D4 .4 – Autonomous piloting of UAV fleet and coordination for remote sensing and identification of wildfire ignition

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List of acronyms and abbreviations

ACRONYM	**Description**
API	Application Programming Interface
DIP	Data Ingestion Pipeline
DJI	Da-Jiang Innovations ('Great Frontier Innovations')
GPGPU	General-Purpose Computation on Graphics Processing Unit
LiDAR	Light Detection and Ranging
KML	Keyhole Markup Language – file format used by Google Earth
MVP	Minimum Viable Product
NiFi	Niagara Files
RGB	Red, Green, and Blue
RoM	Resolution of Mapping
SAL	Storage Abstraction Layer
UAVs	Unmanned Aerial Vehicle(s)
UGVs	Unmanned Ground Vehicle(s)
UUID	Universal Unique Identifier

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Executive Summary

This document is a demonstration deliverable summarizing the outcome of Task 4.6, within WP4 as illustrated by the demonstration that took place during the first review meeting of the project in Brussels on July 5th 2023. The task is centered on UAV coordination and belongs to Work Package 4 (sources of information) of the SILVANUS project, platform for Wildfire Management.

The document, in its first chapter, produces a detailed survey of both the benefits and limitations of the corresponding technology in the global picture of wildfire management. It does so by giving a detailed list of benefits followed by a detailed list of conditions that, when met, prevent the technology from being used and consequently, the benefits from being drawn.

In the second chapter, one gives a brief technical outline of the developed component. The first detailed technical aspect outlines the various algorithms that were used and/or specifically developed for the purpose of the task at hand. The second technical aspect gives the particulars of the platform integration architecture, particularly for data ingestion of the sensor footage collected by the drones during their optimized missions.

In the third, last and most important chapter, the document gives a detailed outline of the main demonstration that was given in association with the task in Brussels with screenshots and detailed scenario phases. An account of actual, real-world, test flights that were conducted in the field for development and testing purposes, particularly in association with the Slovak pilot is also given.

1 Introduction and focus on benefits and limitations on the use of UAVs for wildfire monitoring

Unmanned Aerial Vehicles (UAVs), also known as drones, have been reckoned in recent years to be very useful in all stages of wildfire management: prevention, response and restoration. UAVs are particularly useful because they allow to procure information about the ongoing situation very fast even in hard to access terrain and do so without any need for human personnel to get close to the danger zone themselves. UAVs are typically useful to survey vast wooded areas while equipped with various types of sensors such as RGB cameras, thermal cameras, infra-red cameras or LIDAR. UAV fleets can be used in prevention to survey areas and detect fire ignitions or in ongoing response to monitor fire progress. In addition to live video feeds which provide immediate feedback to firefighters in the field, collected sensor data can be used a posteriori as input for advanced AI algorithms such as fire ignition detection.

While recognized as being increasingly useful in practice, UAVs are a relatively new technology and a number of limitations can prevent their use or limit their outcome. This section provides a detailed list of both benefits and limiting conditions.

1.1 Benefits of UAVs

Real-time aerial monitoring and surveillance: Drones can provide real-time aerial imagery supporting patrol and transferring real-time images to command-and-control centers (Akhloufi et al., 2021).

Multisensor Capability: Drones can be equipped with various sensors such as thermal cameras, smoke detectors, and other sensors for comprehensive data collection (Novák et al., 2020).

Early detection: Drones equipped with thermal imaging cameras can detect hotspots and potential ignition sources, enabling early detection and preventing wildfires from spreading. Drones can help in the initial attack of wildfires for early suppression (Afghah et al. 2019; Aydin et al., 2019; Giuseppi et al. 2021; Gupta et al., 2022).

Faster and efficient response: Drones can be rapidly deployed and cover large areas in a short time, enabling faster response times. Quick to launch and maneuver, especially useful in emergency situations. This can help contain wildfires before they spread uncontrollably and at the same time, allowing firefighters and emergency responders to quickly assess the size, direction and intensity of wildfires. This also helps to make informed decisions about resource allocation and evacuation orders (Ausonio et al., 2021; Akhloufi et al, 2021; Mohapatra and Trinh, 2022).

Resource Allocation: Helps in efficient distribution of firefighting resources based on real-time data.

Instant Analysis: On-board processing can provide instant analysis, allowing for quicker decision-making.

Accessibility: Drones are capable of navigating through difficult terrains, dense forests and remote areas. Drones can be deployed in dangerous or inaccessible areas, reducing the risk to human firefighters (Aydin et al, 2019; Innocent & Grasso 2018, Mohapatra and Trinh, 2022).

Safety: the advantage of accessibility and gathered intelligence and data (critical information about fire behavior, terrain, and weather conditions) enhances the safety of firefighters and other first responders (Mohapatra and Trinh, 2022; Pham et al., 2020).

Search and Rescue: Can aid in finding lost or trapped individuals in forested areas during fires (Ho and Tsai, 2022). Drones are capable of even performing aerial remote triage (Álvarez-García et al., 2021).

Logistics Support: Can be used to deliver small essential supplies such as medicines to isolated teams (Mayer et al., 2019).

Night Operations: Equipped with thermal imaging, drones can operate during nighttime when manned aircraft often cannot (Dilli and Suguna, 2022).

Restoration ecosystems: support restoration planning, implementation and monitoring mapping vegetation composition and structure to monitor plant health and wildlife population dynamics (Robinson et al., 2022) with high-resolution maps.

Damage Assessment: The accuracy, high quality of images and small costs are useful for evaluating the extent of damage due to the fire incident, thus estimating better damage costs and avoiding false statements faster (Akhloufi et al., 2021).

Reduced Manpower: UAVs automate surveillance and reconnaissance tasks that would otherwise require more personnel (Akhloufi et al., 2021).

Cost-Effectiveness: Typically, cheaper compared to the operation of manned aircraft or satellites for similar tasks (Thomson et al., 2013; Pham et al., 2020; Akhloufi et al., 2021; Mohapatra and Trinh, 2022).

Energy Efficient: Electric drones have lower emissions compared to conventional manned aircraft (Arafat and Moh, 2021).

1.2 Conditions limiting the use of UAV fleets

Limited operation time: Battery constraints do not allow for long flights, autonomy is usually limited to a few dozen minutes (Khan et al., 2022; Mohapatra and Trinh, 2022, Ausonio et al., 2021).

Weather Dependency: Ineffectual in poor weather conditions such as heavy winds or rain (Mohd Daud et al., 2022).

Legal and regulatory challenges: Subject to airspace regulations, which may limit their operation. In addition, compliance with regulations and obtaining necessary permits can be time-consuming and restrictive. Uncertainties around liability in case of accidents or failures. Operating drones within airspace regulations can be complex, especially in wildfire-prone areas near airports or populated regions (Lightfoot, 2018; Ayamga et al., 2021).

Limited Field of View: Cameras may have a restricted field of view, missing out on peripheral developments (Burke et al., 2019).

Skill Requirement and human dependent: Requires trained personnel for effective use. Most models require human oversight, limiting their use in extremely high-risk areas (Mohapatra and Trinh, 2022).

Operational Interference: Can conflict with other aerial firefighting efforts if not coordinated properly. **Collision Risks**: Possibility of collision with other aerial objects or natural obstructions like trees (Khan et al., 2022).

Data Overload and analysis: UAVs produce a large volume of data that can be challenging to process and analyze. Efficient data processing and analysis systems are required to extract meaningful insights and make informed decisions (Mahmudnia et al., 2022).

Security Risks: Vulnerable to hacking or unauthorized usage (Yaacoub et al., 2020; Sihag et al., 2023).

Signal Interference: Risk of signal loss or interference, especially in remote areas (Khan et al., 2022).

Cost of Sophisticated Models: Advanced drones with better capabilities (longer flight times, carry heavy weights or water) can be expensive. Acquiring, maintaining (require consistent upkeep and calibration), and operating drones can also be expensive. Training personnel, purchasing specialized equipment, and ensuring compliance with aviation regulations can add to the overall cost (Akhloufi et al., 2021; Mohapatra and Trinh, 2022).

Noise: While generally quieter, some drones still generate noise that can disturb wildlife (Mesquita et al., 2022).

It is important to note that while drones offer significant benefits, they should be seen as a complement to existing firefighting and emergency response strategies, rather than a stand-alone solution. Also, with the evolution of technology, many of the disadvantages/challenges are being confronted, thus making drones even more appealing as supportive mechanisms for firefighting.

2 General Technological Principles: Algorithms, Workflow and Platform Architecture

This section details the technical infrastructure underlying the developed component for drone fleet coordination and trajectory optimization. We give details on three key aspects:

- the fundamental underlying mathematical problems to be solved and associated algorithmic principles to solve them,
- the corresponding algorithmic workflow from problem input definition to drone trajectories to collected data outcome,
- network and storage infrastructure for communication with the SILVANUS platform.

2.1 Underlying Mathematical Problems and General Algorithmic Principles

In its simplest form, coordinating UAVs consists in solving the following key problem, to produce a global trajectory mission, as illustrated in *Figure 1*:

- **Area clipping**, which consists in dividing the target zone into several subzones. We need as many subzones as there are drones. Each drone will then cover one subzone.
- **Area coverage**, which consists in finding a global, raw trajectory for the UAV to cover an area as opposed to going simply from point A to point B. This involves coming up with a fulfilling trajectory in 2 dimensions.
- **Calculation of optimal paths**, which involves advanced computational geometry algorithms to find the best way to go from A to B or to do area coverage. Optimization is made according to a number of operational criteria, typically overall mission duration or minimal fuel consumption.

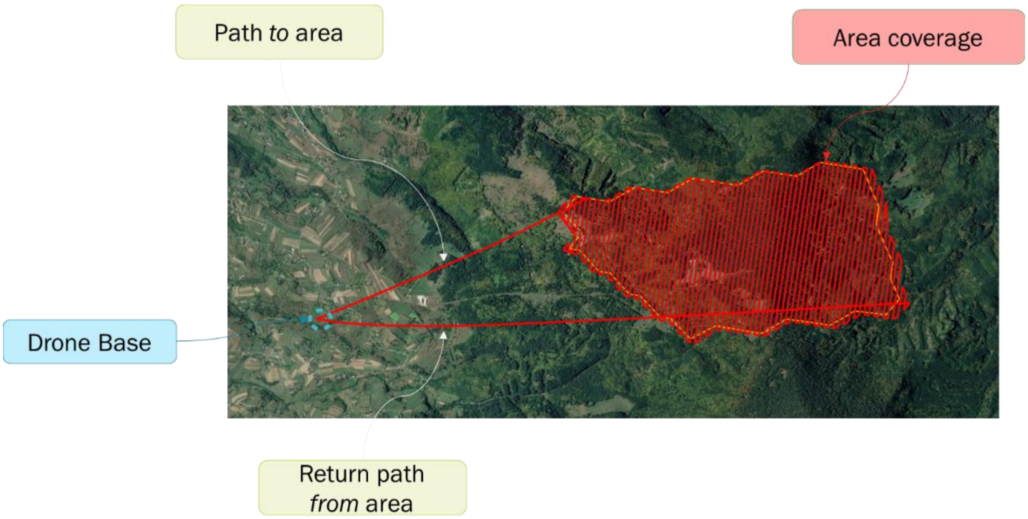


Figure 1 : Global Trajectory Computation

2.1.1 Area clipping

Area splitting, illustrated in *Figure 2*, is a computational geometry problem of high algorithmic complexity, due to the multiplicity of figure shapes to be split (in particular, we wish here to be able to deal with the case of concave polygons). Furthermore, there is rarely a single cutting solution. This problem is deemed NP-hard (i.e. mathematically extremely difficult), as demonstrated by Bast et al., 2000 . Also, approaches without guarantee of optimality take on their full meaning in a context where one wishes to obtain "good" results quickly.

Effective geometrically based heuristic methods exist to deal with such division (such as for example Hert et al., 1998). In particular, we find alternatives based on sub-zones to be constructed containing points fixed a priori, or not.

These algorithms rely on decompositions (Stojmenović et al., 1991) and "recompositions". A key point is to ensure that the "recomposition" of smaller areas into a target surface sub-area does not result in an unconnected sub-area, consisting of pieces thus unconnected. Another difficulty, when it comes to cutting a potentially non-convex polygon, is the fact that a cutting segment between two points of the polygon is not necessarily included in the polygon. Also, it is necessary to retain the sub-segments included, if applicable, and check the relevance of the division thus obtained. In this case, it is not necessary to have an absolutely precise division.

Under these conditions, another way to generate this division is to resort to a discretization of the surface then to use a **clustering algorithm** on the tiles which result from the discretization. Many clustering algorithms exist, based on heuristics empirically evaluated as efficient, which can also be exploited through metaheuristics. A review of these approaches can be found in Pereira et al.'s research (2018). For heuristics, we can cite in particular K-Means, H-Means and J-Means, which can also be mixed to make hybrid heuristics. K-Means is reputed to be efficient, but can lead to a solution with a lower number of clusters than the one targeted (so-called degenerate solution). A modification of the algorithm exists allowing, in such a case, to add new clusters making it possible to return to the targeted number, and to give a new provisional solution better than the local minimum previously obtained. The classic K-Means algorithm can then resume from this new intermediate solution. This modified algorithm named K-Means+ is studied by Aloise et al., 2017.

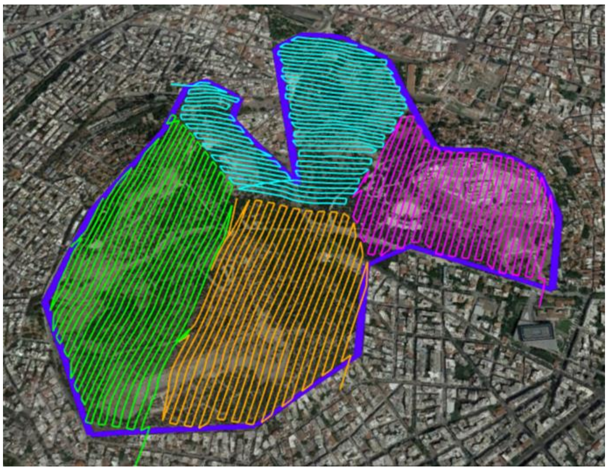


Figure 2 : Area clipping illustrated on a small urban zone on the Acropolis Hill in Athens, Greece

2.1.2 Area coverage

Area coverage (Coverage Path Planning), illustrated in *Figure 3*, has been a very active area of study for many years, particularly in the world of robotics. There are various widely described approaches. A review of these approaches can be found in Sheng Tan et al.'s studies (2021).

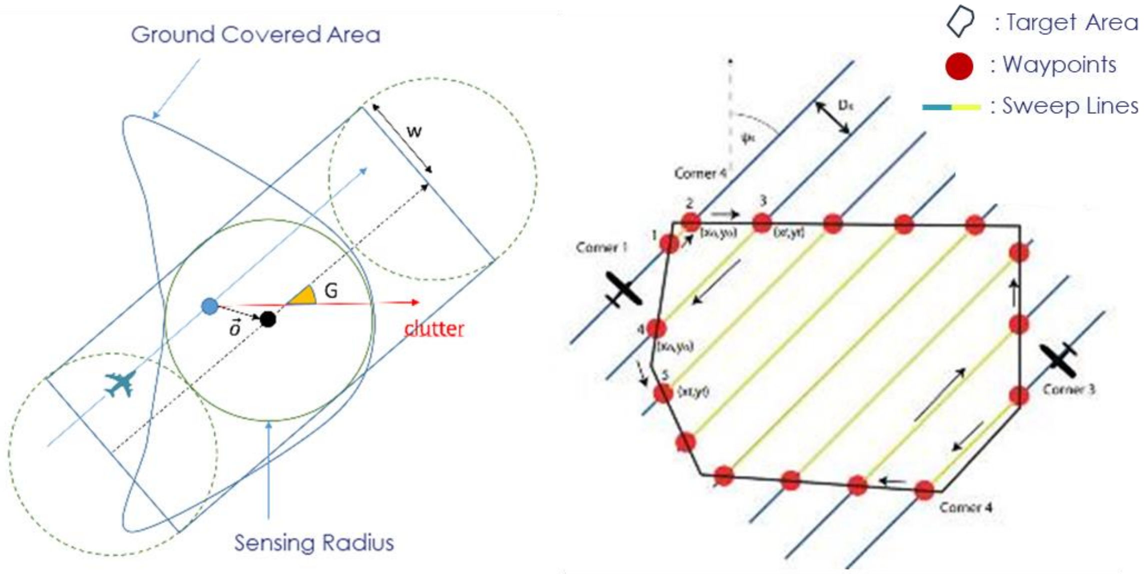


Figure 3: Details of area coverage trajectory computation

The way of processing an area coverage calculation will depend, in particular, on the entity which will carry out this coverage. Depending on whether the entity is holonomic (a mathematical property of its movement constraints) or not, this can result in more or less complex treatments. Area coverage by non-holonomic entities is studied in particular by Khan et al., 2017. An area to be covered may or may not contain holes. The presence of holes makes the task more complex. The classic steps in finding an area coverage path are to divide the area into easily tractable sub-areas (for example, either by successive segments or through a spiral-shaped trajectory) (Kim et al. 2020), then to best order these different sub-zones to optimize a criterion (distance, time, etc.) (Xie et al., 2020). We can then use heuristic methods, graph methods, metaheuristics, or even Reinforcement Learning or Deep Learning.

The calculation of trajectories is done for each sub-zone independently. The principle mentioned above is to start in a defined direction and seek to cover the entire sub-zone using segments following this direction then alternately the opposite.

2.1.3 Calculation of optimal paths

Different approaches are described in the literature for calculating optimal paths. A recent review of these approaches can be found in Sánchez-Ibáñez et al.'s research. Two large families, among others, exist: that of causal algorithms, and that of iterative algorithms. Causal algorithms rely on successive steps processing a local area, each step using the result of the previous step. Iterative algorithms correspond to the calculation of a global state which converges. Calculating a global state requires more processing than for a local area; nevertheless, it is possible to parallelize, for example in a Graphics Processing Unit, parts of the calculation of each global state, which is not possible with the causal approach.

New versions of the traditional Fast Marching algorithm (Mirebeau et al., 2013) for optimal path computation (whose propagation-based principle is illustrated in *Figure 4*), using a causal or iterative approach, have recently been proposed, taking into account for example the non-holonomic aspect of the mobile unit (Mirebeau et al., 2013; Mirebeau, Portegies et al., 2019).

One key objective is to have the capacity to produce trajectories efficiently in terms of computation time, while allowing the inclusion of different constraints such as anisotropy, variable pitch grids, etc. Different versions of the Fast-Marching family have been retained, among others (Sethian et al., 1999). These versions are more or less complex, allowing the computational effort to be adapted to the situation studied.

Once the geographical position of a base has been specified, after calculating area coverage, shortest path algorithms can be used to constitute a global trajectory. To remain consistent with the anisotropy taken into account in the trajectory search for area coverage, the path calculation from the base (and the return to the base) are calculated using a Fast-Marching type algorithm allowing anisotropy to be taken into account (Kimmel, Sethian et al., 1997).

UAVs have a minimum turning radius close to zero. However, to allow the use of drones for which this notion becomes restrictive, post-processing of the calculated trajectory is also considered, taking into account this turning radius and allowing smoothing respecting the constraint, if necessary. The idea is to have a trajectory going from the base towards the area to be covered which allows the drone to join the coverage path without an angle that would be incompatible with its turning radius. The same is done when leaving the area to be covered, for the way back to the base.

The obtained result is a global mission path for a drone, from the base and back, with full coverage of the area dedicated to it, taking into account the anisotropy linked to the wind, and respecting its possible turning radius.

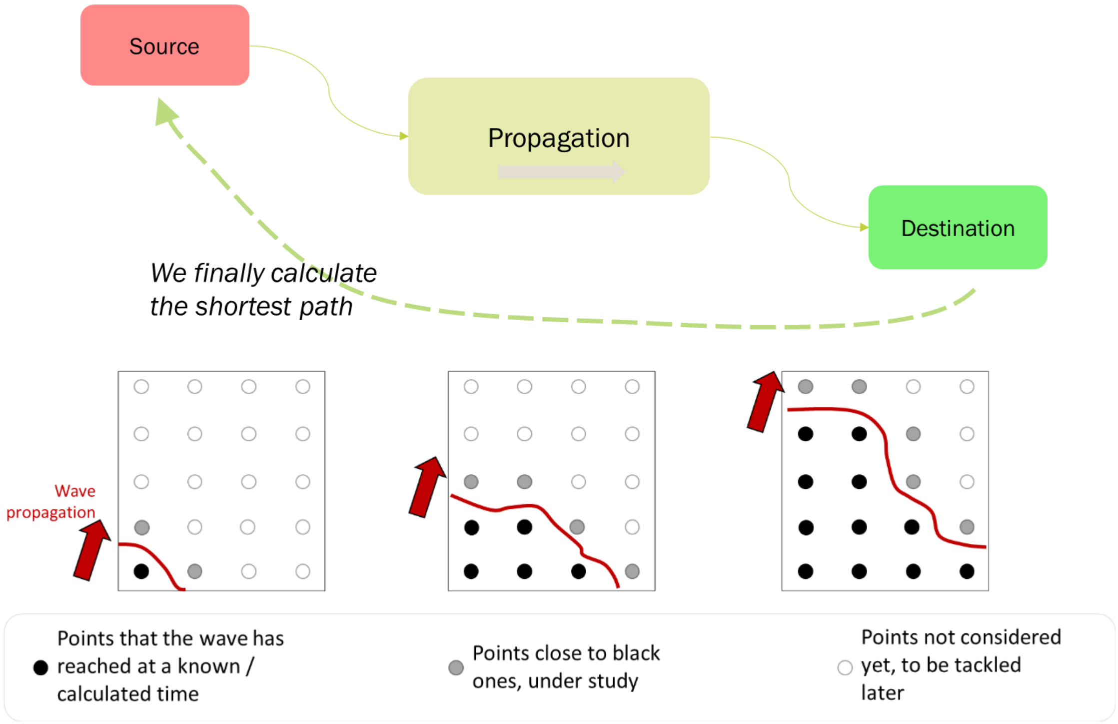


Figure 4: Basic Fast Marching principles

2.1.4 Algorithmic State of the Art Choices Motivation

The state of the art in algorithmic path planning is vast and we made an informed choice for the various algorithmic components at stake here. We were in particular guided by the corresponding module is intended to be uses in near real-time. Computational efficiency was therefore of prime importance. More specifically, we made our research choices and developments along the following lines. For **path optimization**, the Fast Marching algorithm compares favorably because it is particularly fast, being based on neighborhood propagation in one go with a O(n log n) complexity, n being the discretization quantum. Fast Marching is also deterministic, which means reliable and proven to converge to the optimal solution for sufficiently small discretization cells. For **area clipping and coverage**, the spatial clustering approach is both simple and very fast. While not deterministic, it is also known to be very robust and to yield compact, well-cut zones that can be flown with simple sweeping patterns that are familiar and easily acceptable by drone pilots and firefighters.

2.2 Workflow

The following section describes the technical workflow of information as well as the particular algorithm instantiations that were used during component testing on the Slovak pilot zone.

The **Coordination Algorithm** service processes the parametrized request and generates the output – a temporal plan (partial missions) for a provided number of drones and pilots. Technically the responses received to the "MultidronePlanningService" are a set of routes coded in a KML format. To ensure optimal results is necessary to know the following inputs of the algorithm approach:

- number of drones;
- properties of drones (resolution of camera, focal distance of lens, number of pixels on camera chip *NoPCC*);
- ability to import *.kml file;
- wind direction;
- area of interest (polygon);
- resolution of mapping *RoM* or flight height.

The flight height is calculated based on the selected area of interest, the specified properties of the drones and the required mapping accuracy. This calculated height also determines the spacing of the points at which the picture will be taken. When the flight height is specified by a higher aviation authority, it is not calculated and considered an input parameter.

From an algorithmic standpoint, we are using a mathematical method, based on triangulation, to calculate the coordinates of individual points. It is designed in a way to ensure that sufficient pictures overlap is created. The points are calculated in the way that they will be placed in a triangular grid oriented in the direction of the wind. Points are generated sequentially from the starting point, so each point has assigned a serial number of the point creation. This flight path planning very simple. In the process of flight planning all you need to do is to follow the sequence of serial numbers of the individual points. The next step of the service is to divide the area of interest into sub-areas for individual drones (aka area clipping). This equal distribution is ensured by using the K nearest neighbors' algorithm. The number of clusters is set equal to the number of drones. The result of this setting is an evenly divided area. An illustration of the distribution of the points of interest and the division of the surveillance area into sub-areas for 2 or 5 drones can be seen in Figure 5.

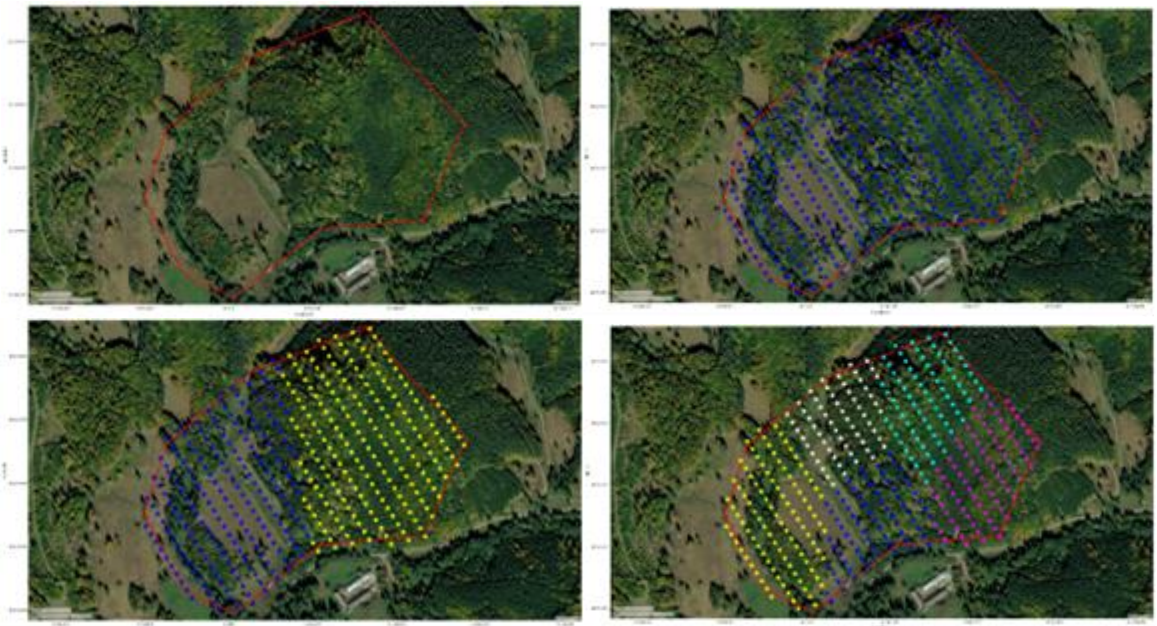


Figure 5: Input polygon of the area of interest (top left), calculated the points to take a photo (top right), divided area by the K-means into two (bottom left) or five (bottom right) sub-areas.

The next step is to create a KML file that can be transferred into the drone. The KML file can be generated in two ways:

- trajectory route planning (an exactly defined path, illustrated on Figure 6 a, b)
- polygon (path will be planning by drone app based on received polygon, illustrated on Figure 6c, d)

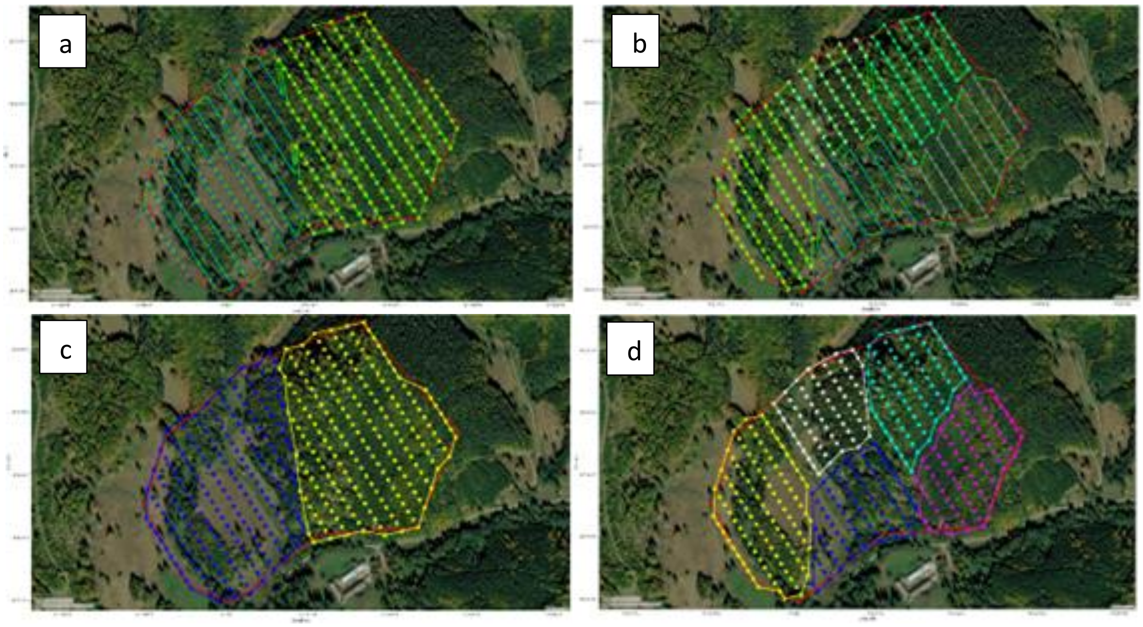


Figure 6: Trajectory route planning output for two a) and five b) sub-areas, polygons output for two c) and five d) sub-areas with marked individual points of interest.

A coordination algorithm service sends a message and creates a KML file back to the EmerPoll system, which is the central command and control software we use. The Slovak pilot used a commercial DJI drone in compliance with the current Slovak legislative requirements. The results achieved in simulation proved the proper working of the proposed concept and were confirmed in the field with actual test flight. The EmerPoll software provides comprehensive coordination and aggregation of data from individual drones. The drone management algorithm theoretically allows coordinating tasks for any number of drones for any vast area. Based on simulation experiments we verified the proposed method as a robust one which enables further expansion. It is worth noting that the algorithm divides the target area into separate smaller areas (partial missions) based on the number of available drones and pilots while ensuring that the paths of individual drones do not collide with each other which is important for the overall safety of the mission.

2.3 Platform Architecture & Data Ingestion Pipeline

This section gives technical architecture information and details the chains of services involved in communicating senor data collected during drone missions to the SILVANUS platform for later consumption by other services such as fire ignition detection.

2.3.1 Data Ingestion Pipeline

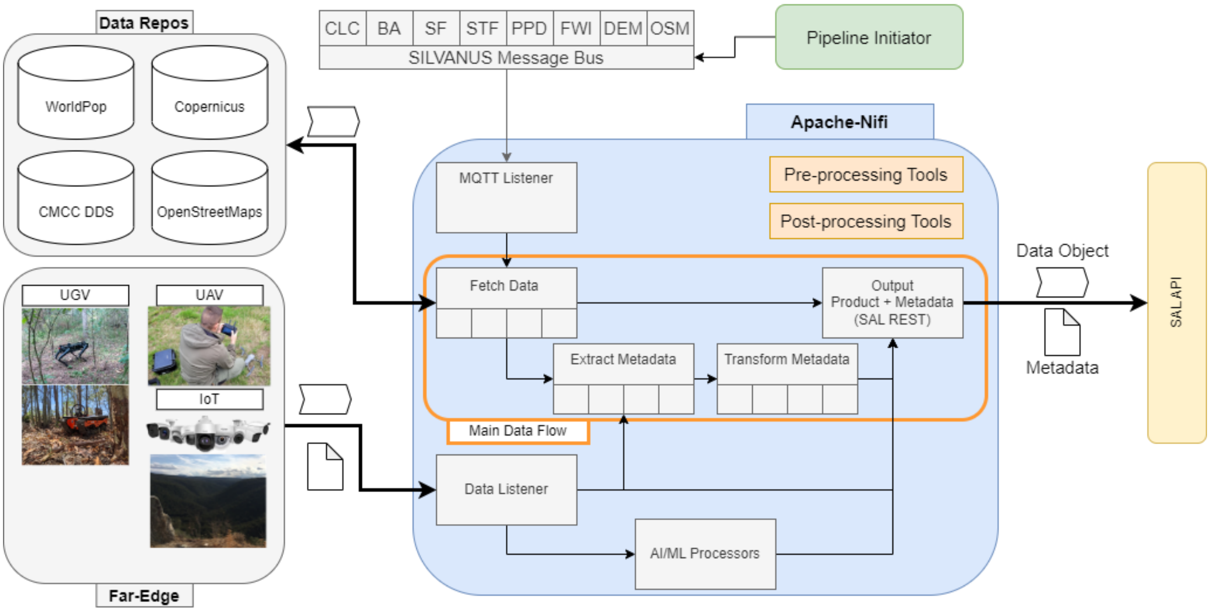
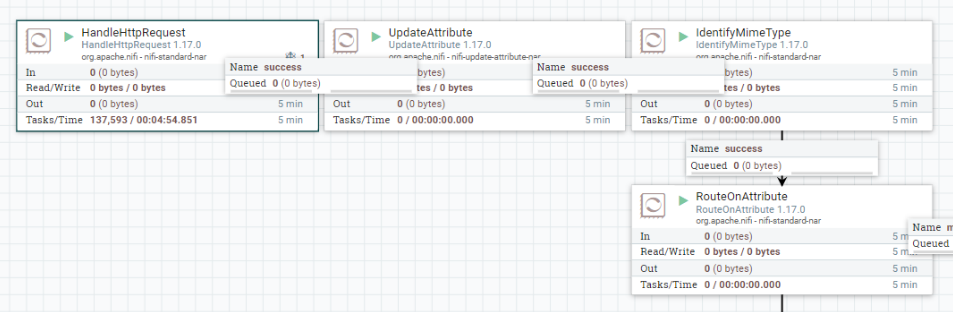


Figure 7: Data Ingestion Pipeline Architecture

Within the Big Data Framework, data sources are ingested into the storage layer via the Data Ingestion Pipeline, as can be seen in Figure 7, a tightly integrated component for managing the ingestion, annotation, and pre-processing of data from a range of third-party and internal data providers**.** An in-depth review of this component, available datasets, and related tooling is available within the Demonstration report D4.1.



HandleHttpRequest
HandleHttpRequest 1.17.0
org.apache.nifi - nifi-standard-nar
In 0 (0 bytes)
Read/Write 0 bytes / 0 bytes
Out 0 (0 bytes) 5 min
Tasks/Time 137,593 / 00:04:54.851 5 min

Name success
Queued 0 (0 bytes)

UpdateAttribute
UpdateAttribute 1.17.0
org.apache.nifi - nifi-update-attribute-nar
bytes)
tes / 0 bytes
Out 0 (0 bytes) 5 min
Tasks/Time 0 / 00:00:00.000 5 min

Name success
Queued 0 (0 bytes)

IdentifyMimeType
IdentifyMimeType 1.17.0
org.apache.nifi - nifi-standard-nar
bytes) 5 min
tes / 0 bytes 5 min
Out 0 (0 bytes) 5 min
Tasks/Time 0 / 00:00:00.000 5 min

Name success
Queued 0 (0 bytes)

RouteOnAttribute
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In 0 (0 bytes) 5 m
Read/Write 0 bytes / 0 bytes 5 m
Out 0 (0 bytes) 5 min
Tasks/Time 0 / 00:00:00.000 5 min

Name m
Queued

Figure 8: Zoom on part of the UAV Pipeline implemented in Apache Nifi

The UAV pipeline implemented for the release of the Data Ingestion Pipeline (DIP) serves the basic pre-processing and annotation functionality required for input into the SILVANUS Storage Abstraction Layer (SAL). Part of the UAV pipeline can be seen in Figure 8. As with other far-edge data providers in the project, the DIP exposes a unique HTTP endpoint for the ingestion, storage and indexing of data generated by UAVs.

Several pre-processing steps are performed to generate a single packet containing a dataset object and metadata as headers, the key to this pre-processing step is the UUID (unique identifier) generated by the data provider and served with the ingestion request. More details and sample details using for an ingestion demonstration follow in the next sections. The testing & demonstration specification for this endpoint follows:

Host: http://192.168.168.2/* **- Port:** 9003 - **Request:** POST / Multi-part form
Body:

1) **Data Object / Dataset** – a data object of any format for ingestion (req. uuid as filename)
2) **Metadata Descriptor** – a JSON format file, specified by JSON Metadata Format v2.2 (req. uuid links to Data Object (1))

2.3.2 Storage Abstraction Layer & Data Retrieval

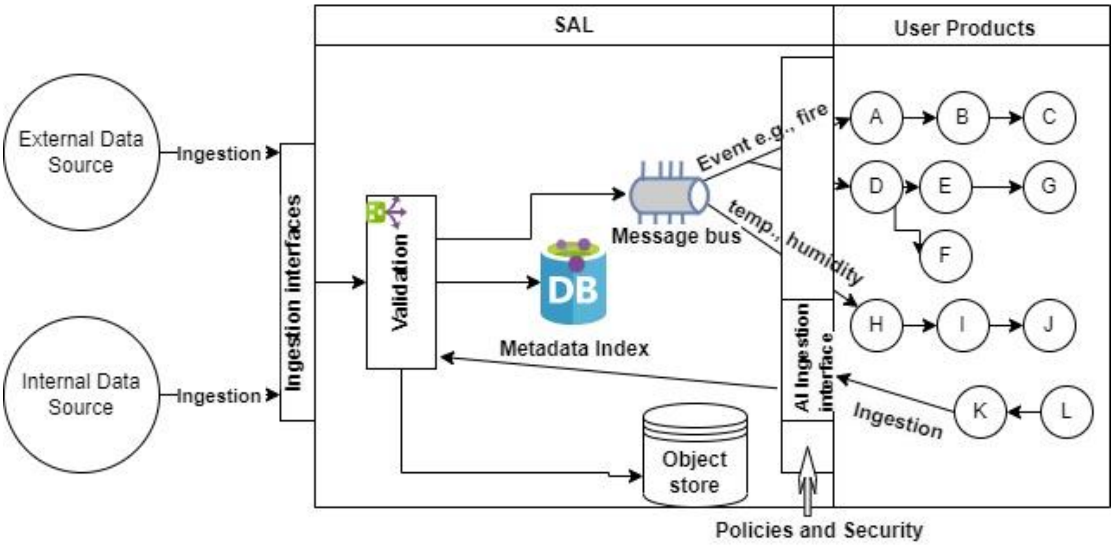


Figure 9: Inner workings of the Storage Abstraction Layer

The Storage Abstraction Layer (SAL), outlined in Figure 9 serves as an intermediary between data sources, user products, and the object stored within the SILVANUS system. As a brief review, its primary function is to abstract the object store, offering two key advantages. Firstly, it enables flexibility in managing data at rest, allowing for efficient data management practices. Secondly, it decouples data from user products in a multi-source, multi-client environment, providing support for security, policy, privacy, and business constraints. By utilizing the SAL, the SILVANUS system achieves enhanced control and adaptability in handling data across various components.

The Data Ingestion Pipeline directly communicates via a REST API with the SILVANUS Storage Abstraction Layer (SAL), an abstraction component of the Big-data Framework and underlying object storage solution. Exposed by the SAL is a single abstract POST HTTP endpoint that is responsible for ingesting all data sources from the Data Ingestion Pipeline. The output HTTP message from the Ingestion Pipeline follows a consistent format containing:

- **HTTP Body – Object data**: A single data object encoded as the HTTP message body
- **Headers – Object metadata, Ingestion Pipeline Attributes:** Extracted object metadata is attached to the same HTTP request, following the SILVANUS Object Metadata specification and format.

Metadata generated by the specific ingestion pipeline is also attached, these are the Apache Nifi flow file attributes generated from the pipeline processors, including the initiating queue, dataset ingestion parameters etc. This allows further enrichment of metadata provided alongside data objects to be leveraged in the SAL.

2.3.3 Data Pre-processing & Storage demonstration

Figure 10: Drone image capture during mission

```
{
  "descriptor": {
      "uuid": "01879876-66bb-7cd4-9bac-3b3b40051722",
      "obj-class": "UAV",
      "format": {
          "type": "jpg"
      },
      "access": "slovak-pilot",
      "dataset-type": "image",
      "created": "1681890268.745728"
  },
  "lineage": {
      "source": [],
      "processing": "primitive"
  },
  "spatial": {
      "type": "Point",
      "coordinates": [
          {
```

```
            "lon": "48.115451",
            "lat": "17.138385"
        }
      ],
      "wkt": "POINT (48.115451 17.138385)",
      "pilot": "slovak",
      "properties": {}
  },
  "temporal": {
      "datetime": "1681890268.745728"
  },
  "tag": {
    "LeftTop": {
      "Latitude": 48.115451591784364,
      "Longitude": 17.138036680355089
    },
    "RightTop": {
      "Latitude": 48.115451591784364,
      "Longitude": 17.138734865055067
    },
    "LeftBottom": {
      "Latitude": 48.115062934582824,
      "Longitude": 17.13803668299569
    },
    "RightBottom": {
      "Latitude": 48.115062934582824,
      "Longitude": 17.138734862414466
    },
    "Center": {
      "Latitude": 48.115451591784364,
      "Longitude": 17.138385772705078
    },
    "Azimuth": 0.0,
    "Altitude": 50.0,
    "FocalLength": 0.0,
    "FieldOfView": 83.0,
    "Angle": 90.0,
    "UploadType": 5
  }
}
```

Figure 11: Metadata Descriptor for drone capture – (SILVANUS Metadata JSON-format-v2.2)

In the above *Figure 11* we see a sample Data Object and Metadata Descriptor generated for a single data point captured during a test flight (see corresponding picture in Figure 10). The Data Object is a simple .jpg image from one point of the mission, while the Metadata Descriptor describes the range of attributes about this data point. Critically within the Metadata Descriptor we consider the 'tags' field, encoding additional indexing data generated during the mission.

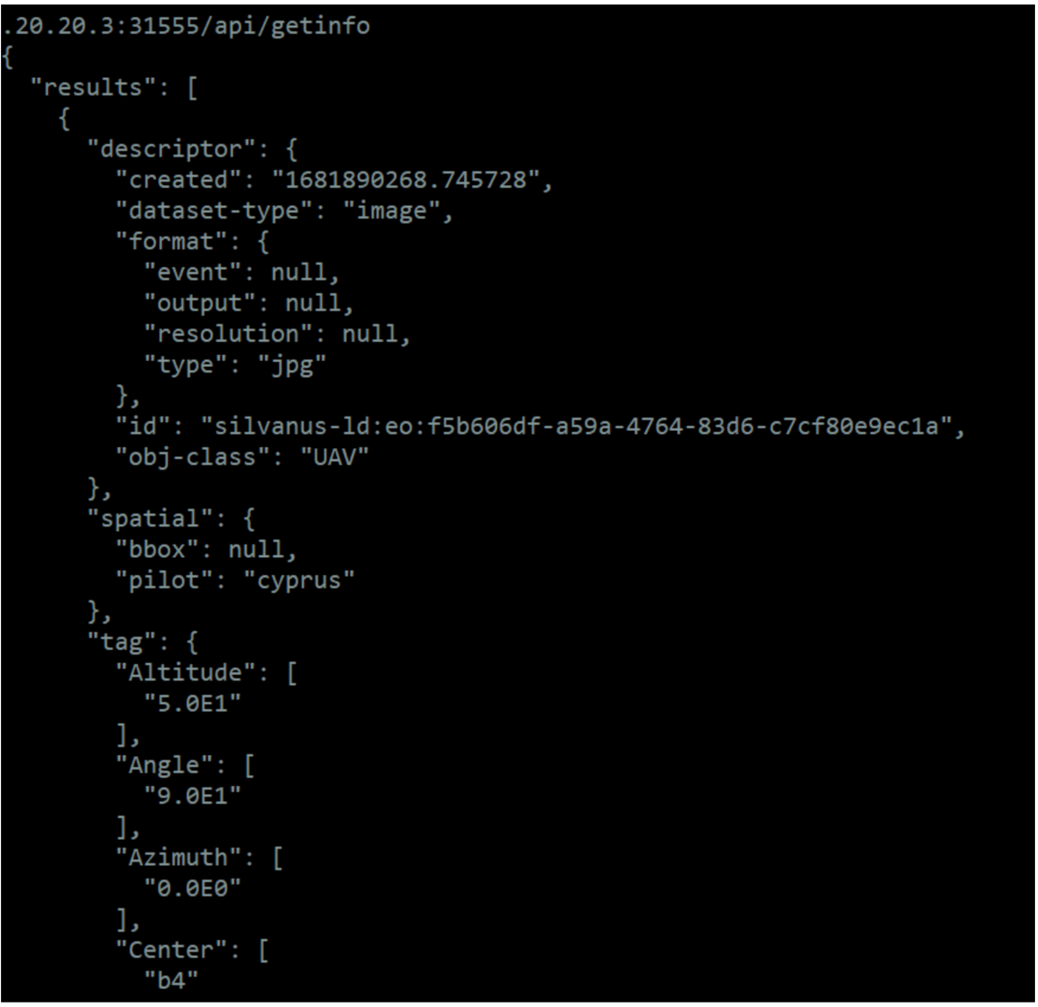
```
curl --request POST \
  --url http://192.168.168.2:9003/ \
  --header 'Content-Type: multipart/form-data' \
  --header 'User-Agent: Insomnia/2023.5.7' \
  --form 'data=@C\...\UAV_Ingestion\01879876-66bb-7cd4-9bac-3b3b40051722.jpg' \
  --form 'metadata=@C\...\UAV_Ingestion\01879876-66bb-7cd4-9bac-3b3b40051722.json'
```

Figure 12: Ingestion Request containing Data Object & Metadata Descriptor from Data Provider

In *Figure 12* we send the two files above to the relevant Data Ingestion Pipeline endpoint, in this case for UAV data, with no faults we should see a request status 200.

```
curl -X POST -H "Content-Type: application/json" -d '{"descriptor":{"obj-class":"UAV","format":{"type":"jpg"},"dataset-type":"image"}}' http://10.20.20.3:31555/api/getinfo
```

Figure 13: Sample query from User Product to SAL Metadata Index API for UAV Data (manual query)



```
.20.20.3:31555/api/getinfo
{
  "results": [
    {
      "descriptor": {
        "created": "1681890268.745728",
        "dataset-type": "image",
        "format": {
          "event": null,
          "output": null,
          "resolution": null,
          "type": "jpg"
        },
        "id": "silvanus-ld:eo:f5b606df-a59a-4764-83d6-c7cf80e9ec1a",
        "obj-class": "UAV"
      },
      "spatial": {
        "bbox": null,
        "pilot": "cyprus"
      },
      "tag": {
        "Altitude": [
          "5.0E1"
        ],
        "Angle": [
          "9.0E1"
        ],
        "Azimuth": [
          "0.0E0"
        ],
        "Center": [
          "b4"
```

p

Figure 14: Result returned to UP from SAL API

```
curl -X POST -H "Content-Type: application/json" -d '{“id”: “silvanus-ld:eo:f5b606df-a59a-4764-83d6-c7cf80e9ec1a”}' http://10.20.20.3:31222/api/getfiles
```

Figure 15: Request to SAL API for Data Object

In Figure 13, Figure 14 and Figure 15 above, we now switch communication to the Storage Abstraction Layer API, specifically the we use a CLI to interact with Metadata Search API to look for our UAV data. The Search API abstracts the semantic database query to a simple JSON string, allowing any combination of fields to be indexed. In the above example we search for UAV image data in .jpg format. Assuming a matching descriptor(s) are found, we can then retrieve these objects via the data retrieval API.

3 Content of the Demonstration

Because this deliverable is of the DEMONSTRATION type, this section is devoted to giving a concise written account of the demonstration of the UAV coordination and trajectory optimization component given - during the first review meeting of the project in Brussels on July 5th, 2023. It also includes a detailed account of how some of the component's functionalities were tested in the field with actual drones, to go well beyond the limitations of tabletop, simulation-based demonstration.

3.1 Main Review Demonstration

3.1.1 *General Scenario*

As illustrated by *Figure 16*, the UAV coordination technology developed in task T4.6 and demonstrated here is one source of information among others, object of research and development in other SILVANUS. All of them contribute to a Common Operational Picture, also known as Situation Awareness, the necessary basis for decision makers to work on.

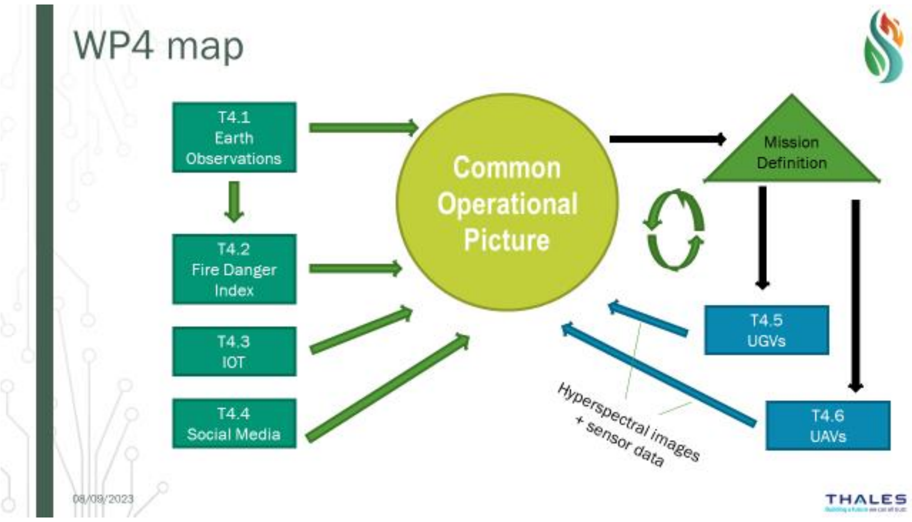


Figure 16: Overall place of UAVs in the global SILVANUS picture

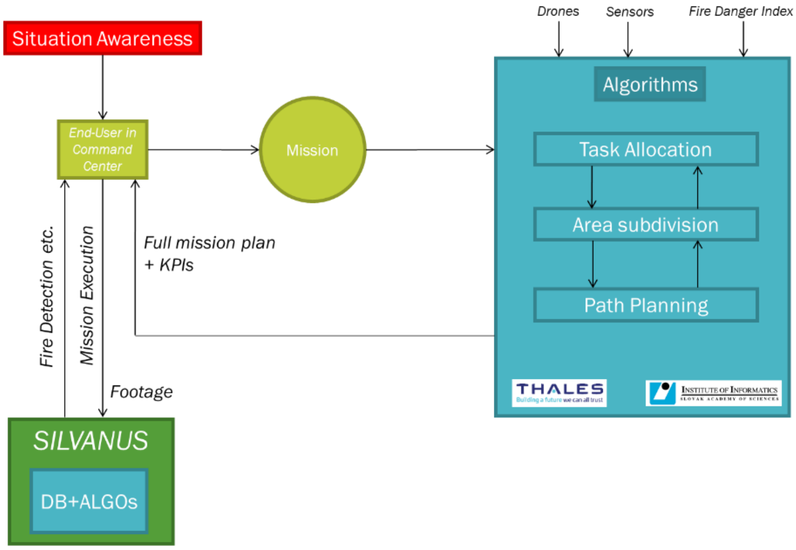


Figure 17: General Scenario for the use of the UAV coordination/optimization component

As illustrated in Figure 17, the general scenario for the use of the SILVANUS UAV component as well as for the assorted demonstration, is as follows. The fire service incident commander is in the command center with easy access to all available information sources so as to have a complete, or as complete as possible, situation awareness. Based on that information, he/she will make a decision on how to use available UAVs by defining a mission describing the area to cover together with sensing requirements and constraints. Based on that mission definition, as well as on necessary input on the available drones, sensors and their technical characteristics, an algorithmic block, composed of several AI-based optimization modules solving the underlying mathematical problems, will compute and propose a full mission plan with assorted operational KPIs such as mission duration, fuel consumption, resolution, overlapping, etc. After examining the said KPIs, the incident commander will either propose a new mission definition with adjusted input parameters or decide to execute the proposed plan. In the latter case, messages will be dispatched to drones and their pilots for them to execute the propose individual missions. Once the missions have been flown and the corresponding sensor data collected, the data ingestion services of the platform will be used to feed data to platform storage for later consumption by other, downstream, algorithms in order to contribute to the global situation awareness and to help firefighters make optimized, well-informed decisions, particularly in the response phase.

3.1.2 Demonstrated Phases

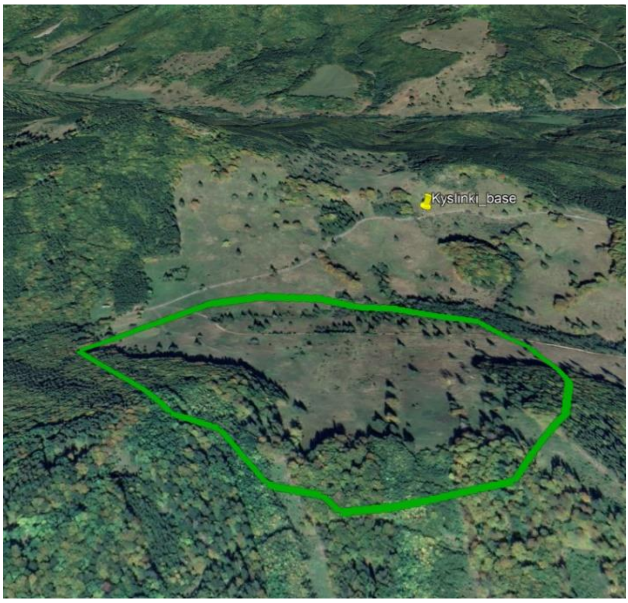


Figure 18: First mIssion definition

The demonstration is based on the area used for the Slovak pilot in the mountain forests of protected natural reserve near Zvolen, Slovakia. As can be seen in *Figure 18*, the first mission definition consists in defining the base, point from which UAVs will take off and where they will return and the area to cover, which is represented by the green polygon, which can be of any, including non-convex, shape. The second step, shown in *Figure 19*, is the outcome of the first algorithmic component: area clipping. One can see, in red and blue respectively, the sub-zones computed by the algorithm, in this case for two drones.

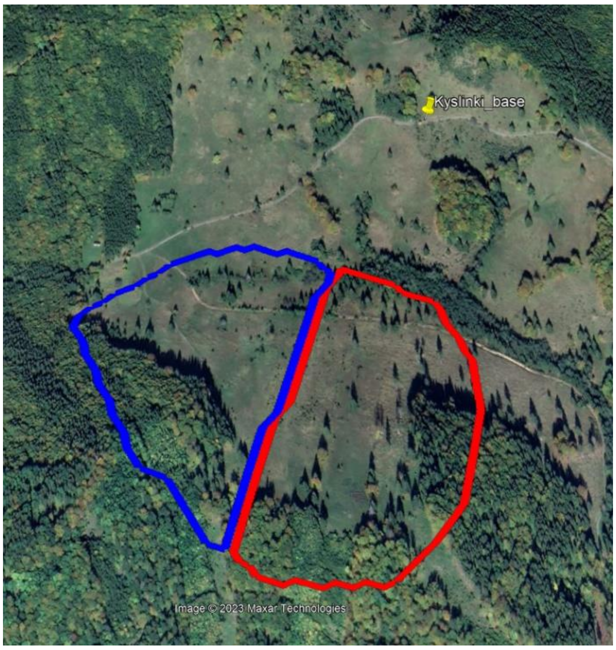


Figure 19: Area clipping for 2 UAVs

Finally, based on this area decomposition, two individual area coverage missions are proposed with full optimal paths from and back to the base. The corresponding flying patterns are shown in *Figure 20*.

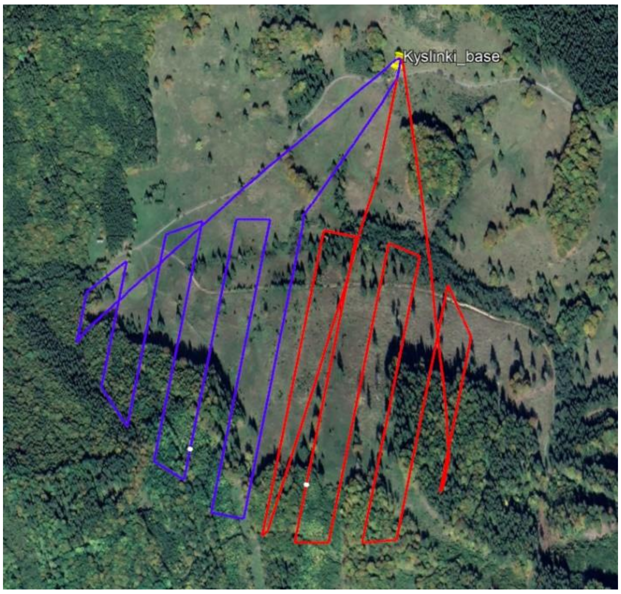


Figure 20: Flying trajectories for two UAVs

Now, let us suppose that the situation has evolved for the worse and that the area of concern grows bigger. The incident commander will define a new mission with a larger area to be monitored, this time with four drones. The new mission definition and the corresponding subdivision for four UAVs can be seen in *Figure 21*.

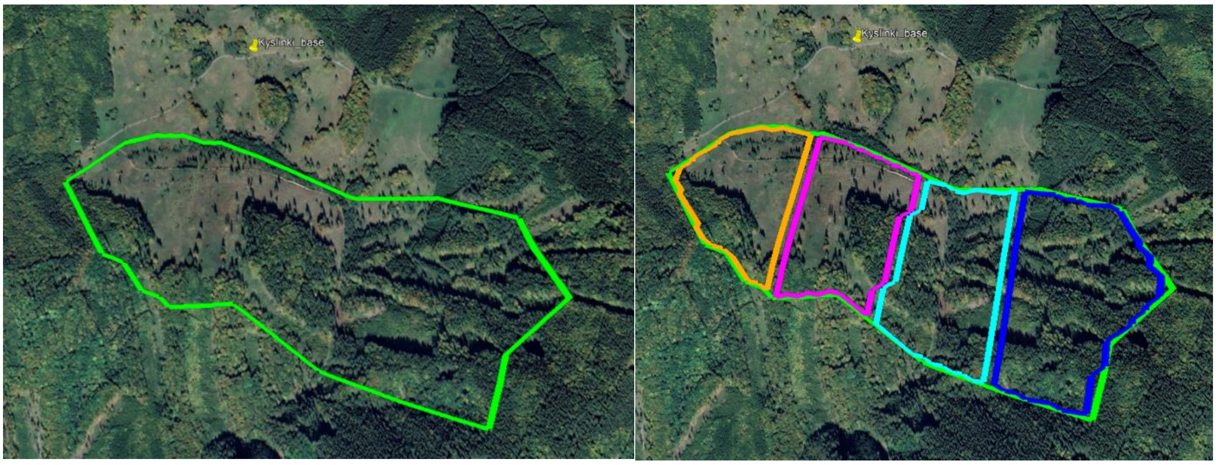


Figure 21: New mission definition for 4 UAVS and assorted work subdivision

The corresponding individual missions are then computed in a few seconds and displayed for the decision maker to observe. The outcome of this phase, the four individual flight plans, are shown in *Figure 22*.

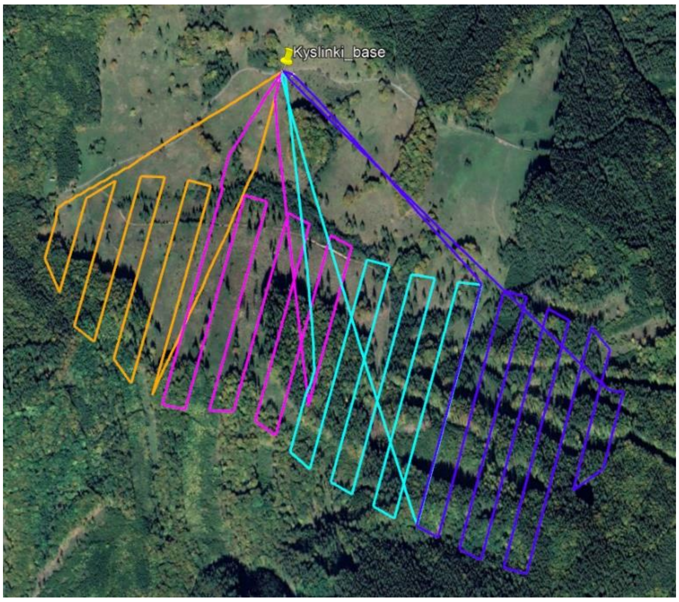


Figure 22: Individual flight paths for four UAVs on the enlarged mission

Now let us suppose that newfound contingencies dictate that a given zone cannot be flown over anymore. Phenomena induced by extreme wildfires for example or safety related constraints such as heavy smoke columns, localized wind turmoil, elevated temperatures or newly observed presence of population can indeed prevent UAVs to be used over certain zones. The decision maker therefore defines a “no-fly zone”, also known as “no-fly zone” over which UAVs are not allowed to fly. The area, the red polygon in our example in Figure 23, will be fed as input to the algorithms for mission computation.

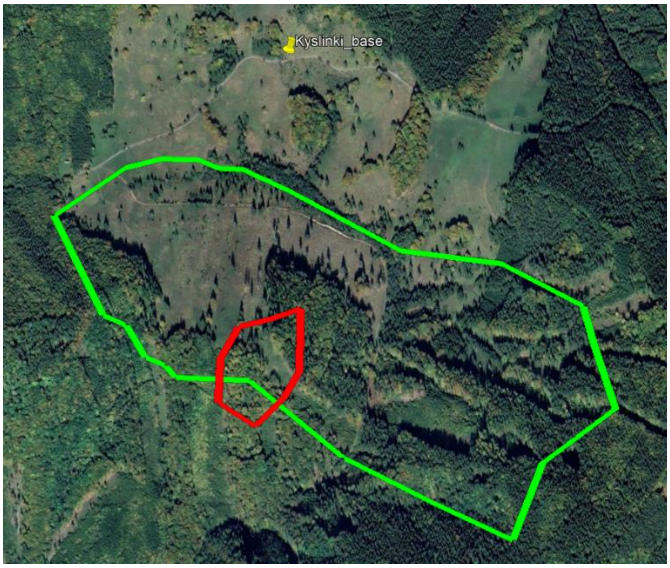


Figure 23: Enlarged monitoring area with an example of "no-fly" zone

The resulting four individual missions are shown in Figure 24. One can indeed observe that the "hot zone" was carefully avoided by flight plans and therefore fully taken into account.

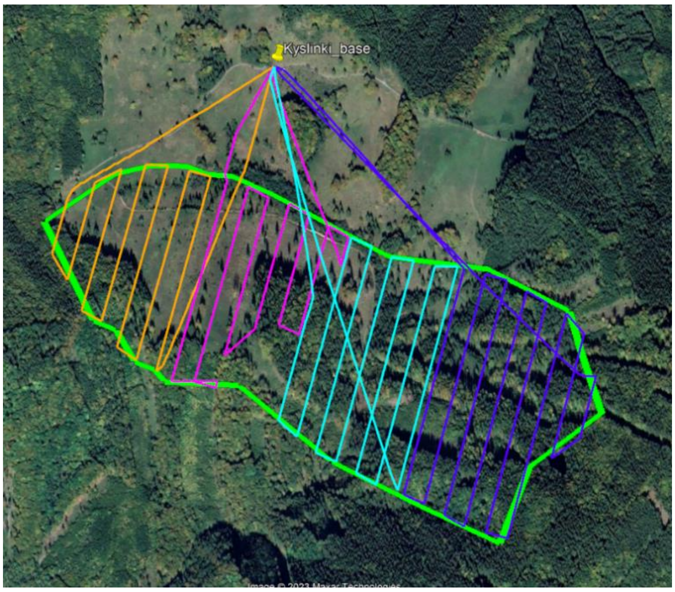


Figure 24: Four individual flight plans taking the hot zone into account

With these successive phases, we have shown an example of how the optimal trajectory computation module can be used in an agile manner to procure efficient mission plans in near real-time for an adaptive efficient use of UAV resources.

3.2 Field Testing

In addition to the tabletop, simulation-based demonstration detailed above, several test flights with real drones were conducted to make sure that the developed technology was fully usable in practice. This section gives details in that regard, particularly regarding the participation in the Slovak pilot exercise.

3.2.1 Slovak Pilot Participation

Coordination of Drones Swarm for Wildfires Monitoring

Slovak pilot (location)

- a case study area is dominated by the massif of Poľana Mountain that is the highest extinct volcano in Central Europe with an altitude of 1458 m.
- area is under nature protection (Protected Landscape Area Poľana)
- located in the central part of Slovakia, the region is typical for its highland landscape with different land-use patterns of commercial deciduous and mixed coniferous-deciduous forests, meadows, pastures, arable land, and areas with non-forest woody vegetation.
- a case study area selected for SILVANUS technologies demonstration (almost forest) is under nature protection, particularly it belongs to Protected Landscape Area Poľana

Figure 25: Generalities on the Slovak pilot

The Slovak pilot area (see Figure 25 and Figure 26) is dominated by the massif of Poľana Mountain that is the highest extinct volcano in Central Europe with an altitude of 1458 m. The Pol'ana area is under protection and is located in the central part of Slovakia. The region is typical for its highland landscape with different land-use patterns of commercial deciduous and mixed coniferous-deciduous forests, meadows, pastures, arable land, and areas with non-forest woody vegetation.

Figure 26: Slovak pilot demonstration area.

During and after the fire, it is imperative to have information available as quickly as possible while minimizing staff requirements (number, training, experience, etc.). When considering a potential deployment of a swarm of robots (either ground or aerial) all the requirements arising from the given situation and scenario must be considered. Having high-quality unmanned vehicle platforms equipped with communication and sensing capabilities is a prerequisite for solving complex technical problems related to the coordination of the robots' swarm. For the sake of executing the exercise during the pilot demonstration several systems and technologies were integrated and utilized, namely:

- DJI Mavic drones – commercial drones with interconnected DJI Pilot application with a remote-control system application (DJI apll, UgSC app).
- EmerPoll - an agent-based system for coordinating and overseeing data aggregation using real-time polls based on the work of (Balogh, 2016), enacted from individual agents (drone pilots) tailored for the robotic swarm coordination.
- GINA Central and GINA Tablet software – part of a professional command and control platform with a digital collaborative map enabling efficient mission and security management used in Slovakia by firefighters.
- Matlab application for the Coordination Algorithm Service implementation.

Further regulatory and legislative constraints must be considered – such as the one that Slovak legislation requires that every drone providing a monitoring service must be registered with the Transport Authority of the Slovak Republic and controlled only by a pilot with a valid pilot license.

As mentioned above, a special system called EmerPoll has been customized and used to coordinate and oversee data aggregation from individual drones in the swarm. The EmerPoll has a web interface (called "Dashboard") which allow to:

- Set up a mission for data collection by a group of drones based on simple semi-structured forms formatted using pre-prepared Templates.
- Initiate a mission by submitting and confirming tasks of the mission to/from individual drones.
- Collect and aggregate data from drones.
- Receive events from drones, react, and intervene in case of a critical event.

The Dashboard also considers the fact that Slovak legislation currently requires each drone to be supervised by a single pilot. The pilots of individual drones will be incorporated into a mission by inputting or confirming the changes in paths and missions with their drones as well as overseeing the drones as required by the respective legislation. Although the primary overall aim of the presented approach is to provide fully autonomous swarm navigation in order to make the Dashboard usable in real-world conditions pilots must be considered as well. Simplified flow diagram for drone coordination for the pilot demonstration during the exercise is shown in *Figure 27*.

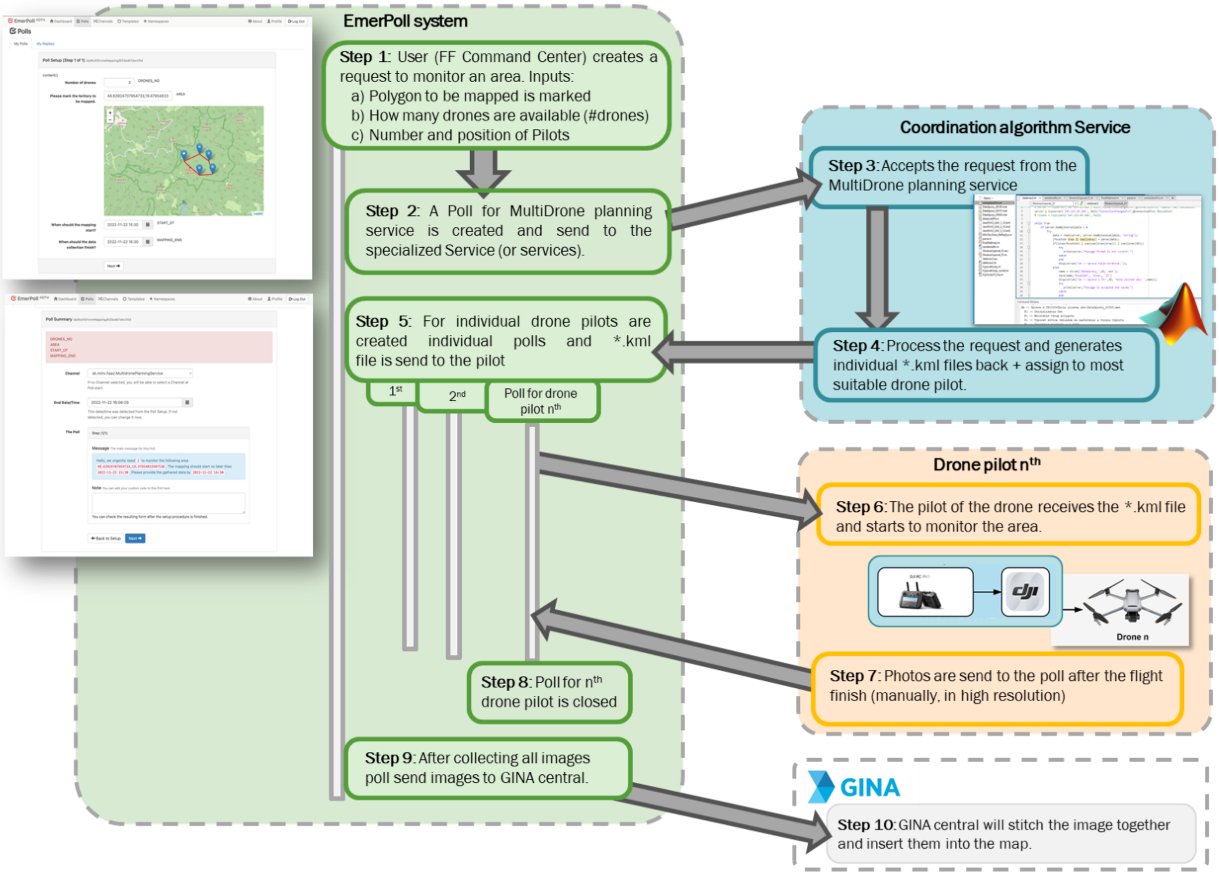


Figure 27: Structured flow diagram for the Slovak Pilot

The description of the steps from *Figure 27* are the following:

- ***Step 1*** - The user (commander or operator from the command center) creates a request to map a specific geographic area marked on a map.
- ***Step 2 and 3*** - EmerPoll creates a poll to Coordination Algorithm Services subscribed to a MultidronePlanningService channel. For the described case only one planning agent is considered while in the future multiple planning agents providing alternative plans for splitting the mission between multiple drones are intended.
- ***Step 4*** - The Coordination Algorithm service (described in more detail in the following section) processes the parametrized request and generates the output – a temporal plan (partial missions) for provided number of drones and pilots. Technically the responses received to the MultidronePlanningService are set of routes coded in a KML[3] format.
- ***Step 5*** - Upon receiving individual partial missions EmerPoll sends out another poll to distribute the partial missions (*.kml files) between available subscribed pilots. The poll assigns partial plans to individual drone pilots.
- ***Step 6*** - Drone pilots receive their flight plans and start the mapping/monitoring with semi-automatic photo/video footage (camera control, such as direction, zoom or shutter control should be the part of the plan).
- ***Step 7*** - Upon completion of the partial or whole planned flight the collected data are returned to EmerPoll for aggregation.
- ***Step 8*** - The poll is closed for a drone pilot either by providing photo/video footage from the assigned partial mission or by a brief failure report.
- ***Step 9*** - EmerPoll aggregates all the received data from drone pilots and can additionally submit data for further pre-processing.

- ***Step 10*** - EmerPoll transfers the collected data through the SILVANUS platform to the GINA central tool for visualization. The GINA Central stitches the received image together and generates a map layer to be shown on a tactical map for further command and control. The GINA system allows live tactical coordination between entities and field units over the same map (GINA, 2023) – for instance every firefighting truck in Slovakia is equipped with GINA Tablet software.

During the Slovak pilot test area, flights were done with the UgSC app, which needs a path described with (latitude, longitude and altitude) points (see trajectories in Figure 28). The altitude value was taken from the Digital Terrain Model DTR 5.0 of Slovak country with 1m resolution. The following figure shows the output trajectories.

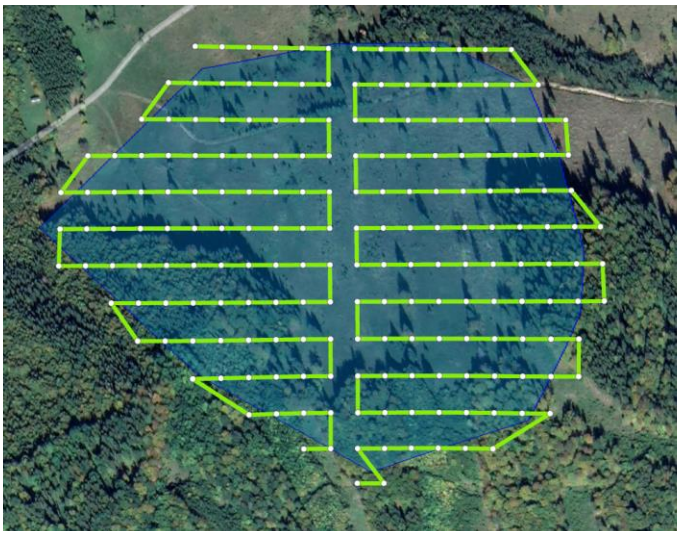


Figure 28: Output trajectories for two drones on the Slovak pilot zone

To illustrate the benefit of collecting data from the air with UAVs, we show, in Figure 29, the orthophotomap created from the successive pictures taken by the drones on the Slovak pilot event day. Figure 30 shows a few pictures taken during the event.

Figure 29: Orthophomap created from successive pictures taken by drone during the Slovak pilot event

Testing UAVs in the field, Slovak pilot

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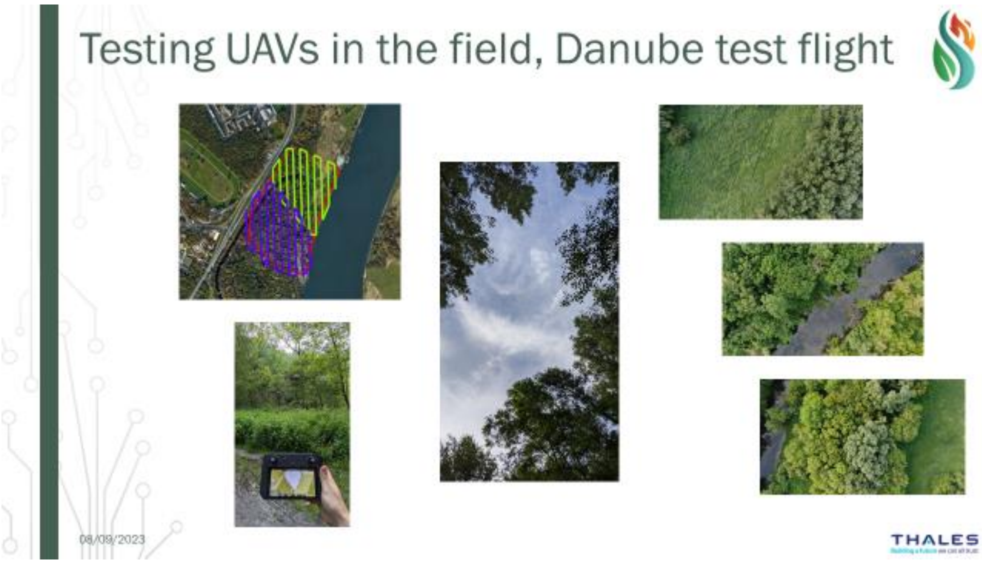
Figure 30: Various pictures taken during the Slovak pilot event

3.2.2 Additional Field Tests

For development and validation purposes, several additional test flights were conducted to ensure that all links of the technological chain of the component indeed work in practice. In particular, 3MON conducted a test flight on a zone located near the Danube River (see Figure 31) to test both trajectory export from the algorithmic modules to the drone software and the data ingestion pipeline as detailed in the corresponding section above. An account of that particular exercise, complete with technical details follows:

For the demonstration purposes we did several tests with two types of drones and two control software. The first test was done by DJI Mavic 2 Zoom in cooperation with UISAV to test the trajectory preparedness for proper identification of needed inputs of altitude, heading, camera angle, photo overlay to have the best result on stitching of the photos to create a real map of the area. The test was started in October 2022 and from that point we did several more tests in Bratislava to understand better all the problems and issues before the Slovak pilot tests. These tests were done by drone DJI Mavic 2 Zoom and a DJI Pilot application. For this purpose, we did two tests so far (As of September, 2023) and the third one is planned. The second way of testing was with a drone DJI Mavic 2 Enterprise with Gina control software. The Gina command and control software is a tool that Slovak firefighters are using on emergencies as a support software that is providing them navigation, communication, map support, data support and other needed features. The tests were focused on mapping the area of potential forest fire site and display the current mapped area of the forest fire in the Gina system. For these tests we flew a drone equipped with a thermal camera and the software created two layers of map (one RGB and one thermal). We did three tests on different places in Bratislava with small camp fire and all were successful. The mapping was especially successful in the thermal layer on which the drone could visibly detect heat from a 0,5x0,5 camp fire from an altitude of 100 m above the ground. Unfortunately, the full test of this second way of testing during the Slovak pilot was not possible due to bad weather (rain and moisture) and that the drone was not waterproof. 3MON is working with TRT on additional test flights for enhancing waypoints creation and flight trajectories for drones to map a bigger area by more drones simultaneously.



Testing UAVs in the field, Danube test flight

08/09/2023

THALES

Figure 31: Various pictures of the so-called Danube zone test flights

4 Conclusion and Perspectives

This deliverable described the work conducted by UISAV, 3MON, DELL, EDP, ATOS and TRT in task T4.6, led by TRT and devoted to UAV fleet coordination as part of Work Package 4 (sources of information) of SILVANUS, collaborative project on wildfire management.

The output of the task, a fully functional coordination and trajectory optimization module for UAV fleets, culminated in the demonstration of the functionalities during the review meeting of the project at M21. The component successfully solves underlying mathematical optimization problems to procure full mission plans, including area coverage and optimal path computation in a fast enough manner to allow for agile “re-planning” of surveillance missions. Besides the main tabletop, simulation-based although based on real data, review demonstration, several real-world test flights were conducted to confirm that this technology, when natural conditions allow, can be used in practice. Finally, to accurately place the outcome of this task in perspective, a critical “benefits versus limitations” analysis of the technology was also attempted in the first chapter of the deliverable.

While we deem the outcome of the task to be significant in both its benefits and reality checking, much work is, nevertheless, still needed to make the component robust enough to be fluently used in a scalable manner and significant undertakings in automation and industrialization are called for as first priority. On a more algorithmic note, a number of possible improvements are possible and will be considered for development during the remaining time available for the project if time and resources allow. These include automated adaptive re-planning, decentralized coordination and automated fleet sizing.

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