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Sense and Avoid Considerations for Safe sUAS Operations in Urban Environments

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Abstract— **Operations involving small Unmanned Aerial Systems (sUAS) in urban environments are occurring ever more frequently as recognized applications gain acceptance, and new use cases emerge, such as urban air mobility, medical deliveries, and support of emergency services. The presence of Detect and Avoid (DAA) capability of sUAS is one of the major requirements for its safe operation in urban environments. The platform or its operator proves a full awareness of all potential obstacles within the mission, maintains a safe distance from other airspace users, and, ultimately, performs Collision Avoidance (CA) maneuvers to avoid imminent impacts. Communication and navigation defined scenarios are designed and performed within the simulation model in Systems Tool Kit (STK) software environment, covering several practical cases. The acquired data supports the assessment of feasibility and requirements for real-time processing. Utilizing Unreal Engine and MATLAB analysis of the findings and simulation results leads to a holistic approach to implementation of sUAS operations in urban environments, focusing on extracting critical DAA capability for safe mission completion. The proposed approach forms a valuable asset for safe operations validation, enabling better evaluation of risk mitigation for sUAS urban operations and safety-focused design of the sensor payload and algorithms.**

Keywords—Detect and Avoid (DAA), small Unmanned Aircraft Systems (sUAS), Safety Operations, Risk Mitigation in Urban Environments.

I. INTRODUCTION

This work is the extension of the conference paper titled "Detect and Avoid Considerations for Safe sUAS Operations in Urban Environments" from the research team presented at DASC 2021 – The 40th Digital Avionics Systems Conference.

For years, a global market for Unmanned Aerial Systems (UAS) has been developing. The global UAS market is estimated to be USD 27.4 billion in 2021 and is projected to reach USD 58.4 billion by 2026, at a Compound Annual Growth Rate (CAGR) of 16.4% from 2021 to 2026 [1]. Small Unmanned Aerial Systems (sUAS) are increasingly being used in urban areas to perform various tasks, including medical deliveries, commercial package delivery, critical infrastructure inspection, and search and rescue operations. These operations necessitate the establishment of safety precautions at the infrastructure and sUAS application levels. The use of sUAS in urban environments needs to satisfy the definition of a safety-critical system whose failure could lead to significant property damage or environmental degradation. The problem is multifaceted, and appropriate levels of safety can be achieved only by holistically considering the infrastructure's hardware, software, and operator components and their interactions with potentially untrusted sUAS [2]. The widespread use of sUAS built for low-altitude flight applications in urban environments has raised public concerns about the overall safety of people, and property on the ground. To enhance the safety of the sUAS flight operations in urban environments, the DAA capabilities are made mandatory by the various regulatory authorities around the world. The primary challenge for DAA capability in the United Kingdom (UK) is meeting the requirements of Civil Aviation Authority (CAA) CAP 722 for detecting and avoiding other aircraft when operating in an urban environment [3]. However, Beyond Visual Line of Sight (BVLOS) sUAS operations in non-segregated airspace will generally be strictly forbidden [4]. DAA systems are intended to enable sUAS to "Remain Well Clear" (RWC) of other airborne traffic and avoid collisions. To accomplish this, an objective definition of RWC is essential. DAA must provide detection and guidance to maintain RWC and regain it if it is lost. To support DAA capability, the DAA system should perform the following functions [5]:

- ***Detect:*** Use one or more onboard sensors to detect obstacles
- ***Track:*** Use detection results to estimate obstacles positions and velocities
- ***Evaluate:*** Assess the collision risk of tracked obstacles
- ***Prioritize:*** Assess threat priorities/hazards (urgency levels)
- ***Declare:*** Alert remote pilot to avoidance action required
- ***Determine:*** Decide what action to take
- ***Command:*** Communicate the action for execution
- ***Execute:*** Execute the commanded action

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The DAA included technologies and approaches that could be used on an sUAS and enable the CAA to understand the types of DAA available for sUAS operating in the civil airspace. Initially, the DAA requirement is derived from sections 111 and 113 of Part 91 of the Federal Aviation Regulations (FAR). The FARs are part of Title 14 of the Code of Federal Regulations (14 CFR). FAR 91.111 addresses "Operating near other aircraft," while FAR 91.113 addresses "Right-of-way rules." FAR 91.111 prohibits operations close to another aircraft from creating a collision hazard. According to FAR 91.113, each person operating an aircraft must maintain vigilance to see and avoid other aircraft [6]. There are various existing DAA capabilities systems were developed by different research groups for UAS such as the Air Force's Multiple Sensor Integrated Conflict Avoidance (MuSICA)/Jointly Optimal Conflict Avoidance (JOCA) [7], the National Aeronautics and Space Administration's (NASA's) Detect and Avoid Alerting Logic for Unmanned Systems (DAIDALUS) [8], Scientific Applications & Research Associates (SARA's) the Terrestrial Acoustic Sensor Array (TASA) acoustic sense and avoid systems [9], Advanced U-space services and technologies (U3 and U4), the development of miniaturization, automated detect and avoid functionalities from SESAR U-space research [10] [11], a NASA developed SAA algorithm Independent Configurable Architecture for Reliable Operations of Unmanned Systems (ICAROUS) [12], and the New Mexico State University (NMSU) and University of North Dakota (UND) Alliance for System Safety of UAS through Research Excellence (ASSURE). However, these DAA capabilities and technologies in UAS mainly focus on larger aircraft and do not support operating in urban environments within sUAS. Integrating sUAS DAA capabilities in urban environments are quite challenging and in the research phase worldwide. Main contribution of this research is the link between DAA and navigation and communications. The main contributions in this paper for safer DAA urban operations are as follows:

- A review of the state-of-the-art technologies used for DAA.
- A set of representative urban scenarios, incorporating elements of DAA potential challenges, such as irregular building height, vegetation, and crowded airspace.
- Heterogeneous missions for the defined scenarios, covering a wide range of practical cases.
- Hazard Assessment considers probabilistic and casualty/damage approaches as well as a volumetric assessment utilizing LiDAR. A disparity map was used as a 2-D risk assessment.
- Complete scenarios simulation by integrating the platform model with DAA supporting technologies, including navigation and communications.
- A set of practical considerations enabling safer sUAS operations in urban environments.

In addition, this paper introduces a sense and avoid analysis with navigation and communications, as the expansion of the DASC 2021 paper on 'Detect and Avoid Considerations for Safe sUAS Operations in Urban Environments', this work analysis the hazard assessment to a more quantitative as well

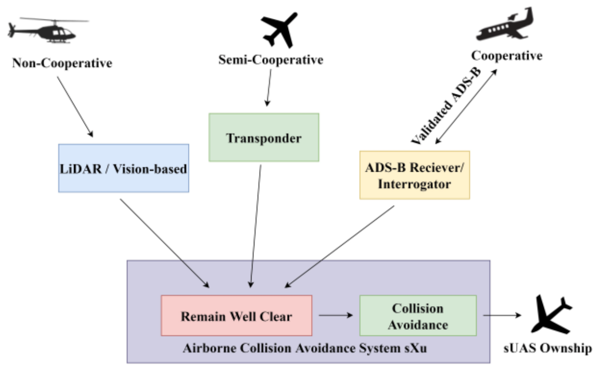


Fig. 1. DAA Architecture overview

as a qualitative method. The proposed approach forms a valuable asset for safe operations validation, enabling better evaluation of risk mitigation for sUAS urban operations and safety-focused design of the sensor payload and algorithms

The remainder of the paper is structured as follows: Section II presents the Detect and avoid technologies. Section III sets out the DAA approach in simulation and the process of Well Clear volumes in sUAS. Section IV compares and analyzes the performance and practical considerations of DAA. Section V concludes the proposed DAA approach.

II. Detect and Avoid Technologies and Architectures

The DAA systems includes technologies and approaches like Remain Well Clear (RWC), and Collision Avoidance (CA) that could be integrated into onboard systems of sUAS. These systems are certified and enabled by the CAA to understand the types of DAA available for sUAS operating in the civil airspace. A standard system engineering approach was applied to define and fully understand the DAA problem, which included evaluating DAA requirements and potential technology solutions. Fig. 1 illustrates cooperative, semi-cooperative, and non-cooperative technologies that were examined using the DAA function on the sUAS. The discussion of non-cooperative technologies includes both active and passive sensor systems.

A. Well Clear Recommendations

A DAA system's "Well Clear" recommendation combines an RWC and an optional Collision Avoidance (CA) function

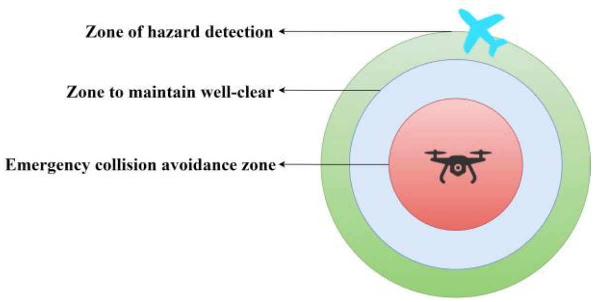


Fig. 2. Proximity of hazards

[13]. The primary distinctions between RWC and CA are summarized in Table I. The RWC function performs tactical maneuvers to maintain a Well Clear status, whereas the CA function performs emergency maneuvers to avoid midair collisions [14]. Collision avoidance is bound to the definitions of the direction kinematics of the intruders and the position of the obstacle within the volume definitions of RWC. The requirement for a Well Clear definition of UAS was identified early in developing the Sense and Avoid (SAA) system. Since the remote pilot of a UAS cannot provide the same level of 'see and avoid' mitigation for potential hazards, the UAS itself must be capable of performing an equivalent function. Fig. 2 illustrates the proximity of hazards in various zones. One of the highest priorities for a "Well Clear" is the assurance of remaining within a specified geospatial containment volume [15], where the threat and the intruder aircraft determine the containment volume. The RWC threshold and RWC volume, collision volume, and collision avoidance threshold are depicted in Fig 3, as defined in the International Civil Aviation Organization's (ICAO) ICAO RPAS Manual [16].

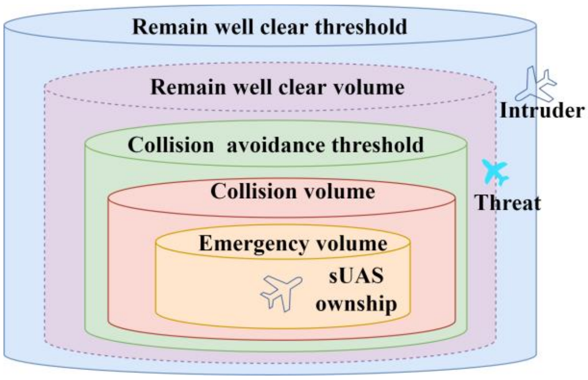


Fig. 3. Definition of Well Clear and Collision Avoidance Volume

There are several "Well Clear" concepts for UAS, including the closest point of approach (CPA) and time-to-CPA concept from NASA; a time-based image with distance modifications from the Massachusetts Institute of Technology Lincoln Laboratory; and an ellipsoidal concept defined by aircraft speed with varying vertical dimension from the Air Force Research Laboratory [17]. In their work, the Well Clear principles are tuned to a standard level of unmitigated collision using Monte Carlo analysis, resulting in tuned UAS Well Clear recommendations with an equivalent risk of a Near Mid-Air Collision (NMAC). Furthermore, the operational suitability of the Well Clear volume is assessed using Monte Carlo simulation, Human-in-the-Loop simulation, Stress-Case analysis, and fast-time simulation.

The metrics evaluated during the various simulation processes mentioned above include the Traffic Collision Avoidance System II Resolution Advisory Rate (TCAS II RA), controller acceptability considerations, Well Clear volume, cross-track deviation, vertical deviation, maneuver initial point, CPA miss distance/time given Well Clear violation, and mitigated risk ratio. These functions had to be redefined for the sUAS. Rather than having separate RWC and CA functions, sUAS will have a single level of alerting and guidance, with volume separation based on intruder type [19]. The Well Clear recommendations influence the scalable separation volume, and the metrics considered were the probability of an NMAC, the probability of loss of Well Clear (PLoWC), the horizontal miss distance, and the vertical miss distance. There have also been studies on collision risk assessment [20] [21] based on the dynamic model of the sUAS, but these methods are mathematically complex to be included in the model.

B. *Cooperative Technologies*

Cooperative technologies are viable technologies that rely on other aircraft in the same airspace. ADS-B and ATAS systems are examples of Cooperative technologies. ADS-B data is a satellite-based broadcast surveillance technology. The system has two components: ADS-B Out and ADS-B In. ADS-B regularly transmits its state position, consisting of horizontal and vertical position and velocity. An aircraft sending ADS-B messages (referred to as "ADS-B Out") broadcasts an omnidirectional signal that can be received by nearby aircraft and ground stations, reporting its estimated lateral position (derived from Global Positioning System (GPS)), altitude, velocity, and other information [22] [23]. ADS-B In is the system's receiving component, which receives communication from other aircraft and ADS-B messages from ground locations. It is possible to establish the relative position and movement of those proximate aircraft concerning the ownship aircraft that use state vector information available from other near aircraft and information re-broadcasted from ground locations [24]. ADS-B is a promising cooperative sensor option for DAA on sUAS. The ADS-B Traffic Advisory System (ATAS) is an application meant to reduce the number of midair and near-mid-air collisions involving general aviation aircraft. It gives verbal communication to flight crews to direct their attention to potential threat aircraft and visual clues to the underlying fundamental traffic situation awareness [25]. The application employs ADS-B data, Automatic Dependent Surveillance-Rebroadcast (ADS-R), and Traffic Information Service-Broadcast (TIS-B) data to give the flight crew indicators of adjacent aircraft in support of their SAA obligation. It is based on all concerned aircraft's constant heading or constant

TABLE I
MAIN DIFFERENCES BETWEEN RWC AND CA [18]

	RWC	CA
Decision factors	Safety, acceptability, Strategic	Safety
Responsibility	It depends on airspace (can be shared with a pilot)	Pilot
Contact Air traffic control	Yes, notably if under clearance	If time allows
Start/End	Conflict / Collision hazard or Clear of Conflict (CoC)	Collision hazard/ NMAC or CoC
Time horizon	Few minutes	Tens of seconds
Maneuver	Smooth	Strong
Maneuver Constraints	Right of Way rules, clearance	None

turn-rate trajectories and provides alerts based on expected penetrations of protected airspace along those trajectories. The algorithm comprises three essential components: creating protected airspace zones surrounding intruder aircraft, trajectory prediction for both ownship and intruder aircraft, and alerting decision logic [26]. The advantages of cooperative technologies are that they can be easily tracked and communicate faster when compared to other technologies. However, the disadvantage of these technologies is that every aircraft and ground system should be equipped with these technologies.

C. *Semi-Cooperative Technologies*

Semi-cooperative technologies are generally cooperative systems, that are mostly equipped into manned aircraft. It means the surveillance systems will only operate if both aircraft have a piece of equipment that can communicate. In most cases, manned aircraft rely on cooperative surveillance systems; however, a DAA system that relied on this information would not protect against an intruder who did not have position-sharing equipment. But, most aircraft would be too large and expensive to include a non-cooperative sensor (such as an air-to-air radar) to identify unauthorized intruders. Transponders and ACAS systems are examples of semi-cooperative technologies. Transponders are a similar type of Secondary Surveillance Radar (SSR) developed to supplement Primary Surveillance Radar (PSR) [27]. By sending out electromagnetic energy (radio waves) and measuring the transmitter's energy, PSR is used to approximate the position and speed of distant objects [28] [29]. The FAA Traffic Alert and Collision Avoidance System (TCAS) program office is working on a family of advanced Airborne Collision Avoidance System (ACAS) systems as shown in Table II.

ACAS X is replaced with TCAS. ACAS Xu is a UAS-specific system designed to be a complete DAA solution. The ACAS sXu extends the ACAS Xu concept to provide a DAA capability for sUAS with various equipment and capabilities that operate under FAA Part 107 or a waiver. A systematic method was proposed to describe and analyze the DAA problem, which included evaluating DAA requirements and possible technology solutions. ACAS X collision avoidance logic is best explained in two distinct phases, offline development and real-time operation. In offline development, the ACAS X provides a statistical representation of the aircraft's future position. It also considers the system's safety and operational objectives, allowing the logic to specific procedures or airspace configurations. In real-time development, the ACAS X collects surveillance data from various sources (approximately every second). Various models (for example, a probabilistic sensor model accounting for sensor error characteristics) estimate a state distribution, a probability distribution over the aircraft's current positions and velocities.

ACAS sXu is a scalable solution suited for a wide range of surveillance sources and platform dynamics [30]. The concept's adaptability allows ACAS sXu to adapt to changing standards and regulatory circumstances. Unlike other ACAS X variants, ACAS sXu includes a set of logic and a series of numeric lookup tables that encode a large portion of the decision-making information. In a compute-intensive surrogate modeling process, these tables are optimized offline before being loaded onto the platform. As part of a Markov Decision Process (MDP), this process computes the tables using a set of trajectory profiles from various airspaces and an appropriately weighted objective function. The tables from ACAS Xu were used without any re-tuning for ACAS sXu version 0. On the other hand, range and speed indexing were scaled independently to account for sUAS dynamics.

Furthermore, the tables were down sampled to make the overall memory footprint suitable for the test platforms. This down sampling was combined with simulation to ensure that safety and operational suitability metrics were not compromised by the DAA software tables written in Julia. The entire Julia is documented as the sXu Algorithm Design Description (ADD), which includes a parameter file that details the dozens of parameters that tune the system's real-time software.

The active surveillance and coordination entry points were removed when switching from Xu to sXu because that functionality was no longer required. However, future sXu

TABLE II
DIFFERENT ACAS X VARIANS

ACAS Family Variants	Description
ACAS Xa	It uses an active SSR transponder, interrogations, and passive data sources like ADS-B
ACAS Xo	ACAS Xo mode of operation is designed for specific functions (Procedures with reduced separation, such as closely spaced parallel approaches)
ACAS Xp	It is used for general aviation
ACAS Xu	It is designed for unmanned aircraft with a wide range of sensor inputs and capabilities
ACAS sXu	It is designed for small Unmanned Aircraft Systems (sUAS)

TABLE III
VERTICAL ACTION SPACE OF ACAS sXu TRM [32]

Action	Description
CoC	No manoeuvre necessary
Do Not Climb	Used for level-off or preventive guidance
Do Not Descend	Used for level-off or preventive guidance
Climb	Climb with a suggested 1000 ft/min rate
Descend	Descend with a suggested 1000 ft/min rate

TABLE IV
HORIZONTAL ACTION SPACE OF ACAS sXu TRM [32]

Action	Description
CoC	No manoeuvre necessary
Turn right	At least 3 degree/sec
Turn left	At least 3 degree/sec

versions will likely restore some functions as the concept and sUAS landscapes evolve [31].

A ground surveillance report was added to facilitate ground sensing networks and other pre-tracked 3D position data sources. ACAS sXu has features that are unique to its concept of use. sXu includes a single level of alerting and guidance, with the separation volume scaled based on intruder type rather than separate RWC and CA functions [31]. ACAS sXu includes real-time dynamic scaling, which means that the system's separation volumes can be adjusted in real-time based on system inputs and states [32].

The ACAS sXu development team collaborates with ASTM International's Committee F38 on Unmanned Aircraft Systems, RTCA Special Committees 147 and 228, and the UAS Science and Research Panel (SARP) to inform the final system's scale factors, protection volumes, and safety metrics [31]. A DAA system includes both an RWC and a CA function. The RWC function provides tactical maneuvers to keep the aircraft Well Clear, whereas the CA function provides urgent maneuvers to avoid mid-air collisions. These functions had to be redefined for the sXu concept. Instead of having separate RWC and CA functions, sXu has a mono level of guidance and alerting, with the separation volume scaled based on the type of intruder. ACAS sXu, like other ACAS X variants, is made up of two main modules: the Surveillance and Tracking Module (STM) and the Threat Resolution Module (TRM) [32]. The vertical and Horizontal Action Space of ACAS sXu TRM is illustrated in Table III and Table IV.

D. Non - Cooperative Technologies

Non-cooperative technologies, which do not rely on other aircraft, are among the most promising technologies for sUAS DAA systems. Non-cooperative technology differs from cooperative technology; it does not rely on different aircraft in the same airspace to avoid collisions. The non-cooperative technologies have the advantage of detecting both ground and aerial objects. Active and passive technologies are the two primary types of non-cooperative technologies. Active systems are used to identify obstructions in the flight path by generating a signal. Active systems include sensors such as radar and lasers. Passive systems do not send out an alert; light and sound are the primary sources of passive systems. Electro-Optical (EO), Infra-Red (IR), thermal, motion sensing, visual, and acoustic systems are examples of passive systems. Some of the active systems in non-cooperative technology are radar, sonar, and laser.

Active systems work primarily in the microwave range of the electromagnetic spectrum, allowing them to penetrate most atmospheric conditions, including cloud cover, which is a problem for passive systems. The radar systems can be either airborne or ground-based [33]. The air-to-air radar is developed to provide an extra layer of collision avoidance and separation for human and unmanned aircraft operating in the non-segregated airspace. For airborne radar coverage, the system will contain one or more antenna elements. Transmit, receive, control, status, and tracking operations are all provided by airborne radar electronics. Ground-based radar is one of the most promising technologies for sUAS to be integrated into the non-segregated airspace. Laser-based Light Detection and Ranging (LiDAR) has emerged as a viable technique for DAA in sUAS [34]. The excellent detection capability, unprecedented angular resolution, and range accuracy of LiDAR have led to its acceptance for various urban applications [35].

TABLE V
COMPARISON OF DIFFERENT TYPES OF NON-COOPERATIVE TECHNOLOGIES [42]

Name	System	Detection Range (Km)	Detection Information	Comparison
Visionary System	Passive	1.9	Position, speed	Small range, affected by the performance of the camera
LiDAR	Active	3	Distance	Small view
Infrared (IR System)	Passive	4.4	Relative bearing, elevation	Not applicable to IMC
Acoustic System	Passive	10	Relative bearing, elevation	Time delay
Optoelectronics (EO System)	Passive	20	Relative bearing, elevation	Susceptible to weather, lacking in the guidance range
Synthetic Aperture Radar (SAR)	Active	35	Distance, relative bearing	Low accuracy

Due to the nature of sound as a detecting medium, the employment of sonar technology in sUAS DAA systems is not optimal. Initially, sonar was an active underwater detecting system, and it performs better in water than in air because sound travels faster in water [36]. However, applying sonar to sUAS is impractical since sound does not travel rapidly enough through the air to be reliably detected by a moving aircraft. Temperature variations can also significantly impact the speed of sound, and atmospheric temperature is substantially more changeable than water temperature.

The passive system has radiometers, which measure the radiant flux of electromagnetic radiation. The passive system also consists of spectrometers and optical instruments that observe spectral lines and measure the wavelength and intensity. The vision-based, infrared, thermal camera, electro-optical and acoustic are passive systems. The Electro-Optical (EO) systems require light as a primary source to detect obstacles and have advantages compared to radar [37]. The sUAS with ground-based radar in the civil airspace has the disadvantages of its massive power consumption and exorbitant cost [38]. However, sUAS with Low SWaP sensors such as EO are now being developed and deployed to detect aircraft in the non-segregated airspace. The Infra-Red (IR) technology assists EO sensor detection at night, unaffected by electromagnetic interference [39]. The IR system can calculate the obstacle range by calculating IR light emitted by objects. The IR is mostly deployed as an onboard sensor instrument for the DAA system. IR systems are widely used in border control and night monitoring, where sUAS equipped with IR technology plays a significant role in these applications [40].

SARA's TASA system is an acoustic phased array system that detects aircraft and classifies collision threats to allow sUAS to fly BVLOS operations safely [9]. TASA can detect aircraft even when trees impede their line of sight, buildings, or topographical obstacles. Another acoustic-based technology from SARA is the Passive Acoustic Non-cooperative Collision Alert System (PANCAS). It is used to detect and tracks the sound of aircraft engines, propellers, or aircraft rotors. [41]. The different types of non-cooperative technologies related to detection and range are compared and shown in Table V.

In conclusion, the DAA system has different technologies, such as cooperative technologies, semi-cooperative technologies, and non-cooperative technologies. The cooperative technologies consist of ADS-B and ATAS systems. The semi-cooperative technologies consist of transponders, TCAS, and different versions of the ACAS system, the ACAS sXu is mainly designed for sUAS systems flying at low altitudes in urban environments. The non-cooperative technologies consist of active and passive systems. The active systems include radar and laser, whereas the passive systems include EO / IR, acoustic, and camera systems. This paper uses airborne DAA sensor technologies concerning monocular cameras and LiDAR, known as vision based DAA.

III. DAA Simulation

Threat awareness and safe distance keeping are fundamental capabilities required from a DAA solution, especially considering the challenging and built-up geometry urban environments present.

This section aims to present the simulation used to analyse the DAA core solution and the supporting technologies. The latter are identified as the data link robustness and navigation reliability, which are modelled and assessed according to the challenges DAA systems.

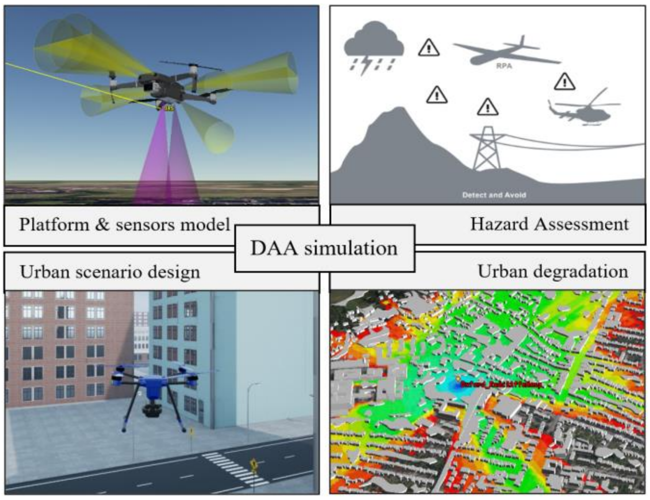


Fig. 4. DAA simulation overview, including realistic drone and sensors modelling, representative scenarios and threats assessment

The simulation environment combines two different software models for which a set of scenarios is defined by the environment requirements. The core DAA functionality is modeled through the integration of MATLAB, Simulink and Unreal Engine recreating accurate platform simulation in a photo-realistic environment. As a result, situational awareness from onboard sensors feeds collision avoidance algorithms against defined obstacles and threats. Threat avoidance prioritizing and the corresponding evasive maneuver are computed based on a hazard assessment methodology, using safety volumes intersection and obstacle typology. DAA supporting technologies are modeled in Systems Tool Kit software from AGI, a mission and systems design platform equipped with urban propagation models for RF communications, accounting for diffraction losses and reflections on terrain and obstacles [43]. This complementary system identifies potential threats to the DAA system integrity, such as loss of datalink or Global navigation satellite system (GNSS) navigation accuracy, ensuring the core system and mission integrity are not compromised for safer operations.

In Fig. 4 an overview of the components composing the DAA simulation is presented. The sUAS is modeled and equipped with selected sensors, and then introduced into urban scenes. Collision risk is measured through a hazard assessment metric which identifies threats and provides recommended evasive maneuvers accordingly. Finally, signal degradation in urban scenes is simulated and DAA-related cooperative technologies are analyzed with the obtained results, exploring how data link and navigation challenges affect the system capabilities. In the following sections in this chapter, a methodical approach to hazard assessment is introduced. Utilizing the ideas of a probabilistic likelihood of obstacles within the environment and the consequence of impact of the intruders to the sUAS. The final section provides the implementation of the hazard assessment with the current sensors used for the sUAS.

A. *Non-Cooperative Hazard Assessment*

This paper introduces an improved hazard assessment metric based on the prior paper from the research team presented at DASC 2021.

Three main methods are introduced for hazard assessment. A probabilistic understanding is considered together with sensor assessment and consequential risk assessment. This allows a holistic approach to produce a risk metric ready for validation and taking into consideration sensor data (LiDAR and vision-based) as well as modeling a prediction model derived from the probabilistic method with utilizing a consequence metric.

1) Probabilistic Likelihood of Event

To estimate the trajectory of dynamic objects and the future collisions the concept of probability of event likelihood is introduced. The concept of probability distribution and the likelihood of classification have been defined in Table VI. In addition, the obstacle occurrence likelihood within the current Unreal Engine simulation environment has been shown in Table VII.

TABLE VI
PROBABILISTIC EVENT LIKELIHOOD

Improbable	Unlikely	Sporadic	Frequent
$0 \le P_E < 0.01$	$0.01 \le P_E < 0.2$	$0.2 \le P_E < 0.6$	$0.6 \le P_E < 1$

TABLE VII
PROBABILISTIC LIKELIHOOD OBSTACLES

Obstacles ↓ Probability→	P_E
Small Foliage (Bushes,)	0.35
Trees	0.6
Buildings	0.7
Intruders (Birds, e.g.,)	0.1
Ground Vehicle	0.15

Works [21][44][45] utilize experimental data and structured analysis techniques for failure rates. [46] suggests a hazard assessment probabilities criterion for sUAS using the FAR Part 23 concepts. To be able to make a clear understanding of the FAR or the CAA regulations for the probability of failure assessment, specific sUAS information is required. This paper uses a relative estimation of sUAS details are used to produce the probability criteria. Based on [21] likelihood scale, the following iteration of the framework was adopted for probability considerations.

TABLE VIII
RISK AND SEVERITY METRIC ASSESSMENT

Risk ↓ Severity→	Minimal Index:[1]	Moderate Index:[2]	Major Index:[4]
Frequent ($0.6 \le P_E < 1$)			
Sporadic ($0.2 \le P_E < 0.6$)			
Unlikely ($0.01 \le P_E < 0.2$)			
Improbable ($0 \le P_E < 0.01$)			

The indexes to define the hazard consequences are accumulated from [21] and modified to also analyze the flight envelopes of the sUAS and potential loss of control. Little information has been published regarding high-fidelity modeling of sUAS vehicles in off-nominal conditions. [21] The consideration of flight envelopes and off-nominal conditions are used when there is an emergency threat present. Table VIII shows the accumulative understanding of consequential risk assessment.

The definition of the severity indexes is given as follows:

1. Minimal: Low-level damage to the environment due to collision
2. Moderate: Non-serious or mild damage to the sUAS and the surrounding obstacle due to impact
3. Major: Fatal damage to the sUAS and the surrounding obstacle due to impact

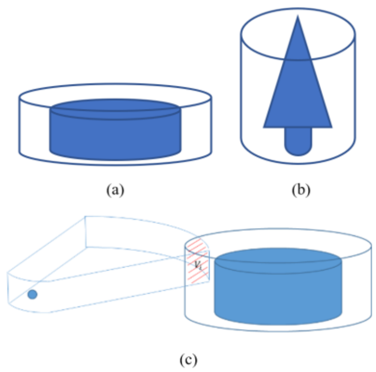


Fig. 5. Hazard assessment volumes representation: safety volume for static objects (a), safety volume for complex shapes (b), and intersection volume between sUAS safety volume (left) and static (c)object safety volume (right)

The given probabilities were associated with obstacles utilizing simulation test data and analysis. The values given for minimal, moderate, and major were decided by trial and error. The following Table VI was used to be the case in most of the simulation testing to imitate the real-life scenario. Table VII describes the probability of coinciding with certain obstacles in the simulation environment. The red colour indicates a high-risk area, orange indicating a high-medium risk, yellow implying a medium-low risk and the green color representing a low risk level The color/risk levels were used for the prioritization of certain obstacles for collision avoidance.

2) Consequential Hazard Assessment

The probability assessment allows the analysis of potential collision likelihoods, to further deepen the understanding of hazard assessment in real-life scenarios event consequences need to be factored in for a more practical approach to risk assessment.

Severity indexes focus on the surrounding object damage and the potential damage to the sUAS. This concept allows the hazard interpretation of the third party and the likelihood of the event. To understand this concept in terms of numerical and qualitative analysis, sensor hazard assessment is utilized.

3) Sensor Hazard Assessment

The hazard assessment starts with the definition of safety volumes for the sUAS and the hazards. The safety volumes of the moving objects, such as sUAS, birds, etc., are defined by considering the velocity of the objects.

As buildings, the safety volume is defined with a set of points apart from the obstacle with the same distance if the object has a simple shape for the static and large obstacles. The complex shapes' safety volume (e.g., trees) is defined as the minimum size of the cylinder covering the object with a certain margin from the objects (see Fig. 5).

For volumetric risk analysis, it was essential to utilize the LiDAR and understand the 3-D geometry of the objects surrounding the sUAS. SLAM was used to map the safety volumes and the objects surrounding the sUAS as shown in

After the calculation of the safety volumes, the common volume V_i is calculated if a hazard i, whose safety volume intersects with that of the sUAS, exists. The score of the priority to avoid a certain hazard is calculated as follows. If the common volume V_i is 0, the score for the hazard i is 0. If the common volume is non-zero, the score for the hazard i is

$$S_h = D_i V_i \quad (1)$$

D_i is the danger level of the hazard defined by the user. Eq. 1 considers both the sensors of LiDAR and the monocular camera. The Di is classified using a vision-base algorithm and the Vi is the volume intersection observed from both the LiDAR and the monocular camera.

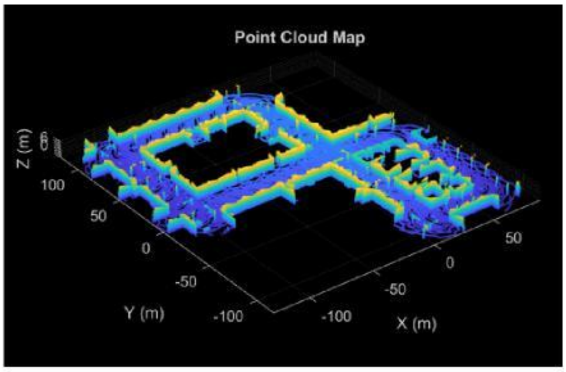


Fig. 6. Visualization of SLAM (Simultaneous Localization and Mapping) US City Block

For example, since it is more dangerous to conflict with the building rather than the sUAS, D_i of the building will be higher than that of the sUAS. The risk/severity metric is utilized to quantify the danger levels of the obstacles. To implement a hazard assessment to the DAA algorithm, relevant hazard criteria need to be prepared. The hazard criteria are determined by assigning priority values by assessing the relationship between the hazard score established in Eq. 1. The priority levels are decided through categorizing the score derived from normalized volume intersection data scaled by constant term, c, introduced by assessing the values of the score S_h.

$$S_h c \propto P_{criteria} \quad (2)$$

$$D_i \propto P_E S_I \quad (3)$$

$P_{criteria}$ is the priority criteria and P_E is the probability of the event. The range and the explanation of the priority criteria is represented in Table IX. The equation can be further expanded as shown below.

$$P_{criteria} \cong K(P_E S_I)V_i \quad (4)$$

where S_I is the severity index and K is a scale constant. After the determination of the $P_{criteria}$, pilot actions can be justified from Table IX. Priority scheme can be represented as given in Fig. 7, demonstrating the sensor roles in the determination of the collision avoidance and detection. In the case of multiple intruder volumes, the sUAS will prioritise the avoidance according to the priority of the hazard.

TABLE IX
PRIORITY CRITERIA POINT CLOUD MAP

Priority Criteria, P_c	Action
Emergency (5)	Immediate avoidance maneuver, aggressive bank rate or pitch rate (Evaluate Risk/ Severity metric)
Urgent (4)	Necessary avoidance maneuver
Medium -prio (3)	Calculated avoidance for path optimization
Less urgent (2)	Establish communication through cooperative sensors, possible avoidance
Low -prio (1)	Re-evaluate the risk of collision at the next time step

In addition to the LiDAR hazard requirements, a vision-based assessment is produced. The determination of the hazard assessment from the monocular camera requires a 2-D risk assessment. Through introducing a threshold limit with the vision-based system, the volumetric ranges can be combined with the LiDAR data to plot the volumetric intersection thresholds. Therefore, Figure. 8 representing the CAA regulations (for a fixed wing) was utilized in defining the ranges for the depth estimation technique for the monocular camera. The ranges were scaled proportionally to suit the synthetic environment ranges by a factor of two. The

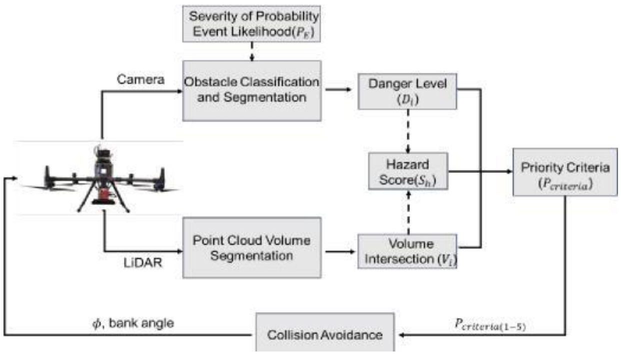


Fig. 7. Priority Criteria Scheme

factor value of two was chosen due to the limited area within the environment. In addition, comparing the size factor of the VTOL used the factor of two was found to be best to resemble real-world avoidance regulations to be fitted into the simulation environment. The defining ranges were put in ranges that are defined in Figure 2 as shown in Table X.

TABLE XII
SAFETY VOLUME RANGES

	RWCT	RWCV	CAT	CV	EV
Distance from sensor	250 m	200m	100 m	50 m	10 m

Finally, to provide a more extensive analysis over DAA vision-based techniques adopting hazard assessment techniques discussed, a simulation environment integrated using MATLAB, Simulink, and Unreal Engine is proposed. The sUAS Toolbox on Simulink connects the DAA model to the simulation environment in Unreal Engine using MathWorks sUAS plugins.

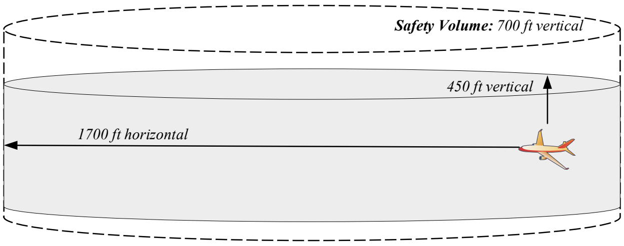


Fig. 8. CAA /FAR Safety Volume Definition

Different scenarios are included in the algorithm, each populated with the correspondent identified threats of interest. DAA simulation incorporates different obstacles frequently found in urban environments devising a contained and representative environment, where hazard assessment and collision avoidance capabilities are tested. Different Synthetic environments were designed to test dynamic and static obstacles and the sUAS for hazard decision making.

The sensors implemented in Simulink for DAA testing are an onboard camera and LiDAR. Considering the onboard camera and LiDAR sensors on the sUAS, a sense and avoid algorithm is developed for hazard assessment implementing results and considerations from the previous simulation setups. To incorporate the risk assessment criteria, the intersected volume of the obstacle is processed and calculated using the disparity and segmentation map output of the Simulink 3D camera. The disparity map allows the depth mapping of the obstacles and intruders. A separate algorithm is utilized for the disparity map to give the ranges within the camera. The segmentation map defines different obstacles observed within the environment through colour coding the environment.

The segmentation map is used for obstacle identification and the disparity map is utilized to visualize the distance of obstacles using Otsu's method of thresholding [47]. LiDAR is used to validate the distances of objects to the depth image. The vision-based algorithm utilizes morphological operators and blob detection techniques on the disparity map, which is communicated through the Unreal Engine. Blob detection allows the extraction of obstacle centroids, areas, and their respective distances. A simple avoidance scheme is utilized considering only the bank angle corresponding to the priority criteria to demonstrate the recognition of 2-D hazard intersections.

High fidelity is considered a key enabler for representative DAA simulation, incorporating close-to-reality photo imagery and representative sensors models. This work proposes an integrated environment based on MATLAB, Simulink, and Unreal Engine.

B. *Cooperative DAA Supporting Technlogies Assessment*

Urban operations are not only subject to potential collision threats but also conditioned by the effects of built-up geometry on communications and navigation. Mission safety relies on a continuous and quality data link, providing the platform and operator with all mission details both from the sUAS itself and the environment, as well as an accurate navigation solution for effective avoidance.

Within the DAA framework, situational awareness derived from off-board sources relies on the data link robustness, which is affected by the urban geometry. These data sources can be divided into air-to-air, air-to-ground, and ground-to-air categories, being the first one communication between aircraft, and the second and third between aircraft and ground stations. Additionally, a further data link between ground stations via the Internet supports larger-scale scene broadcasting, relying on cell tower coverage for each ground station.

Different DAA technologies incorporate the previously defined categories, relying on external inputs which in conjunction with the onboard awareness define the DAA system solution. As previously presented in this paper, examples of these cooperative and semi-cooperative technologies for sUAS are ADS-B and ACAS sXu respectively. In terms of data link degradation effects over their functionality, urban environments present characteristic phenomena as line-of-sight obstruction, reflection, diffraction and multipath.

In a similar way to communications, the heterogeneous scenery characteristic of urban environments greatly impacts the availability of visible satellites from the platform and therefore the navigation accuracy. DAA broadcasting technologies rely on awareness of the ownship location, as it is required to be shared with other airspace users. This requirement is considered a limitation for systems such as ADS-B, listed by different manufacturers as the DJI AirSense technology [47]. Navigation performance in urban scenarios is analyzed in the already defined simulation environment for communications, aiming to identify potential conflictive zones.

In terms of simulation, communications and navigation environments are conceived as larger, region-based scenarios, recreating mission-level analysis rather than at maneuver level, as part of air medical deliveries between different hospitals and selected locations in the area. Therefore, results are studied as regional coverages over defined scenarios, including a set of sample routes that are monitored during the

Fig. 9. Illustration of urban geometry in the STK

flight. Urban geometry is modeled as cuboids defined in shapefiles (.shp) and extruded over the scene terrain, both for buildings and major obstacles as vegetation formations (see Fig. 9). The analysis of these phenomena is performed through the Urban Propagation module from STK (Systems Tool Kit), accounting for diffraction losses and reflections. Furthermore, environmental conditions are implemented in the scenarios, including rain model ITU-R P618-12, clouds-fog model ITU-R P840-7 and atmospheric absorption model ITU-R P676-9, addressing atmospheric adversarial conditions during the mission.

The resulting communications simulation environment provide a comprehensive understanding of the effects of placing the antenna in various locations for diverse scenes and, as a result, a wider coverage of potential risk scenarios operators might encounter in urban scenarios which enables strategic antenna placement and flight routes planning. Navigation simulation is based on GNSS coverage, including GPS and Galileo constellations. Performance is studied through the calculation of Dilution of Precision (DOP), providing the navigational solution degradation; accuracy in meters, enabling identification of potential risk regions for close-to-obstacles flight; and a number of visible satellites, a requirement for most of the sUAS manufacturers for safer take-off and other operations.

IV. Analysis and Discussion

Based on the simulation parameters, this section analyses the identified challenges urban environments pose for sUAS DAA solutions and explores practical considerations to support safer operations. The STK to MATLAB connection is given in Fig.10, states of the agent and environment are fed to MATLAB which allows obstacle detection and avoidance. The analysis is structured as DAA hazard assessment results through sense and avoid simulation, complemented by the communications and navigations identified challenges for DAA cooperative technologies. Finally, a set of applicable safe practices is listed based on the reviewed literature and obtained simulation results.

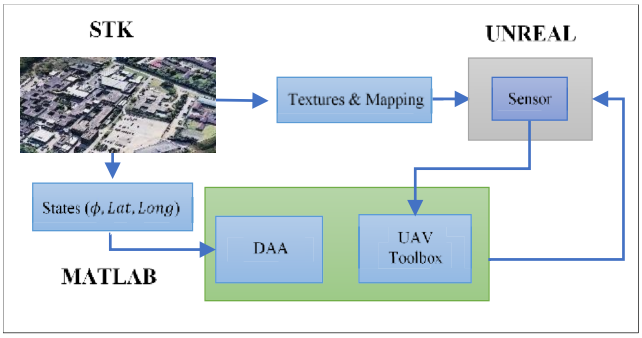


Fig. 10. Illustration of STK – MATLAB Integration

A. *Non-cooperative Technology Hazard Assessment*

Several different environments were created in Unreal Engine to simulate the hazard assessment adopted DAA. The environments were designed to incorporate dynamic and static obstacles. The sUAS in Fig. 12, have a predetermined path to reach the goal (starting point (black cross) and ending goal (red cross)), as an additional intruder is introduced depending on the path of the intruder, the path of the sUAS changes as to avoid collision. As can be seen the LiDAR and the camera sensors proves sufficiency as the sUAS has no collision as well as target reach.

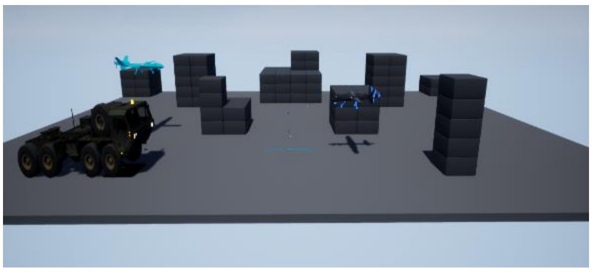
1) *Unreal Engine Environments*

The first environment included only static obstacles with limited obstacles, the main aim was to be able to reach the end goal position whilst minimizing collision. The second scenario uses a city block environment with one dynamic obstacle together with several static objects in a simple environment. The third scenario incorporates multiple dynamic obstacles, UAV MQ-9 Reaper, and Truck M983 HEMTT, and static objects and incorporates a higher fidelity model as shown in Fig. 11 (c) This scenario allows the understanding of dynamic objects and the role of hazard assessment with DAA.

Fig. 11 Unreal Engine simulations were created to resemble the hospital delivery cases given in the communication and navigation maps in STK. As common obstacles surrounding the hospital environments include small and large foliage (bushes, trees e.g.,), buildings, ground, and aerial intruders.

(a) Static Mesh Environment

(b) US City Block



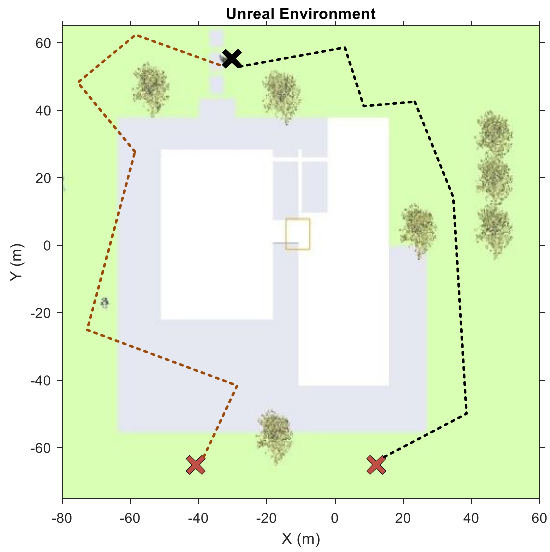
(c) Dynamic Environment

Fig. 11. Demonstration of Unreal Engine in Simulation Environment

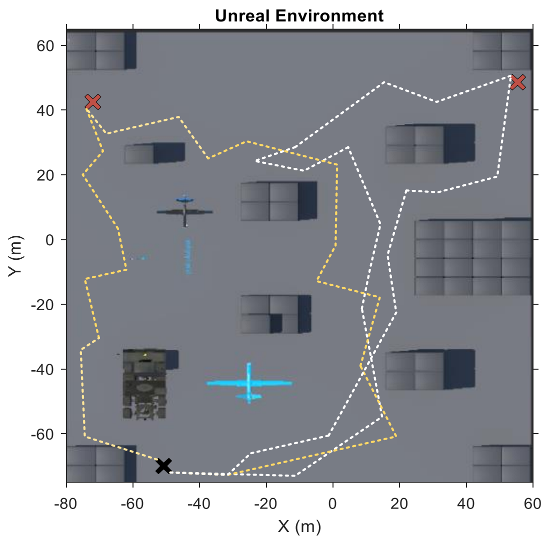
Utilizing MATLAB created dynamic mapping functions; the synthetic environments presented in Fig. 12 were dynamically mapped representing the sUAS behavior in a 2-D map.

In each environment two different start positions (represented as the red cross) were presented to an end goal (represented as the black cross) position. In Fig. 13 (a) (b) two different tests were plotted for each start position with different probability event distributions, PE, where the ground vehicle was favoured over the intruders. The different trajectories mapped are due to the ownship sUAS starting at different starting positions. In all cases the sUAS goes through take-off, cruise, and landing.

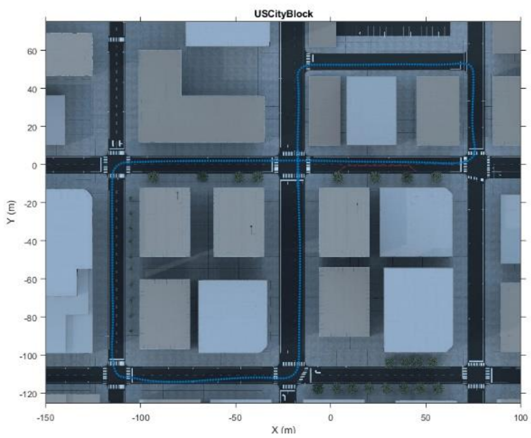
Once collision avoidance is introduced (Fig. 13), the prior results are validated, conferring higher priorities a greater banking angle (negative and positive values indicate left and right turns, respectively), while lower priorities result in less aggressive maneuvers. The required bank angle is commanded to the control unit and executed to maintain a Well Clear distance from it. From the figures we can observe that dynamic objects are favored over static object meshes as the sUAS considers a ground vehicle to have a higher danger level, D_i, hence prioritizes GV over static blocks in Fig. 12 (b). Fig. 12 (b) intruders move across the platform to observe the behavior of the sUAS with the adopted hazard assessment for many dynamic obstacles. The ground vehicle allows the disruption of landing and take-off of the sUAS. Fig. 13 (a) (b)



(a) Top View of Static Mesh Environment representing birds eye view of Fig.11 (a)

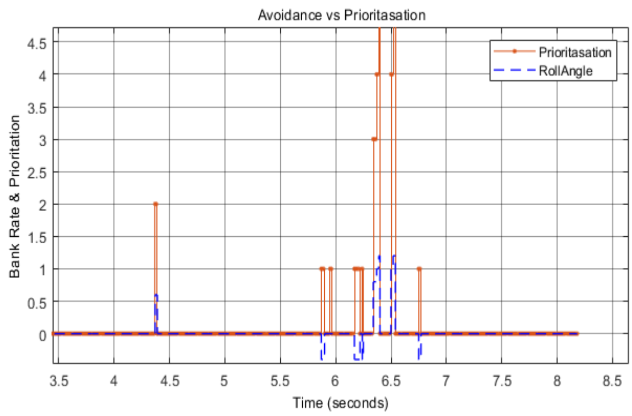


(b) Top View Dynamic Vehicle(s) Environment representing birds eye view of Fig.11 (c)

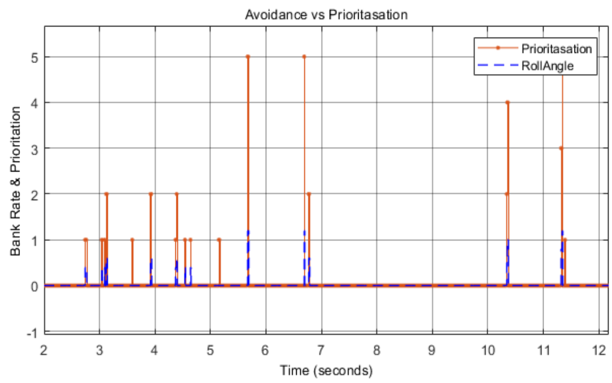


(c) US City Block Environment representing birds eye view of Fig.11 (b)

Fig. 12. Dynamic Mapping of sUAS path



(a) Static Mesh Environment Prioritization



(b) Dynamic Vehicle(s) Prioritization

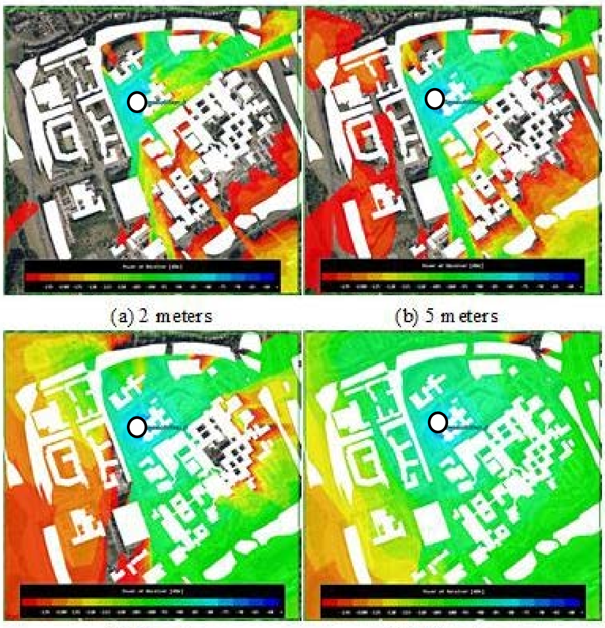
Fig. 13. Prioritization of Obstacles and Avoidance

compliments the priority collision avoidance of the dynamic mapping observed in Fig. 12 (a) (b), respectively.

Noticeably both graphs indicate the prioritization of different dynamic and static objects. For example, as the sUAS gets closer to the trees the priority levels are increased proportionally and the avoidance is greater. For each priority level defined from (1-5) a discreet level of bank rate is set, varying from 0.2 rad – 1.2 rad defining the lowest priority to high risk. In Fig. 13 (b) the sUAS predicts the direction of the collision volume of the UAV MQ-9 Reapers' and undertakes an emergency avoidance scheme whilst decision making the risk/severity index of collision.

B. *Cooperative and Semi-cooperative DAA supporting technologies urban performance*

Simulation of data link degradation in urban environments evidences the impact of built-up geometry on close-to-ground maneuvers in contrast to less obstructed flight phases. Fig. 14 shows the coverage of a ground station transmitting antenna, transmirror in the figures, at different heights for a given delivery mission. The immediate obstacles greatly define the reach of the propagated signals, and therefore its relative height against the ground station antenna. Furthermore, higher terrain proves to provide higher coverage, as expected from the previous results; however, those regions under the line-of-sight due to elevation will only be subject to receive a signal from surrounding obstacles, if any, and therefore not be suitable for safe flight conditions. Similarly, antennas placed on buildings and elevated positions will also suffer from immediate line-of-sight obstruction from the standing surface itself, for instance, the building's roof edge, and therefore fail to cover surrounding airspace if poorly positioned. Route orientation must as well be considered, as while one location would provide further coverage, an alternative might be more suitable in terms of signal strength for a certain route of interest. An example is presented in Fig. 15, where while for



(a) 2 meters (b) 5 meters

(c) 10 meters (d) 20 meters

Fig. 14. Ground station antenna height impact on power at receiver [dBW] RF signal propagation for a sample scenario

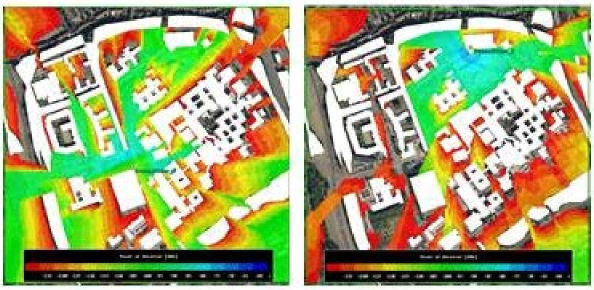


Fig. 15. Ground station placement impact on *power at receiver [dBW]* RF propagation comparison for Fig. 14

the first case a wider coverage is provided, the second offers a more reliable signal strength for its surrounding airspace.

Regarding air-to-air communications, urban degradation can be avoided for above building level flight conditions. As a result, similar conditions are found as for conventional flight

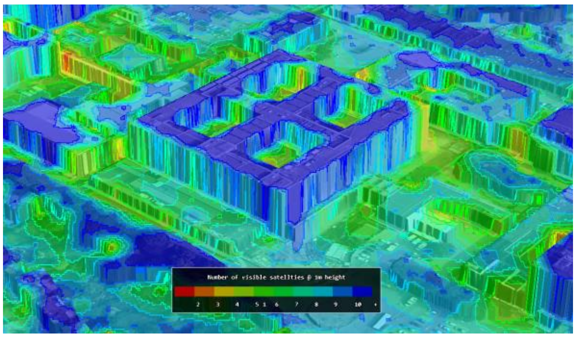
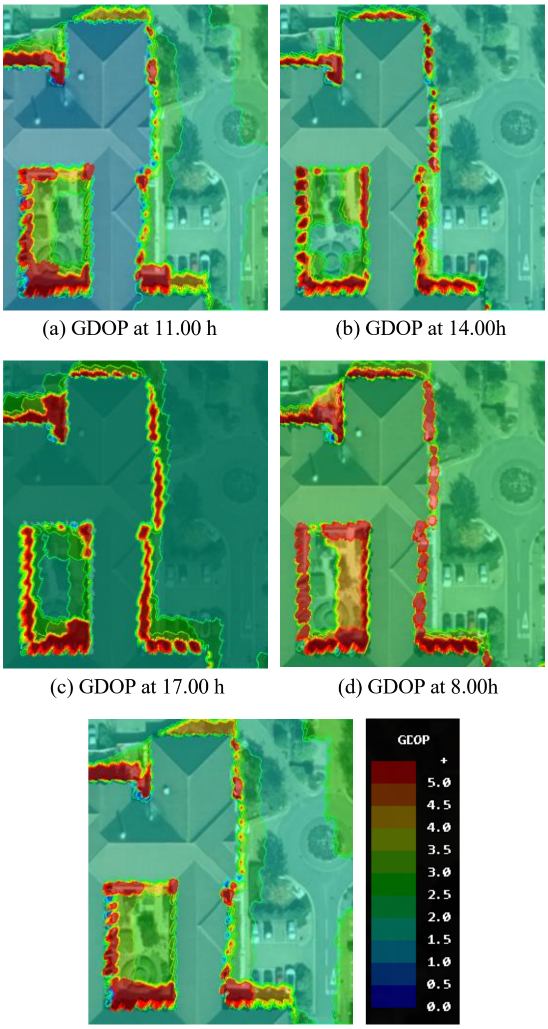


Fig. 16. Number of visible GPS satellites graph at 1 meter over the scenario surfaces, including effects of different-sized buildings and urban canyons at 1 meter **vertically** over

air-to-air links, being remarkable attenuation for environmental factors as absorption from water droplets, among others. On the other hand, data links for flights between buildings will inevitably highly rely on direct line-of-sight visibility given the magnitude from transmitted signals from onboard sUAS. Attenuated signals at immediate obstacles edge from single and double reflection rays might as well be received from the platform, although for practical conditions the operator must design the DAA solution awareness relying on additional sensing layers. Foreign aircraft users' flight data transmitted from a reliable data link from the ground station based on airspace ADS-B data, or strategically placed ground-based DAA sensing covering for the platform sensing limitations, are examples of a robust DAA system devised around the mission.

On top of the intrinsic risks of degraded data link performance for control and further airspace users' awareness, the DAA solution performance is as well affected by the drone positional awareness, identified as navigation system challenges in this study. The obtained results from the GNSS coverage simulation indicate how more built-up scenes entail greater degradation in terms of GNSS coverage.

Simulation analysis shows how operations including take-off and landing maneuvers in enclosed locations, as buildings' inner patios, present a high risk of coverage loss and therefore should be avoided. This phenomenon is reflected in Fig. 16, representing the number of visible satellites at 1 meter from the ground as part of a landing site assessment, for a 20-meter hospital. The enclosed regions might be considered more suitable in terms of personnel access reasons; however, these are subject to line-of-sight obscuration from GNSS satellites,



(a) GDOP at 11.00 h (b) GDOP at 14.00h (c) GDOP at 17.00 h (d) GDOP at 8.00h (e) GDOP at 11.00 h

Fig. 17. GDOP variability over 24h for a sample date during October 2021 for a scenario including open and enclosed regions

severely degrading navigation performance to the point the platform might not be able to position itself, and as a result, would not take off. It can also be appreciated how roofs and elevated surfaces are mostly unaffected and therefore ideal locations for establishing the site. Alternatively, nearby spaces at ground level provide practical operating conditions for over 9 visible GPS satellites and GDOP values under 3, which might be considered as potential site candidates as well.

Navigation performance variability is presented in Fig. 17, a 24-hour time-lapse representation for Geometric DOP (GDOP) for sample building. Potential landing sites include the open spaces the street and parking lots offer, as well as an enclosed patio inside a 3-meter-high building. Regions close to the building present a 1-2-meter boundary in which navigation is heavily degraded during all times of the day. The enclosed region, on the other hand, noticeably accentuates this phenomenon at certain times of the day and, therefore, results in impractical for safe close-to-ground maneuvers. In contrast to the prior, unobstructed surfaces as parking lots and the street present GDOP values which do not exceed values of 2.5 on average, and therefore can be considered as suitable for take-off and landing in practical conditions. It is also remarkable the fact GDOP values worsen from one day to the next, visible in subfigures *b* and *g*, especially over the building roof, illustrating the changing nature of the system performance inherited from the movement of satellites around the globe.

C. Practical considerations

Considering the obtained results from the DAA simulation, together with derived conclusions from the literature survey, a set of practical considerations can be extracted to support safer sUAS operations in urban environments:

1) Casualty/Environmental Damage Estimation: The importance of third-party damage estimation is essential for real-life sUAS integration. This allows an understanding of the prediction of damage or the casualty imposed on the obstacles as well as the sUAS. Ideally, population densities should be considered for civil drone applications, for better integration for experimental validation.

2) Noise or bias on sensors to detect obstacles: The performance of the detection algorithm is dependent on the noise and bias the sensors are subject to. As a result, the avoidance algorithm is as well affected since the avoidance is conducted based on the target information, which is estimated by the detection algorithm of the sUAS.

3) Computational delay: Fast and sudden approaching obstacles detection is conditioned by the computational capabilities from the DAA system, and therefore performance must be assessed for delays reduction and mitigation. As a general norm, the faster the platform design velocity, the faster the detection needs to be performed.

4) Communications challenges: Uninterrupted and quality data link is required to be ensured through the sUAS flight, especially when relying on cooperative and semi-cooperative DAA. Cruise phases over building levels need to ensure the absence of large obstacles between the aircraft and the ground station, which can be achieved by placing the ground antenna in elevated and well clear spaces, achieving higher data link reliability. Close-to-ground operations are more subject to urban signal degradation, especially for take-off and landing maneuvers away from the ground station; therefore, in addition to the prior considerations, signal diffraction and reflection are required to be considered when assessing the transmitter coverage. In practical terms, antenna heights over immediate surrounding obstacles are advised, especially when ground station well clear conditions is not possible, as well as close to the line of sight ground sites selection when direct is not possible, as signal might be able to reach through diffraction and reflection, depending on the obstacles geometry and material.

5) Navigation challenges: In order to assure accurate positioning self awareness for self platform awareness and cooperative DAA system, navigation challenges are ignored. Not only the DAA avoidance functionality relies on accurate positioning, but also broadcasting technologies for cooperative DAA architectures. Enclosed regions, urban canyons, and obstacle vicinities are subject to GNSS signal degradation, and thus either mission planning needs to avoid such conditions, or the navigation system is required to provide redundancy. This can be addressed by implementing multi-constellation GNSS receivers, as well as inertial measurement fusion for higher precision. Loss of satellite sight might lead to the inability of taking off for certain platforms, typically for less than 10 visible satellites in practical conditions, postulating GNSS signal loss is a major concern for urban operations.

6) Environmental conditions: In addition to the challenges the urban geometry poses for signal propagation and threat detection, environmental conditions can as well affect the performance of the sUAS in different ways. Light rain, while within tolerable flight safety conditions, can create noise on light-based sensors, and therefore reduce the DAA system capabilities. Rainfall can also reduce the RF coverage due to signal absorption by water droplets, a phenomenon observed in simulation results by significantly reducing the effective range of communications, observed after heavy rainfall. Atmospheric absorption plays a major role as well in terms of GNSS signal reception, as well as for satellite communication (Satcom) architectures.

V. Conclusion

This paper presents a comprehensive review of the state-of-the-art DAA technologies in conjunction with the simulation of realistic urban scenarios for DAA potential challenges assessment. Different missions are designed and executed for representative scenes accounting for the common threats for obstacles in the sight of sUAS. Quantitative (probabilistic likelihood and severity index) and qualitative (sensor-based) hazard assessment methods were incorporated with DAA of the sUAS. Combination of LiDAR and vision-based sensors proved to be sufficient for take-off, cruise and landing phases of each mission flight. The factor of safety, through volumetric determination allows layers of avoidance strategies to be implemented for autonomous as well as manned flight. As the avoidance function of the sUAS is limited to the bank angle, more intruders within the same safety volume will likely impact the safety of the drone. Therefore, further avoidance maneuvers could be implemented for a better safety factor. Relevant factors such as RF degradation and navigational challenges, including obstructed regions, complete the proposed simulation environment, complemented with DAA hazard assessment leading to effective threat identification.

Acknowledgment

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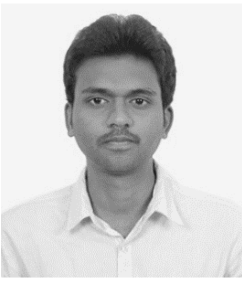

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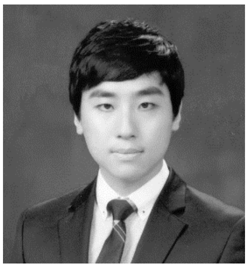

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