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CITY-ATM – LIVE DRONE DEMONSTRATIONS OF NEW CONCEPT ELEMENTS ENABLING OPERATIONS IN URBAN AREAS

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Abstract

In a future airspace management system for unmanned and manned airspace users - especially when enabling flights in urban areas - a large number of constraints and requirements must be considered in order to ensure a safe and efficient integration of new airspace users. These airspace users can be very diverse and include, in addition to VFR traffic, also other participants such as personal air vehicles, cargo UAS, parachute jumpers, weather balloons or prioritizing air traffic, e.g. rescue helicopters. In addition to aspects relating to different UAS/PAV design, performance and capabilities, further requirements for protecting flight areas (so-called geo-fencing) or board autonomous flights are to be considered in an urban ATM concept. In the City-ATM project, a concept for future air traffic management in urban airspace was developed, which enables safe and efficient integration of new airspace users. The concept includes the definition and validation of operational and technical concepts for airspace management, information provision, traffic flow and monitoring as well as defining a communication, navigation and surveillance infrastructure. Based on these concepts, a simulation and demonstration platform for urban ATM has been developed in City-ATM. From 2018 to 2021, the City-ATM project investigated new concept elements enabling drone flights in urban areas. City-ATM was a DLR funded project and was carried out in close collaboration with 6 external partners Auterion, DFS, FlyNex, KopterKraft, NXP, and ZAL. In total, three live demonstrations have been prepared and conducted, showing different aspects on how drones can be operated in urban areas in a safe and efficient way.

Keywords: U-space, live drone trials, bridge inspection, dynamic geo-fencing, dense traffic, autonomous flight

1. Introduction

In 2018, the German Aerospace Center DLR launched the internally funded project City-ATM. The idea was to build a concept for the operation of drones in urban areas – and prove the feasibility of the operational concept by means of live demonstrations. The project was subdivided into three phases, each one having its own focus.

In collaboration with numerous stakeholders (Auterion, DFS, FlyNex, KopterKraft, NXP, and ZAL), a basic City-ATM architecture has been developed based on SESAR U-space Services. The difficulty is to establish a system that makes necessary information available at the right place and time and all subsystems can communicate with each other. A future airspace management system for unmanned and manned airspace users - especially flights in urban areas - needs to comply with a variety of boundary conditions in order to ensure a safe and efficient integration of new airspace participants. These airspace users can be very diverse and, in addition to VFR air traffic, also include other users such as personal air vehicles (PAV), cargo UASs, parachutists, weather balloons or prioritized traffic (such as rescue helicopter). In addition to aspects of different design, performance and abilities, additional requirements for protected flight areas (so-called geo-fencing) or favored, risk-minimized routes must be considered in a U-space concept [1].

In recent years, many initiatives have been launched to develop a suitable, efficient and above all safe system. Eurocontrol [2] provides an overview of the numerous projects and initiatives of national and international organizations. Emphasis shall be put on U-space and the CORUS project (Concept of Operation for European UAS Systems). CORUS defines a Concept of Operations (ConOps) for unmanned aircraft systems in very low-level airspace and provides the foundation for European Unmanned aircraft system Traffic Management (UTM) systems. CORUS is an overarching project for several other UAS projects and sets a baseline for almost all of them. In the ConOps, three types of airspace are described including rules of the air, services and obligations. One airspace („Z“) can only be entered with specific permission. Another airspace („X“) allows easy access but requires the drone pilot to maintain separation by maintaining the drone at all times in Visual Line of Sight (VLOS). The third airspace („Y“) introduced at U2 level [3] provides strategic conflict resolution, therefore access to this airspace requires a flight plan and tracking for all drones; even those flying in VLOS. Tracking drones requires that the drone (or something attached to it) emits position reports and a connection to a U-space service that is creating a track (Tracking Service). This could be realized in numerous ways, but CORUS does not specify how [3][4].

At this point, City-ATM tries to find solutions and to enable the goal of "all aircraft in all airspace". As part of the step-by-step approach, this paper presents the basic system developed within the project. In this context, appropriate feasibility analysis based on flight tests and demonstrations have been conducted.

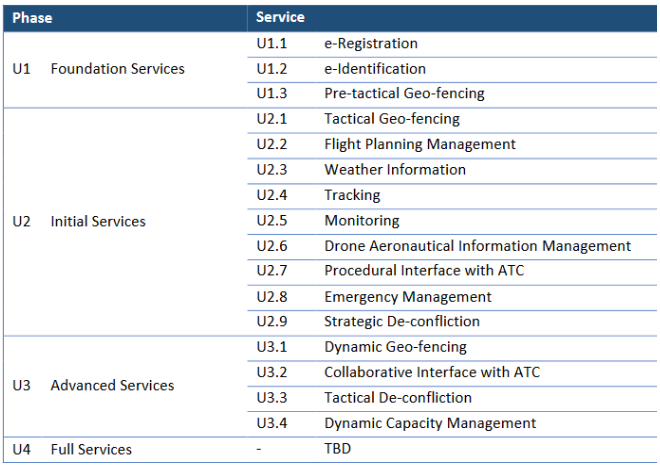
Besides legal and operational requirements, a concept in terms of a suitable architecture has to be established to ensure a safe and efficient integration of new air space users.

The SESAR U-space Blueprint [5] and the European ATM Master Plan [6] take up on this aspect and have compiled a list of services (see

Table 1) that the system must contain. These are linked to the increasing automation and complexity of the system to provide full air traffic management (see Figure 1).

These services each contribute to an overall system behavior and are only useful when they interact with each other and provide necessary information to others. To which extent each service is designed is within the scope of this research. Figure 2 shows a first idea on how these services are linked. The general functions of each individual service are based on the European ATM Master Plan [6] and shall not be repeated.

Table 1 U-space services [7]



Phase		**Service**	
U1	Foundation Services	U1.1	e-Registration
		U1.2	e-Identification
		U1.3	Pre-tactical Geo-fencing
U2	Initial Services	U2.1	Tactical Geo-fencing
		U2.2	Flight Planning Management
		U2.3	Weather Information
		U2.4	Tracking
		U2.5	Monitoring
		U2.6	Drone Aeronautical Information Management
		U2.7	Procedural Interface with ATC
		U2.8	Emergency Management
		U2.9	Strategic De-confliction
U3	Advanced Services	U3.1	Dynamic Geo-fencing
		U3.2	Collaborative Interface with ATC
		U3.3	Tactical De-confliction
		U3.4	Dynamic Capacity Management
U4	Full Services	-	TBD

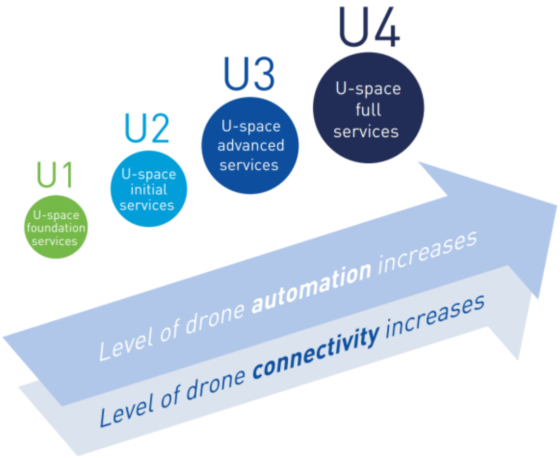


Figure 1 - U-space timeline [5]

In addition to U-space Services, UAS Health Monitoring and Risk Assessment are also included in Figure 2. These have not been assigned to any stage of development and are responsible for monitoring the technical condition of the UAS and carrying out a risk assessment. Figure 2 shows the potential stakeholder involvement in a future U-space. Especially the Urban Service Provider (USP) as well as the Drone Pilot take an important role, where information is retrieved/received and processed. But this may not be the final solution, also de-centralized solutions are imaginable. Furthermore, dashed lines show potential for additional interfaces. Within the scope of this research and besides the general system architecture the information transfer (including the definition of necessary information) as well as the design of interfaces is considered.

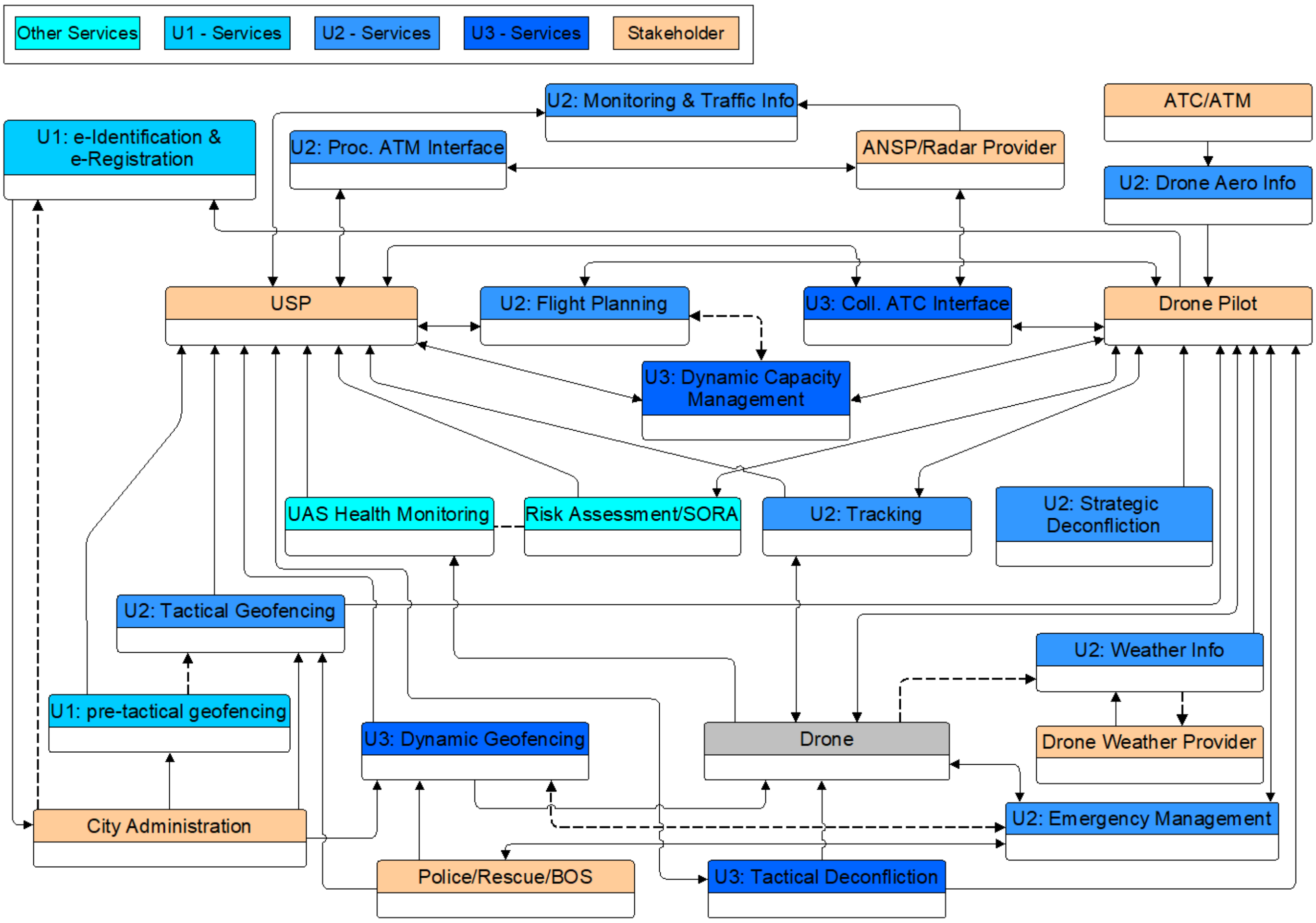


Figure 2 - City-ATM architecture model for U-space services

The paper describes the City-ATM concept, with a focus on the three live demonstrations carried out. The described concept elements contribute to a safe and efficient integration of drone traffic in urban areas. Videos of the three demonstrations are available on YouTube [7]-[9].

2. Phase 1: Bridge Inspection in Hamburg

Phase 1 demonstrated an inspection of the Koehlbrand Bridge in Hamburg [10]. The implemented concept is also the baseline for phase 2 (section 3) and phase 3 (section 4) demonstrations. Only essential baseline services have been considered, implemented and investigated in the first phase.

2.1 System Layout

Figure 3 shows the services included within phase 1. It covers several components starting with mission/flight planning respecting geo-fences, e-registration and e-identification and calculating a 4D-trajectory for strategic de-confliction. All these services take place before take-off.
While the drones are in the air, services in terms of tracking as well as conflict detection and warning have been implemented. This information is joined in the DLR in-house development called U-Fly, providing an air situation display with information on surrounding traffic.
Besides the system components in terms of services, the project also focuses on technical aspects. Three drones have been set up with different communication equipment to validate performance characteristics. Table 2 summarizes the technical attributes of the three main drones, that were also used for phase 2 and phase 3 demonstrations. Technologies from different stakeholders like NXP, KopterKraft and DFS have been implemented. With these technologies, several flight tests have been conducted as described in Volkert et al. [4] and Lieb and Peklar [11]. Within the next section, each of these system components will be described in more detail.
E-identification allows authorities to identify a drone flying and link it to information stored in the registry. The identification supports safety and security requirements, as well as law-enforcement procedures. Necessary information includes:

- Drone characteristics
- Pilot information

- Licenses
- Insurance

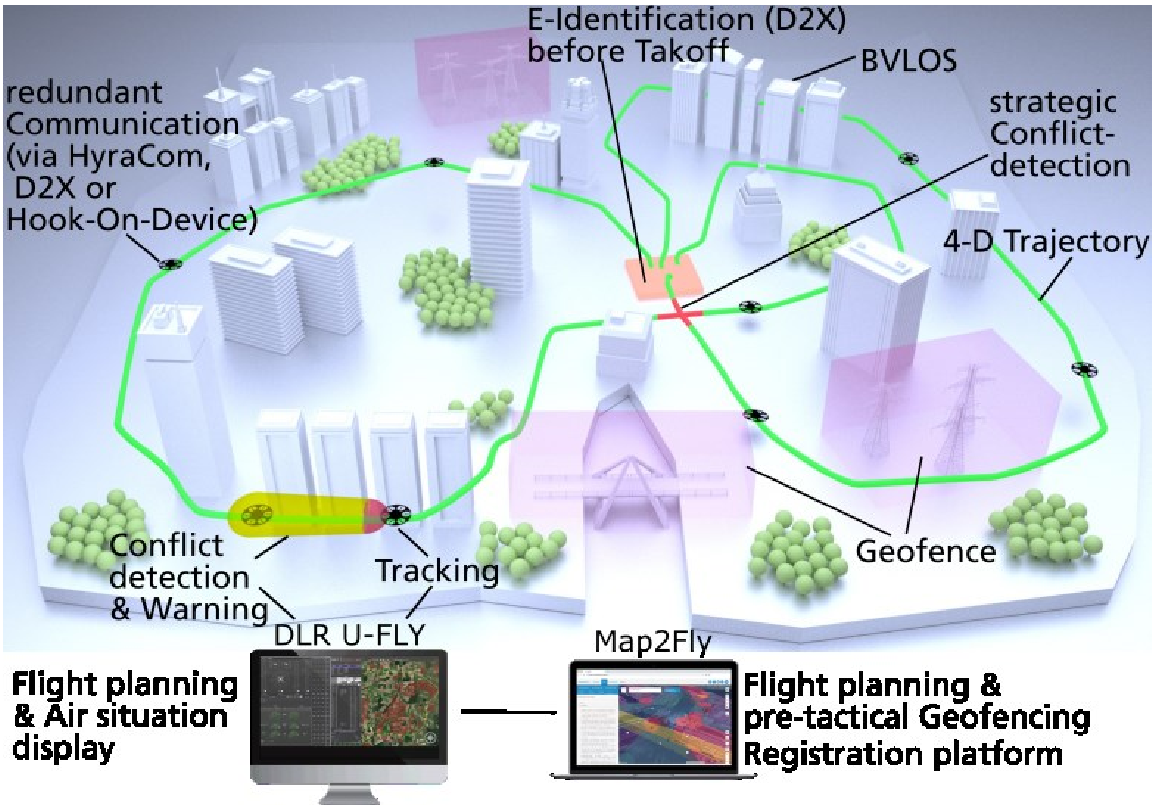


Figure 3 - City-ATM architecture for phase 1

Table 2: Technical attributes of the three major U-Fly drones

Producer:	**DJI DroneX**	**Self-Construction based on DJI M600**	**Self-Construction**
Material:	Carbon	Carbon	Carbon
Model:	DJI S900	DJI M600	DexHawk
Weight:	6.8 kg	10.5 kg	7 kg
Length:	988 mm	1668 mm	1620 mm
Width:	988 mm	1518 mm	1620 mm
Height:	400 mm	759 mm	780 mm
Operated by:	DLR-KN	DLR-FT	DLR-FL
Major Design Aspects	Carrying experimental hardware for development of innovative **communication and navigation solutions** for drones in a partially modular manner.	Automated flights over inhabited areas **beyond visual line of sight** using the new EU regulatory framework.	Designed for bad weather conditions and operations in the vicinity of **maritime environments**. Electronic equipment is located inside the airframe.
Propulsion System	6 x 17-inch propellers.	6 x 21-inch propellers.	8 x 17-inch propellers.
Power Supply	2 x 6S lithium polymer (LiPo) batteries with 10000 mAh each, up to 20 minutes.	6 smart batteries, up to 30 minutes. Redundancy allows up to three battery failures at once.	6S lithium polymer (LiPo) battery with 16000 mAh, up to 20 minutes.
Flight Controller	Pixhawk 2.1 running Arducopter flightstack. RTK GPS available.	Flight controller has been replaced by a Pixhawk 4 running the PX4 flight stack	Pixhawk 2.1 running the PX4 flight stack with a triple redundant IMU component. RTK GPS available.
Parachute	n/A	DRS-M600 by Drone Rescue Systems	DRS-10 by Drone Rescue Systems
Datalink	For command and control a 2.4 GHz and a 433 MHz datalink is installed. RTK correction data is transmitted via an 868 MHz datalink. DFS HOD communicates with the City-ATM system. In addition, a Cohda Wireless MK5 OBU is installed to experimentally test IEEE 802.11p performance and estimate channel parameters.	For BVLOS operation the combination of the mesh network with the 4G (LTE) network allows redundancy. D2X datalink and the DFS Hook-On-Device for communication between the drones and the City-ATM system	Communication via 4G (LTE) connection, 433 MHz, 868 MHz or via D2X technology (5.8 GHz). The HyraCom 4G link transmitting 16 RC channels, MAVlink commands / telemetry and HD video streams allows also BVLOS operation and tracking messages to DFS.
Navigation, Detect and Avoid	JAVAD TRE-3 GNSS receiver, Xsens MTi-G-710 INS as well as a camera system to develop multisensory navigation approaches and enable safe and reliable flight execution	The FLARM transceiver allows detect and avoid functionality regarding manned aviation without the use of a future City-ATM system, based on FLARM and ADS-B messages.	The installed D2X module allows position exchange between drones.

Within the project, expertise from FlyNex and NXP has been used to set up both services. Authentication and approval before take-off are realized by a Near Field Communication (NFC) tag.

Planning a mission includes a start and destination point as well as additional intermediate waypoints.

Pre-tactical conditions, such as terrain, geo-fences or prohibited zones are considered. The planning module is divided in two stages. First part of the mission planning includes information and validation on:

- Mission characteristics (flight plan ID, start and destination, day of operation, time, pilot, etc.)
- Flight route validation (allowed area of operation, controlled zones, information on necessary permissions, warnings, etc.)
- Drone (ID, type, performance data, safety systems, etc.)
- Checklists (general, specifications, etc.)

Besides general mission planning (using FlyNex's online platform Map2Fly), the City-ATM architecture also considers performance characteristics of the drone, itself. Thus, strategic conflict detection and resolution can be performed. Before a drone actually takes off, a 4D-trajectory is calculated and compared with surrounding traffic. Conflicts can be detected already on ground. This is done by DLR's U-Fly in combination with DLR's generic Flight Management System (FMS).

During flight, the developed approach includes a tracking service as well as a conflict detection, which generates warnings in case of predicted separation violations. The surveillance service is enabled by each drone providing its position to a tracking service, that distributes the information to other airspace users. D2X, HyraCom and DFS Hook-On-Device are technologies used to transmit position data to the DFS tracking service. Besides the standard telemetry connection using 868 MHz that was already installed on each drone, the drones are equipped with the Hook-On-Device transmitting position data directly to the DFS and two generic datalinks: the mesh-capable D2X and the threefold redundant Beyond Visual Line of Sight (BVLOS) capable HyraCom:

- The Drone-to-Infrastructure datalink called D2X contributed by NXP [11]: The link uses the 5.8 GHz frequency band. The link is formed between air and ground modules as an open mesh network using MAVLink protocol [14] over 802.11p Wi-Fi standard. Besides telemetry data between a drone and a dedicated ground station, each drone broadcasts its own position data. In this Drone-to-Drone mode (D2D), two air modules exchange position data comparable to ADS-B (Automatic Dependent Surveillance – Broadcast) for proximity warnings. The D2X DSRC solution based on NXP's RoadLINK SAF5400 single chip modem is designed to provide a reliable link with very low latency, fast reconnection time and high data rates up to 27 Mbit/s. SAF5400 is compliant with IEEE 802.11p, IEEE 1609.4 and qualified in accordance with AEC-Q100 grade 2.
- The HyraCom provided by KopterKraft [4]: This link is threefold redundant, using 868 MHz, 2.4 GHz and 4G (LTE) and is mesh-capable. The 4G connection allows BVLOS flights. It transmits 16 RC channels (taken from the trainer port of a conventional RC hand-held unit provided as S-Bus signal on the air unit), MAVLink command and telemetry as well as up to two HD video streams with low latency over unlimited distances, as long as there is a mobile 4G connection available. The ground unit can be used standalone. MAVLink pass-through to ground control stations like QGroundControl or MissionPlanner is available via Bluetooth.
  It can transmit MAVLink UTM_GLOBAL_POSITION messages, e.g., for tracking via UDP or Message Queuing Telemetry Transport (MQTT) to the DFS position tracker. To show the real-time capability of the datalink, the onboard HyraCom module is equipped with a camera that downlinks a live video stream.

The redundancy of datalinks was chosen to meet the technical requirements on C3 datalinks (Command, Control and Communications) for BVLOS flights in sparsely populated areas in accordance with SORA.

In the following, the information flow between the services is described. Initiated by the drone pilot, information about the planned mission (mission planning) generates a flight path from the start point to the destination. Before the process can be completed, information from pre-tactical geo-fencing is required. This service obtains information about the weather situation (Go or No-Go) as well as geo-coordinates from the underlying databases. Thus, during flight path planning possible airspace-related conflicts are avoided. The conflict detection and resolution capabilities are described for the final integration in section 4. Subsequently, a refinement of the mission planning takes place, which is carried out by the flight planning module integrated in the DLR U-Fly. By respecting the flight characteristics, the flight path is converted into a flyable 4D trajectory (see Figure 4).

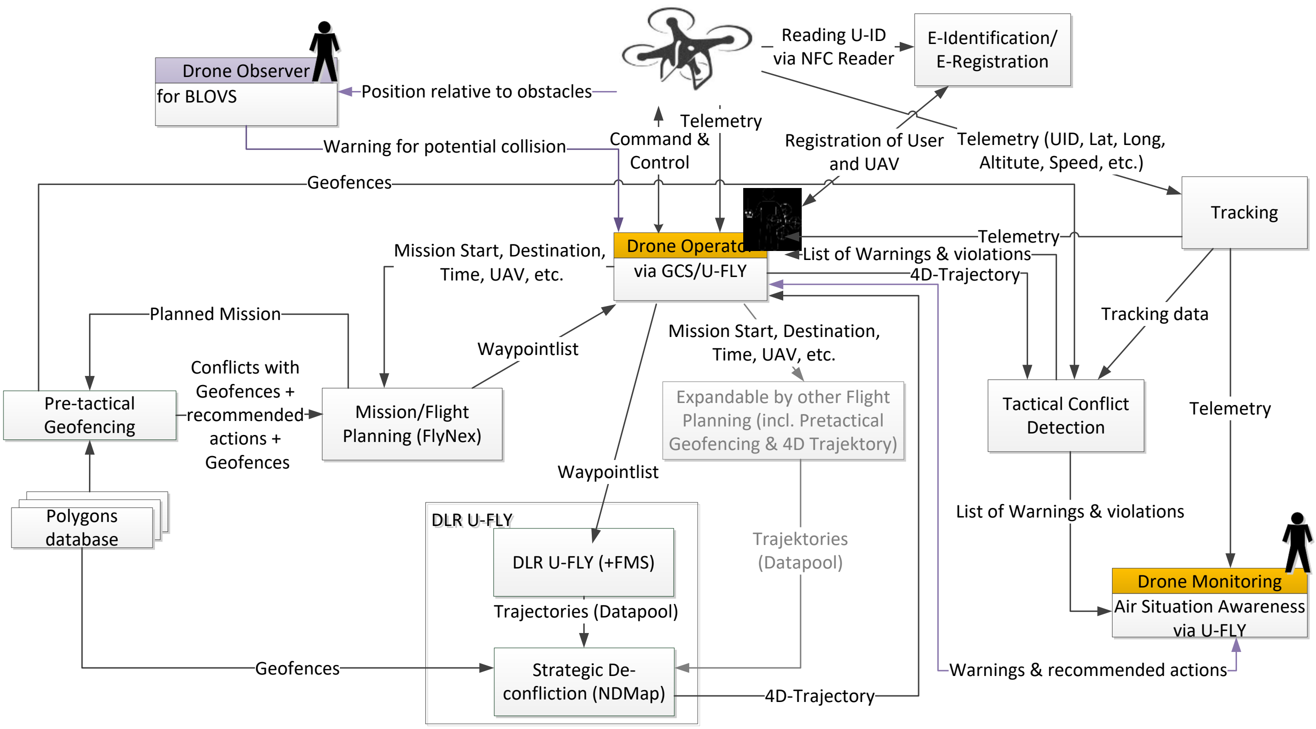


Figure 4 - Information flow-chart

In a multi-drone scenario, the flight clearance takes place after all trajectories have been checked to be free of conflict. Conflicts are resolved by spatial route changes. Also, violations of airspace restrictions (e.g., geo-fences) are resolved by route changes. The drone pilot is thus provided with a conflict-free route, which is also flyable in terms of drone's performance. In the case of a necessary route adjustment, the user is required to confirm.

A parallel process includes e-identification and e-registration. The drone pilot registers himself and his drone on a registration platform, which stores data as described above. The actual identification takes place by reading the serial number of the drone. This is included in all information flows (interfaces) to ensure constant identification.

After strategic de-confliction and authentication, the drone can take off. During flight, the tracking service receives and processes the current telemetry data from the drone. The drone pilot is now able to track the drone's current position. The telemetry data of all drones are also collected and processed into an aerial situation report. By comparing actual flight paths, approaches between drones can be identified and corresponding warning messages are sent out (tactical conflict detection). These alerts are also sent to airspace monitoring (air situation), which processes them, generates solutions, and communicates these alerts and route changes to the drone pilot.

In the special case the drone is operated BVLOS of the pilot, a drone observer monitors the position of the drone for close-by obstacles and warns the drone pilot via radio/telephone if required.

2.2 Execution of flight trials

Main objectives of the use case "Bridge Inspection in Hamburg" were to carry out a multi-drone flight demonstration with a partially performed BVLOS flight and operation of various navigation and communication technologies. Additionally, the general system architecture shall be validated in terms of the feasibility to have an information flow between all relevant actors for flight planning, clearance and flight operation. Therefore, the demonstration included several events showing the technical implementation under realistic environmental conditions.

Since the demonstration was conducted in the urban area of Hamburg City inspecting the Koehlbrandbridge, several authorities had to be involved for permission. For operating several drones in this area, the aviation authority, air traffic control, Hamburg port authority, surrounding industry plants and property owners were involved. Each of them had to agree to the planned flights.

After finishing mission planning, the generated data were read by the U-Fly. By importing the waypoint data, the FMS module calculated the 4D trajectories involving the flight performance. Each mission has then been uploaded to the drones including additional geo-fences for safety reasons (e.g., No-Fly Zone

(NFZ) protecting the bridge's deck).

During flight, each drone transmitted its position to the DFS tracking system via HyraCom, D2X and the DFS Hook-on-device. The MAVLink UTM_GLOBAL_POSITION message has been used to identify each drone during flight. The U-Fly retrieves the data from the DFS Tracker and shows all surrounding traffic. Furthermore, separation violations were tested by forcing two drones flying very close to each other.

In consultation with aviation authority and Hamburg Port authority, shipping had to be respected at all time. Drone operations had to keep a distance of at least 100 m to any ship. Therefore, drone operations only took place at daytimes with low traffic. If a ship was in the vicinity, a coordinated return-to-launch (RTL) had to be performed. With two drones operating at the same time, they were flying in different altitudes, so RTL could be performed immediately to avoid intrusion in ship areas. Reaching the western pillar, drones got separated by observers using position hold commands.

Each drone is secured against sinking by attachment of an automatically inflating float of the company Restube. Furthermore, a boat for salvaging a watered drone in close proximity to the flight area was provided. In case of emergency, the last known position is reported and with the clearly visible floats the drone can be salvaged.

Besides technical equipment, the demonstration team consisted of pilots, five drone observers, a drone monitor, ground station operator and an examiner. For each of the drones operating during the demonstration one pilot was in charge. All missions were uploaded to the drone and flown automatically. The pilots had the opportunity to intervene at any time and take over control. The drone observers were positioned on the bank spread around the flight area. So, all waterways could be surveilled, ensuring separation to shipping and other obstacles. In case a ship approached, the observer transmitted either the command position hold (emergency) of RTL (ship approaching) to the drone monitor by radio. The drone monitor is positioned next to the pilot to pass on the command and to read back. Also positioned next to the pilot, the ground station/U-Fly operator monitors positions, conflict warnings and the drones' health. Accordingly, the information is passed on to the pilot. Last but not least, the examiner is in charge of take-off clearance and termination (in case of emergency) by considering a ship tracking system.

In the following, each mission is described. The first drone takes off on the bank very close to the western pillar of the Koehlbrandbridge and climbs to a height of 10 m. Followed by a slow climb to 30 m at a speed of 5 m/s, the drone flies parallel to the bridge to the eastern bank. There, the drone changes direction to fly closer to the bridge and to return to the yellow position shown in Figure 5. At this position the drone remains for 90 s. Afterwards, the drone returns to the take-off position.

The second mission also starts on the bank close to the western pillar. After take-off and vertical climb to 10 m, the mission contains a slow climb to 20 m at a speed of 5 m/s. First, the mission path is parallel to the bridge, followed by a 90-degree right turn flying underneath the bridge, making a turn and returning to the north side again. The mission is continued by flying to the eastern bank, while crossing the yellow position in Figure 6. In case of correct timing and while crossing this yellow point, the distance between drones flying mission #1 and #2 gets too small, generating a conflict warning. After reaching the eastern bank the drone returns almost directly to the take-off place.

Due to flying underneath the deck and behind a bridge pillar, communication between drone and ground station is very crucial. For safety reasons, this mission is flown with the HyraCom providing a multiple secured communication.

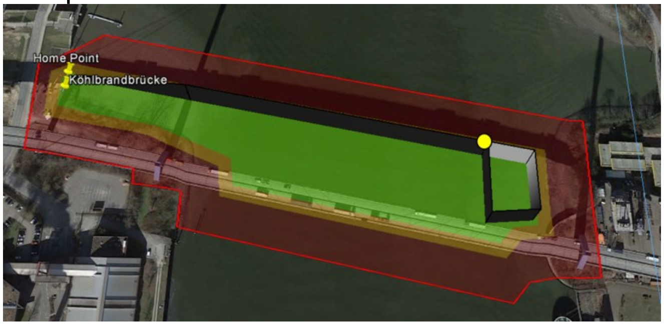


Figure 5 - Mission #1

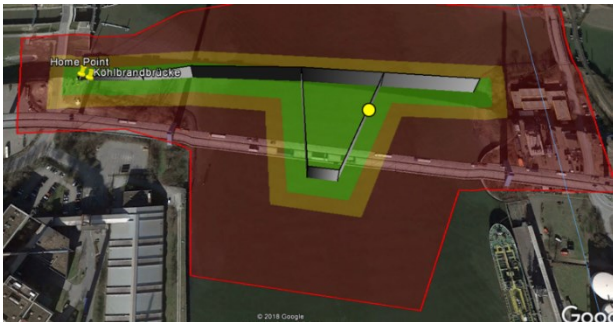


Figure 6 - Mission #2

The third mission is a single flight, with only one drone in the air. As before, the drone takes off at the western pillar and climbs to 10 m. Getting to the mid part of the river, the drone continues its climb to 20 m and afterwards returns in the direction to the take-off location. At the same time, the drone reduces altitude to 10 m again. Before the drone actually lands, the mission is continued by flying underneath the bridge around the western pillar, remaining there for at least 60 s (see Figure 7).

Besides the three missions described, also several manual flights have been performed around this area.

In a multi-drone scenario, separation violations may occur and strategical as well as tactical conflict detection is necessary. Figure 8 shows missions #1 and #2 in direct comparison, depicting several crossing points. To validate the functionality of conflict detection, both drones operating on these missions were timed in a way that separation is violated when one drone is holding its position (yellow point) and the other drone is flying around it. For safety reasons, an additional vertical separation of 10 m was established. When separation is below 70 m, a warning is generated and displayed on the ground station U-Fly.

Performing this demonstration, functionality of all services is required. First, each mission is planned and a 4D-trajectory is generated. Separating take-off of both missions by 20 s creates a conflict (red flight path) by looking at the strategic de-confliction module (see Figure 9).

In order to have conflict detection working during flight, position data need to be transmitted to the DFS Tracker. As shown in Figure 10, DLR U-Fly retrieves the data and detects a conflict between both drones while performing mission #1 and #2. In the shown situation the distance is only 38.6 m and there is a red warning displayed.

As last demonstration point, crack detection was conducted, using a Sony A7 equipped with a Leica Apo Summicron-M 2/90 90 mm lens. Objective of this demonstration was to have a resolution of at least 0.5 mm. Therefore, the camera was focused on a distance of 7.5 m with fixed aperture on f8.0. This results in a sharpness range from 7 to 8 m. Every second a picture was taken.

Positioned 7.5 m away from the pillar the drone was supposed to climb up and down again along the pillar at a very slow speed of 0.6 m/s. Unfortunately, the take-off and landing mode did not work as desired, so that the drone had to be controlled manually. Post-processing flight logs were analyzed filtering the times where the distance to the pillar was between 7 and 8 m.

For the next project phases the basic system architecture was extended by additional U-space services. As use case in phase 2, an emergency scenario was demonstrated.

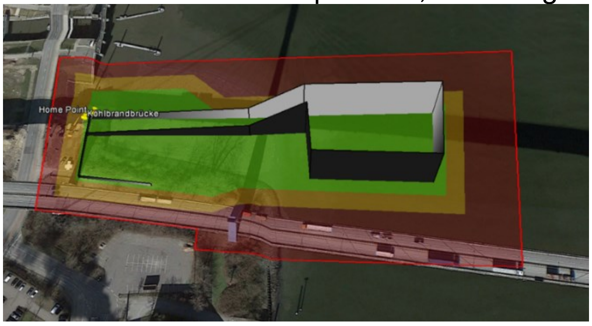


Figure 7 - Mission #3

Figure 8 - Mission #1 and #2 in direct comparison

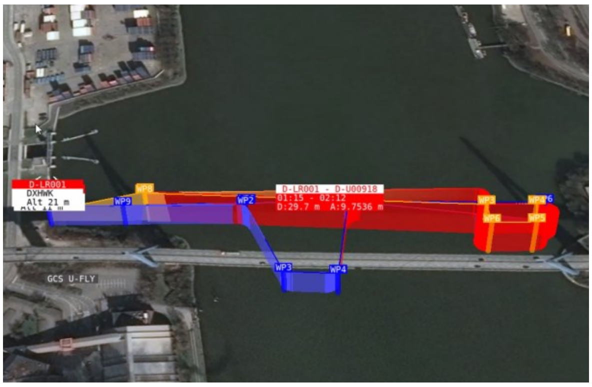


Figure 9 - Strategical confliction detection

Figure 10 - Tactical confliction detection

3. Phase 2: Dynamic Geo-Fencing around Hazard Area

The phase 2 demonstration investigated dynamic geo-fencing [15]. Both the concept and the software/hardware layout are based on the trials of phase 1, enhanced by features enabling dynamic geo-fencing. The corresponding scenario is based on a hazard area that is detected by an emergency service drone. Once identified, a dynamic geo-fence is generated surrounding the danger spot. The data is uploaded immediately to a central management system, storing information for all active no-fly zones. Drones that might already be in air are informed about the new dynamic geo-fence, and can respect it in their progress of flight.

The geo-fence technique is already well-known and widely under investigation for several years. Geo-fences are used to protect sensitive areas (like airports or the car traffic on the Koehlbrandbridge in phase 1), civil aviation uses a kind of geo-fencing to model temporary reserved areas (TRAs) [16], and some research already focused on dynamic geo-fencing [17][18]. Scenarios with dynamic creation and deletion of geo-fences are described by Alarcon et al [19].

Geo-fences are used to model geo-limitations. To implement geo-fencing, a position of an object has to be tested against a geo-limitation; the object is either inside or outside of the limitation. A geo-fence can either be defined as

- “stay-in” by defining a Fly-Zone (FZ) that a vehicle is not allowed to leave, or
- “keep-out” by defining a No-Fly-Zone (NFZ) that a vehicle is not allowed to enter.

A general severity can be assigned to a geo-fence, reaching from an advice to not break the boundaries (e.g., to avoid high traffic situations) to an absolute interdiction as a protection against catastrophic consequences.

Furthermore, a protection level allows defining access rights depending on the type of vehicle. It may be necessary to grant access to emergency service vehicles while all other traffic is refused.

Geo-fence information needs to be distributed in the whole system to reliably avoid violations. Knowledge of geographical limitations is essential on both ground and air-side. In the City-ATM project, the U-Fly collects geo-fence information from the central geo-fence server. Each time an update of geo-fence data is received, all connected drones get the same information via the datalink upload. This way, drones can autonomously detect potential violations by checking their own position against the geo-fence coordinates. This relies on an accurate position knowledge, that is usually calculated from different sources, like Global Satellite Navigation Systems (GNSS), Inertial Measurement Unit (IMU), or other onboard sensors [20].

The drones are equipped with a Pixhawk PX4 flight control software allowing onboard conflict detection. Board-autonomous conflict resolution like planning a trajectory around a geo-fence was not supported by the PX4 for phase 2, but will be shown using a different technique in phase 3, see section 4. The reaction on a potential violation of a geo-fence is configurable (return to launch, land, hold). For these trials, drones are programmed to hold position board-autonomously, rather than violating a geo-fence. Thus, even if the datalink fails, drones will fly according to given constraints.

Since a geo-fence penetration cannot be forecasted by the drones in use, it is not detected before the drone actually violates the geo-fence boundary. Thus, drones may overshoot the geo-fence boundaries, slow down and fly back to the boundary. This behavior must be considered by inflating the protected area by an extra margin, also covering possible position inaccuracies. Since the drones fly rather slow with about 10 m/s, these margins can be small.

Geo-fence information is also taken into account by the U-Fly that is equipped with a complete Conflict Detection and Resolution (CD&R) infrastructure. The CD&R integration is described in more detail in section 4.

Geo-fences can either be static or dynamic. Static geo-fences are well-known before departure, and model static limitations of a geographical area, like NFZs around airports and other sensitive areas. The term dynamic geo-fencing is not used consistently in literature. The term “dynamic” may either be related

- to the shape and position of the fence that may change over time (e.g., to model a tube of protection around the trajectory of vehicles) [17][18], or
- to the dynamic creation or expiration of a geo-fence that may happen when vehicles are already in-flight [19].

In the City-ATM project, geo-fences are dynamic in terms of their declaration time. Vehicles may already be airborne when a geo-fence is defined and opened. Separation violations between vehicles are not modeled by means of geo-fences, but distance metrics.

Geo-fences are generally defined in four dimensions. In the latitude/longitude plane, the geo-fence is defined by a non-self-intersecting closed polygon defined by an arbitrary number of vertices. Also, complex concave boundaries or areas with holes are supported.

In the altitude dimension, the geo-fence is defined by an interval, setting a lower and upper boundary where the fence is valid, reference is mean sea level. Vehicles are allowed to travel below lower and above upper boundary. In addition, a timeframe specifies the earliest and latest time between which the fence is active.

Non-orthogonal side-boundaries are not supported directly. If a geo-fence changes shape over altitude, the fence can be modelled by a vertical stack of different geo-fences, each defined for the corresponding altitude layer. A grouping mechanism allows having one unique identifier for the whole stack.

The same accounts for the time dimension. If the hazard area moves or changes shape over time, for example a cloud of smoke, the corresponding geo-fence can be modelled by subsequent instances of individual fences. In this case, each instance describes the NFZ for a small period of time, for example, 5 minutes. Individual fences can be stacked time-based and grouped to a single object.

A geo-fence used in City-ATM is always defined as a NFZ. A stay-in geo-fence can be modeled easily by a hole in a keep-out fence.

3.1 System Layout

The system layout for demonstration phase 2 (see Figure 11) is based on the modules developed for phase 1. A new server in the system, that is hosted and operated by FlyNex, handles dynamic NFZs. New geo-fences can be generated dynamically on this server using a web frontend.

DLR’s U-Fly connects to the geo-fence server via web sockets and receives updates of recently created geo-fences. Furthermore, the U-Fly reads new missions from the Map2Fly module also operated by FlyNex, ensuring that missions are compliant with all aerial constraints available.

Using the Copter Flight Management System (CFMS), the U-Fly predicts 4D-trajectories that can directly be uploaded to drones. The CFMS is an update of the FMS used in phase 1 and calculates the trajectory based on the flight plan, drones’ performance data and wind information. After activation, the drone will follow the trajectory. Since no real 4D guidance modules are available for drones, the time dimension is currently not considered. Time consistency of the 4D-trajectory is pursued by assuming typical speeds of the drone in the trajectory prediction process.

The conformance monitor module checks if the drones’ positions are in accordance with the assigned trajectories and generates a warning otherwise, leading to regeneration of the corresponding trajectory considering the actual position. Allowed deviations from the trajectory have been set rather low with 5 m horizontally and 5 ft vertically.

The 4D-conflict detection module holds all relevant information, including trajectories and positions of all vehicles in the mission area and both static and dynamic geo-fences. The CD&R is highly scalable and can easily work with several thousand objects. If a conflict is identified, resolution algorithms provide suggestions to the U-Fly operator on how the conflict may be resolved most efficiently. The ground side uses complete trajectories instead of current position to check for conflicts with geo-fences (and other traffic). Therefore, the CD&R suite can calculate separation violations in the future and predict resolutions well in advance. Details on the high-performance CD&R module are described by Kuenz [27].

The CD&R software can be configured to report only relevant conflicts. While a separation violation between two civil aircraft will be of minor interest for the drone operators (while it should be of high interest for someone responsible), an identified conflict between one of the drones under control and a civil aircraft is of high significance. Separation requirements can be adapted to match the vehicles’ configurations. Instead of a simple cylindrical conflict metric, also more complex metrics can be used [21].

In the optimal case, these metrics should not only be different per drone (due to different abilities of each drone to follow a planned trajectory) but also dynamic due to temporary effects like GNSS reception and therefore navigation performance, environmental effects like wind or communication delays.

One aspect in the project is therefore the development of multi-sensor navigation concepts that not only provide the required accuracy but, even more importantly, give reliable error bounds on the current estimated position. While the required high accuracy is already available with commercial systems like Real Time Kinematic (RTK), proving integrity bounds, especially in such a UTM context, is still an open issue that can hardly be solved by satellite navigation alone. A combination of GNSS with local corrections (similar to Ground Based Augmentation System (GBAS) in civil aviation), visual navigation and inertial measurements is therefore proposed to cope with the high requirements in challenging urban environments [22][23]. Using these estimated navigation error bounds for separation and trajectory planning is one aspect in the ability to ensure safe traffic management and deconfliction. For details on overbounding navigation errors and ensuring integrity for such multi-sensor systems, we refer to our ongoing parallel research [24].

Conflict-free trajectories can be directly linked up to the vehicles. In phase 1, the U-Fly had no direct connection to the drones. Flight plans had been transferred to the Q-Ground-Control-Station via USB-stick and then uplinked via the Q-Ground Control Station. Since geo-fences shall be uploaded dynamically to the drones, a direct connection was established for phase 2. The direct connection allows different services:

- Flight data are presented to the U-Fly operator for monitoring position, conflicts (detected by the CD&R module), and health status.
- If the drone is equipped with a Hook-On-Device (HOD), it automatically sends its position data to the DFS. If the drone is not equipped with an HOD, the U-Fly sends the corresponding data to the DFS, alternatively these messages can also be directly sent from the HyraCom air unit.
- Geo-fences received from the FlyNex-server are converted and transferred to each drone. This enables drones to avoid geo-fences board-autonomously.
- The flight can be controlled from ground via the datalink.
- Position and state data are downlinked regularly.

The DFS tracking service called PHOENIX collects position reports sent by UAS, civil aircraft, light aircraft, and drone detection systems. These sensor data consist of primary radar echoes, replies from Mode-S interrogations (Second surveillance radar, Multilateration), passive emitter tracking, active ADS-B and FLARM squitter or active position reports from UAS via mobile communication techniques (MAVLink, comma-separated values). The service interface acts as a publisher/subscriber system using the MQTT protocol. For security reasons, MQTT is embedded in the Secure Websocket protocol. The PHOENIX system receives all position reports and processes these data using multi sensor data fusion. It correlates all sensor data which can be assigned to one vehicle. Based on the Extended Kalman Filter a vehicle can be tracked using multiple sensors redundantly. The PHOENIX system provides the resulting track to all MQTT subscribers. Track data are available in Eurocontrol ASTERIX CAT062 format or as PHOENIX JSON Track Data. One of these subscribers is the DLR U-Fly ground control station.

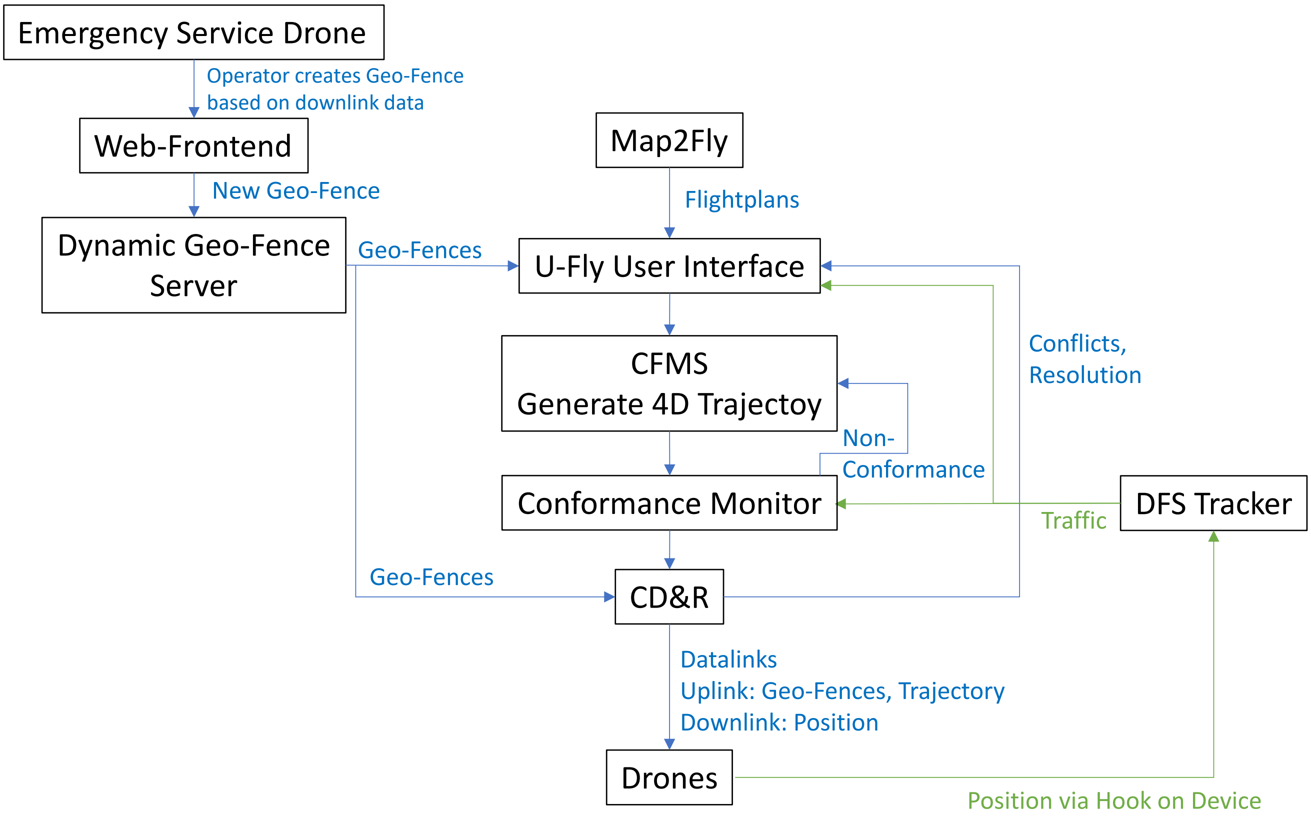


Figure 11 - System layout of flight trials in phase 2

PHOENIX provides track data with 2D-position, altitude and 3D speed vector of civil aircraft, light aircraft, glider, and drone. The calculated altitude of the track data relates to the reference system Mean Sea Level (MSL). Geometric altitudes based on the WGS84 earth ellipsoid are converted to MSL by adding the position dependent undulation. Barometric altitudes (QNE) are corrected by the current QNH of the nearest airport. The ability to convert geometric and barometric altitudes to one reference system enables collision avoidance systems to increase their accuracy.

3.2 Flight Trials

Flight trials were initially scheduled for spring 2020 at the National Experimental Test Center for Unmanned Aircraft Systems in Cochstedt, Germany. Finally, the COVID 19 pandemic postponed the phase 2 demonstration to October 1st in 2020.

Figure 12 shows the demonstration setup in Cochstedt. The red circle shows the hazard zone that was simulated by smoke-bombs. An emergency service drone (red flight path, provided by DLR Institute of Optical Sensors, see Figure 13) was used to explore the area around the hazard zone. The fast flying Vertical Take-Off and Landing (VTOL) drone was equipped with a special version of DLR's Modular Aerial Camera Systems (MACS) [25]. The camera system was developed together with the fire department of the city of Duisburg (DLR research project "Live-Lage") and was deployed by Helmholtz Innovation Lab OPTSAL (Optical Technologies for Situational Awareness Lab). MACS is able to broadcast subsections of aerial images continuously to a ground control station. This is done by an appropriate radio link (IP-based). The subsection of every image is displayed in real-time on the ground as an overlay onto a digital map (e.g. GoogleMaps or OpenStreetMap) [26]. The result is a merged and geo-referenced aerial image mosaic which will be extended continuously as long as the emergency drone is flying. The image mosaic shows the situation on the ground of the area which was flown over by the emergency service drone. This visual information can be used by emergency personnel directly to assess the situation.

Once the smoke-bomb in the aerial image mosaic is identified, the emergency service provider will create a dynamic geo-fence around the hazard point. The geo-fence has a conservative size of 80 m x 70 m to compensate both position accuracy issues of the drones and possible overshoots when approaching the geo-fence's border. Furthermore, being just a virtual and not directly visible construct, the geo-fence was aligned to visual markers on the ground, like runway signs. The area has been marked with barrier tape to allow visual validation of the boundaries.

The NFZ is entered in the web frontend of the FlyNex geo-fence server. The NFZ has orthogonal boundaries, a rectangular shape in 2D, no time limitations and thus will be valid from creation until deletion. Serving mainly the demonstration purpose, the size of the NFZ is selected to allow reasonable lateral avoidance while being big enough to allow some operations within the NFZ when it is not active yet. Vertically, the NFZ starts at ground level and reaches up to 40 m above ground, affecting all flying drones except the rather high-flying emergency service drone. Originating from an emergency service provider, the trust level is high and the NFZ can be generated directly without further validation. The severity of the NFZ is high, protecting all flying vehicles against the danger inside.

At the time the NFZ is created, the well-known three drones (Table 2), all connected to the U-Fly ground control station, are already airborne.

Each drone has an individual flight plan and has knowledge of all strategic NFZs in the operation area. However, none of the drones knows about the hazard zone and the corresponding dynamic geo-fence yet. In contrast, the initial flight plans of all three drones go straight through the area that will later on appear as dynamic NFZ.

Once the U-Fly receives information via web socket connection from the FlyNex server about the newly established NFZ, it informs each connected drone via uplink. From that point on, the drones are able to avoid the NFZs even in case of datalink loss.

The U-Fly also writes the NFZ data to its internal database. The conflict detection software will immediately identify conflicts for all three drones with the NFZ and inform the U-Fly operator.

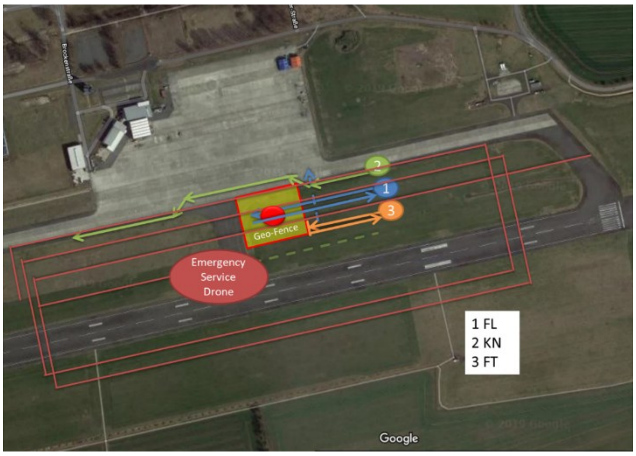


Figure 12 - Demonstration setup at the National Experimental Test Center in Cochstedt, Germany. The large red dot is the danger spot, surrounded by the yellow geo-fence (80 m x 70 m).

Figure 13 - The Emergency Service Drone with integrated MACS aerial camera system for real-time mapping applications

The dynamic NFZ reaches the drones in different phases of flight. Drone 2 (in green) is already airborne, but far enough away to replan the flight via the ground control station on a safe and conflict-free trajectory to the original destination

Drone 1 (in blue) is already inside the hazard area when the dynamical NFZ suddenly pops up. The onboard software will identify the drone being inside of an NFZ and switch to position hold mode, as configured. An onboard evacuation of an NFZ is not implemented on the drone (however on-board capabilities are extended significantly for phase 3, see section 4). The conflict will also be shown to the U-Fly operator who will replan drone 1 to evacuate the NFZ as fast as possible to the north.

Drone 3 (in orange) is still on its way towards the NFZ. Since no operator reacts on the detected conflict, the drone continues its flight until flying into the NFZ. The onboard software identifies the violation of the NFZ immediately when flying into it, flies the drone back to the border of the NFZ and enters position hold mode, as configured. The operator can safely fly the drone back to the launch pad.

On the days of demonstration, flight preparations began with some flight trials, checking all connections between drones and ground control stations, testing the link to the central geo-fence server and the connection from the web-frontend operated by the emergency service drone supervisor. On the second day, the flight demonstration was finally conducted. Already knowing that the smoke bombs would run only for a few minutes, a well-considered timing of the whole trials was essential.

Therefore, the trials started with the emergency service drone, performing a vertical take-off and climbing up to an altitude of 95 m above ground level. There, it started its mission of flying a search-pattern as shown in Figure 12. The high altitude increases the field of view of the downward looking camera and ensures a conflict-free operation with the other drones, which were operated below 30 m above ground level.

The smoke bombs (see Figure 14) were ignited while the emergency service drone was at its furthest distance. Once burning, the three remaining drones were started from the east. Drone 1 was directly flown into the hazard area and started circling around the danger spot to ensure it was inside the dynamic NFZ once activated. The other two drones were approaching the danger spot slowly.

The smoke bombs were detected on the monitor screen of the service drone during the next overflight (Figure 15). The operator generated a rectangular geo-fence around the danger spot. By means of the web frontend, the fence was uploaded to the central server.

Regularly checking the central server for updates, the U-Fly received the recently generated fence. Using its internal CD&R functionality, it detected conflicts with the three drones. The U-Fly also uploaded the geo-fence information to the drones. Once drone 1 received the fence data, it detected a conflict and switched into position hold mode. Drone 3, still flying towards the danger spot, automatically stopped at the fence boundary, also engaging position hold mode. Drone 2 was rerouted by the operator before reaching the fence. Both other drones were flown manually back to their launch positions. The flight trials fulfilled the expectations, each drone performed its work as expected, reacting on the dynamically introduced NFZ as required. An evaluation of recorded flight tracks proved conformance with the expected results.

Figure 14 - Smoke bombs simulated the hazard spot

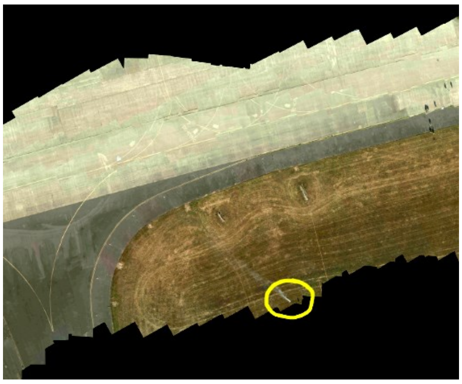


Figure 15 - Real-time aerial image mosaic of MACS was used to detect the smoke bomb, see yellow circle

However, also some shortcomings have been noticed, like the inability to detect NFZ violations on board in advance and to evacuate NFZs board-autonomously. Also, the traffic density could have been higher. These shortcomings have been tackled in phase 3.

4. Phase 3: Safe Operation in Dense Traffic

The phase 3 demonstration concentrated on operating drones safely in dense traffic situations [27]. Dense traffic has been achieved by several physical drones enhanced by many virtual drones, all crowding the same airspace. To reach a deep integration of virtual flights, the underlying simulation engine sent position reports (like also the physical drones do) to the central tracking server operated by the DFS. Thus, DLR's ground control station U-Fly got knowledge of all physical and virtual drones from the DFS server.

Equipped with conflict detection and resolution functionality, the U-Fly can safely operate all connected drones. Those drones only providing position reports are tracked and extrapolated into the future allowing Short Term Conflict Detection (STCD). Furthermore, drones also providing flight intent in the form of 4D-trajectories allow Mid Term Conflict Avoidance (MTCA). One physical drone has been equipped with a novel onboard 4D-guidance module, allowing precise navigation along given 4D-trajectories, predicted by an also onboard trajectory prediction engine.

Besides being able to predict, follow and downlink 4D trajectories, drones have their own CD&R suite aboard. Thus, drones can also operate safely in an autonomous mode. For this purpose, the ground control station also uplinks traffic information to airborne drones. Finally, drones are equipped with onboard LIDAR sensors, allowing detection of non-cooperative vehicles and obstacles.

4.1 System Layout

The simulation trials of phase 3 are based on the City-ATM system realized for phases 1 and 2. The identical three main drones between 6.8 kg and 10.5 kg of the DLR institutes FL, FT and KN are in operation, see Table 2 for details. They are complemented by some drones from NXP and KopterKraft.

The central system extension compared to phase 2 is the onboard companion computer (Raspberry Pi 4b). The additional computer allows the integration of new research developments while avoiding most interdependencies with existing infrastructure. Few interfaces (e.g. to Pixhawk PX4 and U-Fly) allow the integration of several new modules on the drone:

- The trajectory-predictor CFMS, already implemented in the U-Fly, is also integrated on the drone. The module allows to read uplinked flight plans and generate on-board 4D-trajectories.
- A new guidance module allows to follow 4D-trajectories. While the original Pixhawk PX4 guidance module allows limited guidance only by following lateral paths and following altitude commands according to a pre-defined scheme, the new guidance module follows given 4D trajectories in all 4 dimensions (latitude, longitude, altitude and time) precisely as long as operational conditions like weather allow.
- The precise knowledge of the drone's path allows very efficient CD&R with other objects.
- Other objects' positions are up-linked from the ground control station U-Fly, covering all known traffic including all physical existent and virtual drones received from DFS's tracking server. Furthermore, obstacle positions only available on the airborne side are considered, either originating from the D2D datalink or from two LIDAR devices installed on the drone.

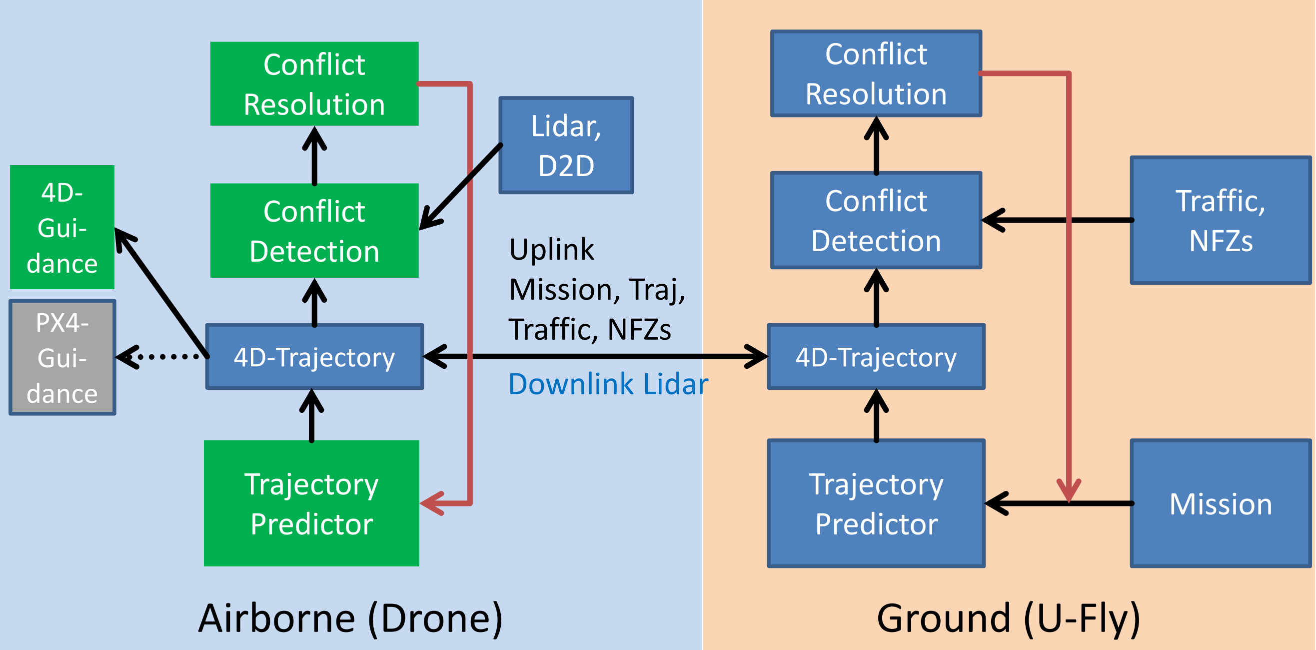


Figure 16 – Air-ground infrastructure sharing several identical modules

The general idea is depicted in Figure 16. All relevant modules already installed in the U-Fly are also installed on the drone for phase 3 to allow autonomous flights. All available data are shared between U-Fly and drones. Thus, drones can either be controlled from ground, or be delegated to fly a mission autonomously. An on-board mission manager takes care that all modules interact as planned:

- The drone receives a new mission via uplink from the U-Fly.
- The on-board mission manager generates the corresponding 4D trajectory.
- The mission is activated via the U-Fly. If necessary, this evokes a trajectory generation.
- The on-board guidance module sends guidance commands to the PX4 in order to follow the trajectory in all 4 dimensions.
- At the same time, the trajectory is entered into the CD&R suite.
- Other data in the CD&R suite are traffic objects from the DFS tracking server, NFZs, object positions received from D2D, and non-cooperative objects detected by the LIDAR sensors.
- Once a future separation violation based on own-ship's 4D trajectory is predicted, conflict resolution algorithms can reroute the drone to avoid the forecasted conflict.
- This results in a new active trajectory that will be followed by the guidance module.
- At any time, the pilot can cancel the autonomous mode and control the drone from the ground.

Virtual traffic is added by means of a simulation engine. The traffic is designed to be highly interactive with the missions to be flown by physical drones. Nevertheless, it might be difficult to force conflicts with real drones because of rather small separation requirements. Therefore, the simulator allows different simulation speeds, from pause-mode via slow motion and real time to fast time simulation.

Both ground-based U-Fly and airborne based companion computer use the identical CD&R suite called NDMap (N-dimensional map). The NDMap is a generic DLR in-house development used in various drone and civil aviation projects. The generic algorithm performs an N-dimensional bisection of global airspace and thus creates easier-to-handle subspaces, generating a hexadecimal tree for the 4D case [28]. The NDMap allows modelling of aircraft's positions and trajectories, strategic and dynamic NFZs and any kind of multidimensional obstacles like those detected by the LIDAR sensors.

Conflict detection is performed by simply inserting new objects into the NDMap. The list of objects, the corresponding tree structure, and the list of detected conflicts is always kept consistent. The CD&R suite is both very flexible and extremely fast, with an almost linear development of detection times. Figure 17 shows the detection performance for a whole day of worldwide civil air traffic. In this particular case, more than 120k separation violations are identified.

Separation requirements are freely adjustable for different kind of objects. Thus, one NDMap can be used to ensure 5 NM separation for civil aviation and 20 m for Vertical Take-Off and Landing (VTOL) drones at the same time. The main result of the conflict detection process is a list of conflicts. Each conflict is described by

- References to both conflict partners
- Start and end time of conflict
- Trends of both objects at time of conflict
- The closest point of approach holds the point where the distance between both objects is smallest. Distances are normalized by the separation requirement first.
- Phase of conflict (e.g., departure conflict or en-route conflict)
- 2D-length of conflict

The NDMap also provides functionality for conflict avoidance. As depicted in Figure 18, three different methods of resolution are implemented. An aircraft or drone may solve the conflict by a lateral detour, a vertical maneuver, or by reaching the initial conflict area at another, conflict-free time.

In any case, conflict resolution is performed in an intelligent trial-and-error manner. New trajectory candidates that might resolve a conflict are calculated and inserted into the NDMap. If the new trajectory does not resolve the conflict, or generates new follow-up conflicts, the trajectory is rejected and a new candidate is predicted. Since insertion into the NDMap is fast (<5 ms), and deletion is even faster, the resolution algorithm can check several hundred trajectories in one second.

For the airborne NDMap, right of way is always given to the other object, and the ownship needs to react. Although this does not reflect reality, it is an assumption simplifying the execution of trials by increasing predictability.

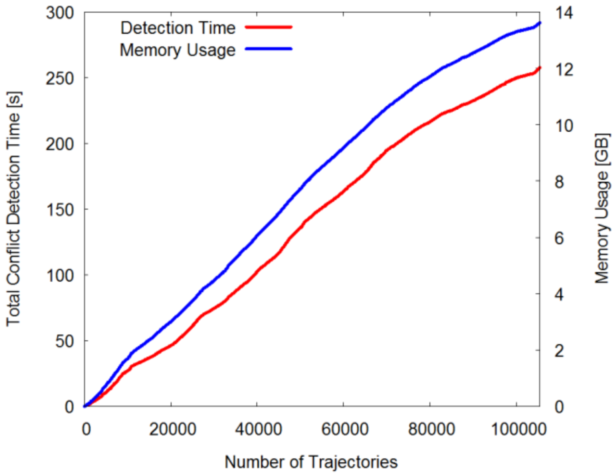


Figure 17- Conflict detection performance for worldwide scenario

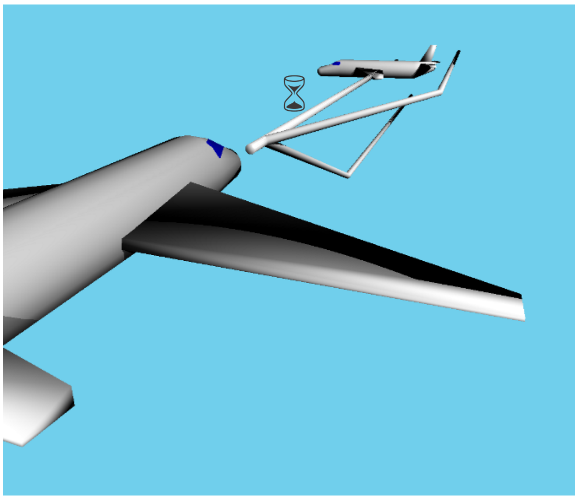


Figure 18 - Lateral, vertical and time-based solution

To detect non-cooperative objects like aircraft, balloons and drones not providing their current position, as well as high buildings, hills and trees, two LIDAR sensors are mounted on the FL drone called DexHawk. An already installed gimbal (that was also holding the camera for the bridge inspection in phase 1), provides the platform for the installation of a horizontal and vertical Leddar Vu8 Solid-State LIDAR on the drone. The sensor features

- 8 segments,
- Frequencies of up to 100 Hz,
- a field of view of 48°,
- and a detection range of up to 118 m.

The installation on the DexHawk drone is shown in Figure 19. Both sensors are connected to the onboard companion computer via serial RS232 connection. The data are handled using the Leddar Enabler SDK in a C++ environment.

Since update rates are rather high, data need to be handled wisely. Figure 20 visualizes how detected intruders are transformed to obstacle volumes. The intruder (in red) is detected by the LIDAR on segments 3 and 4. The LIDAR reports intruders on two segments, each parameterized by distance and the corresponding angle of the segment. Based on the drone’s 3D-position and heading (pitch and bank are compensated by the gimbal), the LIDAR reflections can be transformed to geo-coordinates with latitude, longitude and altitude.

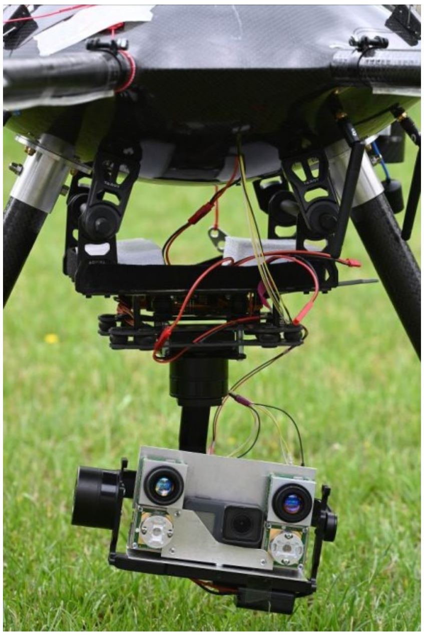


Figure 19 - Horizontal and vertical LIDAR installed on gimbal, together with a small camera in the center

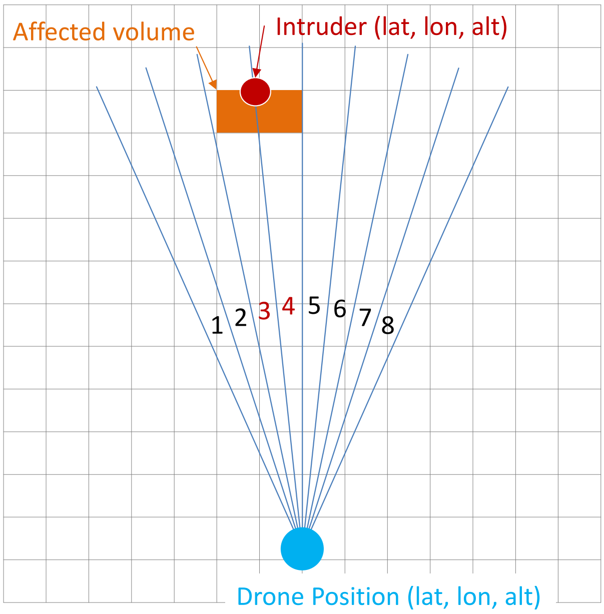


Figure 20 - LIDAR detection and resulting volume

However, the resulting positions are not used directly but discretized in all dimensions. Current discretization in use is one meter laterally and one foot vertically. That way, a volume containing the measured position is calculated (in orange), and this volume is written as a new obstacle into the NDMap. The backside of the red object is not detectable from drone's position using LIDAR. The performed discretization has several advantages:

- If a static obstacle is detected with high frequency influenced by a jitter (e.g., originating from LIDAR sensor, drone's position and angular uncertainty), there is a good chance that the resulting obstacle volume stays constant.
- Independently of the detection frequency, the number of created obstacle volumes stays stable and low.
- Reflections of one object-part will most probably result in the same obstacle volume. This behavior can be used to increase a confidence value of the obstacle volume for multiple detections, resulting for example in a longer lifetime in the NDMap.
- Discretized obstacle volumes can simply be identified by their three indices for latitude, longitude and altitude. This allows a very efficient downlink of LIDAR obstacles to the U-Fly, where obstacles can be displayed on the operator's display.
- The neighborhood of obstacle volumes is easily detectable. Thus, obstacles can be grouped to reflect real world objects. A grouping of obstacles is beneficial for an automatic detection of moving objects. Moving objects can be modeled accordingly in the NDMap.
- The discretization values are freely adjustable to any needs.

Obstacles very close to the ground are omitted by comparison with the drone's take-off altitude (in absence of a radio altitude measurement). Otherwise, the elevation model of the ground would also be modelled within the NDMap, resulting in a ground proximity warning system.

Once inserted into the NDMap, the obstacle volume is also part of the conflict detection process (like a small NFZ). If the ownship trajectory penetrates an obstacle volume, the NDMap will report a conflict. Thanks to the generic trial-and-error resolution process, conflicts with aircraft and obstacles can be resolved by the identical algorithms.

Obstacles have an assigned lifetime, helping to model moving objects and sorting out faulty detections from the LIDAR. The lifetime is not a constant value, but is composed from different metrics like the detection amplitude of the LIDAR sensor and the number of detections.

4.2 Flight Trials

Phase 3 flight trials have been carried out late 2021 at the National Experimental Test Center for Unmanned Aircraft Systems in Cochstedt. In total, three different setups have been tested:

First of all, the 4D-trajectory prediction engine CFMS together with the 4D-guidance module has been validated. A mission has been loaded onto the DexHawk drone. A manual take-off has been performed, and the mission has been activated by enabling the off-board modus. The CFMS generated the corresponding 4D-trajectory for the mission and started sending guidance commands to the PX4. The DexHawk followed the given mission with high precision. The on-board trajectory was automatically downloaded into the U-Fly to allow monitoring of the flight progress.

The second experiment involved the in-flight DexHawk, virtual traffic and two more physical drones, the latter trying to create a conflict the DexHawk should avoid. Conflict metrics have been defined to 10 m horizontally and unsolvable 1000 ft vertically. This allows to operate all physical drones on different altitudes and create a separation violation nevertheless. At the same time, the large vertical separation requirement renders vertical resolution impossible.

Unfortunately, the positions of the physical drones got lost each time in the U-Fly once the drones took off. Thus, there was an issue on the transmission way from the on-board Hook-on-Device, via LTE to the DFS, processing at DFS and the way back into the U-Fly. The problem could not be solved during the trials. Therefore, the physical drones have been placed on the ground sending their positions, with the DexHawk flying its mission straight above these drones. Once the U-Fly got the position updates and uplinked them, the DexHawk detected the separation violations and resolved the conflicts with horizontal maneuvers.

The last experiment showed the detection of non-cooperative obstacles using the LIDAR sensors. The DexHawk was flying towards a lamp post, see Figure 21. The targets detected by the LIDAR were inserted into the internal NDMap. The data were also downlinked to the U-Fly, where the detected targets were visualized to the operator.

To get an impression on how dense drone traffic can be handled safely, simulations have been performed using the identical conflict detection and resolution suite that is also installed on the drone. A complex scenario has been set up, where all drones fly in different directions, and a lateral separation requirement of 20 meters was set. The City-ATM system managed to handle up to 85 drones/km^2 in one altitude layer at the same time in a safe and efficient way (see Figure 22).

Figure 21: Detection of a lamp post with LIDAR sensors

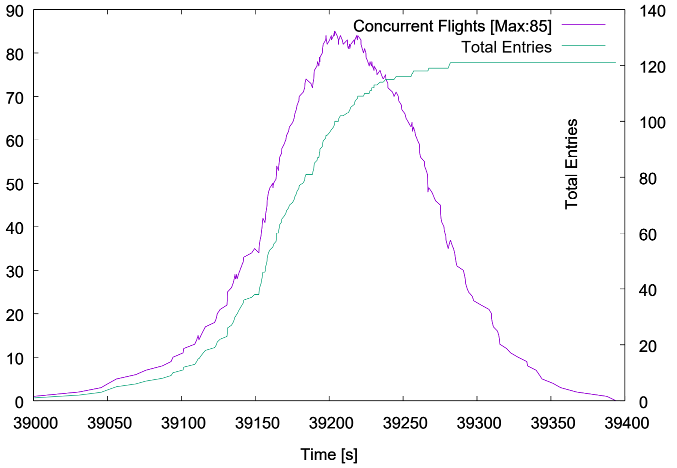


Figure 22: Concurrent Flights/km^2

5. Conclusions and Outlook

Based on the developed concepts, a first demonstration platform for an urban ATM was set up for the City-ATM project. It is based in its first version on the use case "bridge inspection" with several drones in a limited area. With the expertise of the individual stakeholders in the various subject areas and under highly realistic conditions the project team demonstrated how several drones can work in parallel. During the first project phase the services flight planning (strategic flight planning and geo-fencing), registration and identification, tracking and tactical conflict detection were brought together in one test system. In addition, the technical feasibility was always respected.

During the flight demonstration, which was conducted during April 2019, both drones flew along pre-set routes to the side of and underneath the Koehlbrandbridge. Two of three drones available were in the air simultaneously.

The share and processing of information was described. Furthermore, it was shown how important redundant communication and navigation is. Especially when flying underneath and behind bridges (BVLOS), this becomes essential.

The extension of the phase 1 system with new modules like the Dynamic Geo-Fence Server, the new Copter FMS and the advanced CD&R suite allowed a successful demonstration of dynamic geo-fencing. A complete run, starting with the detection of a hazard area, generation of a protecting geo-fence, distribution of the dynamic NFZ from the central server onto single drones and their appropriate reaction have been demonstrated.

Finally, putting the CD&R suite, the CFMS trajectory predictor, the new 4D-guidance system and LIDAR sensors onto the DexHawk drone enabled autonomous flights with high 4D accuracy. The drone was able to reroute its own trajectory in dense traffic, while even respecting non-cooperative objects detected by the LIDAR sensors. The City-ATM project demonstrated new concept elements for the integration of unmanned aerial vehicles in urban areas. The developed base system allows easy extension with new features, like demonstrated with the dynamic geo-fencing and dense traffic exercises.

The concepts and technologies developed in City-ATM will be further deployed in on-going and future DLR projects. For example, the project HorizonUAM focusses on extending the elaborated ConOps and U-space services to meet the requirements of Urban Air Mobility (UAM) applications. Technical components and software solutions from City-ATM will be applied in real-time simulations and flight demonstrations to e.g. enable vertiport operations in dense urban traffic. The City-ATM base system will as well be further developed to integrate and demonstrate full U-space U3/U4 services. Further on, it is planned to implement the U-space system at DLR's National Experimental Test Center for Unmanned Aircraft Systems in Magdeburg-Cochstedt. The airport Magdeburg-Cochstedt (ICAO-Code: EDBC) facilitates research and flight demonstrations in the area of U-space and UAM, e.g. by providing the airspace and airport environment to investigate integration aspects between manned and unmanned aircraft within controlled airspace and essential collaboration concepts between U-space Service Providers, UAS Pilots and Air Traffic Control.

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7. Copyright Statement

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