TOWARDS A 4D TRAFFIC MANAGEMENT OF SMALL UAS OPERATING AT VERY LOW LEVEL

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Abstract

While the ATM systems are strongly evolving through major ATM programs, a revolution is under progress: the number of small drones operating at very low altitude is exponentially increasing. However, the regulation that is currently under definition may limit their potential development. This paper proposes to tailor the 4D contract concept initially defined for the commercial air transport to small drones operations.

1 Introduction

The Air Traffic Management (ATM) community is currently modernizing its own systems through major programs such as SESAR or NextGen [1]. In the meantime, new airspace users, such as Unmanned Aircraft Systems (UAS) or drones, should maintain cognizance of how the ATM environment will evolve in the next decades. The objective is to avoid obsolescence of their systems [2] and benefit from new communication, navigation and surveillance capabilities foreseen. In parallel, the ATM community has been tasked [3] to integrate Remotely-Piloted Aircraft Systems (RPAS), a sub-category of UAS, in the ATM system of tomorrow, which will necessitate some unique procedures due to the absence of an on-board pilot [4].

Many studies, including demonstration projects [5], have been launched on this topic of UAS integration, most of them being focused on integrating medium/large Unmanned Aircraft (UA) into non-segregated airspace. In the meantime, small drones have recently become ubiquitous, with the development of various commercial applications, but also the increasing affordability of aircraft models often operated by amateurs with limited aeronautical knowledge. To face the safety, security and privacy issues associated to the development of these UAS operations, many European countries have already promulgated their national UAS regulation (e.g. the French UAS regulation [6]) and a harmonization at the European level is imminent [7]. However, very few actions have been launched to analyze the change of paradigm introduced by these small UAS flying at Very Low Level (VLL) [8], i.e. under 150 m.

As symbolized by the ongoing NASA initiative UAS Traffic Management (UTM) [9] [19], it is urgent to build a structure to accommodate these new airspace users. Such initiative in Europe must be supervised by Civil Aviation Authorities (CAA) and Air Navigation Service Providers (ANSPs) that have the responsibility to provide sufficient information for both types of aircraft (manned and unmanned) to coexist in the same airspace [7].

The challenge is now to identify what kind of ATM system could be developed to manage these small UAS operating at VLL. Two main approaches can be considered: to mirror the future ATM concepts planned for the foreseeable future [10] with the appropriate downscaling, or to experiment futuristic concepts presented as potential candidates in a longer term vision [11]. At the heart of these two approaches, we elaborate in this paper on the possibility to use the 4D contract concept (based on an accurate planning of the trajectories of all the air vehicles, optimized in 4 dimensions, i.e. space and time), previously defined and assessed in simulation for commercial air traffic [12], to manage small drones' VLL operations over highly populated areas

2 4D contracts for small UAS VLL operations

2.1 The 4DCo concept for commercial air transport

The 4D contract (4DCo) concept has been primarily defined in the frame of the European project IFATS [13], with the objective to increase the safety level of air traffic operations by a full automation of the Air Transport System (ATS). To reach this objective, the way air traffic is managed was completely rethought: optimal and conflict-free trajectories would be computed (in 4D) for the whole traffic and aircraft would commit to accurately fly according to their assigned trajectories. This creates a “contract” between the ground and air segments of the ATS. After the IFATS project, the 4DCo concept has been refined and simulation have been performed to assess its feasibility and performance during the European project 4DCo-GC [12]. The key features of the 4DCo concept are summarized in Table 1.

Table 1. 4D contract concept key features

4D contracts are computed at a large scale (continent) by a centralized entity in charge of managing the whole system. They are based on the aircraft performance, forecasted weather, airports capacity, etc.
Before take-off, each aircraft receives a 4D contract.
The 4D contracts are conflict-free: as long as all aircraft respect their contract, there is no collision risk.
Each aircraft has the responsibility to respect its assigned contract and so to ensure the safety of the whole system.
If the contract cannot be respected any more, the aircraft is granted an updated one. This updated contract is computed taking into account the current traffic situation.

The 4DCo concept is more complex than just those simple general “rules”. In our case, the most interesting feature of the 4DCo concept is the use of dynamic “bubbles” around the aircraft and its trajectory ensuring the safety and stability (in terms of number of contract updates) of the flights: these are the Safety Bubble and Contract Bubble (Figure 1) – the Freedom Bubble being a combination of the previous ones.

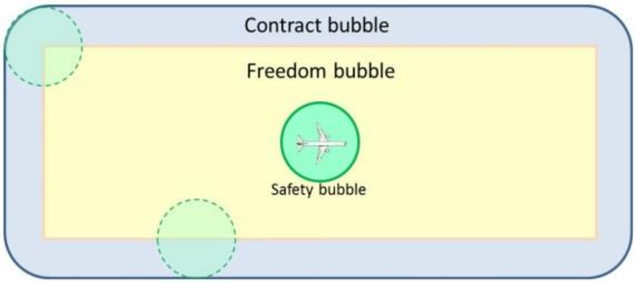

Fig. 1. Illustration of the 3 types of "bubbles" of the 4DCo concept

2.2 Application to the small UAS VLL operations

Despite the fact that it was defined for the commercial ATS, the 4DCo concept can be derived to other systems sharing similar characteristics: high level of automation, high number of flights, high density areas, time-critical operations, complex replanning (i.e. difficult to be quickly and efficiently handled by humans). All these characteristics apply to small UAS VLL operations in high density areas.

Of course, small UAS flying at very low level are not a simple downscaling of the commercial air traffic. When considering its application to the 4DCo concept, such system brings specific strengths and weaknesses

2.2.1 Strengths

Maneuverability

The major strength of small drones is their high maneuverability; combined with automation, it enables to provide them with complex trajectories, limiting route lengthening when avoiding obstacles (can they be other flying objects or not).

Predictability

One of the main characteristics of the 4DCo concept is the predictability of the system. With regard to this aspect, UAS drastically reduce the uncertainty related to human behavior. For example, when considering air traffic, the time necessary for boarding is an important case of uncertainty regarding the take-off time; depending on the robustness of the 4D contracts, it can have a major impact.

Hovering capability

Most of the small drones currently operated are multicopters, or at least vehicles with hovering capability. When considering conflict avoidance or traffic replanning, this ability to reduce speed down to zero is a decisive advantage. Indeed, whatever the situation, at least one solution will always exist to maintain safety: stopping the involved UA. However, stopping will probably be used only for very rare situations, speed reduction being sufficient most of the time. The point is that even a high speed reduction can be considered, as there is no risk of stalling.

Potentially reduced margin size

The size of the margins (Safety, Contract Bubbles) to be used for small drones can probably be reduced when compared to large transport aircraft (relatively to the vehicle size). As an example, the wingspan of an A320 is 35 m and the Safety Bubble diameter (corresponding with current separation minima) is 5 NM (around 9,260 m). This gives a ratio: $r = \frac{SafetyBubbleDiameter}{wingspan} = 264$.

Now if we transpose to small drones: the diagonal size of a DJI Phantom 3 [14] is 0.59 m. With the same ratio, the diameter of the bubble should be about 150 m (155.76 m). Due to their very high level of automation and the high precision of localization (GPS or similar locating devices) and taking advantage of their low inertia and high maneuverability, a much smaller diameter can be considered, without negatively impacting the system safety- however, this must be assessed by dedicated studies and experiments. As an illustration, a diameter of 100 m corresponds to a ratio r = 170, which would then be reduced by 35%.

2.2.2 Weaknesses

Weather vulnerability

On the other hand, small UAS also bring weaknesses, when considering their adaptability to the 4DCo concept. The main difficulty to overcome for the implementation of the 4DCo concept is the resilience of the system with regard to weather. Indeed, strategic planning is set up based on weather forecast. So the ability of the aircraft to respect their 4D contracts despite difference between forecast and real weather is a key challenge. Small drones are light and, as so, very sensitive to wind. Especially, wind gusts can cause major deviation to their trajectories, resulting in 4D contract non-compliance (possibly in large proportion).

Failure or emergency reactivity

Besides, in case of emergency situations, automated procedures should have been anticipated as the remote pilot will not be able to evaluate the impact of the mitigation procedure chosen. This aspect must be dealt with with a specific care or it could raise high safety concerns.

3 Initial CONOPS

Based on this quick overview of the characteristics of the 4DCo concept with regard to its applicability to the VLL operations of small UAS, it seems interesting to push the investigation farther and to detail the concept of operations (CONOPS) in order to perform a first performance assessment.

3.1 Use case

The CONOPS detailed in the next chapters was built upon a first use case idea. This use case is goods delivery: small packages are transported from a warehouse directly to the customer. This choice has been motivated by the declarations and the first experimentations of several companies (Amazon [15], Google [16]), or postal services (e.g. in France [17] or Switzerland [18]) that consider the use of drones for their activities.

In our example, the delivery companies operate from warehouses located around a large city. These warehouses are distributed in order to ensure a good geographical repartition, whereas avoiding “restricted” zones (such as the airport, located at the north-west of the city in the example illustrated by Fig. 2). The delivery zone is defined by a circle of a given radius: all the deliveries (i.e. the customers’ locations) are located within this circle (Fig. 2).

Fig. 2. Illustration of the considered use case: warehouses and delivery zone definition

The trajectory followed by each drone is composed of one or several direct straight lines between a warehouse and the delivery point; after delivery, the drone flies back directly to its original warehouse, as illustrated by Fig. 3. According to the CONOPS, each drone is provided with a 4D contract including a 4D Bubble and composed as follows:

- The drone takes off from its warehouse and climbs up vertically until it reaches its cruise altitude.
- Then it cruises to its delivery point.
- The drone performs a vertical descent and lands on the delivery point, where the delivery is performed.
- The flight back to the warehouse is similar: vertical climb, cruise as constant altitude, vertical descent and landing.

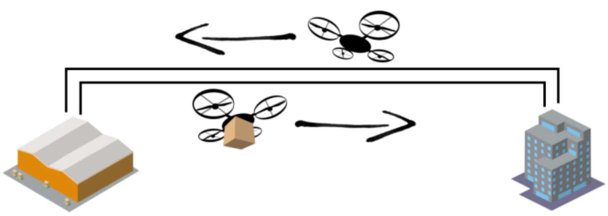

Fig. 3. Illustration of the 4D trajectory followed by the drone

With such a use case, the concept presented in this paper fits the most advanced UTM Research Technical Capability Level [19], Capability 4, which characteristics are:

- Beyond Visual Line Of Sight;
- Urban environments, high density;
- Autonomous vehicle-to-vehicle, internet connected;
- Large-scale contingencies mitigation;
- News gathering, deliveries, personal use.

3.2 General principles

The 4D contracts are generated to manage small UAS predictable Beyond Visual Line Of Sight (BVLOS) operations over high-density areas such as cities, in a way comparable to the tubes concept of the METROPOLIS project [20]. UAS are assigned a very simple contract including 4 points (single flight), 8 points (return flight), or 8+ points depending on the number of obstacles (Fig. 4).

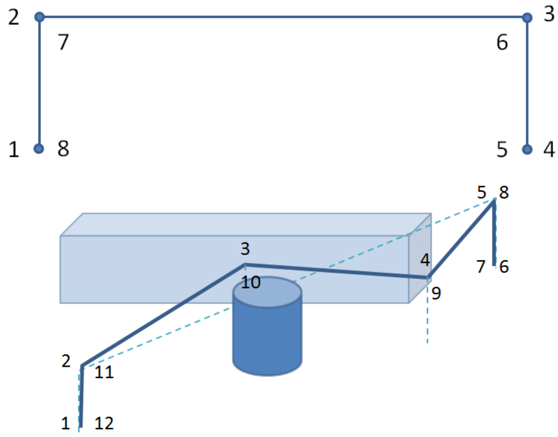

Fig. 4. Examples of simplified trajectories

The drone takes-off to reach its cruise height layer, included within the limited range of [50m - 150m] above ground. Then the 3D trajectory to the arrival point is built to be as direct as possible, depending on the obstacle. The aircraft descends to the target height, and in the case of a return flight (e.g. a delivery drone) wait a moment before going back to its initial departure point, with the same route and the same behavior (speed and acceleration).

Airspace below 50 m is reserved for lesser-equipped vehicles, as aircraft models, and non-transit operations such as surveying, videography or inspection, as described in

Amazon position on UTM [21] from which is extracted the Fig. 5.

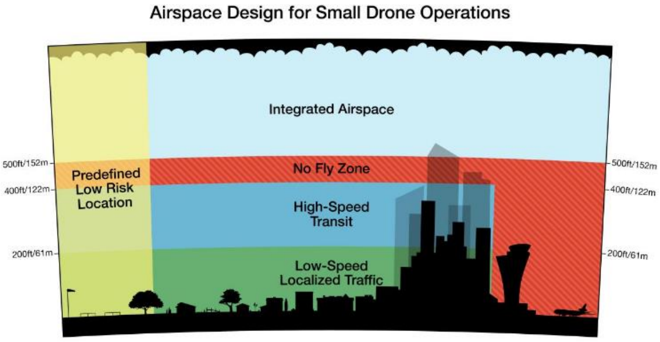

Fig. 5. Amazon proposal for airspace design for small drone operations [17]

UAS are managed as automatically as possible. Nevertheless, a remote pilot is always allowed to manage the flight. So the drone is not considered as an "autonomous aircraft" according to ICAO definition [22]. As RPAS, these systems will be more easily integrated in the foreseeable ATM system, at least in a first step.

Along its 4D trajectory, the UAS would have to remain within a Protection Bubble (sort of adapted translation of the Safety Bubble of the original 4DCo concept) with the form of a cylinder. If it manages to stay within this volume, it is ensured to be appropriately separated from other aircraft operating in the area.

The UAS operator is in contact with a local Airspace Service Provider (ASP) [23], in charge of VLL operations within a limited geographical area. This actor is in charge of ensuring the safety of operating aircraft and the equity between operators.

3.3 Planning phase

A few hours before take-off, the UAS operator is sharing its flight intentions to the local ASP, in charge of the considered area, including the information from Table 2.

Table 2. Example of flight information shared with ASP

Information	Data
Aircraft registration	
Main aircraft performance	hovering capability, climb/descent rates, cruise speed, endurance
Departure location (e.g. warehouse position)	latitude, longitude and altitude
Arrival location (e.g. delivery point position)	latitude, longitude and altitude
Type of flight	single or return
Time needed at destination (e.g. foreseen delivery duration)	
Flight priority	None, state aircraft, emergency, etc.
Requested take-off time	time when the aircraft is ready to take-off

The ASP is then building a 4D contract based on:

- Weather information: for instance wind gusts could increase the safety bubble diameter, if not prevent any flight during a given time period;
- ATM constraints provided by the CAA in charge (e.g. segregated areas);
- Capacity already determined by previous 4D contracts according to a priority policy to be defined (potentially based on a first-come, first-served principle).

The 4D contract is optimized to reduce conflicts with other contracts (safety) while limiting the delay at take-off (efficiency) in case of demand and capacity imbalance. Stochastic optimization methods can be used to rapidly provide an acceptable solution to all airspace users. For instance, the following mono-objective optimization based on the Simulated Annealing (SA) [24] technique is defined to minimize both the total duration of the remaining conflicts (in seconds) and the sum of all delays affected (also in seconds).

The duration of a conflict, i.e. is the time during which the 4D protection bubbles of two

4D contracts $C4D_i$ and $C4D_j$ are overlapping is noted:

$$d\left(C4D_i, C4D_j\right)(\Delta t)$$

The total duration of the remaining conflicts is noted:

$$D(\Delta t, C4D) = \sum_{(C4D_i, C4D_j) \in C4D^2} d(C4D_i, C4D_j)(\Delta t)$$

The delay affected to a 4D contract, i.e. the difference between the requested takeoff time and the realized one, is noted:

$$delay\left(C4D_i(\Delta t)\right)$$

The sum of all affected delays is noted:

$$delays(\Delta t, C4D) = \sum_{C4D_i \in C4D} delay(C4D_i(\Delta t))$$

The objective function considered for the SA is the following:

$$Obj(\Delta t) = \alpha \times conflicts(\Delta t) + (1-\alpha) \times delays(\Delta t)$$

Within the 4D contract, the 3D trajectory is defined as the most efficient path from departure to arrival, taking into account potential obstacles. The 4D trajectory is built from this 3D trajectory by associating target times based on nominal performances of the drone. If the maximum acceptable delay is reached, the 4D contract cannot be generated and the airspace user is requested to modify its demand. At any moment before take-off, the airspace user can modify its initial demand and request a new 4D contract.

The 4D contract plan, picturing all the 4D contracts already generated, is continuously shared to airspace users that can hence anticipate density peaks, and to CAAs that can check the safety mitigations and the equity between airspace users.

The figure hereafter shows the results of a fast time simulation instantiating a deconflicted traffic of 100 flights and 1 hour scenario.

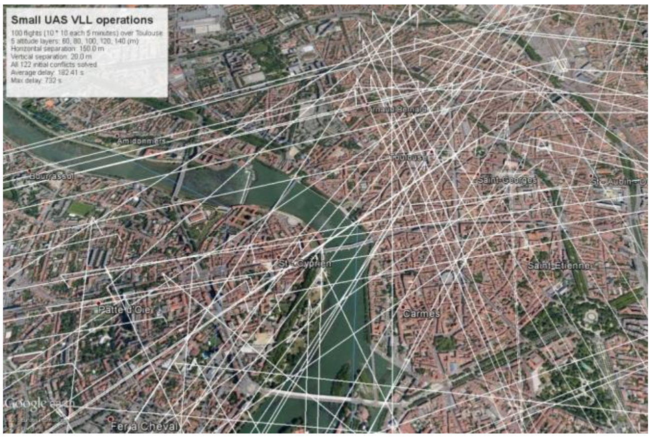

Fig. 6. Visualization of deconflicted 4D trajectories

3.4 Execution phase

From take-off, the drone must fly the 4D contract received in the planning phase. If this contract can be revised, at the initiative of both the pilot and the controller, there will be a chance to obtain a less favorable 4D contract according to a first-come, first-served principle prioritizing 4D contracts previously filed. Therefore airspace users will comply as far as possible with their initial 4D contract, which will drastically reduce the collision hazard rate for two reasons:

- The traffic density is more uniformly distributed through the Demand and Capacity Balancing (DCB) process realized in the planning phase;
- The 4D contracts are conflict-free, so the protection bubbles never intersect by definition;

The 4D contract is followed through automated dynamic geofencing [25] capabilities in charge of recentering the drone within its bubble, as soon as it operates too closely of its protection bubble frontiers.

If a drone operates out of its bubble, it is requested to trigger coordination with all aircraft in its vicinity. This cluster of drones can be calculated from clustering algorithms applied to the latest 4D contracts. An initial assessment will be done before the take-off, to anticipate all aircraft clusters during the flight, or 4D clusters.

This cluster will be tasked to self-separate by applying a local optimization based on collaborative intelligence, as detailed in next paragraph. After this process, the drone is requested to catch up with its 4D contract as soon as possible. If it cannot reach this objective (e.g. due to limited performances), a 4D contract revision is initiated. This revision is coordinated by the ASP, using the same 4D contract optimization system as in the planning phase - the Airspace Optimizer.

3.5 Focus on "out of bubble" operations

As soon as a drone operates out of its 4D protection bubble, the pilot is informed that a coordination process is launched. Due to the complexity of this coordination process, all actions are executed autonomously by an intelligence onboard system. At any moment, the pilot is informed of the next steps foreseen and can launch a contingency procedure, if he deems that the coordination is too risky.

The UAS immediately coordinates with all other drones in its vicinity and potentially interacting during the coming timeframe. The list of drones is deduced from the 4D clusters' information computed in the planning phase - from 4D contracts- and potentially updated from latest surveillance information.

The drone sends through ADS-B a message with the following information:

- The need of a cluster coordination;
- The list of drones concerned by this coordination, each drone having potentially a different 4D cluster;
- Its current position and velocity;
- Its next five positions foreseen, computed by its flight management system to catch up as fast as possible with its 4D bubble, depending on aircraft performances and other criteria (e.g. passengers' tolerance to variations).

From this initial message, all UAS involved in this coordination will regularly broadcast ADS-B messages containing their position, velocity and next five positions foreseen.

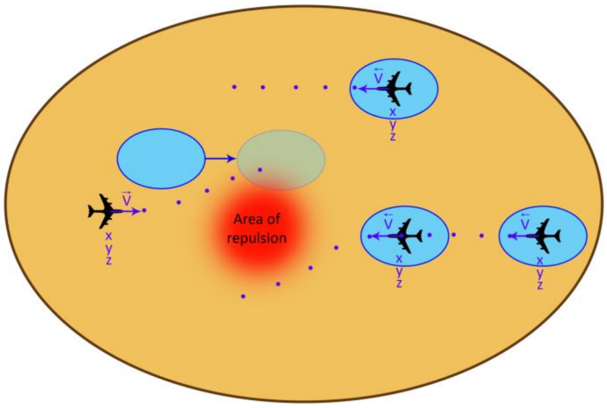

Fig. 7. "Out of bubble" clustered coordination

From these messages, each drone will be able, through its intelligence system onboard to adapt its trajectory prediction to minimize separation losses while trying to remain within its 4D bubble, or to catch up with it when operating out of its bubble. The control is hence fully distributed amongst the cluster drones.

This self-separation strongly relies on the performances of this intelligence onboard, which could be based on latest swarm intelligence principles [26], by instantiating for example Particle Swarm Optimization [27] (PSO) algorithms, able to determine velocities based on previous best and global (or neighborhood) best.

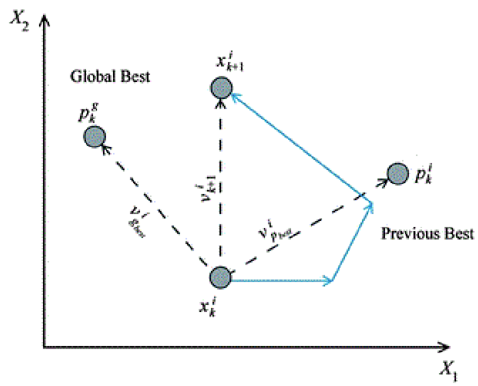

Fig. 8. PSO principle

If some stochastic behavior can be considered within this clustered self-optimization process, it is nevertheless important that all drones use the same intelligence algorithms. They will be also used by ASP on ground to evaluate the network impact of this coordination (emergent behavior), which could lead to the triggering of a contingency management procedure.

3.6 Safety and security issues

This UAS management system relies on several rules:

- The need of a cooperative ADS-B equipage to communicate within drones clusters;
- The obligation to trigger a coordination process with its aircraft cluster when operating out of a 4D bubble;
- The compliance to collaborative intelligence algorithms' resolutions in case of coordination.

If any infringement to these rules can lead to safety issues, security aspects must also been considered.

If drone operates without any cooperative device, the surrounding drones will not be able to update their traffic prediction through its ADS-B messages. If a drone operates out of its bubble without coordinating with its cluster, this could also be considered as a potential security issue, as other potentially interacting drones may be in danger while remaining within their 4D bubble, which is contradicting the main principles of our concept.

The ground system -ASP- will therefore coordinate centralized actions to fight efficiently reckless or malevolent flights: potential solutions have already been explored to fight illegal small drones' operations, for example with the use anti-drones drones around nuclear power plants [28].

In the meantime, drones will rely on self-protection mechanisms based on the participative cooperation of the community of drones within each cluster. If a drone equipped with non-cooperative detection device detects a non-cooperative aircraft, it will immediately broadcast the potential danger at the level of its aircraft cluster, in the same way as the community of drivers reporting an incident on the road via their GPS apps.

Besides, as soon as they will be alerted, ASP operators will immediately indicate a potential hazard zone before verifying the information it with its own means, in the same way as the management of dangers on highways. Airspace Optimizer algorithms will be able to deviate 4D contracts from this hazard zone, by creating a new virtual priority 4D bubble following the danger.

Reaching this vision will necessitate to overcome many operational, technical and even societal challenges. Nevertheless, many research initiatives could rapidly provide key elements to the necessary enablers. In particular, research done on the new paradigm of small UAS flying at VLL [29] could lead to the definition of a comparable concept of operations and the development of suitable technology bricks. It is hence likely that main dynamic geofencing principles and technologies will emerge from research coordinated by NASA on the UTM [9] topic. In that sense, the UTM initiative can be considered as a perfect laboratory to experiment new ATS paradigms that could be potentially adapted to the traditional system, if proved relevant.

From now on, it is important to complement research done on the future ATM system by breakthrough studies, inventing on what the next ATS paradigm will be based and how it will modify the air traffic over our cities [20].

3 Future work

The proposed concept for managing small UAS during very low level operations can be summarized as a twofold process:

The planning phase takes advantage of the predictability of the 4D contracts to ensure the most efficient possible "starting situation", based on trajectory optimization;

The execution phase benefits from this well-organized traffic and manages deviations by local self-separation using swarm intelligence techniques.

The next steps lie in the definition and assessment of contingency processes and procedures, in order to face failures or unwanted situations such as a geo-fence breach, a loss of the command and control link or any type of emergency.

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