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Effect of CNS Systems Performance on Autonomous Separation in U-Space

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***Abstract*—The integration of unmanned aerial systems (UASs) into existing airspace is imminent as the concept is maturing. U-Space is a concept in which UASs are allowed to fly alongside general aviation aircraft, requiring all aircraft in the airspace to transmit navigation data using radio and network identification. Nevertheless, a consensus is required for the separation in case of conflict amidst the limitations of communication, navigation, and surveillance (CNS) systems. Update rate and probability depict the uncertainty in the communication systems, while spread around the ground truth in position describes the navigation accuracy. Then, BlueSky, an open-source simulator, produces thousands of conflict detection and resolutions to evaluate the CNS limitation on the intrusion prevention rate and loss of separation severity. This paper concludes that higher update rate, probability, and position accuracy lead to safer conflict resolution, and selecting 50 meters as the radius of the protected zone results in a 25-meter intrusion in the worst case.**

***Keywords*—CNS Systems; Autonomous Separation; U-Space; Conflict Detection and Resolution; BlueSky**

I. INTRODUCTION

The increasing use of Unmanned Aerial Systems (UASs) poses a challenge to existing air traffic control systems. Recent efforts, such as the European U-space ConOps as developed by the CORUS projects [1], have been launched to adapt air traffic management to accommodate the integration of UASs into current airspace, with a concept called U-Space. The proposed concept allows UASs to operate in the existing airspace, flying alongside general aviation (GA) aircraft. To enable surveillance in U-Space, regulations require both manned and unmanned aircraft to be electronically conspicuous [2]. Each aircraft's navigational data must be communicated to the surroundings using radio or network identification. With this concept, aircraft flying in the airspace can detect incoming traffic and execute separation if a conflict exists.

Next to the surveillance ability, we also need a consensus on the separation procedures accounting for the limitations of the communication, navigation, and surveillance (CNS) systems. Thus, this paper aims to study the impact of data availability and navigation accuracy on conflict detection and resolution (CD&R) performance. Moreover, different CD&R parameters such as lookahead time and horizontal separation is analysed. The evaluation is executed in BlueSky to evaluate intrusion prevention rate and loss of separation (LoS) severity as the safety metrics. These analysis serves as preliminary results for a set of recommendations for CNS requirements and flight rules in U-Space.

II. METHODOLOGY

Communications, navigation, and surveillance requirements for autonomous separation can be evaluated using simulation in BlueSky, an open-source simulator [3]. A potential scenario must be defined to capture a representative case. Figure 1 shows an overview to allow a safe GA and UAS integration into the U-Space.

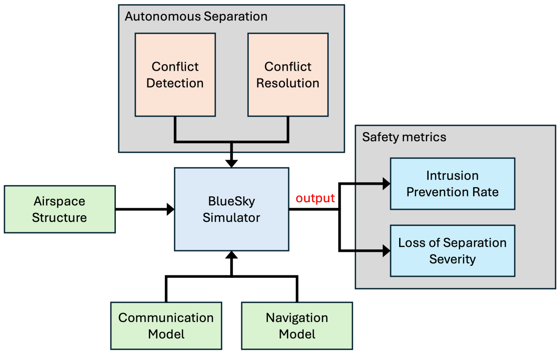

Figure 1: Methodology to evaluate impact of data availability and navigation accuracy on conflict detection and resolution.

A conflict between GA and UAS has an unbalanced flight performance that needs to be addressed. For instance, ICAO in Rules of the Air [4] proposes right-of-way, a priority-based rule to avoid collisions with similar and different types of aircraft. Thus, for this preliminary study, the conflict is limited only between UASs.

A. Communication, Navigation, and Surveillance

1) Communication: The communication systems in manned and unmanned aircraft are currently using different frequencies. In U-Space, a new identification service called ADS-L [5] is introduced to enable communication between general aviation and UASs. This system is based on both radio and mobile telephony (network) communication, called Automatic Dependent Surveillance – Light (ADS-L). ADS-L can be modelled in terms of update rate and reception probability for air traffic management analysis. For this study only the radio-based communication is considered.

2) Navigation: The navigation system aims to determine an aircraft's position, heading, velocity, and altitude at any given time during the flight. These days, manned and unmanned aircraft navigation systems benefit from inertial navigation systems (INS) and satellite-based navigation systems. The measurement navigation systems is subject to measurement uncertainties. For this study, the uncertainties in navigation systems is formulated as a 95% accuracy bound. As an example, 10 meters position accuracy means 95% of the data is within 10 meters from the ground truth.

3) Surveillance: In general, surveillance systems are classified into centralized-dependent, distributed-dependent, and independent systems. In U-Space, radio-based communication is distributed-dependent since the aircraft communicates directly. On the other hand, mobile telephony is centralized dependent because each aircraft sends and receives information to the U-Space service provider. The availability of data for surveillance is a crucial aspect, and it is intertwined with communication systems. Thus, both surveillance and communication are considered as one compiled system for this study.

B. Airspace Structure

One of the critical aspects of air traffic management is the airspace structure. Metropolis project by Sunil et al. [6] investigates four different airspace structures and their effect on capacity, safety, and efficiency for high-density airspace, namely full mix, layers, zones, and tubes. The Full mix airspace allows aircraft to have no restrictions regarding their flight trajectory. In contrast, a layered airspace consists of stacked bands that requires the heading of an aircraft to be in a specific range for a each layer. Another concept is the zones, which uses segments to separate aircraft based on the overall travel direction. The structure for this airspace is more suitable for aircraft flying in a city layout. Lastly, the tubes concept proposed predefined routes connected at nodes and finding a conflict-free path before departure. In the context of U-Space, full mix and layered airspace are the most relevant ones, and the first is chosen to evaluate the effect of CNS systems in more complex conflict cases.

C. Autonomous Separation Algorithm

An autonomous separation algorithm can be divided into two parts, namely conflict detection and conflict resolution. These algorithms generally require at least the position, ground speed, and heading information from the ownship and intruder aircraft. Figure 2 illustrates two UASs flying close to each other, defined to be in conflict since the closest point of approach (CPA) is within the radius of the protected zone (R_{PZ}).

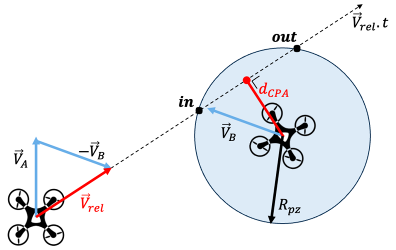

Figure 2: Conflict is detected when the calculated distance at the closest point of approach is less than the radius of protected zone.

Most conflict resolutions are based on the geometry of the conflict to find the solution. In [7], the intruder or obstacle is quantified as an ellipsoid, and the resolution is calculated by assigning a new waypoint tangent to the ellipsoid. Modified Voltage Potential (MVP) offers an advisory heading and speed change based on a 'repelling force' from the predicted CPA [8]. Velocity Obstacle (VO) presents a resolution by drawing a collision cone around the protected zone of the intruder and translating it as far as the intruder's velocity [9][10]. The MVP [8] is chosen for this study since it is the default conflict resolution method available in BlueSky and has proven to be very effective also in comparison with other more advanced algorithms due to the emerging properties [11].

D. Safety Metrics

The effect of CNS on conflict detection and resolution is evaluated by using two metrics: intrusion prevention rate (IPR) [12] and loss of separation (LoS) severity. This intrusion prevention rate describes the number of conflicts (n_{cfl}) that result in intrusion (n_{LoS}), as shown in Equation (1). The value range of IPR is between 0 and 100 percent. When none of the conflicts evolves into an intrusion, the IPR is a hundred percent. An effective conflict detection and resolution results in zero intrusion. However, this is not possible in real life scenario due to low communication rate and navigation uncertainty.

$$IPR = \frac{n_{cfl} - n_{LoS}}{n_{cfl}} \tag{1}$$

LoS severity quantifies the proximity of the intruder aircraft to the ownship during an event of loss of separation, represented mathematically as depicted in Equation (2). In this context, R denotes the radius of the ownship's protected zone (RPZ), while d_{CPA} signifies the minimum distance between the conflicting aircraft. The LoS severity metric spans a value range from 0 to 100 percent. When two aircraft collide mid-air, the closest distance between them is zero, resulting in a LoS severity of one hundred percent. Conversely, a lower LoS severity value indicates more effective conflict detection and resolution.

$$LoS_{sev} = \frac{R - d_{CPA}}{R} \tag{2}$$

III. PRELIMINARY EXPERIMENTS AND RESULTS

In this section, we present a preliminary experiment and its results. A Monte Carlo simulation is executed for the experiment to explore the range of safety metrics under specific communication models and navigation uncertainties.

Three models have been selected for the communications: Ideal, ADS-L, and ADS-L with delay. The first model assumes the data exchange between the UASs happens every 0.05 seconds (i.e., equal to the simulation rate). Next, the ADS-L considers the update rate to happen every 1 second, as mentioned in [5]. Lastly, a probability of receiving 67.5% and 97.5% of the message within 3 and 5 seconds is added to the ADS-L model, introducing a delay similar to ADS-B in [13].

TABLE I.: Parameters range and randomization

Parameters	Range	Randomization
Nb of UASs per scenario [-]	800	-
Nb of scenarios [-]	32	-
Lookahead time [s]	6, 15, 50, 100	-
Radius of protected zone [m]	30, 50	-
Position accuracy (HPOS) [m]	3, 10, 30	-
Initial CPA [m]	$[0, 2 \cdot R_{PZ} \cdot HPOS]$	Uniform
Initial relative heading [deg]	[10, 350]	Uniform
Ground speed [kts]	[15, 35]	Uniform
Ground speed std dev [kts]	[1.5]	Normal

The navigation models in this study consider three levels of position accuracy (HPOS), that is, 3, 10, and 30 meters. These values are chosen from [5], representing the top three accuracies. For example, 10-meter accuracy means that 95%

Lastly, the UASs are considered to fly in a full mix environment. Thus, the heading of the intruders spans a full circle. However, even in a high density, most of the conflict is pairwise [14]. The conflict is arranged with different parameters summarized in I..

A. Intrusion Prevention Rate

The intrusion prevention rates corresponding to varying sets of parameters are depicted in Figure 3 and 4 for R_{PZ} distances of 30m and 50m, respectively. When data is updated at intervals of 0.05s (Ideal), the intrusion prevention rate approaches 100% across all lookahead times, except at the lowest lookahead time. In contrast, changing the data update interval to 1s (ADS-L) results in decreased conflict resolution performance, with further degradation observed when introducing a delay in ADS-L.

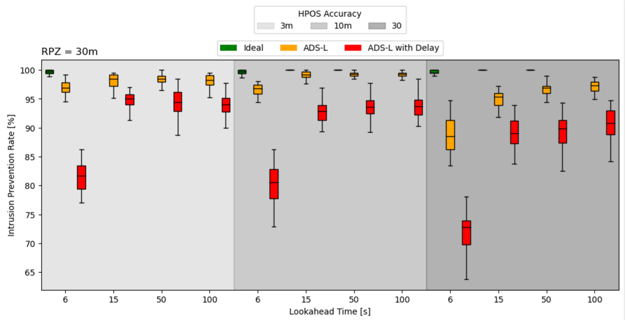

Figure 3: Intrusion Prevention Rate for $R_{PZ} = 30m$.

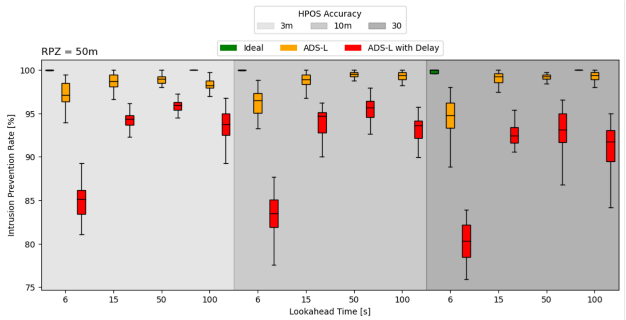

Figure 4: Intrusion Prevention Rate for $R_{PZ} = 50m$.

From a navigational uncertainty perspective, lower Horizontal Position (HPOS) accuracy leads to increased potential conflicts, resulting in loss of separation. The lowest intrusion prevention rate occurs with the lowest HPOS accuracy and the shortest lookahead time for both RPZ distances of 30m and 50m. Performance substantially improves with a lookahead time of 15 seconds compared to 6 seconds, with marginal improvement observed at 50 seconds and 100 seconds lookahead times. Even under conditions of lowest HPOS accuracy, the median intrusion prevention rate exceeds 90% for lookahead times equal to or greater than 15s.

B. LoS Severity

This section presents the outcomes of Loss of Separation (LoS) severity across various parameters outlined in the simulations. Regarding the communication model effect, as illustrated in Figure 5 and 6, increased communication rates correlate with lower LoS severity. Notably, delay exerts a substantial influence on the closest approach between aircraft, evidenced in Figure 5, where increased delay corresponds to escalated LoS severity.

The impact of navigation accuracy reveals a direct relationship between decreased accuracy and increased LoS severity.

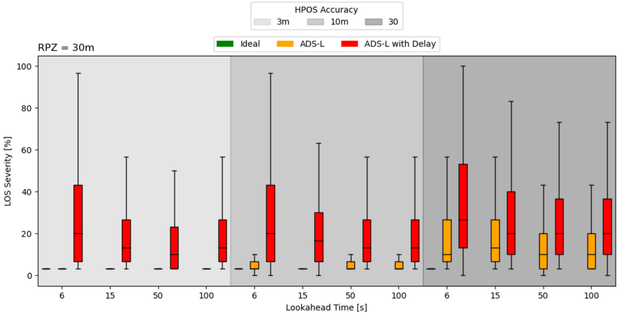

Figure 5: LoS Severity for $R_{PZ} = 30m$.

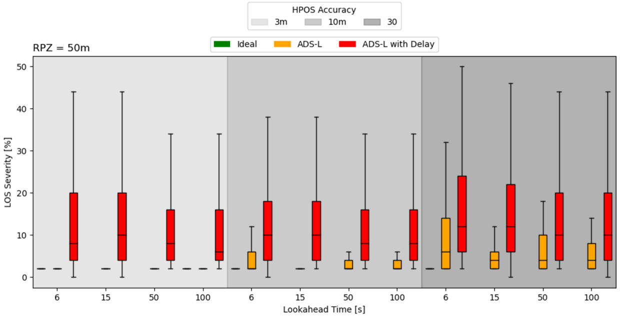

Figure 6: LoS Severity for $R_{PZ} = 50m$.

Notably, augmenting the lookahead time from 6s to 15s yields a significant reduction in severity, albeit with diminishing returns beyond 15s. Significantly, adjusting the radius of the protected zone can markedly mitigate LoS severity, as evidenced by a decrease from 100% for RPZ 30m to slightly above 50% for RPZ 50m.

IV. CONCLUSION AND FUTURE WORK

To measure the effect of communication delay and navigation accuracy on automated separation algorithms, thousands of conflicts between pairs of UASs are simulated in BlueSky. Each simulation uses a different set of parameters such as lookahead time, radius of protected zone, data availability, and position accuracy. Then, the intrusion prevention rate (IPR) and loss of separation (LoS) severity are used as safety metrics to evaluate the separation performance in a full mix airspace structure.

For the intrusion prevention rate, a lower communication update rate significantly increases the number of conflicts that proceed to an intrusion. Moreover, higher certainty in the position measurement leads to higher IPR. From the automated separation side, increasing the lookahead time from 6 seconds to 15 seconds improves the results significantly, but only a tiny advantage beyond this value. Lastly, a higher radius of the protected zone reduces the IPR since the separation becomes more conservative as it grows larger.

These type of results can also be used to define the separation minima. For example,, a higher communication rate and navigation certainty lead to a lower severity. Increasing the lookahead time beyond 15 seconds also does not reduce the severity significantly. Moreover, selecting 50 meters as the radius of the protected zone results in the worst intrusion as close as 25 meters, while choosing 30 meters can lead to a mid-air collision.

The CNS systems model can be refined for future work by introducing internet-based communication and exploring sensor fusions for navigation systems. Next, a layered airspace structure and different automated separation algorithms should be assessed. An encounter between GA and UAS in the scenario will ultimately cover the real-life scenario in the U-Space.

REFERENCES

[1] EUROCONTROL. *U-Space Conops 4th Edition*. SESAR Joint Undertaking, 2023.

[2] Mikko Huttunen. “U-space: European Union’s Concept of UAS Traffic Management”. In: *BI Scott, The Law of Unmanned Aircraft Systems*. Kluwer Law International, 2022, pp. 98–100.

[3] Jacco M Hoekstra and Joost Ellerbroek. “Bluesky ATC simulator project: an open data and open source approach”. In: *Proceedings of the 7th international conference on research in air transportation*. Vol. 131. FAA/Eurocontrol USA/Europe. 2016, p. 132.

[4] ICAO. *Annex 2 to the Convention on International Civil Aviation: Rules of the Air*. International Civil Aviation Organization, 2005.

[5] EASA. *ED Decision 2022/024/R: Technical Specification for ADS-L transmissions using SRD-860 frequency band (ADS-L 4 SRD-860)*. European Union Aviation Safety Agency, 2022.

[6] Emmanuel Sunil, Jacco Hoekstra, Joost Ellerbroek, Frank Bussink, Dennis Nieuwenhuisen, Andrija Vidosavljevic, and Stefan Kern. “Metropolis: Relating airspace structure and capacity for extreme traffic densities”. In: *ATM seminar 2015, 11th USA/EUROPE Air Traffic Management R&D Seminar*. 2015.

[7] Rianto Adhy Sasongko, SS Rawikara, and Hansel J Tampubolon. “UAV obstacle avoidance algorithm based on ellipsoid geometry”. In: *Journal of Intelligent & Robotic Systems* 88 (2017), pp. 567–581.

[8] Jacco M Hoekstra, Ronald NHW van Gent, and Rob CJ Ruigrok. “Designing for safety: the ‘free flight’air traffic management concept”. In: *Reliability Engineering & System Safety* 75.2 (2002), pp. 215–232.

[9] Paolo Fiorini and Zvi Shiller. “Motion planning in dynamic environments using velocity obstacles”. In: *The international journal of robotics research* 17.7 (1998), pp. 760–772.

[10] Animesh Chakravarthy and Debasish Ghose. “Obstacle avoidance in a dynamic environment: A collision cone approach”. In: *IEEE Transactions on Systems, Man, and Cybernetics-Part A: Systems and Humans* 28.5 (1998), pp. 562–574.

[11] Jacco M Hoekstra and Joost Ellerbroek. “Aerial robotics: State-based conflict detection and resolution (detect and avoid) in high traffic densities and complexities”. In: *Current Robotics Reports* 2.3 (2021), pp. 297–307.

[12] Emmanuel Sunil, Joost Ellerbroek, Jacco Hoekstra, Andrija Vidosavljevic, Michael Arntzen, Frank Bussink, and Dennis Nieuwenhuisen. “Analysis of airspace structure and capacity for decentralized separation using fast-time simulations”. In: *Journal of Guidance, Control, and Dynamics* 40.1 (2017), pp. 38–51.

[13] Asma Tabassum and William Semke. “UAT ADS-B data anomalies and the effect of flight parameters on dropout occurrences”. In: *Data* 3.2 (2018), p. 19.

[14] Yazdi I Jenie, Erik-Jan van Kampen, Coen C de Visser, Joost Ellerbroek, and Jacco M Hoekstra. “Selective velocity obstacle method for deconflicting maneuvers applied to unmanned aerial vehicles”. In: *Journal of Guidance, Control, and Dynamics* 38.6 (2015), pp. 1140–1146.