7], external piloting (VLOS based control), especially for landing, is often a cause for RPAS accidents. For this reason, the switch to the more intuitive FPV perspective for the remote pilot is expedient. Other causes for RPAS control related accidents mentioned in [7] are transfer of control and interaction with automation. Both of these are still relevant with FPV-based control and require attention in the design of the control station as well as operational procedures and training. In [8] different pilot control interfaces for unmanned aircraft were assessed. Its conclusion is, that the type of control input system is not as important as the level of control. It indicates, that flight controller assisted modes, where the pilot commands e.g. bank angle and vertical speed, are more effective compared to direct mode control. The findings from [8] are revisited in [9]. Higher control levels like guided and objective control are added to the assessment, but the continuing validity of the aforementioned conclusions was confirmed. It also explicitly mentions the main negative human factors effects associated with remote control of an unmanned aircraft: the loss of sensory cues (such as peripheral visual cues, aural cues, and kinesthetic/vestibular cues) and latency in the transfer of information.

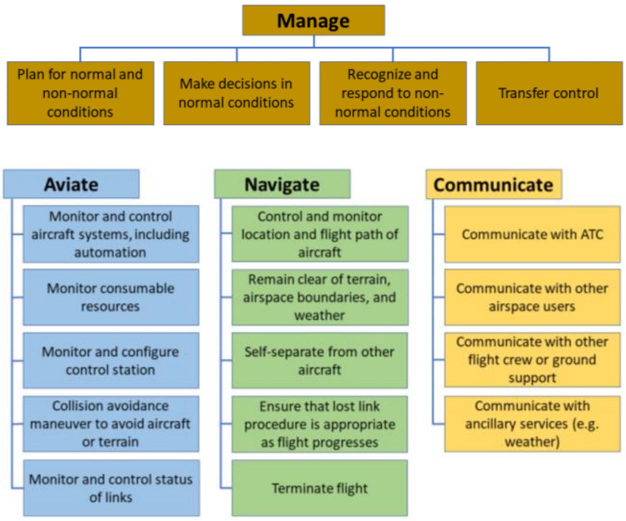


Fig. 2: Responsibilities of the remote pilot [10]

A good summary of the human factors considerations is provided by [10], starting with an overview about the unique challenges of unmanned aviation and showing common problems with existing RPAS control stations like e. g. textual information, complicated menus or unguarded safety-critical controls. Furthermore, a model of the responsibilities of a UAS pilot which is cited here (see figure 2) is presented.

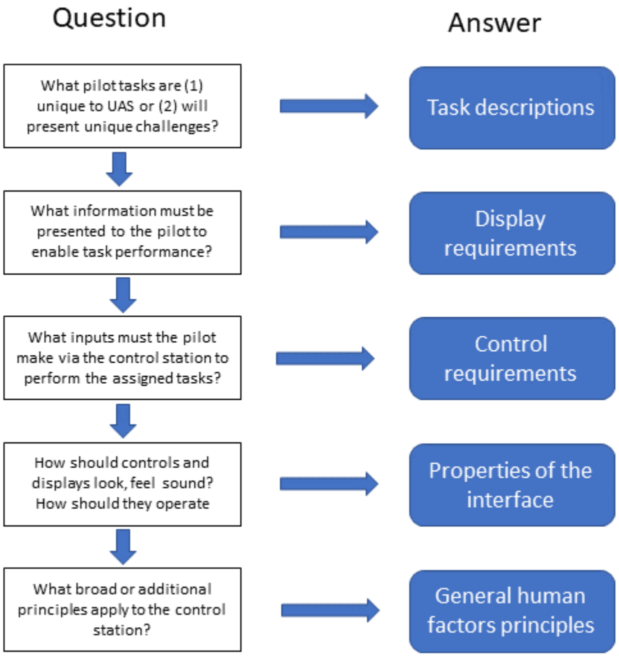


Fig. 3: Questions to identify topics for control stations [10]

Figure 2 summarizes the diversity of tasks of a remote pilot in general and is mostly also applicable to flight-testing, although the remote test pilot is assisted in some of the tasks by other flight-test team members. The paper [10] finally concludes with five questions that can assist in identifying topics for control station guidelines, as shown in figure 3. In the development of the remote test pilot control station, these five questions were loosely followed.

Apart from the human factors, technical aspects of the realization of a remote test pilot control station provide a challenge. In the last years, FPV control of RPAS has become increasingly popular in the hobby sector. From this trend more and more hardware becomes available at very affordable prices, enabling also experiments with smaller RPAS with this technology [11]. Also, several technical solutions to improve sensory cues have been researched in the past. These solutions include stereoscopic vision [12], motion cueing [13] and different synthetically generated views [14] [15].

2.2. Robust system architecture

The ALAADy demonstrator aircraft system architecture is designed to be as simple as possible while fulfilling the safety requirements for operations in the specific class of EU 2019/947 [5], currently up to SAIL II.

Compared to the VLOS-Operation of an RPAS an FPV GCS adds an additional level of technical complexity. The FPV-Display (or another primary flight instrument) is flight-critical because without it the remote pilot is not able to control the aircraft. In order to achieve a near equal level of safety, the complete system needs to be very reliable. The simplest way to achieve a basic fault tolerance is by avoiding single points of failure with the use of independent backup systems. Different technologies exist to create an FPV instrument which gives enough reference to the remote pilot so he can control the aircraft. The most obvious is an onboard camera with a live video datalink and a display showing the video on the ground. Either an analogue or a digital video transmission signal can be used. Various display types – from standard screens to video glasses – have been used for this type of FPV. While video based FPV flight would be comparable to flying under visual flight rules (VFR) in the manned aviation world, instrument flight based on sensor data is also possible with an RPAS. The onboard sensor data has to be sent to the ground and is displayed in the form of e. g. attitude indicator etc. for this. So, with a combination of live video transmission and primary flight instruments, a system is already available where neither the failure of the video link nor the failure of the instrument link will lead to an immediate loss of control. Still, it is not desirable to attempt a landing only by instruments or only by video.

Based on these considerations it should be the goal to have both live video as well as instruments available with high reliability. However, increasing complexity comes at the cost of increased error possibilities. A good methodology for flight testing RPAS is therefore an incremental approach [16], where subsystems are implemented and tested in sequential order, from low risk to high risk. For this reason, the first flight test with the remote test pilot control station should be conducted using a very simple system architecture, while the technically already proven VLOS remote pilot acts as a back-up. An overview about how such a simple architecture could be implemented is given in figure 4. The 2.4 GHz command link and the 912 MHz C2 datalink from the Flight Control Computer, which serves for receiving onboard sensor data and commanding the autopilot system, are already proven from previous flight tests. New is one 433 MHz datalink for the FPV remote test pilot control inputs and one datalink for the live video transmission. The video link could be either an analogue 5.8 GHz link or based on a mobile network (LTE/4G). The mobile network solution uses networks from different providers to achieve low latency and good coverage (this will be discussed later in section 2.4).

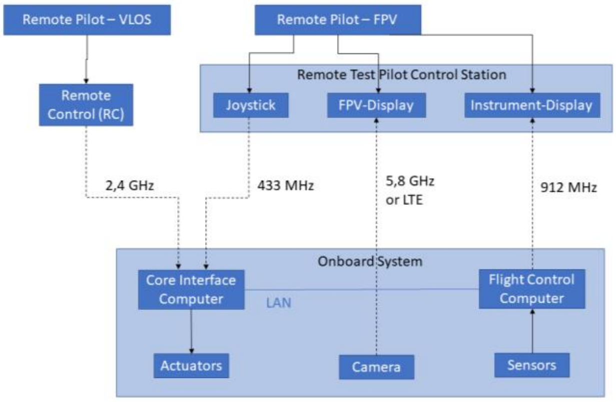


Fig. 4: Datalink architecture for VLOS and FPV

Extending the flight area working towards BVLOS operation in the future, the VLOS remote pilot will be removed and will not be available as a fallback anymore. Therefore, the remote test pilot control station will be the only way of manual control input. To counteract the loss of fallback options, redundant datalinks for the joystick input as well as FPV video are planned. An exemplary system architecture for this is shown in figure 5. For the FPV video transmission a new digital datalink in the 2.4 GHz range, which was used by the RC before and is now available, is used while the LTE video transmission remains. For the joystick signals the same 2.4 GHz + LTE datalink combination is used as well, additional to the 433 MHz link. As explained, this architecture increases the overall system complexity, but comes with the benefit of fault tolerance for the datalinks.

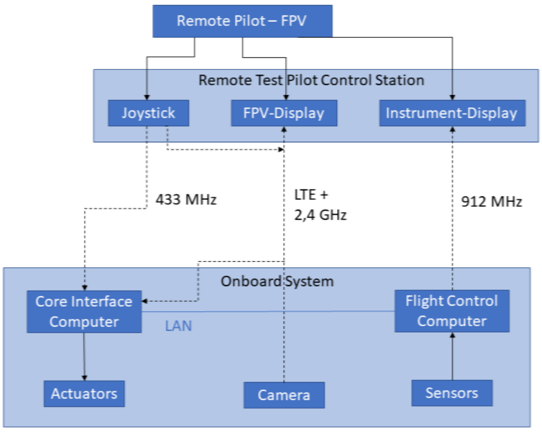


Fig. 5: Datalink architecture for FPV

To choose suitable datalinks, their range has to be considered. Regarding datalink range, the manufacturer information can only be used as a starting point. The actual datalink performance can vary due to interferences, bad antenna positions or other less than ideal conditions. Testing is the best option to gain knowledge of actual datalink performance. For datalink testing it has to be differentiated between ground-ground and ground-air testing. The ground-ground range will be lower than ground-air range most of the time, due to the Fresnel zone of radio transmission. So, ground-ground range testing can usually give a lower limit of an actual datalink range. The ground-ground range must be good enough to cover at least the take-off and landing area of the RPAS plus safety buffers. To achieve this, it might be necessary to position antennas quite high. For the ALAADy demonstrator's 433 MHz joystick datalink ground-ground range tests have been performed. The result was, that with a receiving Antenna approximately a half meter over the ground (on the aircraft), to achieve a range of around 1.6 km the transmitting antenna had to be at a height of 7.5 m. Ground-air datalink tests are obviously more complex to perform, since either another UAS or a manned aircraft are needed. However, for unproven and critical datalinks like the joystick and FPV-video datalink it is recommendable to perform such tests.

2.3. Pilot's situational and spatial awareness

A human pilot can be very capable in recognizing the aircraft state, malfunctions and overall steering the aircraft during complex tasks. The difficulty is, however, to enable the human pilot of an RPAS to use his capabilities to the fullest potential. In contrast to the pilot of a manned aircraft, the remote pilot is not sitting inside the actual aircraft. Therefore, the remote pilot cannot get a real "feeling" of what the aircraft does, he can only interpret what he sees on his displays. The goal of control station development should be to make it as intuitive and as easy as possible for the remote pilot to recognize the aircraft state. This is especially true when manual control is desired as with the remote test pilot control station.

The sensory cues that are important for piloting are mainly visual cues, aural cues and kinesthetic/vestibular cues. Of these, kinesthetic/vestibular cues are arguably the most difficult to generate synthetically. Motion platforms are known from flight simulators and have been applied to RPAS piloting as well [13]. While they can generate some cues, they are limited by their maximum range of motion. On the other hand, motion platforms are large and expensive, so the limited effect might not be worth it. Similarly, control loading systems or force-feedback joysticks can help pilots, e.g. recognizing a stall in a fixed wing aircraft. Generating these stick forces is challenging and wrongly implemented forces can possibly have negative effects. Although simulated stick forces can contribute to improved flight behavior, they are negligible in most flight conditions so that the high effort involved in implementing them is not worthwhile.

Aural cues are usually much simpler to implement and can therefore bring benefit at low cost. Two types of aural cues can be differentiated. First, voice indication systems, as they are known from manned aircraft, can be used to relay important information such as warnings or the height above ground on landing approach. Second, the general sound of the aircraft, that pilots of manned aviation hear directly but remote pilots do not. This sound can e.g. help the pilot to hear a power setting without checking the engine RPM indicator or hear small changes that indicate engine problems. To provide these sounds for a remote pilot, twos possibilities exist: either the real sound is recorded onboard and sent to the GCS or a synthetic sound is generated on the ground based on the engine RPM data. The real sound has the advantage that the informative value of the real sound might be higher, but it needs an onboard microphone and the datalink transmission. Also, for microphones that are somewhere outside in the airflow, sound quality might not be that good. Synthetic sound relies only on data like e.g. engine RPM and airspeed, that are already available on the ground. High frequency low amplitude changes, e.g. engine vibrations, might not be audible if they are not detectable in the RPM data. Still the implementation is relatively simple and it increases the remote pilot's situational awareness.

The most important sensory cues for the remote test pilot are the visual cues. In the previous section it was mentioned that in case of a failure in the FPV video system, the remote test pilot might have to rely on instrument flying. From manned aviation it is known that manual instrument flying is very challenging for the pilot. A synthetic vision system can help increasing the situational awareness of the pilot and has already been applied to RPAS [17] [18]. Since the necessary data is usually already available, a synthetic vison system is simple to implement. The aircraft state information (position and attitude information) from the onboard inertial navigation system (INS) is sufficient. For the visualization, commercially available flight simulation software is suitable. The benefit for the remote pilot is, that the synthetic vision image is similar to the FPV video image, so compared to traditional instruments like attitude indicators or turn indicators switching from video to synthetic vision reference is very intuitive. GPS/INS accuracy and virtual/real world calibration differences limit the suitability of synthetic vison for high precision flying tasks like landing, but it is very suitable for normal flight or the approach.

With a single front-facing camera, even if the camera is equipped with a high field-of-view (FOV) lens, the remote pilot loses some peripheral vision compared to most manned aircraft, so his spatial awareness is limited. This makes it more difficult e.g. to fly a traffic circuit, because at some point in the downwind leg visual contact with the runway is lost. Without the runway in sight, it is difficult to judge the base leg and the turn to final. A map display with the aircraft's position and direction depicted can help, but is not very intuitive. Other possibilities to overcome the problem are more cameras or a camera on a pan-tilt-unit. More cameras come with the need for increased datalink bandwidth. A pan-tilt unit has to be controlled by the pilot, either manually or e.g. by headtracking. A very interesting technology in this context is virtual reality (VR). A VR synthetic vision system could solve the spatial awareness problems by making the "flying experience" of the remote pilot very similar to a pilot in manned aviation. In a VR environment, the remote pilot can naturally turn his head to look around, as if he is sitting onboard the actual aircraft. A drawback of VR is, that the VR-headset fully covers the view of the real world, so the pilot is not able to see any real controls, buttons or switches anymore. A solution to this could be augmented reality (AR) or mixed reality (MR), which means that elements of the real physical world and the virtual world are combined.

2.4. Latency

Another issue that has to be considered with RPAS control stations is latency. Latency is a long-known problem in human-controlled RPAS flight. Typically, latency is the more of a problem the lower the level of control and the more agile the aircraft handling is. So, while for the easy-handling mode of perfectly tuned flight controller a latency of a few hundred milliseconds might not be an issue, in a direct-mode system it can cause severe controllability problems. A consequence of such problems can be pilot induced oscillations (PIO).

PIOs are known from manned aviation and have become a common problem since the first fly-by-wire aircraft were developed. Typically, PIOs occur in the pitch or the roll axis of an aircraft [19] and can have catastrophic consequences. Three different categories of PIO are distinguished [20]: category 1, essentially linear PIOs, e.g. due to latency, category 2, quasilinear PIOs, e.g. due to rate limiting and category 3, nonlinear PIOs. Different criterions have been developed to predict category 1 and category 2 PIOs [21] [22] [23] while category 3 PIOs are still difficult to predict. The focus of most PIO research is on manned aviation, but in [24] some of the PIO criterions have been applied to an unmanned aircraft controlled by a VLOS remote pilot. The research showed, that not all of the criterions were useful in predicting PIO of an RPAS controlled in VLOS. No literature was found on PIO criterions applied to FPV controlled RPAS, but it is reasonable to assume that category 1 PIO problems are very likely if excessive latency is present in the system and category 2 PIOs are also possible, e.g. due to actuator rate limiting.

In the system of the remote test pilot control station latency can have many different causes. The overall latency is composed of two parts: the joystick to actuator latency and the FPV camera to video display latency (alternatively INS sensor to instruments / synthetic vision display). Using different systems or different technologies for these can have an influence on the overall latency. For example, analogue video transmission typically has a lower latency than digital video transmission over LTE. Also, the (VLOS) remote control to actuator latency can differ from a solution with a joystick and a different datalink. Therefore, it is important to measure latency to get a good understanding of the system. Measuring latency is not always easy, but in general a good option is using a camera with a high framerate to record a sudden input and the output in the same image and calculating the time based on the number of frames between input and output. This method was used for evaluating both the stick to actuator as well as video transmission latency.

Before the first flight tests, simulation is useful to examine the controllability, check for the occurrence of PIOs and train the remote test pilot. To achieve good results with simulation, it is essential that the latency in simulation is similar to reality.

3. RESULTS

3.1. Control station setup

Fig. 6: Control station setup in piloted simulation

Figure 6 shows the simulation setup of the remote test pilot control station. It is based on the hardware-in-the-loop simulation of the ALAADy UAS, which is described in [6]. The datalink from the joystick input to the onboard core interface computer is emulated by a serial cable. The onboard computers, including their software, are equivalent to the flying system.

The remote test pilot's task is to safely fly the unmanned aircraft in manual control mode. During automatic flight the pilot shall be able to recognize unusual or faulty behavior of the automatic flight system and take over control in manual mode. The control station setup should look, feel and sound familiar and intuitive to the remote test pilot. The remote test pilot for ALAADy will be a pilot with experience in manned gyroplanes.

Another design principle for the control station was simplicity. The remote test pilot's task of manually flying the aircraft is quite a difficult task. The remote test pilot control station should enable the test pilot to focus on this task, without being distracted by less important tasks or displays. This also includes transfer of control and interaction with automation. The remote test pilot has only one switch to switch from manual to automatic mode and back. The mode selection or programming of the automatic mode is done by a different person of the test team to keep workload from the remote test pilot. Therefore, clear communication and training is essential to avoid misunderstanding.

3.1.1. Control input devices

The input devices for the remote test pilot comprise of a joystick positioned as a sidestick on the right side, a throttle lever on the left side and rudder pedals, as shown in figure 7. The control input devices are based on high-end consumer-grade flight simulator equipment. No control loading or other force feedback system is implemented to keep the complexity to a minimum. The general setup is similar to a manned gyroplane except for the sidestick instead of a center stick.

Fig. 7: Control input devices of the control station

On the sidestick, buttons and switches are used for roll and pitch trim and to control the gyroplanes pneumatic system and pre-rotation. The sidestick also has a button to take over control from the VLOS pilot. On the throttle unit, switches are used for autopilot on/off, rotor flight/brake mode, engine ignition (Mag 1/Mag 2), choke and flight termination (two switches). For the engine starter, a button on the throttle lever is used. A slider next to the throttle lever is used for wheel brakes. The choice for rudder pedals instead of e.g. a 3-axis twist joystick was made for the familiarity of manned gyroplanes pilots.

3.1.2. Vision

Fig. 8: First-person-view simulated with synthetic vision

The camera for the FPV video is positioned in front of the rotor mast of the ALAADy demonstrator. For the simulation, a DLR in-house developed virtual environment [25] is used. The simulated FPV during landing approach is shown in figure 8. A virtual 3D model of the ALAADy demonstrator is implemented to give the pilot a view similar to the real flight. The FPV video is displayed on a large 55” screen in the center of the pilot’s view. It is important that the FPV screen is large enough so that the remote test pilot always still has the attitude information in his peripheral vision when looking at the map display or the instruments.

The simulated virtual environment can also be used as a synthetic vision in real flight. A synthetic vision display, as a back-up for the FPV video, is placed on a display below the FPV video screen on the left side. The synthetic vision is fed by onboard sensor data with an update rate of 4 Hz.

3.1.3. Instrument displays

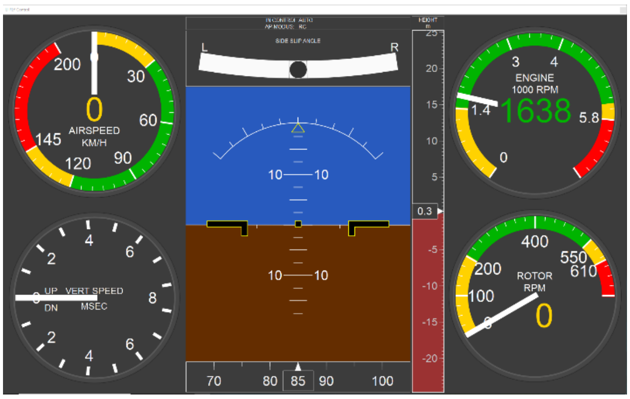


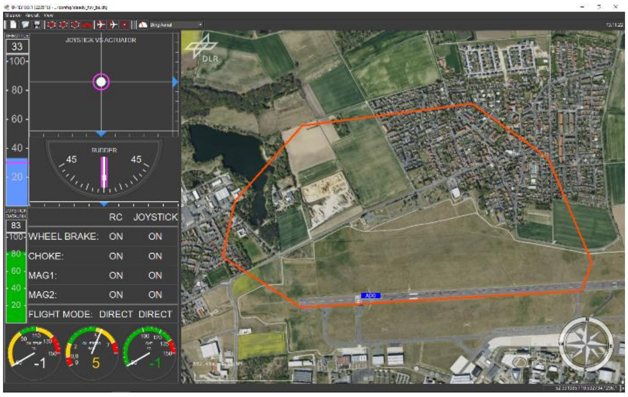
Fig. 9: Primary flight display

The displays should ideally give the remote test pilot all the necessary information but not more. A screen in the center below the FPV video displays the primary flight instruments (see figure 9):

- airspeed
- engine RPM
- rotor RPM
- variometer
- attitude indicator
- sideslip indicator
- altimeter
- heading

The central instrument display provides mainly round instruments similar to (typical) manned gyroplanes. Though this might not be the optimum in terms of a human machine interface, the similarity can help with a quick familiarization process for manned gyroplane pilots.

On the right side of the instruments a secondary flight display shows additionally the 2D position of the aircraft on a map in top-down view and further information for the remote test pilot (see figure 10). Both the instrument and the map display are based on the U-Fly ground control station developed by DLR’s Institute of Flight Guidance [26] and specially developed for the ALAADy gyroplane.



	RC	JOYSTICK
WHEEL BRAKE:	ON	ON
CHOKE:	ON	ON
MAG1:	ON	ON
MAG2:	ON	ON
FLIGHT MODE:	DIRECT	DIRECT

Fig. 10: Secondary flight display

As explained, the remote test pilot has a lot less cues to get his situational awareness than the pilot of a manned aircraft. For the spatial awareness, the map display plays an important role because the camera only gives a forward-facing view and the field of view is therefore limited. The map display shows the boundaries of the flight geography. Additionally, the secondary flight display shows stick, pedal, and throttle position together with the corresponding actuator position feedback and the current trim setting for each axis, the control datalink status and engine status instruments (oil temperature, oil pressure cylinder head temperature). To avoid mismatches in the switch positions of the VLOS and FPV pilot, the switch positions for both pilots are also displayed.

3.1.4. Latency evaluation

Latency measurements have been conducted with different configurations to acquire enough system knowledge for a substantiated assessment and comparison of real and simulation values. Table 1 shows the latencies from stick deflection to actuator deflection measured using a GoPro camera recording at 240 frames per second. For the remote control of the VLOS remote pilot this latency is in the range of 100 ms to 110 ms in direct mode. Due to the control signal being communicated and processed by additional programs on a different computer, the latency is around 20 ms higher in the flight controller assisted (ASST) mode. For the joystick planned for the FPV remote pilot the latency is 160 ms to 170 ms in direct mode and 180 ms to 190 ms in assisted mode. The reason for this is a difference in the system architecture. While the (VLOS) remote control is an integrated system from model flying supply, the joystick is connected to a PC running Windows. On the PC a dedicated driver forwards the input data to a modem. This process seems to take significantly more time.

System	Latency
VLOS Remote Control (Direct Mode)	100-110 ms
VLOS Remote Control (ASST Mode)	120-130 ms
Joystick (Direct Mode)	160-170 ms
Joystick (ASST Mode)	180-190 ms

Table 1: Stick to actuator measured latencies

For the live video transmission two systems were tested. An XLRS analogue 5,8 GHz system comes with a small included screen and a ground antenna with an analogue video output. With the included screen a latency of 50 ms to 60 ms was measured. To get the analogue video (AV) to a larger screen, an AV to HDMI converter was used. However, this converter added an additional latency of 70 ms to 80 ms. The used screens itself can also be the cause for additional latency. The input lag of screens was found to be typically in the range of 10 ms for computer screens and around 40 ms for TVs.

The other video transmission system that was tested is based on mobile internet streaming via LTE, 4G or 5G. This theoretically allows an unlimited range, if the flight area has LTE coverage. The tested Soliton system achieves a stable transmission with low latency by parallel streaming via several mobile networks from different providers. Due to the characteristics of mobile networks, the latency in this solution is not as stable as in point to point communications. However, initial tests have shown that in regions with good mobile network coverage of at least two providers a stable 90 ms to 100 ms latency is possible. With only one available provider, latency is much less stable and typically can go up to 150 ms. The overall measured latencies from camera recording to display are summarized in Table 2.

System	Latency
XLRS analogue system (with included screen)	50-60 ms
XLRS analogue system (with AV to HDMI)	120-140 ms
Soliton LTE system	90-150 ms

Table 2: Live video to display measured latencies

Simulation is an important tool to evaluate the control station and to train the pilot before the first real flights. The simulation setup for the remote test pilot control station will be presented in more detail in the following section. For the evaluation and training to be efficient, the latency in simulation needs to match the latency encountered in the real system. Therefore, with the simulation setup the overall latency, from joystick input to actuator movement on the screen was measured to be approximately 300 ms in direct mode. This is in the same range as what to expect with a combination of the joystick latency and the FPV latency of XLRS with AV to HDMI or the Soliton FPV system. From the joystick input to actual roll movement of the simulated aircraft on the screen the latency was measured with approximately 500 ms. This includes the simulated gyroplane flight dynamics and is the actual latency the remote pilot will encounter in the simulation.

System	Latency
Joystick – Actuator Movement on Screen	Approx. 300 ms
Joystick – Aircraft Roll Movement on Screen	Approx. 500 ms

Table 3: Simulation measured latencies in direct mode

3.2. Pilot-in-the-loop simulation

For a first evaluation of the developed remote test pilot control station, a pilot-in the-loop simulation study is conducted. The simulation study focusses on a traffic pattern flight similar to the planned first real-world flight test. Since a VLOS pilot is used as a back-up pilot for the first flight tests, the flight geography dimensions are limited to the VLOS range. The traffic pattern and flight geography dimensions for the simulation tasks are shown in figure 11.

The flight dynamics model of the gyroplane used for the simulations is a modified version of the model presented in [27]. This flight dynamics model was developed for the manned gyroplane AutoGyro MTOsport and was improved and validated by system identification [28].

Four gyroplane pilots are used as test candidates. Two of the pilots have low to medium gyroplane flying experience with 75 and 150 gyroplane flying hours while the other two are very experienced gyroplane pilots and gyroplane flight instructors with 700 and 5000 gyroplane flying hours. None of the pilots have formal test pilot training, but all have an academic background in the aeronautical field with a focus on gyroplane research.

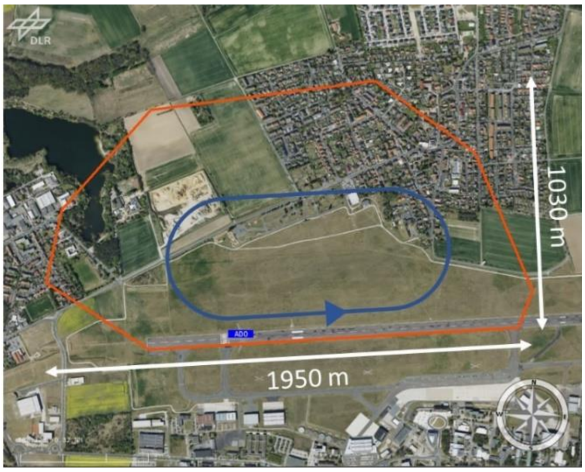


Fig. 11: Simulation task with flight geography dimensions

At first, each pilot had the chance to familiarize himself with the flying characteristics in a free flight session of approximately one hour or at least 5-10 successful take-offs and landings. Afterwards, each pilot had to perform four tasks:

1) Flight in assisted mode (no wind)
2) Flight in direct mode (no wind)
3) Flight in assisted mode (crosswind 5 m/s)
4) Flight in direct mode (crosswind 5 m/s)

Direct mode means, that the control commands of the pilot directly translate to an actuator position. Assisted mode means, that the control commands of the pilot are processed by the flight controller before commanding the actuators. The flight-controller-assisted mode used in the simulations only introduces a slight pitch rate and roll rate damping and a yaw damper. The yaw controller additionally controls the heading to match the course because it was originally developed to aid the pilot during crosswind landings.

For each task, the pilot has to perform a take-off maneuver, a complete circuit flight at a specified altitude without landing (including an overflight of the runway in landing direction) and an approach to a full-stop landing on the runway.

The following criteria are used to evaluate the tasks:

- Successful landing on runway
- No breach of flight geography boundary
- Maintaining target altitude
- Maintaining target course parallel to runway

Additionally, after each task the pilots are asked to rate the handling qualities and workload based on the Cooper-Harper rating scale. As adequate performance is defined, that the flight path stays inside the designated area, no envelope limits are reached, no abnormal attitude (bank angle < 45°, pitch angle < 25°) is encountered and the landing is successful. The landing is rated successful if no rollover happens, the touchdown is on the runway and no excessive sink rate (max. 2,5 m/s) is present. As desirable performance, additionally to the already mentioned criteria, the maximum altitude deviation shall be ±20 m and the maximum course deviation shall be ±20°

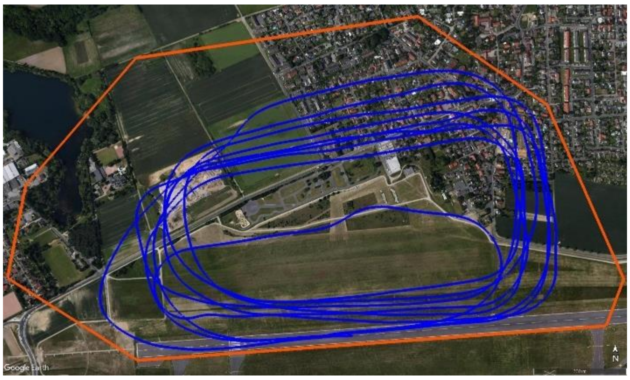


Fig. 12: Exemplary flight path plot

All pilots managed to stay inside the designated flight geography during all tasks. Figure 12 shows an exemplary flight path of one pilot flying all four tasks. The plot of the flight path shows that the pilot used the available flight volume almost to the maximum but still managed to stay inside the boundaries.

The deviation from the target course of the pilots was found to be up to 30° on the downwind leg and up to 10° on the upwind leg. On the upwind leg, the runway could be seen in the FPV and be used as a reference for maintaining the target course. On the downwind leg, the only reference for the target course were the flight instruments and diffuse landscape features such as a lake, houses and trees. Course deviation on downwind and upwind legs of the circuit were slightly higher in tasks 3 and 4 (with crosswind) than in tasks 1 and 2 (without wind).

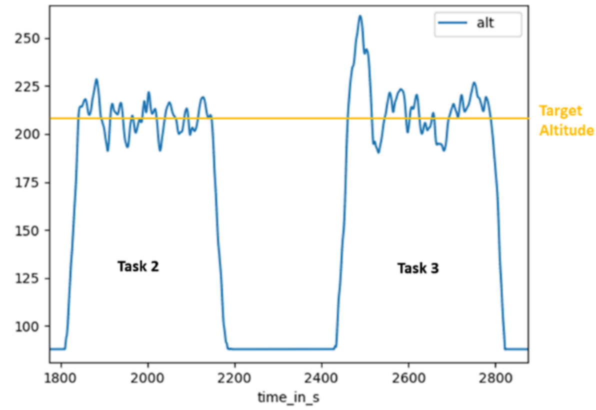


Fig. 13: Exemplary altitude plot of task 2 and task 3

The altitude variations of the pilots can be seen to be typically in the range of ±25 m around the target altitude in tasks 1 and 2 but significantly higher during the tasks 3 and 4 with crosswind. Figure 13 shows the exemplary altitude plot of one pilot during task 2 and task 3. The plot shows an overshoot of the target altitude of more than 50 m during task 3, which can be attributed to the increased workload of maintaining the desired track due to the wind.

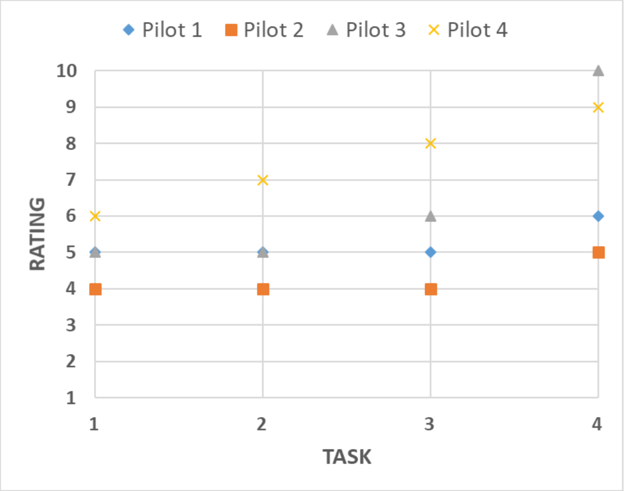


Fig. 14: Cooper-Harper ratings of the simulation tasks

The pilots mostly managed to land successfully during all tasks, except for two landings during task 4. The Cooper-Harper ratings of the simulation tasks are shown in figure 14. The resulting pilot ratings show that the flight-controller assisted mode is only slightly better in no-wind conditions. The tasks with crosswind were generally more difficult, but were rated significantly better with the assisted mode than with direct mode.

Generally, the pilot ratings show that adequate performance requires at least moderate to extensive pilot compensation, even in almost ideal conditions. The pilot workload during the tasks was considered high by all pilots. One experienced gyroplane pilot considered the workload so high, that adequate performance would not be attainable with maximum tolerable pilot compensation even in ideal windstill conditions. Task 4 (direct mode with crosswind) required the highest effort by all pilots. Two pilots lost control on landing, so it is reasonable to assume that the aircraft controllability is in question for direct mode operations in crosswind conditions.

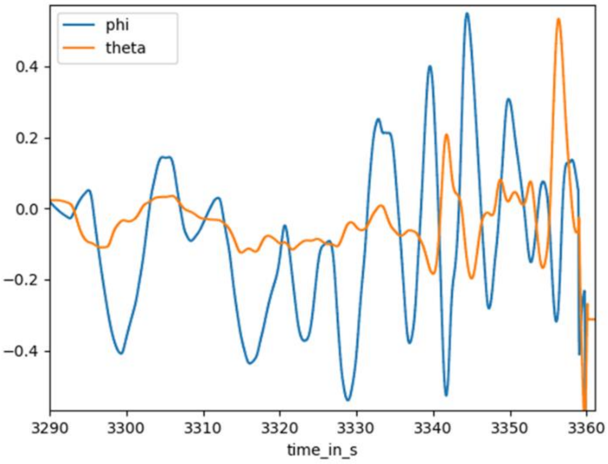


Fig. 15: Roll and pitch attitude during PIO event in task 4 (direct mode, crosswind)

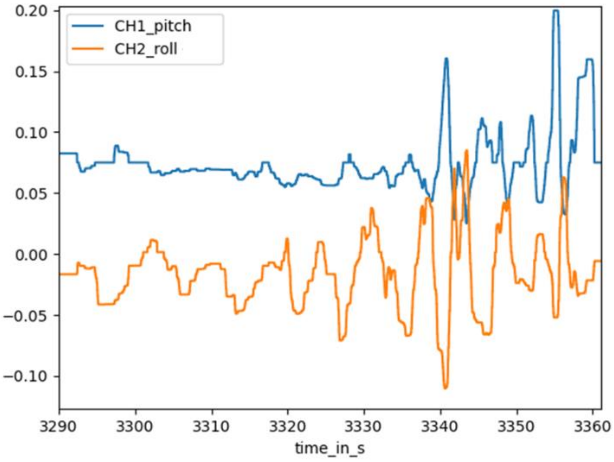


Fig. 16: Roll and pitch control inputs during PIO event in task 4 (direct mode, crosswind)

The subsequent loss of control of one pilot was the consequence of a PIO event. PIO could be observed during the pilot-in-the-loop simulations several times, especially during the initial free-flight familiairization training. PIO in the pitch axis often occurred immediately after take-off. During approach, PIO in the roll axis could be observed several times. The figure 15 and figure 16 show the pitch and roll attitude and the corresponding pilot control inputs of the PIO event subsequently leading to a crash during landing in task 4. It can be observed, that the event started with a PIO in the roll axis that increased in amplitude and frequency. During the flare, PIO of the pitch axis occurred as well. The combined pitch and roll PIO lead to a loss of control followed by a roll-over of the gyroplane on touch-down.

After the simulation was completed, each pilot was asked to comment on the remote test pilot control station and give feedback on desired improvements. The comments regarding the remote test pilot control station design were generally very positive. Although the control of the gyroplane drone is challenging in general, it was noted that the intuitive controls and well-readable instruments helped in achieving the tasks. The following feedback for improvements was given (in brackets the number of pilots who gave the same feedback):

- The Altitude is not visible enough on the primary flight display (3/4)
- The variometer was not used and is unnecessary (3/4)
- A Pilot monitoring is needed to reduce workload (3/4)
- The throttle is too sensitive around the cruise power setting (2/4)
- The joystick is too stiff, centering is too hard (2/4)
- A track indication instead of a heading indication would be more useful (1/4)
- A center stick instead of the sidestick would feel more familiar (1/4)

4. DISCUSSION

A first test setup for a remote test pilot control station for unmanned research aircraft has been developed. Pilot-in-the-loop simulation tests have shown that the general concept is feasible for the ALAADy gyroplane drone. The interface was found to be generally simple and intuitive for pilots of similar manned aircraft.

Latency measured in the simulation was found to be similar to the latency that will be present in the real system. It is evident from the first pilot-in-the-loop simulations, that a total latency of about 300 ms can lead to PIOs, especially in direct mode control. In [22] similar findings are shown for manned fixed wing aircraft: when injecting a time delay from 0 to 500 ms, the Cooper-Harper-Rating of tasks like landing approach or terrain following gets gradually worse with 250 ms in the range of 5 to 7. Also, [24] shows for an unmanned fixed wing aircraft, that no PIOs occurred at 200 ms delay but some PIO was observed at 300 ms and significantly more at 400 ms.

The pilot-in-the-loop simulation showed that flying a gyroplane drone with an FPV control station is a difficult task, especially in direct mode with challenging wind conditions. Compared to the manned gyroplane, the handling qualities are much worse for the remotely piloted gyroplane. The main reason for this is presumably the direct position-based command of the actuators instead of the control stick and rudder pedals with force feedback by direct linkage of the controls to the rotor / rudder in the manned gyroplane, which is the reason for strong reactions coupled in all axis of the aircraft e.g. when changing the power setting. Due to these challenging handling qualities requiring constant pilot compensation, the workload of the pilots was very high managing speed, altitude, course while staying inside the flight geography. Due to the VLOS mission, the flight geography is rather small, which leaves very little time for the pilot to stabilize and trim the aircraft.

To reduce the workload of the pilot flying, a pilot monitoring should be used to assist the pilot flying. The pilot monitoring should focus on giving the pilot flying the most important information verbally, e.g. if the aircraft is leaving the flight geography, the pilot monitoring shall say “turn now” or “increase turn rate” or during landing approach the pilot monitoring shall announce the airspeed and altitude. Also, the importance of training has to emphasized here. Analyzing the simulation results, it has to be considered, that the pilots had only very little training before the tasks. The VLOS remote pilot of the ALAADy demonstrator was trained in 25 sessions with 384 landings before reaching an acceptable level of training [29]. Compared to this, it is a very encouraging result that all four pilots were able to control and land the gyroplane almost immediately. Based on this evidence it is reasonable to assume that the FPV control station improves the controllability of the gyroplane drone compared to the VLOS piloting. Nevertheless, to achieve a safe operation, an intense training of the FPV pilot with the focus on safe take-offs and landings is required before the first flight.

Furthermore, the pilot-in-the-loop simulation results showed that crosswind exacerbates the controllability problem dramatically. It would therefore be wise to conduct the first flight test with as little crosswind component as possible. Flight-controller-assisted mode can help making crosswinds less challenging. The assisted mode used for the simulation already showed that even a very simple flight controller design can improve the handling qualities. The next step will be a higher-level flight-controller-assisted mode such as a rate-command / attitude-hold mode.

One Drawback of the current setup is the limited field of view of the single camera. This can limit the spatial awareness of the pilot in high workload situations. A combined vision system with the synthetic vision extending the camera view could be used to improve this. Especially interesting in this context would be a virtual reality or augmented reality solution.

5. CONCLUSION AND OUTLOOK

In this paper an overview about the developed remote test pilot control station for unmanned research aircraft was given. This control station is in active development and will be further enhanced in the process. The next steps are a more in-depth simulator study and further datalink and system tests such as taxi tests with the ALAADy UAS. Afterwards first flight tests are planned with smaller fixed wing UAS first and the ALAADy gyroplane later. Also, it is a development goal to adapt the remote test pilot control station for other unmanned research aircraft, which can be fixed wing as well as helicopters.

In parallel the concept of virtual and augmented reality in combination with synthetic vision for the manual control of RPAS will be explored further. The remote test pilot control station can serve as a basis for experiments with VR and AR in simulation as well as flight tests. The problem of latency will also be further evaluated. An idea to compensate latency would be e.g. model-based prediction on the ground.

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