SERVICE-ORIENTED SEPARATION ASSURANCE FOR SMALL UAS TRAFFIC MANAGEMENT

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Abstract

Small UAS vehicles are projected to bring substantial economic benefits, but separation assurance is a challenging problem and the subject of on-going research. Here we survey the research contributions, analyze the remaining challenges and key drivers, and propose a system architecture solution for small UAS traffic management and separation assurance, incorporating airspace structure and legal authority.

Introduction

Unmanned aircraft systems (UASs) are revolutionizing our national airspace system (NAS). They can perform existing missions more efficiently and can perform new missions that are difficult, unsafe, or impossible for crewed vehicles. UAS missions include: cargo shipping, agriculture, construction, weather surveillance, news gathering and reporting, entertainment and media, earth resources, mining, firefighting, disaster response, border patrol, real state, property and asset surveillance, infrastructure monitoring, photography, land surveying, environmental assessment, security, public safety and law enforcement, and package and food delivery, to name a few.

UAS traffic levels are expected to escalate in future years. One recent forecast predicts as much as twenty thousand UAS missions per hour to be flown in the skies above Paris by the year 2035. [1] With rising traffic levels, the benefits due to UASs will be rising as well. Studies variously estimate the international UAS market to exceed $10B or even $100B. [2] Therefore, there is a mandate to remove impediments and enable the UAS market by providing acceptable levels of risk for people and property on the ground.

Managing this risk is particularly challenging for small UASs (sUASs). A key problem for sUASs is to maintain safe separation between vehicles, while simultaneously making productive and efficient use of the airspace in ways that are equitable. This is an on-going area of significant research. To be sure, solutions have been proposed and much good progress has been made. But many facets of the problem still have significant challenges, and several solutions are not economically or operationally feasible.

This paper presents a solution which to date has not received significant attention. The following section presents a survey of representative research and solutions that have been proposed for the sUAS separation assurance problem. For each of these proposed solutions we note the important technical challenges. The next section summarizes these challenges, and analyzes them to find the chief, key drivers underlying the challenges. Several of these key drivers are inherent to sUASs. These drivers are fundamental to sUASs, and mitigating or eliminating those challenges would detract from the UAS mandate.

One key driver that can be addressed, however, is the lack of significant airspace structure. We argue that this key driver is significant. It impacts most of the technical challenges to the sUAS separation assurance problem, and addressing it makes the problem substantially more tenable. Therefore, we outline a sUAS traffic management architecture that includes an airspace structure component. We believe this approach lays the groundwork for an efficient, sustainable, and scalable sUAS traffic management solution. Future work will research and evaluate this architecture concept in detail.

Literature Survey of Proposed sUAS Separation Assurance Solutions

This section summarizes sUAS separation assurance technologies and infrastructure proposed in recent years, making particular note of the implementation challenges in each category

Radar

Traditional ground-based air traffic control radar systems are active (i.e., a signal is transmitted, not merely received) and cooperative, exploiting the aircraft transponder response. For surveillance of sUASs, which may not be transponder-equipped, non-cooperative radar are an alternative. But such designs face several challenges. Mechanically-steered, fan-beam, radars are expensive, have relatively show update rates, do not measure elevation angle, and are not effective for very low level (VLL, i.e., low-altitude) traffic. In response to this a narrow-beam, phased array radar system has been proposed, with fast update rate and wide field of view (FOV). [3] The system employs digital beamforming, for multiple target tracking. Nonetheless, the low-altitude tracking requirement means the radar has a relatively short range, of 100-250 m. Consequently, a larger number of installations is needed, which would be expensive in dense urban areas. Such an architecture would also require robust communication links.

Airborne radars provide an alternative to ground-based solutions. This obviates the cost of ground installations. It also lessens the communication requirements for integrated, on-board, sense-and-avoid (SAA) architectures combining both the sensor and conflict detection and resolution (CD&R) decision making. These challenges are being addressed with recent advances in small, low-power, K band, frequency-modulated continuous-wave (FMCW), radar technologies. [4-5] These radars measure azimuth, elevation and range for a full three-dimensional position fix, though the accuracy, particularly of the angular measurements, may be an issue. While detection ranges are limited to only a few nmi, this likely is sufficient for sUAS SAA. [6] Airborne sUAS radar is an active area of research and future improvements are likely. [7]

Electro-optical or infrared (EO/IR)

Whereas radar is active and is most accurate in its range measurement, electro-optical and infrared instruments are passive and provide relatively accurate angular measurements. The lack of a range measurement can be mitigated by maneuvering to achieve geometric variation, though at the cost of fuel and time. But accurate angular measurements alone, even without range, can be useful in a traditional proportional navigation approach. [8] Another strategy is to combine different EO/IR sensors, such as wide and narrow FOV sensors. [9-10]

But EO/IR sensors challenge sUAS size, weight, and power (SWaP) constraints, as well as computational limits, given the significant image processing required. Another challenge is that EO sensors degrade in low-light conditions. And while such conditions are not a problem for IR, both EO and IR degrade in poor weather conditions, such as clouds, fog, and precipitation. One field test found significant false positives, under varying weather conditions and flight encounter scenarios. [11]

Dependent surveillance

Dependent surveillance which relies on targets transmitting their own navigation data has several advantages. UASs will have satellite-based (Global Navigation Surveillance System [GNSS]) navigation data, possibly augmented by inertial or other navigation sensors, so there are no additional sensor requirements. Their navigation solutions will be of superior accuracy, resolution, and update interval compared to other surveillance technologies. Intent information could also be included in the message. The mandated use of ADS-B (Automatic Dependent Surveillance-Broadcast) for manned vehicles, by the year 2020, has served to advance the technology, with lighter, smaller, and low-cost electronics. ADS-B is an all-weather solution, and has longer range than existing approaches. Early tests on UASs demonstrated a 20 nmi range. [12] All of this makes ADS-B a promising surveillance technology for sUASs, and subsequent work has continued to refine ADS-B concepts for sUAS DAA application. [13-14]

Dependent surveillance is, however, not without limitations and challenges. For instance, as with radar surveillance, low altitude targets can be challenging for ADS-B. The ADS-B network of ground stations was not designed to monitor such low altitudes. And vehicle-to-vehicle transmissions may degrade due to terrain, structures, and multipath. Furthermore, dependent surveillance is only as good as a vehicle's own navigation data. Urban canyons, for example, can degrade GNSS signals used by sUASs for navigation.

Another challenge for dependent surveillance is its dependence on widespread adoption. This solution is contingent on all neighboring traffic being equipped and actively transmitting surveillance messages. While ADS-B is mandated for manned aircraft by the year 2020, there is no such mandate for sUASs. But such widespread adoption of ADS-B by sUASs will cause signal congestion. ADS-B uses a time-division multiple access scheme with pseudorandom message intervals, and was not designed for the high levels of future sUAS traffic that are forecast, particularly in urban areas. [15-17]

Finally, ADS-B surveillance does suffer from both signal integrity and security challenges. Signal integrity problems include both data anomalies and data dropouts. A study of more than 12 million messages found that almost one-third had update intervals of 3 sec or greater (32%). [18]

In addition to integrity issues, ADS-B lacks authentication and encryption, and is vulnerable to a range of cyber-attacks, including spoofing and corruption. [19]

LTE and 5G networks

The low altitude typical of sUAS flights suggests that terrestrial communication networks, such as LTE (Long-Term Evolution) and 5G, may be important components of successful surveillance solutions. Given the 5G improvements, such as reduced latency, various solutions, including both time- and frequency-based solutions (e.g., time of arrival and frequency of arrival) perhaps augmented with angle of arrival measurements, have been proposed. [20]

The proposed "Vigilant" system combines LTE with ADS-B in an attempt to expand ADS-B to lower altitudes. And ADS-B helps to offset LTE's weak rural area coverage and latency. The Vigilant concept also calls for a separate ADS-B frequency to separate sUAS message traffic from the manned vehicle messages, and potentially address some of the other ADS-B challenges identified above. [21]

Alerting boundaries

The concept of an alert boundary or threshold helps to maintain proper separation with other vehicles. Most concepts employ at least an inner and an outer boundary. The nomenclature and definitions vary, with the inner threshold boundary representing a near-collision and the outer threshold boundary representing the final maneuver opportunity to assure the inner boundary is not violated. For example, the inner threshold has been referred to as NMAC (Near Midair Collision) and WCV (Well-Clear Violation), and the outer threshold has been referred to as CAAT (Collision Avoidance Alerting Threshold), and SST (Self-Separation Threshold). [22]

Substantial research has investigated this alerting threshold problem. [23-26] First, new values for both the inner and outer boundaries are needed for sUAS traffic. Given the substantial difference in size and performance, traditional separation boundaries for manned aircraft, as well as boundaries derived for large UAS vehicles, are not suitable for sUASs. Second, it is not obvious what these new sUAS boundaries should be. The inner boundary could scale with wingspan or characteristic vehicle size, with the inner boundary for manned aircraft defined, for example, as 100 and 500 ft separation, vertically and horizontally, respectively.

The outer boundary, on the other hand, is more complicated. Important metrics are the number of missed, late, and false alerts. Various approaches have been proposed, such as basing the calculation on the time-to-point of closest approach (PCA), τ, or variations thereof. But regardless of approach, for an arbitrary encounter, the outer boundary varies with the encounter geometry, vehicle speeds, vehicle performances, and winds. [27] It may also account for surveillance and navigation errors (resolution, noise, dropout, latency) and maneuver latency. [28] Whereas the inner boundary may be fixed, the outer boundary is, generally, both spatially and temporally varying. [29]

Another outer boundary complication arises from target maneuver considerations. Nominally, the target can be assumed to be non-maneuvering. A more conservative approach assumes a detrimental maneuver that increases closure rate, reduces the separation at PCA, etc. On the other hand, the target may be assumed to be cooperative, and maneuvering according to the adopted rules-of-the-road and a specified avoidance maneuver, thus mitigating the ownship maneuver requirements. This points out the need for the universal adoption of an alerting threshold boundary approach, and avoidance maneuver strategy.

Tactical separation assurance and recovery maneuvers

When a sUAS encounters the outer boundary threshold, in order to maintain separation, it must initiate a maneuver. Once this maneuver is completed the sUAS is then faced with the question of how to reestablish its mission. Several objectives may be considered in designing these separation assurance and recovery maneuvers. In general, there is no closed-form solution to this complicated problem, and it has been an active area of research for half a century. Today, very different algorithmic approaches continue to be investigated. [30-37]

When designing separation assurance and recovery maneuvers, an important complicating factor are the various engagement uncertainties. These include navigation and surveillance uncertainties in the current state of the vehicles involved, uncertainty in the timing of the separation assurance maneuver, uncertainty in the maneuver execution, uncertainty in the wind field, uncertainty in the target vehicle trajectory, and so forth. These uncertainties are important in determining the maneuver initiation time. An early initiation time (prior to encountering the outer boundary threshold) can allow for more efficient maneuvering. But the efficiency gain may be lost if there are substantial forecasting errors in the engagement data. A concept proposed to assist or solve the separation assurance problem is geo-fencing, in which flights are restricted to operate within temporary, and perhaps dynamic, geographic boundaries. [38]

Another challenge, particularly in heavy traffic scenarios, is the possibility of follow-on, or secondary, conflicts. That is, the separation assurance or recovery maneuvers may inadvertently cause a new loss of separation to arise with another neighboring vehicle. In heavy, unstructured, traffic scenarios, such secondary conflicts may escalate, with tertiary, etc., conflicts, as each new conflict causes yet more conflicts as vehicles continue to maneuver. This highlights yet another challenge, which is that the separation assurance and recovery problem is complicated in random traffic patterns, compared to structured patterns.

As with the alerting threshold problem, a universal separation assurance and recovery solution probably needs to be widely adopted. A heterogeneous environment, with different vehicles using different maneuver solutions, could become quite complicated and perhaps untenable.

Strategic deconfliction and path planning

To assist with the separation assurance challenge at the tactical level, as summarized in the previous section, architectures have been proposed that add additional layers of separation planning, such as at the strategic planning level. [39] Strategic deconfliction and path planning [40] use forecasts of the weather, aggregate traffic, obstacles, etc., to design routes with few or no conflicts, thus off-loading the tactical separation assurance task. This layered approach is analogous to how strategic traffic flow management (TFM) works with tactical air traffic control (ATC), in the traditional national airspace system (NAS).

Compared to the traditional NAS, a major difference in strategic sUAS deconfliction is the lack of a legally responsible authority. In traditional manned aviation, the Federal Aviation Administration (FAA) has legal responsibility and authority for separation assurance. In the sUAS separation assurance and strategic deconfliction problems, it is not clear where such authority lies, or if it even exists. Nor is it clear what entity would generate strategic deconfliction. If third party service suppliers provided deconfliction advisories, would they be consistent across suppliers, and would operators accept or conform to the advisories? Furthermore, in the traditional NAS, collaborative decision making (CDM) collectively between the service provider and operators, has been found to be important in strategic planning. But CDM concepts have been largely ignored in sUAS strategic deconfliction research. One proposed concept calls for sUASs to conform to 4D contracts, dictating both the route and crossing times. [41]

A major challenge for 4D contracts, CDM, and strategic deconfliction concepts in general, is that these seem to contradict the very sUAS modus operandi, including short flights and less predictability. For airline operators, long-term schedule planning, and flight adherence to the schedule, is very important. Most sUAS missions, on the other hand, either have more schedule flexibility (e.g., land surveying) or are operating on an as-soon-as-possible basis (e.g., emergency response). Long-term, repeatable, schedules are not likely to be the norm for sUAS operations. Furthermore, even given a flight plan, sUASs have far greater conformance uncertainty due to their greater sensitivity to wind and weather. So unlike traditional aviation, the sUAS system demand (e.g., airspace loading) is difficult to predict hours, and probably even minutes, into the future, thus compromising strategic planning concepts.

For many sUAS operators, it is precisely this lack of predictability and flexibility that is important to their business model. Many will operate on much shorter time scales compared to traditional aviation, responding to dynamic requirements, and according to just-in-time business practices, and scheduling. Enforcement of 4D flight plan contracts, or even long-range strategic planning requirements, would strip sUASs of the important flexibility they need to operate efficiently. Also, such strategic concepts of operations would be highly sensitive to flight plan nonconformance, adding substantial complexity to the traffic management system and user operations. Finally, such strategic planning is algorithmically highly complicated, and it raises challenging and difficult equity issues.

The sUAS Separation Assurance Challenge

For such small vehicles, sUASs pose a large separation assurance problem. As outlined above, every facet of sUAS separation assurance faces several significant challenges. Table 1 summarizes them by category.

Table 1. sUAS separation assurance challenges.

Traditional manned aviation	Small UAS challenges
Consistent vehicle performance	Diverse vehicle performance
Good maneuvering capability	Limited maneuvering capability
Performance robust in weather	Performance poor in weather
High situational awareness	Limited situational awareness
In situ decision making	High levels of autonomy
Highly reliable communications	Comm link failures common
Emerging, ADS-B, surveillance	ADS-B not scalable to dense ops
Air data and weather radar in *situ*	Little or no *in situ* weather data
Ground-based surveillance radars	No independent surveillance
Ground-based navigational aids	No navigational aids
Structured routes and airspace	Little airspace structure
High-altitude flight, good LOS	VLL, often blocked LOS, clutter
NAS-wide ATC services	No ATC services
Homogeneous O-D missions	Diverse missions types
Ops segregated from public	Ops integrated with public
Scheduled predictable ops	Unscheduled, unpredictable ops
SAA is time-tested and mature	DAA can fail in high density ops
Simple separation criteria	Complex separation assurance
Clear lines of legal responsibility	Legal responsibility unclear

Not surprisingly, it is difficult to design a sUAS traffic management system that is low-risk, and is economically and operationally feasible. Consider, for example, the RAVEN project, [42] which proposes a system that includes:

- ADS-B dependent surveillance.
- Ground portable radar systems.
- On-board first Person View (FPV) video systems for pilot-in-control (PIC) situational awareness.
- Four RF (radio frequency) communication links for autopilot-GCS (ground control station), PIC manual control, video link, and dependent surveillance.
- Extensive vehicle telemetry data transmitted to the GCS.
- Use of geo-fencing and a flight termination system (FTS).
- Extensive off-line Monte Carlo simulations to support avoidance maneuver decision making.

As can be seen, in order to meet the sUAS separation assurance challenge, RAVEN proposes an extensive technology and infrastructure suite. This raises the risk that many potential sUAS operators will be unable to afford the requirements. Furthermore, several of the Table 1 risks remain. For example, the ground portable radar systems may be costly to implement in crowded urban environments. The radar system will face LOS restrictions due to terrain and buildings, and will be relatively short range due to the sUASs VLL flight. The ADS-B system may face capacity limitations. The four communication links add cost, and their reliability will be important. The unstructured traffic creates a challenging avoidance maneuver problem, and there do not seem to be safeguards against secondary and tertiary conflicts, and system overloading. It is also not clear how conflict avoidance maneuvers distinguish between cooperative and non-cooperative scenarios, and where the legal authority and liability lie.

These challenges faced by the RAVEN system highlight the difficulty in architecting an approach for sUAS separation assurance. It seems that while there is a strong economic mandate for sUASs, this is matched by the significant separation assurance problem. It therefore seems prudent to perform an analysis of the Table 1 challenges, and attempt to derive a system that can meet those challenges. By deriving a minimal system that can meet the challenges, we can minimize the economic impact and hopefully support economic and efficient sUAS missions. Our analysis of the Table 1 challenges finds that there are seven core challenges, or driving factors, to which the Table 1 challenges can be traced. They are:

- PIC loss of situational awareness
- High traffic volume
- VLL flight altitude
- SWaP, and vehicle performance limitations
- Highly diverse missions
- Lack of ATC authority
- Unstructured airspace

Of these seven driving factors, the first five are either (i) overly expensive to resolve (e.g., PIC loss of situational awareness) or (ii) a desirable attribute of sUASs (e.g., VLL flight altitude) which we prefer not to alter.

This leaves the final two driving factors: the lack of ATC authority, and the unstructured airspace, as two candidate driving factors which we can attack to resolve the sUAS separation assurance problem. We make two observations about these factors.

First, the questions of (i) ATC legal authority and responsibility, and (ii) unstructured airspace have received little attention in the sUAS separation assurance research literature. [43 and 44 are exceptions] Geo-fencing, no-fly zones, dynamic restrictions, and so forth, all add structure to the airspace. But they often are temporary and sometimes dynamic. This adds yet more complexity and does little to address the Table 1 challenges. Beyond these structures, the common assumption is that sUAS operators are free to file arbitrary routes, and are not significantly restricted, for example, to fixed routings. Likewise, the problem of legal authority, airspace access rights and responsibilities, and the consequent equity and gaming issues, have not received significant attention in the separation assurance literature.

Second, these two driving factors, and in particular unstructured airspace, have an enormous impact on the sUAS separation assurance problem. Simply put, most of the Table 1 challenges can be mitigated or resolved by attacking these two core driving factors.

A Structured Airspace sUAS Architecture

The sUAS separation assurance problem is very challenging. Many solutions burden the sUAS system operationally or economically, or otherwise detract from the sUAS mandate. Our analysis of the challenges, and driving factors, of the separation assurance problem suggests that structured airspace is a key component to the solution. This section outlines a high-level candidate architecture that implements such structure, along with a legal conformance monitoring authority and airspace access rights, and minimal infrastructure and services.

Structured airspace

Studies of airspace and traffic complexity have demonstrated the importance of airspace structure. For example, maneuvering flights can greatly increase ATC workload and effective traffic loading in an airspace sectors. Studies of dynamic density have shown the effective loading can easily exceed twice the nominal loading. [45] This highlights the importance of airspace structure. When flights are aligned along fixed routes, the ATC problem is greatly facilitated, moving from a three dimensional to, essentially, a one dimensional problem.

Even more importantly, structured sUAS airspace can resolve many of the Table 1 challenges. The PIC's situational awareness is improved, alert boundaries and CD can be greatly simplified, tactical separation assurance and recovery maneuvers are also simplified, and rules-of-the-road are facilitated. Communication links become less critical, and autonomous flight becomes more feasible.

For example, consider a typical urban environment with high-density sUAS traffic performing missions such as package delivery. The sUAS airspace structure could be based on the surface roads and highways. Small UASs would fly along corridors above the streets (perhaps with a lateral offset), analogous to how surface vehicles travel on the surface. An important different, however, is that altitude can be used to separate traffic. In this concept, rather than flying on the right side of the corridor, the two opposing directions of travel along a corridor are assigned low- and high-altitude, respectively. Rules-of-the-road then dictate right of way at intersections. [46]

Fig. 1 illustrates a possible intersection design, where the rules-of-the-road state that traffic must yield to (i) traffic on the right, and (ii) traffic at a new altitude, when changing altitude. Given the altitude assignments of the two intersecting corridors, and the rules-of-the-road, an intersection's right of way and yield rules can be determined. In the Fig. 1 example, northbound and eastbound traffic are at the low altitude, and southbound and westbound traffic are at the high altitude. Black arrows indicate traffic with the right of way, red arrows indicate traffic that must yield to traffic on the right, and blue arrows indicate turning traffic that must change altitude, and so yield to the traffic at that new altitude.

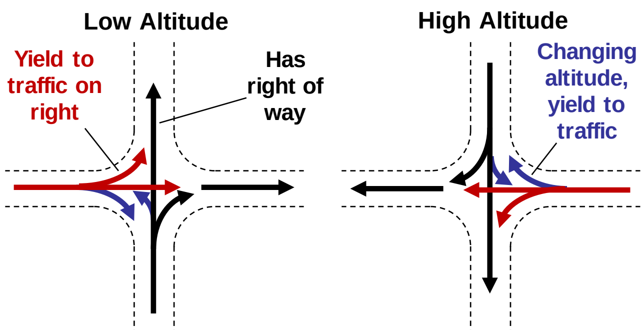

Figure 1. Example intersection rules-of-the-road. See text.

In this approach, the airspace structure needs to be defined for each local region. Small UAS traffic, and mission types, tend to be local. Clearly very different types of airspace structure will be needed in different regions. Urban, rural, agricultural, heavy industrial, public works and government infrastructure, forest land, border, utilities, etc., may all require different, unique, airspace structure. Some may be much more flexible than others. Some may even use an "open airspace" concept with little structure if that is appropriate. Corridors mapping to surface roads may be appropriate for urban areas (as described above), but not elsewhere. The airspace structure should be as simple as possible, but no simpler. For each region, the airspace structure will need to be developed and designed collaboratively, involving the appropriate stakeholders in the region.

Note that in the Fig. 1 configuration, the north and southbound traffic have the advantage—they yield only when turning left. The east and westbound traffic, on the other hand, must always yield—regardless of whether or not they are turning. More generally, the advantaged flow direction has departing traffic on its right, whereas the disadvantaged direction has arriving traffic on its right. Fig. 2 illustrates how this design rule can be used for a sequence of consecutive intersections.

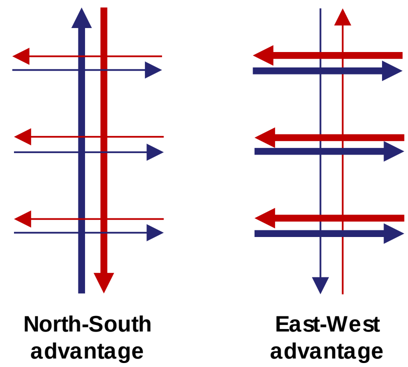

Figure 2. Flow advantages in sequenced intersections.

In Fig. 2, The blue arrows indicate traffic at one altitude level, and the red arrows indicate traffic at the other altitude level. By merely switching these altitude assignments of the north-south traffic, the advantaged traffic flow direction is switched from north-south to east-west, as illustrated in the figure (heavy arrows indicated advantaged flow direction).

Communications, navigation and surveillance (CNS)

Given that the appropriate airspace structure is in place for a region, the CNS problem can be simplified. The existing (and emerging) commercial technologies of GNSS, ADS-B, and cellular communications (LTE/5G) will likely meet the required CNS capabilities for autonomous sUASs. An additional C2 (command and control) link is also required for sUASs controlled by the GCS. An example of the advantage of airspace structure is that the ADS-B can be low power since only neighboring traffic need to be surveilled. It could be an air-to-air surveillance system, integrated with the terrestrial cellular network, as has been proposed. [21]

Note that third parties could provide traffic monitoring and routing advisory services. These services could, for example, be analogous to the existing Google Maps and Waze services, collecting real-time traffic data, and providing operators with valuable strategic planning advice to avoid route delays.

Conformance monitoring and enforcement

In this structured airspace approach, conformance monitoring, enforcement, legal authority and responsibility, and access to airspace are all simplified. First, there need not be a concept of a flight plan. The flight plan concept, and associated claim to airspace, raise potential equity and gaming issues. Instead, analogous to how surface vehicle travel, sUASs would access corridors at will.

There would be no conformance monitoring, as it is typically construed in the sUAS literature. Instead, there needs to be enforcement of the altitude assignments, and rules of the road, including ground speeds as well. Analogous to surface traffic, the sUAS airspace would be policed by legally-empowered government authorities. Police sUASs, or "police-copters," could be equipped with additional CNS technology to monitor, identify, and track offending sUAS vehicles. Enforcement could also be performed remotely using surveillance data.

Equipage and autonomy

This structured airspace concept could use a "best-equipped, best-served" policy. For example, in the urban environment airspace structure described above, hover-ability will be important when yielding to traffic. Vehicles that lack this capability may be limited to certain corridors, time-of-day windows, etc.

Small UASs that are sufficiently equipped with on-board decision-making can be autonomous. While such autonomy typically is highly complicated, in this structured airspace concept it becomes more feasible, given the simplicity of operating within the structure. Fig. 3 notionally illustrates the urban environment structured airspace (image adapted from Google Maps).

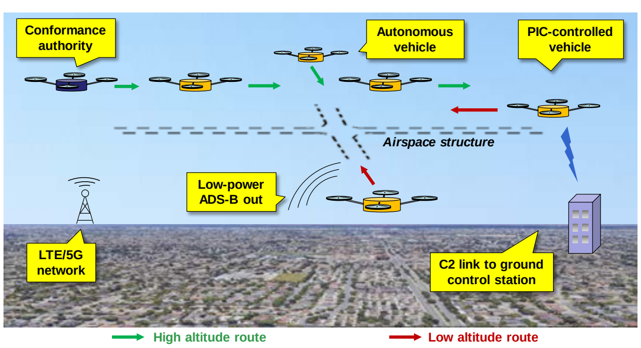

Figure 3. Notional sUAS traffic management.

Fig. 3 shows sUAS traffic flying at different altitudes according to their direction of flight. Low-power ADS-B is used by all vehicles, and is integrated with cellular network communications. Some vehicles are controlled by their GCS, and so require a C2 link, while other vehicles are autonomous. The police-copter monitors conformance. Traffic may join and depart the route structure away from intersections, yielding the right-of-way to traffic in the airspace structure.

Conclusions

This paper first summarizes designs and solutions that have been proposed for the different facets of the sUAS separation assurance problem, including radar, EO/IR, dependent surveillance, LTE and 5G networks, alerting boundaries, tactical separation assurance and recovery maneuvers, and strategic deconfliction and path planning. In each category we identify existing challenges, including technical, operational, economic, and legal challenges.

The paper summarizes the challenges for sUAS separation assurance, and derives underlying driving factors. These challenges and driving factors need to be addressed in sUAS separation assurance solutions. We identify two key driving factors: the lack of airspace structure and unclear lines of legal authority and responsibility. We use this analysis to derive a sUAS traffic management system architecture, providing separation assurance. We describe key aspects of this system, including the structured airspace; communications, navigation and surveillance; conformance monitoring and enforcement; and equipage and autonomy. Further research is required to develop a detailed system design.

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