Engage 2

HYPERSTREAM

Final technical report

Engage 2 catalyst fund project

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THE SESAR 3 KNOWLEDGE TRANSFER NETWORK

Engage 2

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1 Introduction

1.1 Abstract

The project introduces an integrated approach to reducing traffic complexity in dense drone operations by combining adaptive airspace corridor generation with a conflict-free traffic optimisation framework. A bio-inspired algorithm dynamically designs cyclic corridors that connect vertiports while avoiding no-fly zones and maintaining smooth, flyable geometry. Building on this structure, an optimisation method based on Selective Simulated Annealing manages large-scale UAV flows by coordinating layer selection, entry timing, and speed adjustments. This ensures safe separation and efficient throughput even under high traffic density. Tested with realistic scenarios of urban layouts and 10,000 UAVs, the approach achieves full conflict elimination with minimal trajectory adjustments and computation times compatible with real-time UTM applications, supporting future automation of flight-centric drone traffic management.

1.2 Executive summary

HYPERSTREAM develops and evaluates a new approach for managing dense drone traffic by combining two complementary innovations: the automatic creation of adaptive airspace corridors and the large-scale optimisation of UAV flows within those corridors. The project builds upon developments from the previous Engage KTN's catalyst fund 'Flight centric ATC with airstreams' project which proposed disruptive changes to traditional air traffic management (ATM) architecture. HYPERSTREAM extends and integrates this concept to create a flight-centric framework suitable for high-density urban drone operations.

The first component of HYPERSTREAM is an adaptive corridor-generation method based on a bio-inspired Slime Mold Algorithm. This decentralised, agent-based process dynamically creates cyclic navigation corridors that connect vertiports while avoiding no-fly zones (NFZs). The resulting corridors are smooth, efficient, and robust to changes in the urban environment. Tests in several realistic urban scenarios show fast convergence, reliable obstacle avoidance, and operationally suitable geometry.

The second component is a traffic-optimisation framework for large flows of UAVs using a simplified two-layer circular airspace structure. Each UAV can adjust its altitude layer, entry timing, and speed. Conflicts are modelled at both link and node levels, and a tailored Selective Simulated Annealing (SSA) algorithm resolves them. SSA reduces memory use through local updates and prioritises UAVs that cause the most congestion.

In a 10,000-UAV scenario, the optimisation produced fully conflict-free operations with minimal changes to scheduled trajectories. Layer usage was balanced, most UAVs kept their original speeds and timings, and the computation time remained compatible with real-time requirements.

HYPERSTREAM demonstrates that combining adaptive airspace structuring with scalable automated deconfliction can significantly reduce complexity in dense drone operations. The approach supports future U-space automation, provides a basis for managing structured corridors in cities, and offers a pathway for TRL growth through integration with industrial partners and U-space service providers.

Outcomes

The outcomes concern two areas (Dynamic design and Traffic optimisation), as explained in section Operational/technical context (page 8) **Methodology**

a. Dynamic design

The method demonstrates strong performance across a variety of urban conditions:

- Fast convergence (around 200 iterations in all scenarios).
- Robust avoidance of obstacles, with no incursions into no-fly zones.
- Adaptability to new layouts, demonstrated by transferring pheromone maps between scenarios.
- Geometric realism, with splines that maintain smooth curvature and avoid self-intersections.

Operational metrics indicate that flights inside the corridor remain efficient: the additional distance relative to a direct path remains modest (7–12%), acceptable in structured UTM designs where predictability and safety take precedence.

b. Traffic optimisation

A scenario with 10,000 UAVs was simulated using two 30-meter radius rings, each with 36 entry-exit points. UAV speeds, entry times, and layer selections were randomly assigned within realistic ranges.

The key outcomes are:

- Full conflict elimination was achieved.
- Runtime was suitable for tactical-level UTM updates.
- Balanced layer use and minimal disruption.

These patterns indicate that the system resolves congestion while preserving the intended behaviour of most flights. The framework demonstrates robustness, scalability, and realistic operational performance.

HYPERSTREAM advances the maturation of flight-centric approaches by showing that:

- Corridors can be generated automatically, adapting to urban changes.
- Structured airspace significantly simplifies traffic patterns.
- Large-scale autonomous deconfliction is feasible using coordinated adjustments to layers, timing, and speeds.
- The approach is compatible with existing U-space/UTM concepts and can support future, higher-TRL developments.

The project has also established contact with drone operators and U-Space Service Providers, who expressed interest in corridor-based operations for logistics, inspection, and surveillance missions.

Contribution to advancing the state of the art/improving the potential application of the concept

HYPERSTREAM will contribute to the maturation of the flight centric approach. In the drone domain, this approach can target TRL2-3 and experiments can be conducted.

2 Overview of catalyst project

2.1 Operational/technical context

Problem

The problem addressed is the automation of conflicts resolution in air traffic by using Airstreams. Airstreams are an airspace infrastructure consisting of corridors comprising several lanes. The aim is to evaluate conflict resolution strategies.

Operational environment

In densely populated areas, increased structure is necessary. Introducing lanes, tubes, or corridors provides a more structured airspace, and also utilizes an already-established traffic-management system, enabling smoother integration of urban air mobility. One such emerging concept is cyclic corridors, structured and looped aerial routes that allow for continuous, multi vehicle usage. These corridors offer benefits such as predictable flow, fair access, and simplified deconfliction strategies. However, unlike traditional static corridors, cyclic corridors require dynamic adaptability to accommodate real time changes such as shifting demand, weather conditions, and temporary airspace restrictions.

In the traffic optimisation part of the study, we assume the existence of a network of Airstreams. We deliberately consider the case where this network is entirely defined automatically. As part of the project, we have significantly simplified the airspace geometry. The Airstream network is symbolised by a ring consisting of 2 lanes using only one direction of traffic. We assumed that all aircraft are fully controlled centrally and there is no uncertainty, for example regarding weather conditions.

Methodology

We had to break the problem down into two sub-problems:

a. the **dynamic design of Airstreams**, taking into account local constraints (no-fly zones, vertiport locations), and
b. the **optimisation of the drone traffic** within the Airstreams.

It is possible to replace the theorical circular airspace by one produced by the dynamic design.

Tools

The HYPERSTREAM project used an adaptative corridor generation algorithm and a traffic optimisation algorithm.

- The dynamic design generates a corridor for connecting vertiports while avoiding no-fly zones. It allows us to design cyclic airspace corridors by using Slime Mold Algorithm (SMA).
- The traffic optimisation is based on the deterministic algorithm Selective Simulated Annealing (SSA) where the shape of the Airstream is fixed and simplified as much as possible (circular shape).

2.2 Project scope and objectives

Scope

HYPERSTREAM explores flight centric strategies. The project objective is to evaluate the performance of flight centric approach with automated tools.

Our project supports the thematic challenge 3: Disruptive ATM system modernization.

Objectives

Demonstrate the feasibility of a conflict avoidance algorithm in an Airstream context.

Research questions:

- Can we use a network of Airstreams created automatically by an adaptive corridor generation algorithm? This algorithm makes it possible to avoid no-fly zones and optimise access to vertiports for drone take-off and landing.

- Evaluate the effectiveness of an algorithm that predicts and avoids conflicts in a dense traffic environment.

2.3 Research carried out

a. Dynamic design

A novel bio-inspired method has been developed for designing cyclic airspace corridors to support high-throughput, bidirectional flows of Unmanned Aircraft Systems at Very Low Level.

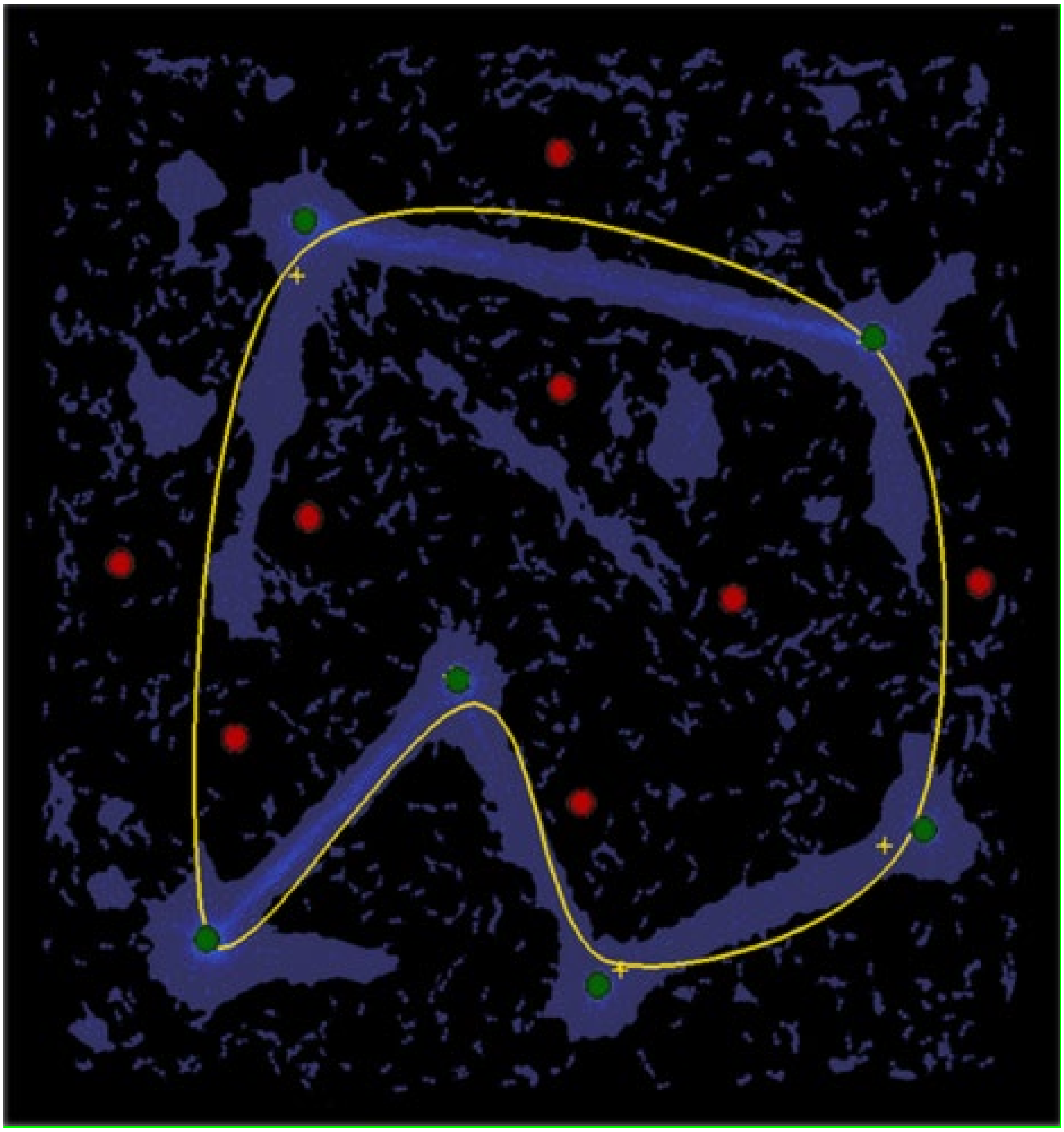

Figure 1: Corridor generated by the Slime Mold Algorithm (SMA)

The Slime Mold Algorithm was used for generating a corridor connecting vertiports (in green) while avoiding no-fly zones (in red). The blue distribution is the pheromone grid, the media used by all the slime agents to communicate. They deposit pheromone to make a global distribution they can follow to reach all interest points.

Agent creation

Three types of agents operate within a 2D airspace: Exploiters move greedily toward vertiports (attractors) and away from no-fly zones (repulsors); Explorers favour discovering unused areas (high entropy); and Trail-thickeners: reinforce existing high-pheromone regions.

The agents sense the environment through multiple forward-oriented sensor rays. They select movement direction by maximizing a weighted score combining pheromone concentration, attraction to vertiports, repulsion from obstacles and a small randomness term. Each agent deposits pheromones, which then diffuse and decay across the grid. To avoid agents clustering around the same vertiport, each agent uses a *cooldown timer* based on average inter-vertiport distances. This enforces regular transitions between vertiports.

Corridor Extraction

After each SMA iteration, high-pheromone cells are identified and clustered (k-means) into control points. Then a closed Catmull–Rom spline is generated through these points. It ensures smoothness (continuity), avoids overshoots, and produces flyable curved paths. The result is a cyclic corridor that can support clockwise/counter-clockwise flows at different altitudes.

Evaluation of the algorithm

Three large-scale, realistic urban scenarios were tested:

- Scenario I: Sparse vertiports and few obstacles.
- Scenario II: Denser layout, more obstacles.
- Scenario III: Large, cluttered urban area with 15 vertiports and 10 no-fly zones.

Two categories of performance metrics were produced:

- Algorithm-centric (i.e. Vertiport proximity, Obstacle incursion avoidance, Self-intersection, Curvature smoothness and Corridor length).
- Operational metrics (Total flown distance vs. ideal point-to-point, Entry/exit distances, Maximum route lengths and Corridor usage rate).

b. Traffic optimisation

To address the growing complexity of UAV traffic in urban and peri-urban airspace—where existing UTM systems rely heavily on tactical deconfliction and lack scalable, strategic organisation—the HYPERSTREAM approach introduces an adaptive airspace structure coupled with optimisation algorithms. Together, these elements enhance safety, efficiency, and scalability for high-density UAV operations.

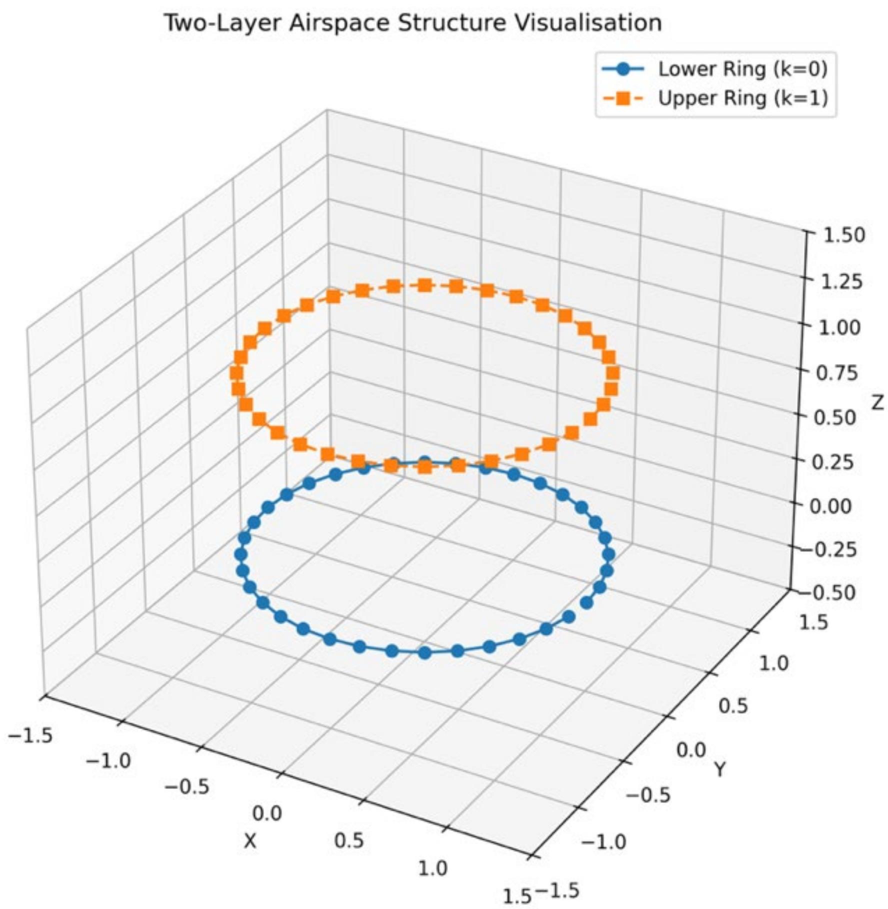

Figure 2: Example of two-layer airspace

The airspace concept is a two-layer structure inspired by a roundabout design, where each layer is a circular ring of waypoints at a fixed altitude. This configuration offers a simple yet effective representation of structured airspace or networked UAV nodes. Each layer represents distinct operational zone. The number of nodes (waypoints) per layer is flexible and scalable and the structure can be extended to more layers without redesigning the framework.

This provides a lightweight, modular, memory-efficient representation of airspace for simulation and optimisation.

In this two-Layer UAV Traffic Management Model, each UAV optimises three parameters simultaneously:

1. Layer selection (which altitude layer to use).
2. Entry time adjustment (shifting entry within a ±5-minute window).
3. Speed adjustment (±60% around nominal speed).

Together, these allow flexible rerouting without redesigning flight paths.

Two types of conflicts are modelled:

- Link conflicts result from unsafe spacing when two UAVs fly the same segment too close in time or speed.
- Node conflicts result from unsafe temporal overlap at waypoint “junctions” (each node has a protection radius).

Both conflict types must be zero in the final solution.

The optimiser simultaneously aims to avoid conflicts (primary goal) and minimise deviation from planned schedule and speed (efficiency). This is handled through a weighted objective function balancing safety and efficiency.

It is to be noted that the search space is exponentially large because each UAV can choose one of several layers, one of many time slots, and one of many speed values. This makes the problem NP-hard, requiring advanced heuristics.

The Optimisation Algorithm used is the Selective Simulated Annealing (SSA). The SSA is a customised variant of Simulated Annealing implementing two improvements:

- The “Come-back” Operator only modifies one UAV’s decision at a time. If rejected, only that UAV’s vector is reverted. It greatly reduces memory use and is ideal for large simulations.
- The Conflict-guided Neighbourhood Search: UAVs that contribute more to conflicts get higher probability of being selected for modification, so that the algorithm focuses computation on the “worst offenders”.

The algorithm interacts in real time with the simulation environment and updates costs incrementally.

2.4 Results

a. Dynamic design

Results show convergence within 200 iterations, rapid adaptation to topological changes, and the potential to support more complex corridor structures giving promises to the method's suitability for real-time, dynamic airspace design in UAS traffic management.

The algorithm reacts well to topology changes (high adaptability), is scalable up to medium-large city layouts. It avoids obstacles and maintains connectivity (robustness) and is completely decentralised.

- The SMA algorithm converges rapidly (≈200 iterations) for all scenarios. We observed no self-intersections or no-fly zone incursions in any corridor. Initializing Scenario II using Scenario I's pheromone map demonstrated strong adaptive responsiveness.
- The corridors closely follow vertiports, avoiding obstacles effectively. All waypoints of the corridor were used at least once (100% usage). The Catmull–Rom splines produced operationally realistic trajectories.
- The extra distance compared to point-to-point ranged from 7–12% average.

b. Traffic optimisation

The SSA algorithm has been evaluated with a 10,000 UAV Scenario on two circular rings with radius of 30 m (superimposed in altitude).

The other simulation parameters were set as follows:

- The rings are sampled in 10-degree increments (36 entry-exit points).
- A speed for each UAV randomly drawn from the interval [10,25] (m/s).
- A separation standard of 2 metres is applied.
- Traffic is spread over 4 hours (entries and exits randomly selected from among the 36).
- Each UAV is allowed to change its speed (+-10%), a delay of +-5 minutes to enter the rings, and to choose the ring.

The algorithm's performance is excellent: the objective function converges well and the algorithm achieves conflict-free rerouting consistently. The average optimisation time is 324 seconds (~5 minutes).

- The Layer selection is almost perfectly balanced (layer 0: 49.92% and layer 1: 50.08%).
- Entry time adjustments are moderate: 66% need no adjustment and most adjustments are small (within ±5 slots = ±25s).
- Speed adjustments are moderate: (51% unchanged, 30% within ±5% of nominal).

This means the optimiser resolves congestion with minimal disruption to planned flights.

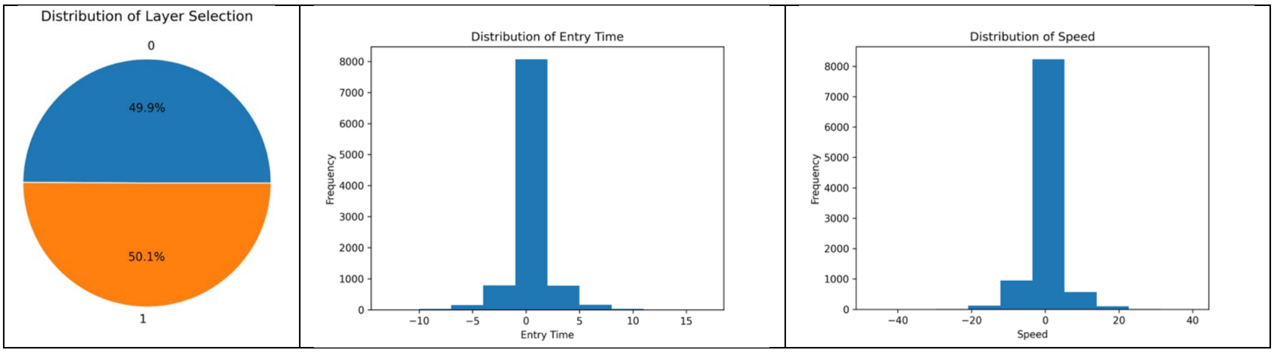

Figure 3: Decision patterns

3 Conclusions, next steps and lessons learned

3.1 Conclusions

a. Dynamic design

A bio-inspired swarm algorithm, augmented with a pheromone grid and spline extraction, can effectively generate smooth, adaptive cyclic air corridors for drone traffic in urban environments.

The method converges quickly, adapts to changes, maintains safety constraints and offers a promising foundation for real-time UTM airspace design.

Certain limitations have been identified:

- Only static scenarios have been tested; dynamic environment adaptation would improve the approach.
- Agent and pheromone parameters require empirical tuning. reinforcement-learning could be used to tune the parameters.
- Real-time performances are not fully benchmarked. The integration into mixed-reality UTM simulations could be envisaged.

b. Traffic optimisation

A scalable framework for large-scale UAV traffic management has been developed. It integrates layer selection, entry time adjustments, and speed modifications to reduce congestion and maintain safe operations. Using SSA-based optimisation, the framework demonstrated rapid convergence and consistent performance across scenarios involving 10,000 UAVs. The results indicate that UAV decisions are well-balanced: layer selections are evenly distributed to optimise capacity, while entry time and speed adjustments are applied selectively to minimise conflicts and delays.

The proposed approach effectively balances operational efficiency and traffic safety, highlighting the practical applicability of the framework for future UTM systems. Moreover, the analysis of decision patterns provides valuable insights into UAV behaviour under high-density traffic, which can inform the design of automated traffic management strategies.

Future work may extend the framework to incorporate heterogeneous UAV performance characteristics, and dynamic airspace constraints, further enhancing its robustness and applicability to complex urban air mobility environments.

Various contacts have been established with industry to validate the relevance of the HYPERSTREAM concept. These include drone operators who have to carry out repetitive operations in dedicated areas, such as surveillance of sensitive sites or parcel delivery. These operators can use a fleet of drones to cover several types of operations and must take account of environmental constraints, in particular to limit ground and air risks. They must therefore operate within corridors, following trajectories that take account of prohibited zones (NFZs), which can be diverse and potentially dynamic (e.g. meteorological events, gatherings of populations) and vertiports areas. Contacts have also been made with U-Space Service Providers with the objective to involve them in the concept adaptation and potentially integrating the services and products resulting from the project.

3.2 Next steps

Future research should explore the improvement of the operational efficiency, capacity and safety. In priority, the industrialisation of the concept will require to integrate dynamic modification of the Airstreams geometry (because of the evolution of no flight zones or meteorological conditions) and the emergency landing management. The urban airspace should be structured so that UAVs-based-urban-logistics can be performed efficiently and ease accessibility of the logistics service while ensuring the safety of traffic in the urban airspace.

Another area of research is related to the design of local networks and the design of corridors between different urban subareas. Finally, with the development of drone deliveries, it will be necessary to study the saturation of the Airstreams, the strategies for balancing the traffic in the different lanes and the adaptation of the number of lanes according to the traffic demand.

3.3 Lessons learned

We appreciated Engage 2's flexibility in handling changes to the project scope. We also appreciated the network’s understanding regarding the delay in submitting the final report and we would like to express our gratitude.

4 Dissemination

Table 1: Dissemination activities

Output	Status	Event	Date	Further info
Paper: *Bio-inspired Algorithm for Designing an Adaptive Cyclic Corridor for UAS Traffic Management*	Presented	44th AIAA DATC/IEEE Digital Avionics Systems Conference (DASC 2025) Montreal	14-18 September 2025	Approximately 350 researchers, industry leaders, and subject matter experts. 255 technical submissions in 9 tracks
Paper: *Investigating Cyclic Airspace Corridor Optimization for UAS Traffic Management based on Deep Reinforcement Learning*	Presented	44th AIAA DATC/IEEE Digital Avionics Systems Conference (DASC 2025) Montreal	14-18 September 2025	Approximately 350 researchers, industry leaders, and subject matter experts. 255 technical submissions in 9 tracks
Paper: *Evaluating Interoperability of Deconfliction Algorithms in UAS Traffic Management*	Presented	44th AIAA DATC/IEEE Digital Avionics Systems Conference (DASC 2025) Montreal	14-18 September 2025	Approximately 350 researchers, industry leaders, and subject matter experts. 255 technical submissions in 9 tracks
Background Paper: *A Two-Level Structure for Efficient Logistics in the Urban Airspace*	Presented and published	IEEE/CoDIT2024 Conference Malta	July 2024	Approximately 350 researchers
Presentation: *HYPERSTREAM Project*	Presented and published	Airspace World 2025 Lisbon	14 May 2025	Approximately 30 researchers
Conference paper: *Hybrid Real-Simulated Validation of Separation Assurance and Vector Field Guidance for Safe and Conformant Airspace Corridor Integration*	Submitted	15th SESAR Innovation Days, 2025	December 2025	
Poster: *HYPERSTREAM Large scalable UAV Flow Structuring*	Submitted	15th SESAR Innovation Days, 2025	December 2025	
LinkedIn page	On-line			

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5 References

5.1 Project outputs

Table 2: Project outputs

Output	Summary
<u>Conference Presentation</u>: HYPERSTREAM Project	Presented at **Airspace World 2025**; May 2025
<u>Conference Paper</u>: Bio-inspired Algorithm for Designing an Adaptive Cyclic Corridor for UAS Traffic Management	Presented at **44th AIAA DATC/IEEE Digital Avionics Systems Conference** (DASC 2025); September 2025
<u>Conference Paper</u>: Investigating Cyclic Airspace Corridor Optimization for UAS Traffic Management based on Deep Reinforcement Learning	Presented at **44th AIAA DATC/IEEE Digital Avionics Systems Conference** (DASC 2025); September 2025
<u>Conference Paper</u>: Evaluating Interoperability of Deconfliction Algorithms in UAS Traffic Management	Presented at **44th AIAA DATC/IEEE Digital Avionics Systems Conference** (DASC 2025); September 2025
<u>Conference Poster</u>: Large Scalable UAV Flow Structuring	Presented at **15th SESAR Innovation Days** conference; December 2025
<u>LinkedIn Posts</u>: HYPERSTREAM activities	https://www.linkedin.com/company/hyperstream-engage2-sesar-project/posts/

6 List of acronyms

Acronym	Description
ATC	Air Traffic Control
ATM	Air Traffic Management
NFZ	No Flight Zone
SESAR	Single European Sky ATM Research Programme
SMA	Slime Mold Algorithm
SSA	Selective Simulated Annealing
UAS	Unmanned Aircraft System
UAV	Unmanned Aerial Vehicles
UTM	Unmanned Traffic Management

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