EuroGNC CEAS Bristol, UK June 11th-13th 2024 University of BRISTOL ROYAL AERONAUTICAL SOCIETY AIAA

A Flight Operation Strategy for Highly Automated Parallel BVLOS Operations

Yavor Dobrev Research Engineer, flyXdrive GmbH, 52074, Aachen, Germany. dobrev@flyxdrive.com

Nicolai Voget Research Engineer, flyXdrive GmbH, 52074, Aachen, Germany. voget@flyxdrive.com

Lennart Danielmeier Research Associate, Institute of Flight System Dynamics, RWTH Aachen University, 52062, Aachen, Germany. danielmeier@fsd.rwth-aachen.de

Johannes Krimphove Research Associate, Institute of Flight System Dynamics, RWTH Aachen University, 52062, Aachen, Germany. krimphove@fsd.rwth-aachen.de

Sebastian Seitz Chief Engineer, Institute of Flight System Dynamics, RWTH Aachen University, 52062, Aachen, Germany. seitz@fsd.rwth-aachen.de

Johanna Holsten CEO, flyXdrive GmbH, 52074, Aachen, Germany. holsten@flyxdrive.com

Dieter Moormann Head of Institute, Institute of Flight System Dynamics, RWTH Aachen University, 52062, Aachen, Germany. office@fsd.rwth-aachen.de

ABSTRACT

In this paper we discuss practical aspects of conducting parallel beyond visual line of sight (BVLOS) flight operations of highly automated tiltwing unmanned aerial vehicles (UAV) for agricultural land use monitoring. First, the implemented mission control setup, facilitating safe and efficient operations, is presented. We elaborate on the roles of the individual crew members and on the deployed on-site equipment. Furthermore, we offer insights into the planning, monitoring and control of multiple simultaneous BVLOS missions, with special attention to aspects of safe integration into the general airspace.

Keywords: BVLOS; UAV operations; parallel operations; mission control; airspace integration

Nomenclature

BVLOS	=	Beyond Visual Line Of Sight
ELP	=	Emergency Landing Point
MCS	=	Mission Control Station
POI	=	Point Of Interest
SBD	=	Short Burst Data
UTM	=	Unmanned Traffic Management

Fig. 1 TW-Neo during take-off

1 Introduction

In July 2023, flyXdrive GmbH conducted a major unmanned aerial vehicle (UAV) flight campaign in Saxony, Germany, with the aim of gathering imaging data for monitoring agricultural land use under the European Union's Common Agricultural Policy. Throughout the campaign, as many as four TW-Neo tiltwing UAVs (Fig. 1) operated simultaneously generating a total of 24 000 images and flying a total distance of 10 300 km. The beyond visual line of sight (BVLOS) flight campaign was carried out under an operational permit in the specific category, which was granted by the German Federal Aviation Office for the entire state of Saxony. For more information regarding the authorization process refer to [1].

This paper concentrates on some of the practical and organisational considerations involved in preparing and executing the campaign. Those include the implemented mission control setup, personnel assignments, selected equipment and logistical challenges. The project's constraints allowed only for a limited time between the release of the points of interest and the subsequent image collection. Therefore it was crucial for the complete setup to be rapidly deployable and adaptable, while prioritising both safety and cost efficiency. The implemented operational setup is presented in Sec. 2.

Another time-critical aspect was the generation of rule-compliant and efficient missions from the given points of interest (POI). However, due to the limited project preparation time, full automation of the process was not achieved. As a result, the flight paths required manual adjustment, which is detailed in Sec. 3.

During the initial stages of the project, it became clear that the most efficient way to process the points of interest can be achieved by employing multiple UAVs operating simultaneously from a single take-off location. However safe parallel operations pose significant challenges to the mission planning and control as well as to on-site logistics. The way those were solved in this particular instance is described in Sec. 4.

2 Operational Setup

2.1 Organisational Structure

The implemented operational structure was developed based on the project assignment's scope. As the points of interest were not known in advance, preliminary calculations were made using randomly generated points. These indicated, that four TW-Neo UAVs are necessary to cover the entire state of Saxony within the designated time frame, while also accounting for down time due to adverse weather

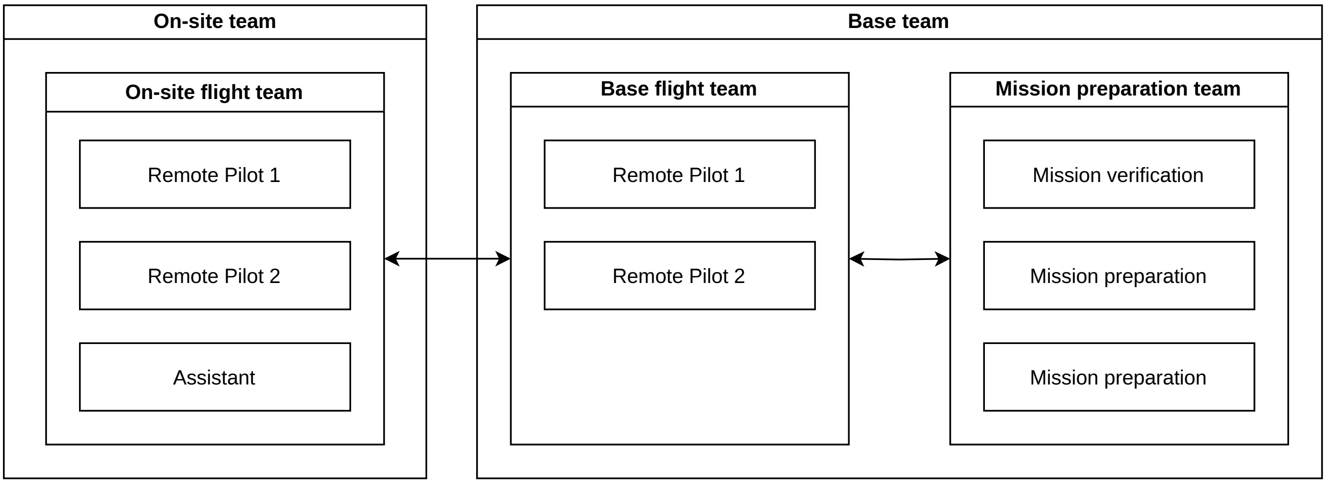


Fig. 2 Personnel organisation structure

conditions and unforeseen circumstances. In order to reduce cost and complexity all aircraft were operated by a single team on site, even though splitting them in multiple teams would have allowed for greater flexibility. The on-site team collaborated closely with a second team in Aachen. The latter was responsible for preparing the individual missions and providing redundant mission monitoring and control. Efforts were taken to establish clear communication channels and facilitate the necessary data exchange between the teams.

Fig. 2 displays the detailed personnel organisation structure. The on-site flight team includes two remote pilots, each responsible for concurrently operating two UAVs. An assistant provides support with turnaround operations, battery management and assembly and disassembly of the drones. The base flight team consists of two remote pilots, who monitor the same aircraft as the on-site pilots, thus providing redundancy in the case of connectivity or power supply issues.

The mission preparation team is tasked with providing ready-to-fly missions to the flight team. The process consists of several steps and is described in detail in [2] and [3]. A feasible mission must comply to the flight geography constraints stipulated in the operational permit and not exceed the available battery capacity even in a worst case wind situation. The mission feasibility is verified by the mission preparation team lead, who than releases it to the flight crew.

The base flight crew handles the mission scheduling, ensuring that collision risk is minimized, and the missions are executed in an efficient manner. Since rainfall can degrade the quality of camera images, the crew must make on-the-fly adjustments to the schedule to avoid areas where there is a chance of precipitation.

2.2 Launch Sites

Over the course of the campaign many different locations (Fig. 3) were used to deploy the drones. These were selected to provide the most efficient coverage of the specified points of interest and always had a point of interest in the immediate vicinity. However a viable launch site must also fulfil a number of practical criteria, such as:

- Reachability by road vehicle
- Suitable vegetation cover
- Sufficient take-off and landing space for four drones
- Sufficient distance from residential areas, major roads, railways, etc.
- Good cellular internet coverage

Fig. 3 Launch site

The launch site selection process began with a review of satellite and aerial imagery of the area and marking of several potential locations. Following a site visit, the final decision was made and the site coordinates were provided to the mission preparation team. Satellite and aerial imagery provided a general overview of the area, although the lack of up-to-date data and sufficient detail impeded a definitive assessment of site feasibility. Hence, it was necessary to visit the locations in person. The potential launch sites had to be scouted a couple of days ahead of flying in order to give the mission preparation team enough time for final adjustments to the flight paths.

In the initial stages of the project, we considered using established model or glider airfields as launch sites. These have the advantage of providing basic infrastructure and are, by definition, suitable for drone operations. However, their geographical distribution is uneven and concessions would have to be made in terms of overall project efficiency. In addition, the effort involved in obtaining permission and coordinating with club members was considered to be significant.

Depending on the geography and the distribution of the points of interest, the number of missions at a particular launch site can vary greatly. Due to the travel and preparation time required, two major sites could usually be processed on one day. To simplify the logistics for the field team, the launch sites were grouped with a single base of operations (hotel) somewhere in the middle.

2.3 On-site Equipment and Mobility

Two vehicles were utilized to ensure the mobility of the on-site flight team. The first was a van, which transported the drones in specially designed containers. When the UAVs were deployed, a mobile mission control centre was set up at the back of the van, allowing the crew to monitor operations without being exposed to the elements. As cost efficiency was a priority, we rented a van without any custom modifications and used simple camping equipment to set up the workstations. The drawback of this approach was that significant time was lost in assembling and disassembling the drones and the mission control equipment, which had to be repeated at every launch site.

The second vehicle was an electric SUV with bidirectional charging (vehicle-to-load,V2L) support, which served multiple purposes. First, it offered an easy, efficient and environmentally friendly method of recharging the UAV batteries and powering the mission control station in the field. The V2L feature can handle a maximum load of 3.6 kW, which was sufficient to charge four sets of batteries simultaneously. Furthermore the electric vehicle provided flexibility in situations, where the drones were deployed, but mobility was required. For instance, in the event of an emergency landing beyond the visual line of sight, the EV could move out and secure the distressed drone without waiting for all other drones to land and be loaded in the van. In such a situation the mission control station would continue to operate on backup battery power. In the event of an extended absence of the electric vehicle, a petrol generator could also be used as a backup power source.

The UAV batteries were charged using standard chargers that were integrated in racks with dedicated battery slots for ease of use. Each drone was equipped with two sets of batteries, so one set could be recharged, while the other one was in flight. As missions varied in duration, it was crucial to have high-current, fast-charging capabilities to prevent delays caused by the drone having to wait for its battery to fully charge. For safety reasons, flying with batteries that were not fully charged was not permitted.

Connectivity in the field was established using a 5G router supporting two SIM cards. A SIM with unlimited data from one of the major telecommunication companies in Germany was used as a primary. The backup card was an IoT SIM, which could connect to all operators, however at significantly higher costs. Reliable cellular connectivity was of paramount importance, as the C2 link of the drones and the communication with the base team depended on it. The router therefore had its own battery backup, allowing it to operate for several hours without external power.

3 Mission Planning

3.1 Automatic Flight Path Generation

In order to efficiently process all points of interest, we utilised a path-finding algorithm [2] to find groups of routes originating from the same take-off point, each covering as many distinct points of interest as possible. Three different flight geographies (S0, S1, S2) were defined based on their proximity to buildings. As the distance decreases, the constraints on altitude and velocity become more stringent to mitigate ground risks [1]. For example, in S2 only hovering flight with a maximum velocity of 10 m/s is allowed. The path-finding algorithm generates 2D waypoint sequences based on a 50 m grid avoiding no-fly zones and taking into account the different energy requirements for flying in the different flight geographies. In the following step, turns in the form of circle segments are added to smoothen the transition between waypoints. Finally, the flight paths are assigned altitude and velocity constraints, according to the respective flight geographies [3].

3.2 Flight Path Adjustments

Even though the automatically generated trajectories are flyable, several adaptations have to be made to ensure that both efficiency and safety are maximized.

3.2.1 Take-off Point

First, the take-off point[1] of the route is modified. During the path-finding phase one of the points of interest is selected as the take-off location, yet not all of them necessarily satisfy the requirements stated in Sec. 2.2. Once a suitable launch site has been identified, it is necessary to re-plan the take-off and approach flight paths. It is essential to ensure that there is no risk of collision with ground obstacles in the launch area.

3.2.2 Points of Interest

In the following stage, adjustments are made to the flight paths above the points of interest. Previously, the points of interest were treated as singular points, but in reality they are polygons with known geometry. Due to aerodynamic, weight and cost reasons, the camera of the UAV is not mounted on a gimbal. As the photos are to be taken straight down, the UAV must pass over the points of interest maintaining a zero roll

[1]The take-off point was always identical with the landing point of the route.

angle. In combination with the camera's frame rate of 3 Hz, this implies that the point of interest needs to be flown over on a linear path that is sufficiently long for the UAV to capture at least three photos at its given velocity. This path should also be contained within the borders of the field for as long as possible, as displayed in Fig. 4. The minimum distance where the UAV has to fly on a straight line (dashed black) at its current velocity is marked by the green and red markers on the path. These markers also indicate the camera activation and deactivation points.

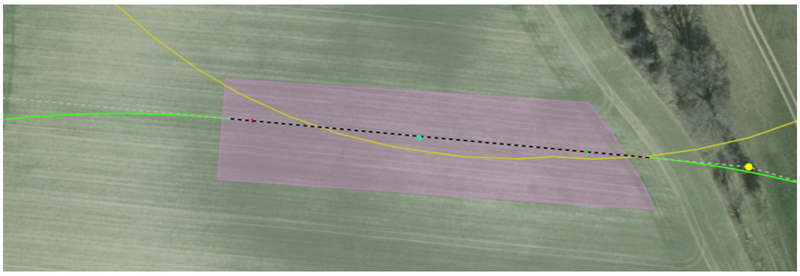


Fig. 4 Flight path over a point of interest

3.2.3 Energy Efficiency

As already mentioned, the path-finding algorithm worked in two dimensions, thus ignoring the effects of altitude change on energy consumption. However, due to the limited altitude band assigned to UAVs by regulation, they must actually fly following the terrain. Therefore, flying over hills on a straight line would require frequent climb and descent phases, which may be inefficient, when compared to flying around the hills at a constant altitude. In such situations, the routes generated by the path-finding algorithm may require significantly more energy than anticipated, rendering them unfeasible. Therefore, mission verification included running flight simulations of the route under different wind conditions and ensuring that the total energy consumption is within the prescribed limits. If this was not the case, the route needed to be reviewed and adapted by hand to reduce climbing and descending phases. The next paragraphs show some further examples, how energy efficiency could be improved by flight path modifications.

Sometimes the approach to a point of interest would be planned as shown in Fig. 5. According to

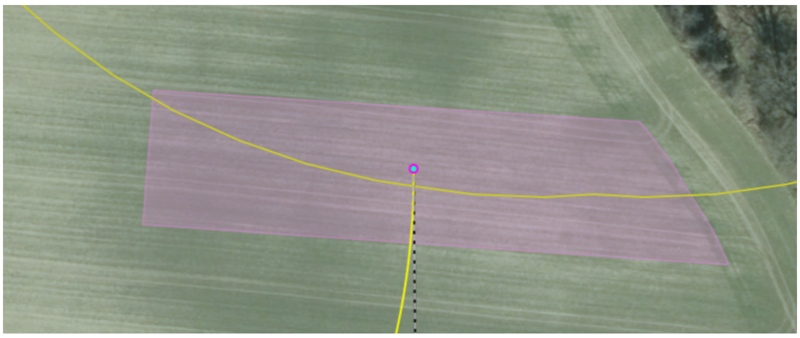
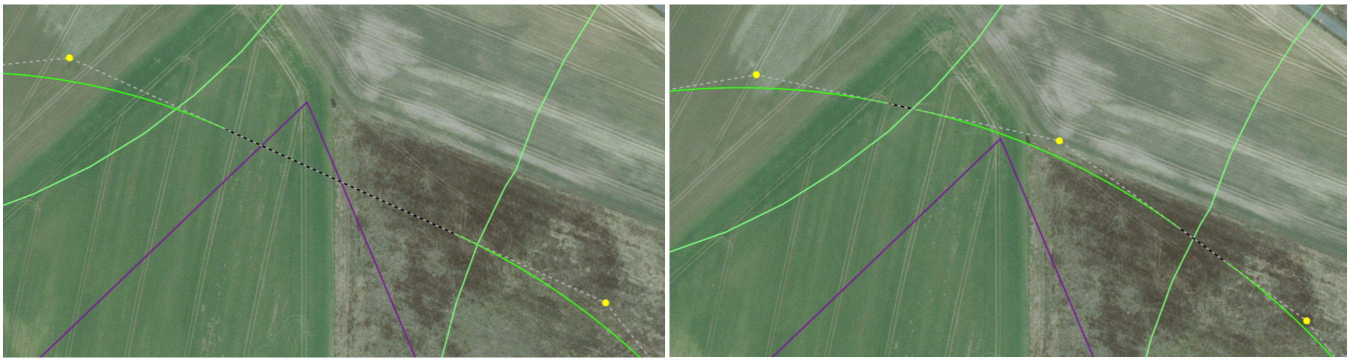


Fig. 5 Raw flight path over a point of interest

the generated path the UAV would enter the area from the south and execute a 180° hovering turn before exiting to the same direction. This is suboptimal, as it necessitates the UAV to enter a hovering state, which is very energy consuming. To reduce energy consumption, the path is modified so that the UAV passes the point of interest without the need for a complete stop.

The path shown in Fig. 4 is not the most energy efficient option for the given situation. This is because the path crosses into an S2 flight geography (north of the yellow line) to capture a photo of a field that is located both in S1 and S2. As the points of interest were placed at the center of the fields without consideration of the boundaries of the flight geography, this is a common occurrence. There are two potential solutions to address the issue. First, the point of interest can be relocated within the field polygon to the flight geography with the weakest possible constraints. The alternative is to fly over the point of interest at a slight offset. As the pictures are captured at an altitude the point of interest will remain in the frame.

Further restrictions on flight altitude may apply when flying over nature conservation areas, with some areas requiring a minimum altitude for overflight. To further optimize the energy efficiency, nature conservation areas should be completely avoided in some cases. For instance, in Fig. 6a, the path leaves an S1 flight geography from the west passes through a nature conservation area (purple polygon) and then enters an S1 flight geography to the east. To follow this path the UAV would have to climb from the maximum S1 altitude to the minimal overflight altitude of the nature conservation area and then rapidly sink again for the next S1. This is inefficient and instead the path is altered as shown in Fig. 6b. With this path, the UAV can stay at the S1 maximum altitude between the two S1 flight geographies at the cost of a very small increase in path length.



(a) **(b)**

Fig. 6 Energy inefficient path through a nature conservation area (a) and energy efficient path around a nature conservation area (b)

Finally, the turn radii of the generated path can be optimized. As previously mentioned the path is created by connecting waypoints on a 50 m square grid and then inserting turns with the maximum possible radius. When waypoints are close together, the turn radius decreases, requiring the UAV to enter thrust-born flight to complete the turn. This occurs in particular when the path-finding algorithm follows the shapes of flight geographies as seen in Fig. 7. The figure shows the path (straights in black, turns in

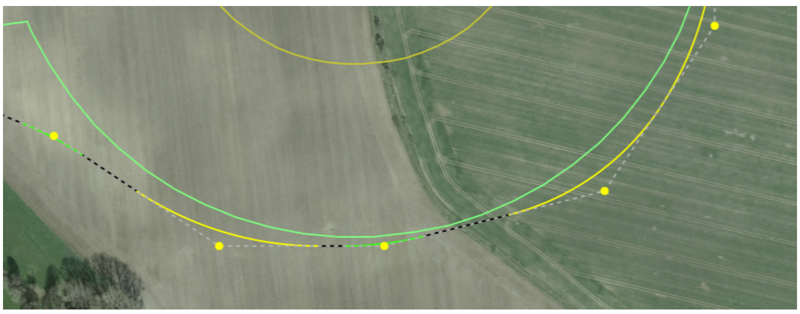


Fig. 7 Flight path with potentially inefficient turn radii

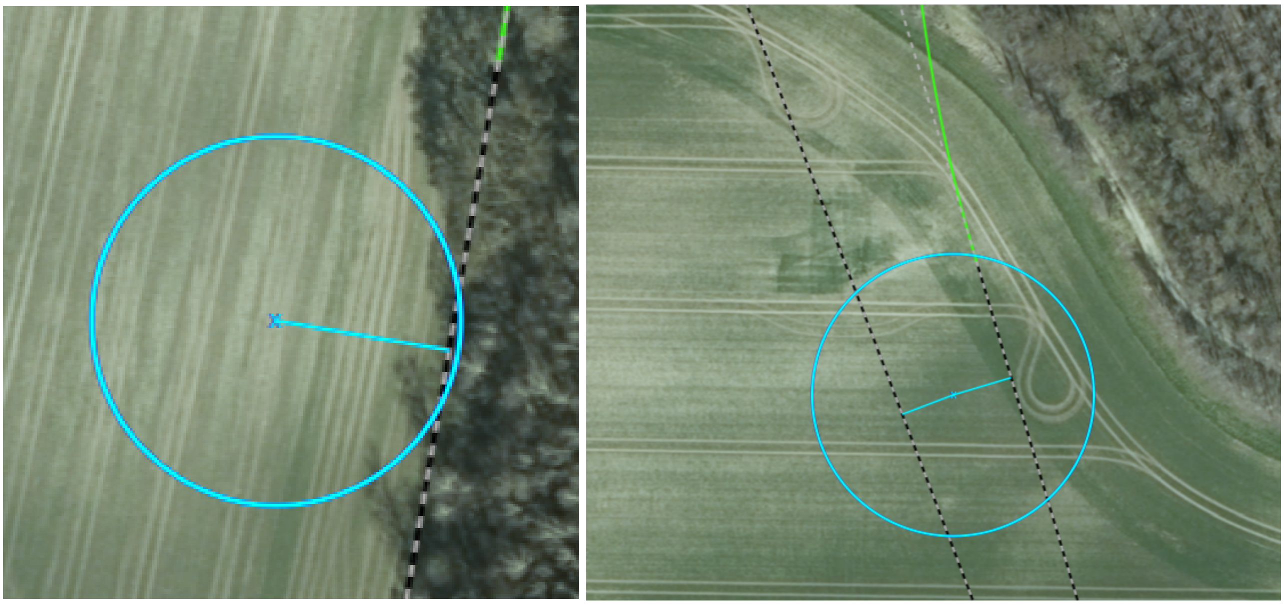
yellow or green) in an S0 flight geography looping around the contour of an S1 flight geography. Turns, which under adverse wind conditions may cause the UAV to enter thrust-born flight are marked in yellow. By moving or removing waypoints the turn radii can be increased, which results in a longer path, but overall higher energy efficiency.

3.2.4 Safety Features

After validating the energy usage, the flight path is reviewed regarding safety. First, the path is adjusted to cross highways, railways and power lines at as close to a perpendicular angle as possible. This minimizes the time spent over these structures, where a potential system failure could cause extensive damage.

Next, emergency landing points (ELPs) are automatically placed every 3 km along the path. An ELP is a safe landing point, which will be used by the UAV, if the remote pilots triggers an emergency landing [4]. The automatically generated points need to be checked regarding their suitability as the algorithm has no knowledge about any terrain features. ELPs are always placed on fields in order to minimize the risk of endangering people and equipment on the ground. This also reduces the likelihood of damaging the UAV in case of an emergency landing.

An ELP consists of the point itself and a zone around it, denoted by a blue cross and circle (Fig. 8).



(a) **(b)**

Fig. 8 Emergency landing points and their zones

The zone allocates paths segments that intersect it to the emergency landing point it surrounds. It is used when the ELP cannot be placed directly on the path. Fig. 8a shows an example where the path goes over a forest, so the zone is used to move the safety point onto a field. If the path repeatedly crosses the zone of an emergency landing point this point will be assigned to multiple path segments as illustrated in Fig. 8b.

4 Parallel Mission Operations

4.1 On-the-fly Scheduling

The simultaneous operation of multiple aircraft at a single launch site requires precise scheduling of each mission. The scheduling must ensure that the drones flying different missions do not collide with each other. In addition, the downtime of each aircraft should be minimized.

To achieve this, a software application was developed for the project, allowing the scheduling of all missions. As many flight paths intersect, it is not practical to strictly avoid intersecting flight paths in general, as this would result in long downtimes. Instead, high-resolution simulations were used to

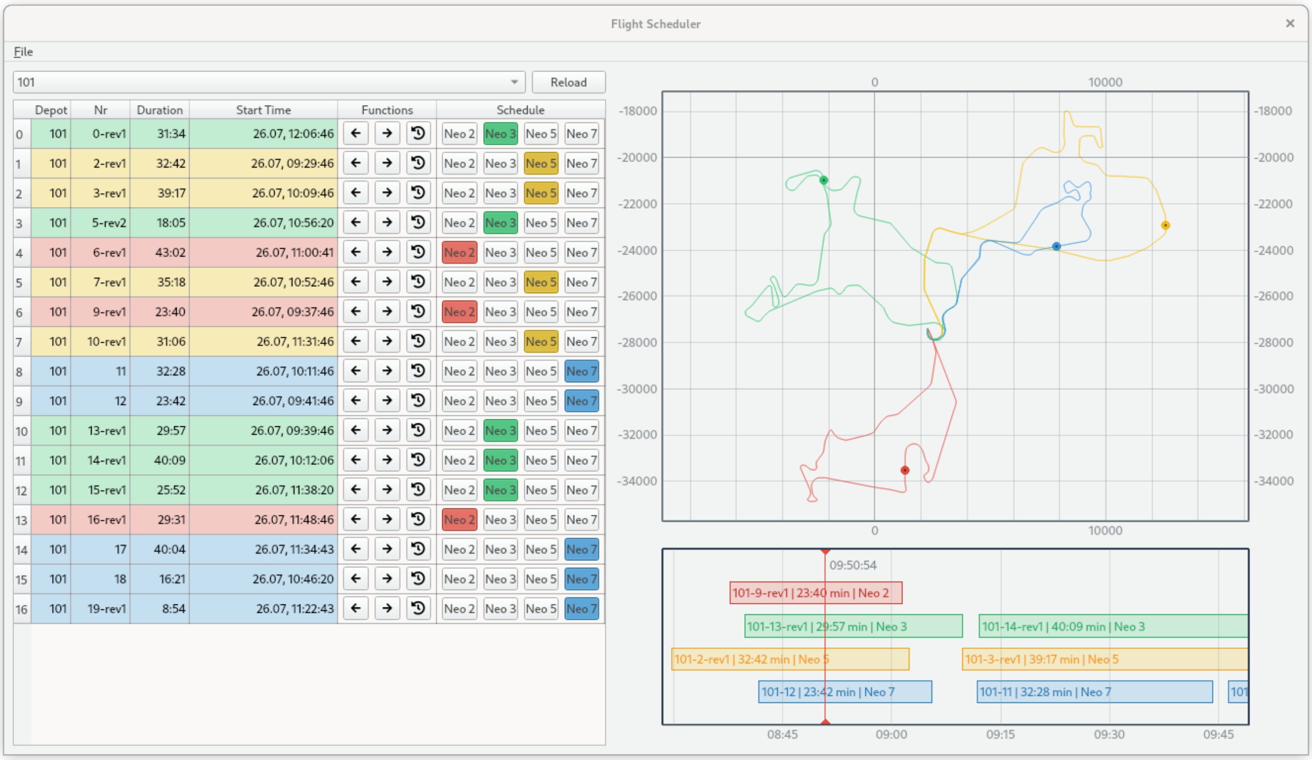


Fig. 9 Mission scheduling tool

generate time-resolved trajectories that provide a temporal map of the aircraft's position in space. These trajectories are used in the planning software to assign them to the individual aircraft. The resulting schedule is visualized, highlighting potential collisions during the planning step. Scheduled start and expected end times for each aircraft mission are displayed in a time bar chart and can be adjusted if necessary (Fig. 9).

In a future release, it will be possible to generate an automatically optimized schedule. In addition, a comparison between the planned positions and the actual positions of each aircraft can be developed using telemetry data. This would allow the schedule to be monitored and adjusted in real time.

4.2 Data Link Architecture

With the current state of the art the missions are flown in a fully automated manner, however the remote pilot is required to continuously monitor the status of the aircraft and to initiate emergency procedures in the event of an abnormal situation. Such situations include not only technical malfunctions but also instances where there is a risk of collision with incoming traffic. Therefore, maintaining a dependable data link between the drone and the mission control station is crucial.

Fig. 10 displays the implemented data link architecture. The aircraft utilize cellular internet as their primary communication method ([5], [6]). All data exchanged between the drones and the mission control stations is relayed through a central cloud server. Here, telemetry data received from the different drones through various communication channels is consolidated, logged and served to the mission control station applications for the remote pilots to view.

On the aircraft side, the telemetry data is transmitted concurrently through two distinct cellular modems for the sake of redundancy. Both modems utilize IoT-SIM-cards, enabling connection to any accessible cellular network and ensuring maximal data link availability. Therefore, the aircraft will usually be connected to the cloud server via two different cellular networks. This setup minimizes

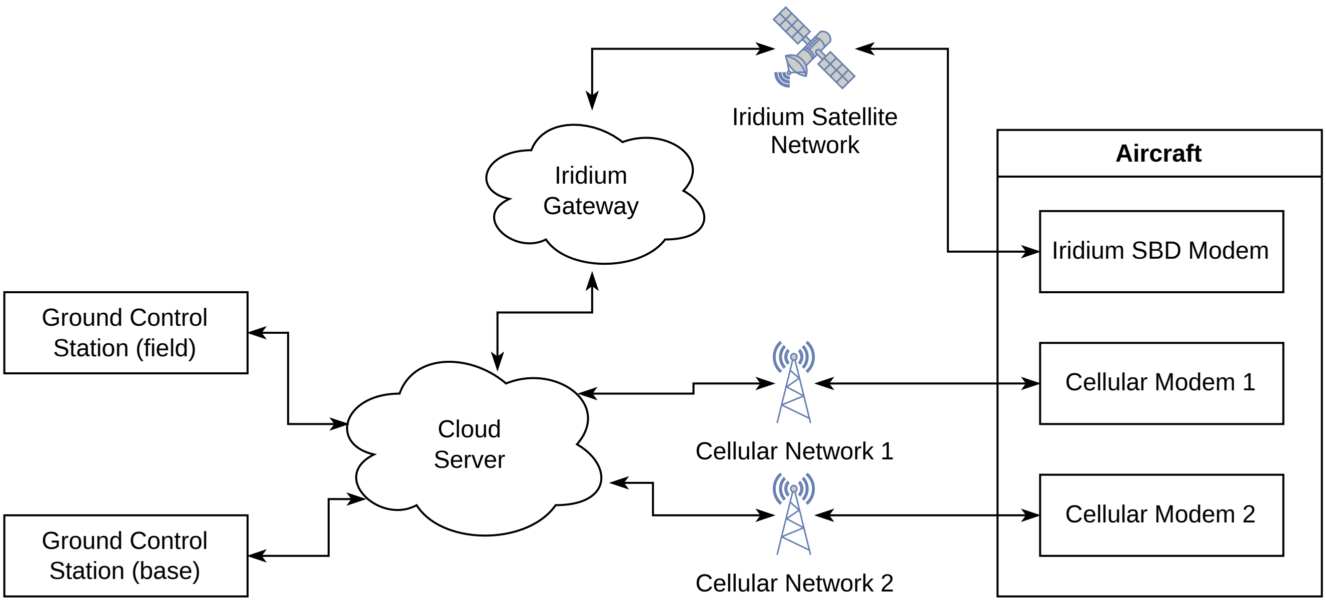


Fig. 10 Data link architecture

outages resulting from signal blocking by the UAV's components or due to flying in dead zones of single operators.

The availability of the cellular connection is constantly monitored by exchanging a heartbeat signal between the drone and the cloud server. Should the connection be lost, a backup link using satellite communication is activated. It is based on the Iridium Short Burst Data (SBD) service, which allows the transmission of small data packets at intervals of a few seconds. The packets are relayed through the Iridium LEO satellite network to a terrestrial gateway, which then delivers them to the cloud server. As the bandwidth is very low, only key aircraft parameters, such as position and general status are transmitted at a low frequency. It is also possible to send command parameters from the ground control station via satellite, enabling high-level control of the drone even when flying in a cellular dead zone. Iridium SBD is available globally and the equipment required is very compact and lightweight, but the high latency and the low throughput make it viable only as a backup connectivity service.

4.3 Mission Monitoring and Control

Mission monitoring and control was realised using in-house developed software. The system architecture allows multiple instances of the Mission Control Station (MCS) application to be connected to a single drone. During this project each drone was monitored by two remote pilots, one in the field and one at the base in Aachen. This feature provided redundancy, for instance in the event of connectivity and power problems or trivial issues such as a computer crash.

The remote pilots were in constant communication with one another and could take turns in monitoring the drones, while being able to take care of additional tasks. In the field, such tasks mostly encompassed the turnaround process, although there were occasional instances of responding to bystander enquiries. At the base the scheduling process had to be executed concurrently with mission monitoring. In summary this flexible operational setup increased both safety and efficiency.

As most aviation accidents occur during take-off and landing, we opted to enhance safety measures during those phases. The remote pilot can manually take control of the drone using a handheld remote control transmitter, while the drone is in visual line of sight. This allows for a faster reaction in the event of an emergency situation. It should be noted that during take-off and landing, the remote pilot in the field does not sit at their control station. Instead, they visually track the UAV, prepared for manual intervention, while maintaining voice communication with the remote pilot at the base, who is monitoring the aircraft's parameters.

Upon landing, the drone undergoes a turnaround process in which new batteries are inserted and a pre-flight check is conducted. A new mission is then uploaded onto the drone, before it takes off at its scheduled time. Once it is out of visual range, the field remote pilot would return to their control station and continue monitoring.

The MCS software provides the remote pilot with comprehensive information concerning the following aspects:

- UAV health and status
- Mission progress and points of interest
- Relevant geo-zones, for instance nature preserves, no-fly-zones, etc.
- Air traffic information
- Weather: Wind speed and precipitation zones

The software also enables the remote pilots to trigger several emergency functions, for instance commanding the UAV to stop and hover on its scheduled path to let air traffic pass. For a thorough discussion of the available safety functions refer to [4].

4.4 Airspace Integration

According to EASA regulations UAVs must always stay clear of manned traffic. Our operational permit allowed us to fly at a maximum altitude of 110 m above ground level. At this altitude, collisions with police and rescue helicopters, sailplanes, paragliders and other drones pose the greatest risk. As the use of transponders or other collision avoidance equipment is not mandatory the reliable identification of potential conflicts is not a trivial problem. Furthermore, automatic evasion procedures with proper consideration of flight geography and energy constraints are still being developed. Therefore it is currently the responsibility of the remote pilot to manually identify collision risks and activate mitigation procedures.

In order to give the remote pilot the best possible situational awareness, air traffic data from different sources had to be consolidated, filtered and properly displayed. These included a FLARM and ADS-B [7] receiver fitted to each drone, along with the Droniq/Deutsche Flugsicherung Unmanned Traffic Management (UTM) system. The UTM system itself consolidates traffic data from both stationary receiver stations and onboard tracking devices received via internet protocol.

The two air traffic data sources are complementary to each other. The onboard receivers have limited range. Nevertheless, they cover the most crucial areas within close proximity of the aircraft. Tracking station networks span broader regions, but they exhibit numerous gaps in coverage. The active transmission of the aircraft's own position to a UTM system offers the benefit of being independent of external tracking, although it is reliant on available connectivity, mainly cellular network coverage. This method of collision avoidance is in development and not yet widely used.

Currently, FLARM is the most relevant collision avoidance system for UAVs as it is extensively used by general aviation aircraft, helicopters, and sailplanes, which bear the greatest collision risk [8]. All flyXdrive drones are fitted with FLARM transceivers which enable their detection by manned aircraft. In addition, visibility is enhanced by streaming position data to the UTM system.

As current collision avoidance systems do not guarantee successful conflict identification, relevant stakeholders were contacted prior to the campaign in order to raise awareness and avoid dangerous situations in the air. For instance, we coordinated with police helicopter squadrons, so the crews could be briefed about the drone activities in the area. We would also contact paragliding clubs, should a paragliding launch site be in the vicinity.

5 Conclusion

In this paper we presented some practical and organisational aspects concerning our 2023 BVLOS flight campaign in Saxony. Even though the campaign was deemed highly successful, there remains room for improvement and refinement. A key objective is to further automate and optimise processes, hence reducing personnel requirements and costs. For instance, there is substantial room for improvement of the mission planning process, which involved numerous manual steps. Currently additional automatic processing of the flight paths is being developed, which would eliminate most of the steps mentioned in Sec. 3.2. To reduce the preparation time at each launch site, the use of pre-assembled drones packed in a suitable container is being considered. We are also working to further automate the mission monitoring process with the goal of reducing the number of on-site personnel required.

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