Characterizing UAS collision consequences in future UTM

Rattanagraikanakorn, Borrdephong; Sharpanskykh, Alexei; Schuurman, Michiel; Gransden, Derek; Blom, Henk A.P.; De Wagter, Christophe

DOI
10.2514/6.2018-3031

Publication date
2018

Document Version
Accepted author manuscript

Published in
2018 Aviation Technology, Integration, and Operations Conference

Characterizing UAS Collision Consequences in Future UTM

Borrdephong Rattanagraikanakorn,[1] Alexei Sharpanskykh,[2] Michiel Schuurman,[3] Derek Gransden,[4]
Henk A.P. Blom,[5] and Christophe De Wagter[6]
Delft University of Technology, Kluyverweg 1, 2629 HS Delft, The Netherlands

UAS will be integrated into the airspace in the near future, but the risk of UAS collision is not well understood which hampers the development of adequate regulations and standards. As risk has two constituents: frequency and consequence, collision risk analysis of UAS operations in future UTM asks for a quantitative assessment of various types of frequency and consequence. However, prior to studying such quantitative assessment, it is a prerequisite to identify the various types of collisions and consequences. Doing the latter is the objective of this paper. This paper follows a step-wise approach in identifying the various types of collision consequence under a given UTM ConOps, focusing on the very-low-level UAS operations. The first steps address the analysis of the UTM ConOps, rules, and infrastructure considered, and the identification of types of objects and UASs that will operate in the very-low-level UTM system. The follow-up steps are to characterize impact materials by applying zone of impact analysis, followed by analyzing the types of collision consequence. The result is a systematic identification and characterization of types of collision consequences as well as applicable impact materials and conditions that will form the basis for safety risk analysis in follow-on research.

Nomenclature

ASSURE = Alliance of System Safety of UAS through Research Excellence
BVLOS = beyond visual line of sight
ConOps = concept of operations
ELOS = extended line of sight
MAC = mid-air collision
NMAC = near-mid-air collision
UAS = unmanned aircraft system
USA = United States of America
UTM = UAS traffic management
VLL = very low level
VHL = very high level
VLOS = visual line of sight

[1] Ph.D. Candidate, Section Air Transport and Operation, Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS Delft, The Netherlands, AIAA member.
[2] Assistant Professor, Section Air Transport and Operation, Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS Delft, The Netherlands, non-member.
[3] Assistant Professor, Aerospace Structures & Materials Department, Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS Delft, The Netherlands, AIAA member.
[4] Assistant Professor, Aerospace Structures & Materials Department, Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS Delft, The Netherlands, non-member.
[5] Full Professor, Section Air Transport and Operation, Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS Delft, The Netherlands; and Principal Scientist at NLR, The Netherlands.
[6] Researcher, MavLab, Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS Delft, The Netherlands.

I. Introduction

A. Safety of UAS Traffic Management (UTM)

The idea of integrating unmanned aircraft systems (or UAS) into the airspace system and having this technology as part of daily operations is getting closer to a reality as the immense effort has been put into developing the unmanned aircraft system traffic management (UTM), rules, regulations and supporting infrastructure that are crucial to a safe operation. Several safety organizations and research institutes, such as the National Aeronautics and Space Administration (NASA)[1] and EUROCONTROL[2] are currently designing the UTM system to support a large-scale implementation of UAS technology into manned airspace. Federal Aviation Agency (FAA)[3] or European Aviation Safety and Agency (EASA)[4] are also currently devising prototype rules and regulations to ensure safety for both airborne and ground personnel. At the very same time, much effort has been made to understand the safety risk posed by UAS to other airspace users, ground vehicles, ground personnel and infrastructure within the UTM. This is a crucial process in the design of the UTM system which ensures that the high-level of safety standard in aviation can be retained, as well as to ensure the harmonization of the integration process of the system.

Many safety risk assessment methods have been proposed by many research groups in which both a qualitative and quantitative risk analysis approach, and probabilistic model-based approach have been employed. Burdett[5] proposed the implementation of the functional hazard assessment (FHA) method to understand the risk of UAS operations via the derivation of hazards and an analysis of the consequence of such hazards. Belcastro[6] also identified current and future hazards from UAS in the future UTM based on a collection of UAS mishaps data and UAS safety cases – such analysis formed an essential basis for further safety risk analysis. Building on the identified hazards by Belcastro[6], preliminary risk assessment of UAS operations was done by Barr[7] using both a standard qualitative risk analysis approach and a probabilistic model-based approach based on the Bayesian Belief Networks (BBNs) model. Clothier[8] developed a bow-tie model[9,10] for structuring a safety case for UAS operations, including mid-air collision scenarios. Clothier[11] also extended this bow-tie model to ground collisions for UAS operations near populous areas to support the development of regulations and safety cases.

For a quantitative approach to determine frequency or probability of UAS collision, Tyagi and Zhang[12] proposed a system-wide UAS safety analysis model for estimating the probabilities of safety occurrences such as near-miss and mid-air collision (MAC). The model was coupled with Bayesian Belief Network based analysis tool to determine the most likely root causes and the most effective mitigation strategies of such collisions. Ground collision frequency was investigated by Lum[13], who proposed a method for estimating a number of pedestrian collisions per flight hour using satellite imagery and census information. Complementary to these frequency directed studies of UAS collisions, there is an obvious need to study the large spectrum of possible collision consequences.

B. Consequence of UAS Collision

In recent years, significant research has been directed to understanding the effect of UAS collisions with various types of objects, including manned aircraft and human on the ground. Through the collision task force research group, EASA[14] identified important impact consequence research directions that remain to be addressed. To improve an understanding of impact severity, the Alliance of System Safety of UAS through Research Excellence (ASSURE)[15], investigated the consequence of UAS ground and airborne collisions. The research group employed both numerical analysis and experimental techniques to determine impact severity on the human body due to UAS collision at various impact conditions. In addition, a biomedical research team at Virginia Polytechnic institute and State University (Virginia Tech)[16] investigated injury risk to human due to UAS collision by using live flight test and drop impact test on a human dummy. Regarding UAS collision impact on aircraft, an analysis model of UAS ingestion into high-bypass engines was developed by Crash Lab at Virginia Tech[17,18]; the results showed that UAS can pose a serious threat to commercial aircraft jet engines. Also, a particular interest was paid to impact analysis of UAS collision on small aircraft and rotorcraft by the UK Department of Transport[19] in collaboration with industry which pointed out that even a small UAS can inflict a critical damage to rotorcraft tail rotors and non-impact-certified windscreen.

With the introduction of the new operational paradigm, such as the beyond-line-of-sight (BVLOS) operation with increasing use of autonomous systems, UAS operations become more complex. Moreover, UAS operations tend to be operated among other airborne vehicles, ground vehicles, infrastructure, as well as a human on the ground. This widens the scope of the collision consequence analysis of UAS operation. Therefore, the aim of this paper is to address this wider scope of collision consequence modeling and analysis.

C. Modeling and analysis of UAS collision consequences

For a systematic modeling and analysis of consequences of UAS collisions with other objects, primary and secondary collisions are differentiated. A primary collision refers to the first contact between a UAS and another object. A secondary collision refers to a subsequent collision with another object that happens as a result of a primary collision. To limit its scope, the current paper addresses primary collisions only. In order to capture the large spectrum of potential types of primary collisions and consequences, the modeling and analysis are organized along the following sequence of systematic steps:

1. *UTM Dimension Analysis*
2. *Object Identification and Classification*
3. *Zone of Impact Analysis*
4. *Materials Identification and Classification*
5. *Collision Consequence Analysis*

The first step aims to conduct an analysis of the UTM ConOps, rules and regulations. The second step aims to identify and classify the various objects that are exposed to UAS collision risk. The third step analyzes the possible zones of impact for each of the object classes. The fourth step identifies the relevant materials for each type of impact zone. The last step characterizes the types of collision consequence for each impact zone. The elaboration of this systematic modeling and analysis of UAS collision consequences is expected to provide a useful framework for the collection and organization of consequence modeling, simulation, and experimentation of primary collision of UAS with another object.

D. Organization of the Research

This paper is organized as follows. Section II provides an analysis of the UTM dimensions. Section III presents the identification of UAS and the objects that are exposed to UAS collision risk. Section IV presents an analysis of the Zone of Impact of a UAS collision with focus on the various types of general aviation aircraft and rotorcraft. Section V presents an identification and classification of the materials for different zones of impact of selected objects. Section VI presents the results of the collision consequence analysis for different zones of impact of the selected objects. Section VII presents conclusions.

II. UTM Dimension Analysis

This section analyzes the UTM concept of operations, rules, and regulations, which form the legal basis of what type of UAS will be allowed to operate in different airspace classes. Currently, both in the USA and in Europe, the future UTM concept of operations (ConOps) is in development, along with new rules and regulations. This section presents an outline and a dimension analysis of UTM currently in development in Europe and in the USA.

A. UTM in Europe

In Europe, UTM is being developed by several collaborating organizations. To fully understand the whole UTM architecture, each component needs to be analyzed separately, namely; UTM ConOps, rules and regulations, and supporting infrastructure. First, the prototype rules and regulations proposed by EASA[20] are analyzed. Rules and regulations significantly dictate the operational requirements of UTM. They also specify performance requirements and operational limitations of UAS in the airspace. Next, the UTM ConOps that is under development proposed by EUROCONTROL[2] is investigated. Furthermore, the support infrastructure that is proposed by SESAR[21] called "U-Space" is examined. This digitalized infrastructure is aimed to enable complex drone operations with a high degree of automation to take place in all types of operational environments, including urban areas. Finally, the important dimension of European UTM is summarized in the table at the end of this section.

1. EASA UAS Prototype Rules and Regulations

To ensure safe operations of UAS, EASA[20] has published the prototype rules and regulations for UAS operations in the Open and Specific categories. Another category is the Certified category which has not been fully proposed yet during the write up of this paper. As the risk of operating UAS varies according to the type of operations and the characteristics of UAS, different rules are applied to different categories based on risk-level that EASA has foreseen. EASA proposed that, for the lower risk operations, regulations should have less-stringent requirements. Open category is a lower risk category, while the Specific and Certified categories are for higher risk operations which require much stricter rules and certification. Detailed elaborations of each category are presented below.

Open Category:

For the Open category, there are 4 sub-categories which are A0, AI, AII, and AIII category. Open A0 applies to micro UAS with a maximum weight of less than 0.25 kg. Open AI and AII apply to both micro and small UAS with a maximum weight of 25 kg and a maximum altitude of 150 ft. Open AIII has the same weight threshold as AI and AII but with a higher operational altitude of up to 500 ft.

Specific Category:

Furthermore, the Specific category is designed for more advanced commercial UAS operations, such as infrastructure monitoring, aerial photography in urban areas, or operation in the vicinity of airports. However, to operate in the Specific category, the operation must comply with the 'standard scenario' requirements specified by EASA.

Certified Category:

For the Certified category, there is no information available during the write-up of this paper, however, this category is expected to be applied to specialized high-risk operations. Different sub-categories have different UAS requirements and the important requirements are summarized in Table 1.

Table 1. Overview of important UAS performance and operational requirements from EASA prototype rules and regulations. The UAS Open category applies to recreational, buy-and-fly UAS type which only allows operation below 500 ft. The Specific category is for commercial UAS operation in VLL airspace. The Certified category is for UAS operations that may pose higher risk to other objects.

UAS Category		Weight (kg)	UAS Type	Max Alt (ft)	Horizontal Separation (m)	Operation Type
Open	A-0	0.25	Micro UAS	150	Not specified, but less than 100 m away from operator	VLOS
	A-I	25	Micro UAS Small UAS	150	Not specified, but within VLOS range from operator	VLOS
	A-II	25	Micro UAS Small UAS	150	50 m away from uninvolved person	VLOS
	A-III	25	Micro UAS Small UAS	500	20 m away from uninvolved person for rotorcraft, or 50 m otherwise	VLOS, EVLOS
Specific		-	-	-	-	VLOS, EVLOS, BVLOS
Certified		-	-	-	-	-

2. *EUROCONTROL UTM System ConOps*

Recently EUROCONTROL[2] proposed the first draft of UTM ConOps that aims to enable UAS operations in manned airspace. The concept is to integrate UAS into manned operations, without disrupting or modifying the already existing manned air traffic system. Figure 1 illustrates how different UAS classes specified by EUROCONTROL will be integrated into different manned airspace classes. The main idea is to differentiate UAS operations based on traffic classes without segregating UAS categories. According to EUROCONTROL[2], a traffic class is a set of flying rules, operational procedures and system capabilities applicable to the UAS and to the operator when operating the UAS in a portion of the airspace. Each traffic class already, in its own description, specifies what type of operations are allowed. Traffic class I to IV fall within VLL airspace below 500 ft while traffic class V to VI belong to IFR/VFR airspace. Lastly, traffic class VII belongs to the very high-altitude airspace. Each UAS traffic class is elaborated below.

UAS Class I - IV

For VLL airspace, UAS class I is designed for recreational use without any structured route for UAS to follow, and the maximum height is only 150 ft above ground level. This class is allowed to operate in airspace class G and falls into EASA Open category. UAS class II is designed for commercial operations that do not need or cannot follow a structured route, such as survey or search and rescue. UAS class III is designed to accommodate complex commercial operations such as parcel delivery by using a structured route approach where a route structure can follow a river or railway. Both UAS class II and III are allowed to operate in airspace class G but need to follow

EASA Specific and Certified category rules. This already widens the scope of objects that will be involved with UAS operations, such as, trains or maritime vehicles. Moreover, UAS class IV is designed for special operations in urban areas, airports, and other restricted airspace. This UAS class is allowed to operate in airspace class B, C, D and E, and must comply with EASA Specific and Certified category rules.

UAS Class V - VI

For IFR/VFR operations that are higher than 500 ft, the UAS operation falls under UAS class V and VI. UAS in these classes are required to comply with the airspace requirements as set for IFR/VFR manned aviation. Operations from this class can include airport operations, terminal maneuvering area (TMA) or enroute. Therefore, rules and regulations for these classes will not follow EASA rules for UAS but will follow airspace rules for manned aviation.

UAS Class VII

Lastly, UAS class VII is designed to accommodate very high altitude UAS at flight level above 60,000 ft. Even though the operation will take place above IFR/VFR flight corridor, UAS in this class is expected to comply with IFR/VFR flight rules since the transition has to pass through this corridor. Therefore, IFR/VFR requirements need to be met by this UAS class. Operations that are envisioned to operate in this class are, for example, long-endurance UAS operation for relaying communication across the globe, or suborbital UAS operations.

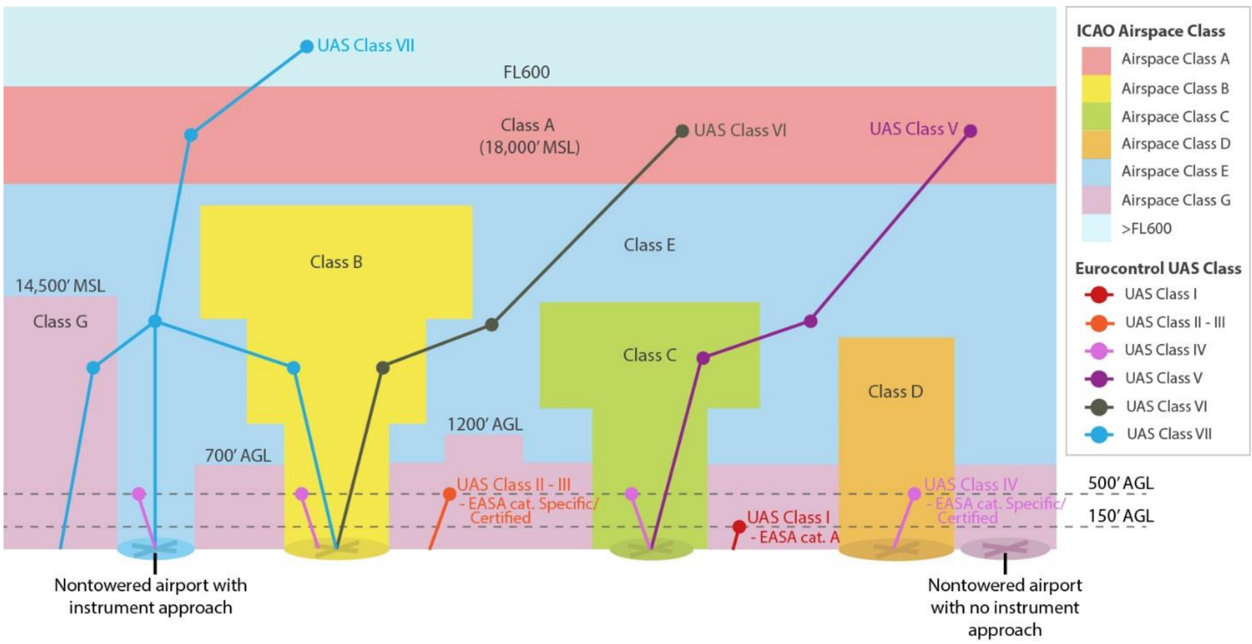

Figure 1. The lines and dots show how various Eurocontrol[2] UAS classes operate through various ICAO[22] airspace classes in Europe. The idea of this presentation is based on a figure in the Instrument Flying Handbook[23]. For VLL operation, UAS class I, II and III will only be allowed to operate in airspace class G and UAS class IV will be allowed to operate in airspace class B, C, D and E.

The analysis shows that the complexity and interdependencies of the ConOps, rule, and regulations lead to an intricate multi-dimension problem. Therefore, it is necessary to identify relevant dimensions that can be analyzed in a logical manner.

3. *SESAR U-Space Concept*

In order to accommodate high UAS operational demands and UTM system complexity, SESAR Joint Undertaking proposed the concept of U-Space in 2016.[21] U-Space provides complete services and procedures designed to support safe, efficient and secure access to airspace for high-density UAS traffic. This aims to enable complex drone operations that will take place in all types of operational environment (including urban area) with a high degree of automation. U1 is the first phase of implementing U-Space system. E-registration, E-identification, and static geofencing will be available to help control UAS from entering the segregated airspace. In the next phase, U2, flight planning management system will be introduced. Dynamic airspace information, such as dynamic geofencing will be employed to protect a certain type of manned aircraft operations that could take place without prior notice, for example, search and rescue operations. U3 phase introduces capacity management and assistance for conflict detection. This phase relies on the availability of automated ‘detect and avoid’ system that allows UAS to operate in dense traffic area or urban area. The last phase is the U4 phase which aims to assist the full integration of UAS operations to manned airspace by providing infrastructure for information sharing and connectivity between UASs and manned aviation. In short, the U-Space system will provide the necessary support infrastructure that will allow UASs to operate fully with manned aviation, even in dense traffic areas or urban areas.

B. UTM in the USA

UTM in the USA is also under development and has many similarities to UTM development in Europe. This subsection examines the UTM ConOps, rules and regulations for UAS operation in the US. To enable safe integration of UAS into airspace, NASA, working in collaboration with the FAA, is developing UTM while into account the legacy of air traffic management (ATM) for manned aviation. FAA oversees the prototyping of appropriate rules and regulations for UAS operations to ensure that such operations will not interfere or pose any harm to the current air traffic activity or human on the ground. In this subsection, first, the rules and regulations posed by the FAA are investigated and summarized. Then, the UTM ConOps proposed by NASA is examined.

1. FAA UAS Rules and Regulations

Rules and regulations for UAS operating in the US airspace are specified by the FAA, under the Title 14 of Code of Federal Regulations Part 107.[24,25] Unlike EASA rules and regulations, the FAA version does not categorize UAS into different categories. The regulations mainly enforce that UAS must weigh less than 25 kg and must be operated within visual line of sight (VLOS) not higher than 400 ft above ground level. Operation above people who are not involved with the operation is also prohibited. Airspace class G is the only airspace that UAS can operate in without the need to have any certification by the FAA or clearance by ATC. Operations in controlled airspace class B, C, D, and E are not allowed and the ATC permission is also required before an operation can be commenced. Nevertheless, the FAA offers UAS operators the option to apply for a waiver certification, which allows certain restrictions to be removed. Night time operation, beyond-visual-line of sight operation, the operation of multiple UAS, operation over people, operation in controlled airspace or operation of UAS exceeding specified operating limits; these are possible through the waiver certification system.

Rules and regulations specified by the FAA are very similar to the EASA rules and regulations in combination with EUROCONTROL ConOps. The differences are non-significant, such as the maximum height of 400 ft for the US and 500 ft for Europe. Both in Europe and in the USA, UAS operations are allowed automatically in airspace class G, while accessing controlled airspace class B, C, D or E are only possible after a special request to the authority.

2. NASA UTM ConOps

Due to the heterogeneous mix of UAS types in combination with a wide range of existing manned aircraft, there is a need to develop a system that can enable safe and efficient low-altitude airspace operations. NASA[26] UTM ConOps is designed with an aim to provide a comprehensive digitalized service, such as, airspace design and dynamic configuration, dynamic geo-fencing, congestion management, route planning and re-routing, separation management, sequencing and spacing, and contingency management. To achieve such aims, a cloud-based platform is developed to provide a wide range of services that seamlessly connect a UAS operator to other UAS operators, UAS service suppliers, and air navigation service providers. The services are, for example, registration of UAS, flight plan submission, dynamics geofencing setup or controlled-airspace access management. This NASA UTM ConOps is similar to the U-Space concept in Europe, which focuses on providing a digitalized supporting infrastructure to accommodate UAS operations.

C. Dimensions of UTM

From the analysis of UTM ConOps, rules, regulations and supporting infrastructure, important dimensions of UTM are identified and summarized in Table 2. Each row in this table presents for one specific dimension the spectrum of possible values. The full spectrum of all potential UTM possibilities is defined by combining values for each of the dimensions. For instance, a UAS of dimension Eurocontrol UAS Class I, can fly in ICAO airspace class G. To continue the dimension values for this example, the main UAS category that will operate within VLL airspace is the Open category (A0-AIII) and all UAS in this category will not weigh more than 25 kg, falling into micro and small UAS types. Furthermore, several types of micro and small UAS exist, namely; fixed-wing, multi-copter, tiltrotor, hybrid or blimp UAS. This UAS example typically flies in unstructured airspace, without authorization level, under VLOS, RLOS and may encounter static geofencing.

Table 2. Overview of UTM dimensions

Dimension	Variables within Dimension						
EuroControl UAS Class	Very Low Level (GND - 500 ft.)				IFR/VFR 500 ft. - FL600		VHL (Above FL600)
	Class I	Class II	Class III	Class IV	Class V	Class VI	Class VII
ICAO Airspace Class	A	B	C	D	E	F	G
EASA Category of UAS	Open				Specific	Certified	
	A 0	A I	A II	A III			
Type of Operation	Recreation	Land Survey	Agriculture	Infrastructure Monitoring	Commercial Transport		
	Law Enforcement	Forest Monitoring	Border Patrol	Surveillance	Search and Rescue		
UAS Type	Fixed-wing	Mono-copter	Multi-copter	Tiltrotor	Hybrid	Blimp	
Weight Class	<= 0.25 kg	0.25 - 25kg	>= 25kg				
Flight Rules	VFR	IFR					
Airspace Structured	Unstructured	Structured					
Operation Authorisation Level	None	Declaration	Authorisation	Special Authorisation			
Range Scheme	VLOS	EVLOS	BVLOS				
UAS C2 Link	RLOS	BRLOS					
Geofencing	Static	Dynamics					

The above UAS example in using the UTM dimensions from Table 2 applies to most buy-and-fly UAS operations. Because commercial aircraft do not operate within class G airspace, this means that for this UAS example, an encounter with a commercial aircraft will be less likely comparing to an encounter with general aviation aircraft. The difference in vehicle types affects the collision speed and impact materials. Moreover, UAS airspace structure also defines what objects will be affected by UAS operations. Also, a certain type of UAS operations may follow ground structures, such as a river or train track; this means that train or boat needs to be incorporated in collision consequence analysis as well.

To summarize this section, the European UTM ConOps along with rules, regulations and supporting infrastructure are investigated and decomposed into main dimensions as shown in Table 2. UTM in the USA is shown to be in line with the European UTM and is therefore not specifically addressed further in this work. The analysis of the UTM ConOps and EASA prototype regulations clearly show what types of UAS will be allowed to operate in different airspace classes. This enables the next analysis step which is the identification of types of UAS and other objects.

III. Identification & Classification of Objects Exposed to Collision Risk

This section describes an identification process of the objects within the VLL part of UTM that are exposed to UAS collision risk. The goal of object identification is to identify, as many as necessary, the various objects within the UAS operational airspace. Objects are divided into two main types: (i) ground objects and (ii) airborne objects. In addition, different types of UAS that will be allowed to operate within VLL airspace are identified as well. To set the analysis scope, an operational area in the Netherlands is selected as a representative site for European UTM. The following sections describe the identification of ground objects, airborne objects, and UAS types.

A. Identification of Ground Objects

Since UAS operational airspace can cover large different areas across the country, scoping of the investigated area is necessary. Three representative areas based on NASA[7] definition of operational areas are selected for investigation. These areas are the suburban area, the urban area, and the congested area. Each area is characterized by the population density, ranging from low to high population density. For the suburban area, the area North of Nijmegen (with a population density of 600 per sq. km)[27] in the east of the Netherlands is selected as it is a potential site for several applications, such as parcel delivery, precision agriculture, infrastructure monitoring and etc. The city of Rotterdam (with a population density of 3060 per sq. km)[27] is selected for the urban operational area as it contains several landscape features suitable for operation such as urban parcel delivery, aerial photography, traffic monitoring, or law-enforcement. Lastly, for the congested operational area, the city center of Amsterdam (with a population density of 6200 per sq. km)[27] is chosen. This is a possible operating site for operations such as event photography and security, law enforcement or emergency response. Ground object identification is performed by employing map analysis based on different map types, such as satellite map, airspace class map, land-use map, and land/building elevation map. A satellite map is used to point out different objects on the ground within the operational area – this is done by visual observation. To narrow down the analysis domain, an airspace class map is superimposed to cut out any irrelevant area that UAS cannot operate in. In addition, land use map is employed to help to categorize different areas. Object identification is then done for each land use area. Lastly, a land/building elevation map is used to determine the amount of small buildings and tall buildings within the area. Figure 2 shows the layers of the different map types that are used in the analysis for the three different operational areas, namely; the suburban, urban and congested areas.

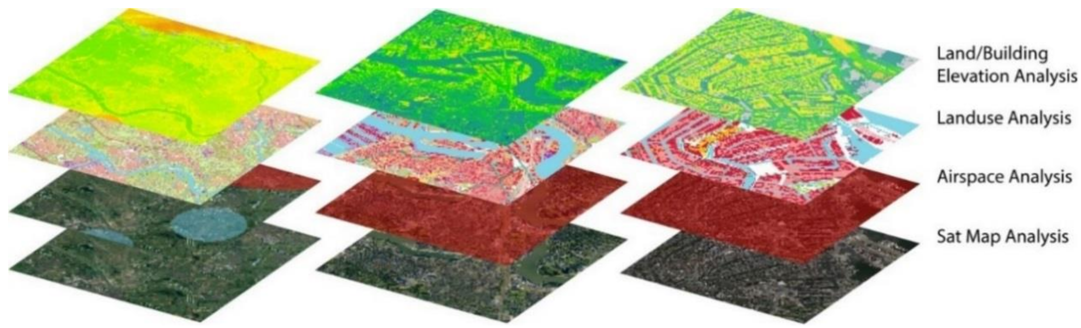

Figure 2. Map analysis of different operational area ranging from low population density to high population density; (i) rural area (the area around Nijmegen), (ii) urban area (city of Rotterdam) and (iii) congested area (city center of Amsterdam). Different map types such as satellite maps, airspace class maps, land-use maps, and land/building elevation maps are used.

From the map analysis, 10 categories of land use types (including the percentage of area) are identified and shown in Figure 3. The suburban area consists largely of an agricultural area of approximately 42% of the overall land area and approximately 17% of forest, park meadow and open, pedestrian areas. The composition of the low-rise buildings is 9.5% while the amount of high-rise buildings in the suburban area is considerably lower with only 0.5% of the total land area. In an urban area, around 31% of the area consists of low-rise building and almost 21% of the area is river and canal. Forest, park, meadow and open, pedestrian areas are 18% and 15% of the total area respectively. It can be observed that, for the congested area, a large amount of area is covered with high-rise buildings (23%) and low-rise buildings (22%). Open/pedestrian areas are quite significant as well in congested airspace as these open areas are often used for public events where a large crowd is expected.

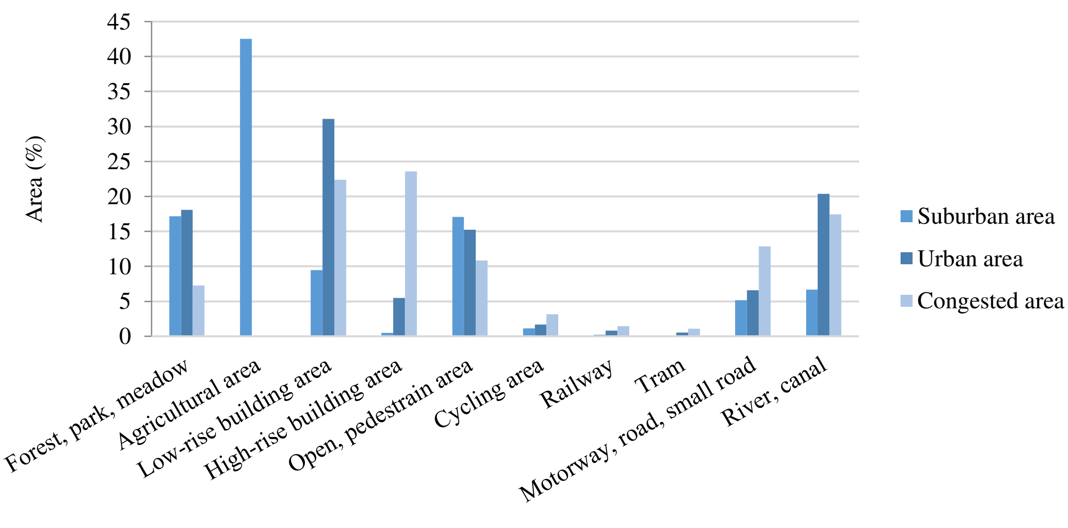

Figure 3. Land-use type percentage of three operational areas (suburban, urban and congested operational areas)

For each land-use type, ground objects are identified using the land-use database and satellite map analysis. The land-use database comes with data fields which describe the type of object, while satellite map offers visual evidence of the actual objects in the area. Several objects that are deemed irrelevant or insignificant to the safety of human are excluded, for example, light poles, signs, small roadside structures, grass, trees or animals on the ground. The aim is to identify as many relevant objects as possible without classifying them yet, then the classification of these objects is done in a later stage. The results of the identification are shown in Table 3.

Table 3. Variation of ground objects over land-use types

Land-use Type	Objects within the land-use type
1. Forest, Park, Meadow	Human (pedestrian, hiker, camper)
2. Agricultural area	Glasshouse, Small house, Car, Truck, Tractor, Human (pedestrian, farmer, worker)
3. Low-rise building area	House, Retail store, Apartment, Condominium, Other low-level building
4. High-rise building area	High-level condominium, Other high-level building
5. Open, Pedestrian area	Human (pedestrian), Cyclist, Car (slow-speed, parking), Scooter
6. Cycling area	Cyclist, Motorcyclist (Motorbike, scooter)
7. Railway	Train, Worker
8. Tram	Tram, Worker
9. Motorway, road, small road	Car (Sedan, van, truck), Coach, Lorry, Human inside vehicle, Motorcyclist
10. River, canal	Small boat, Medium boat, Sail, Yacht, Ship

The estimated land use type area percentages in Figure 3 together with the types of objects per land use type in Table 3 provide valuable qualitative insight. These estimations illustrate what types of object are highly expected in the operational area. However, to transform this information into quantitative estimates of frequencies of collision requires significant complementary analysis, which falls outside the scope of this paper.

B. Airborne Objects Identification

Within VLL, several types of UAS and non-UAS airborne objects are expected to share the airspace with UAS. Based on pilot and aviation expert opinion, and rules of air specified by EASA[28], 6 main types of airborne objects are identified. Firstly, commercial aviation such as commercial airliner or business jet is expected to share airspace with few UAS operations, such as UAS class IV that can operate in airport areas. Nevertheless, it is expected that an encounter with commercial aviation will be minimal since UAS class IV is reserved for specialized operations. Furthermore, general aviation aircraft are certainly expected to share airspace with UAS since this type of aircraft often operates at low altitude in a regulated but uncontrolled airspace. Flight training, leisure flight, commercial flight, or agricultural operation are normal operations that are performed by general aviation aircraft. Rotary wing aircraft are also largely used by the military, law enforcement, emergency services, news, and media, which often operate at very low level. It was already witnessed before when a small drone (DJI Phantom 4) collided with the US army UH-60M helicopter while operating under visual flight rules within Class G airspace about 300 ft above sea level.[29] Next, the lighter-than-air vehicle type, such as blimps, balloons or lanterns, is identified as one of the types that is susceptible to UAS collision risk. Collisions with a manned airborne vehicle can lead to direct injury or fatality to any human on-board. Furthermore, collisions between UAS are also considered. Lastly, birds are also considered as a relevant collision thread. UAS to UAS or UAS to bird collisions could potentially lead to damage on the ground due to fallen debris.

Table 4. List of identified non-UAS airborne objects

Type of Object	Object Instantiations
1. Commercial Aviation	Commercial airliner, business jet
2. General Aviation (GA)	GA (light a/c, light sports a/c, trainer a/c, cargo a/c, ultralight a/c, glider a/c)
3. Rotary Wing	Small size helicopter, Medium size helicopter, Military helicopter
4. Lighter-Then-Air	Blimp, Balloon, Lantern
5. Remotely-Piloted Aircraft System (UAS)	Micro UAS (Fixed wing, Rotary wing, Multi-copter), Small UAS (Fixed-wing, Rotary wing, Multi-copter, Blimp)
6. Other	Bird

C. Non-UAS Object Classification

In Figure 4, the relevant objects within VLL airspace are classified into appropriate categories. The first distinction is between static objects and dynamics objects. Static objects consist of permanent infrastructure and non-permanent infrastructure while the dynamics objects consist of liveware and hardware. Liveware refers to human and animal, either in the air or on the ground, while hardware refers to aircraft, automobiles, trains or marine vessels. Similar objects, such as houses, retail stores or apartments, are grouped together into the low-rise structure type for example. This classification builds an overall picture of what types of objects are expected to share an airspace with UAS. For the follow-on work in the later section, only general aviation and rotary wing will be further elaborated. This focus is selected in order to allow detail elaboration on these objects.

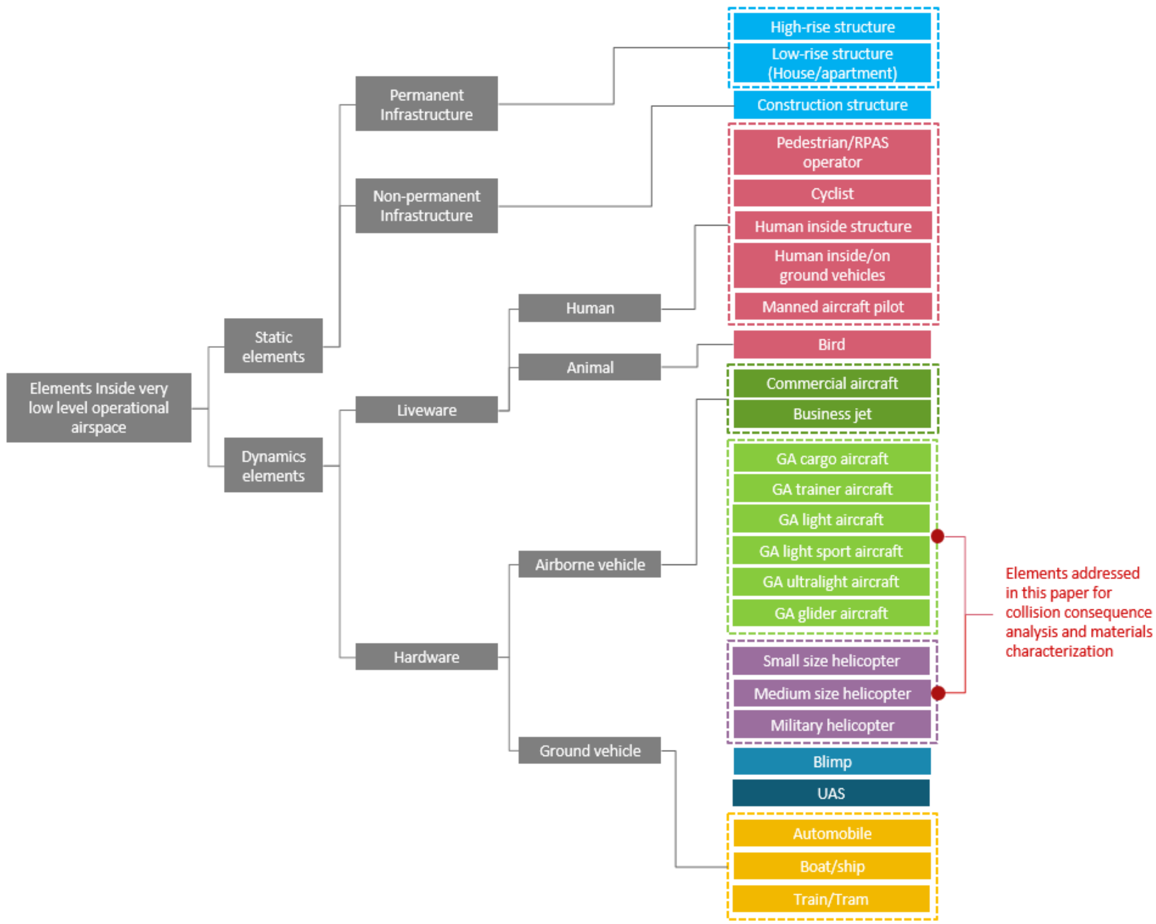

Figure 4. Object classification flowchart, combining both ground and airborne objects. For airborne objects (GA aircraft and rotorcraft) this paper elaborates the remaining steps in consequence analysis.

D. UAS object classification

A Large variety of UAS even further complicates several aspects in terms of regulatory arrangement as well as safety risk assessment. The identification process of UAS is important as different UAS weight classes consist of different design attributes, fabrication materials, and flight performance, which significantly affect collision consequence severity. Within VLL airspace, only traffic class I to IV are allowed. Traffic class I only allows UAS Open category A0 to AIII (0.25 kg for A0 and 25 kg for AI-AIII of maximum take-off gross weight). A0 category falls into a micro UAS category that is specified by the United States Department of Defense[30]. Open category A1-A3, which refer to UAS of maximum take-off gross weight of between 0.25 kg to 25 kg, falls into the small UAS category. For UAS class II, III, and IV, similar take-off weight threshold of 25 kg is expected. In summary, it is expected that only micro UAS and small UAS can operate in VLL airspace. The identification and classification flowchart of UAS in VLL operation is illustrated in Figure 5. It is worth mentioning that for the outside of VLL airspace, UASs are required to comply with IFR/VFR requirements same as manned aircraft. Most of the tactical

UASs and some of the military-grade UAS are equipped with necessary technology to operate in IFR/VFR airspace. Medium Altitude-Long Endurance (MALE) UAS also operate in IFR/VFR airspace. However, due to performance limitations of the MALE category, MALE UAS are not likely able to reach the very high-level operational airspace. This final traffic class VII only accommodates high altitude-long endurance (HALE) UAS. UAS class V to VII are not addressed in the follow-on analysis of this paper. Only small fixed-wing UAS and small multi-copter UAS are further elaborated in this paper since these are the most used types of UAS.

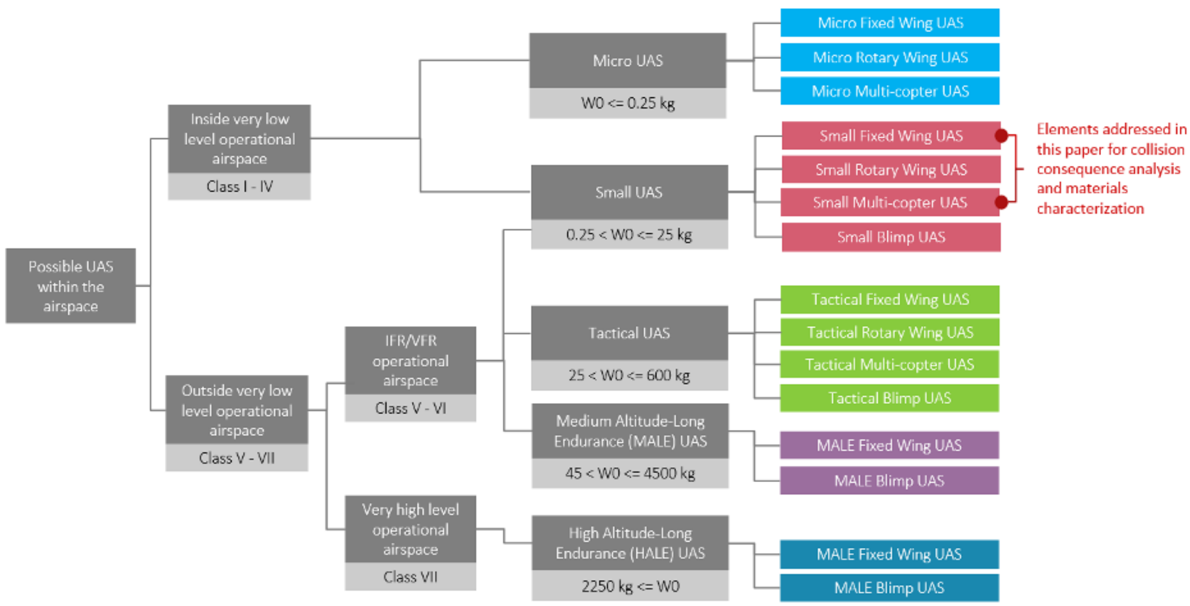

Figure 5. UAS identification and classification flowchart. Only small fixed-wing UAS and small multi-copter UAS are further elaborated in later sections since these two types are the most used types of UAS.

IV. Zone of Impact Analysis

Having identified and classified the objects within VLL airspace, the zone of impact analysis aims to characterize impact materials. The main purpose of this analysis is to identify zones that are susceptible to primary impact so that representative materials and collision consequence of those zones can be identified and categorized. The zones of impact are presented in term of area percentage, allowing for future quantitative analysis. First, the frontal diagrams of different objects are collected, and the silhouette areas are projected onto the diagram. Then, the percentage of each area is estimated. This section describes the decomposition and analysis of zone of impact of two types of objects: Non-UAS airborne objects of types general aviation and rotorcraft and subsequently UAS objects.

A. Zone of Impact Analysis for General Aviation and Rotorcraft

Different types of general aviation (GA) aircraft are analyzed for the zone of impact. GA cargo aircraft, GA trainer aircraft, GA light aircraft and GA light sports aircraft share similarities in terms of configuration, size, and engine placement. Therefore, these types of GA are considered together. These GA aircraft are divided into single-engine and twin-engines. GA ultralight and GA glider are included in this analysis as well. The representative models of these aircraft are selected based on their popularity and number of shipments in the past years.[31] The list of representative aircraft under consideration is shown in Table 5. Frontal impact analysis is performed, and the results are presented in this section.

Examples of the object diagrams and overlay silhouette areas are shown in Figure 6. The analysis is done for every representative aircraft example and then averaged over these examples. The average values of the composition of different zones of impact are shown in Figure 7. The results show that, for single-engine GA, the largest part is the propeller which is about 52% of the entire aircraft frontal area and second largest part is the wing which is 36%. It should be noted that the windshield of single-engine aircraft seems to be obstructed by the front propeller, however, some UAS or UAS debris can potentially slip pass the propeller. This makes windshield become one of the primary impact points. Propeller area is even larger for twin engines general aviation aircraft with takes up almost 57% of the entire area. The main wing also takes a large portion of the area with about 18% of the entire area. Ultralight, on the other hands, has 41% of wing area and 25% of the propeller. This is due to the typical rear-engine placement of the ultralight. The majority of ultralight analyzed in this paper shows the absence of a windshield, exposes human pilot which takes up to 12% of the whole area. Due to the high aspect ratio of ultralight, the wing portion is considerably large compared to other types of airborne objects and take up 76% of the area. Windshield and fuselage skin covers 7% each. For medium to large rotorcrafts, main rotor blade and fuselage skin cover 58% and 21% of the entire area. Due to large field-of-view required in rotorcraft design, almost 14% is covered with a windshield which is significantly larger compared to other types of aircraft.

Table 5. Representative GA and rotorcraft examples selected for the zone of impact analysis.

Aircraft Type		**Representative examples**
GA Cargo Aircraft, GA Trainer Aircraft, GA Light Aircraft, GA Light Sport Aircraft	Single Engine	Cirrus SR22, Cessna Skyhawk 172S, Pilatus PC-12, DA20-C1, Daher TBM930, Air Tractor AT-802A
	Twin Engines	Beechcraft King Air, Beechcraft Baron, Diamond DA42, Piper PA44
GA Glider		Pipistrel Taurus M, ASH 30 Mi, DG-1001 Club Neo,
GA Ultralight		Quick Silver, Pegasus Quantum 145-912, Huntair Pathfinder Mark 1
Rotorcraft		Robinson R44 Raven, Sikorsky UH-60 Black Hawk, Airbus H145,Airbus H125,Bell 407GXP

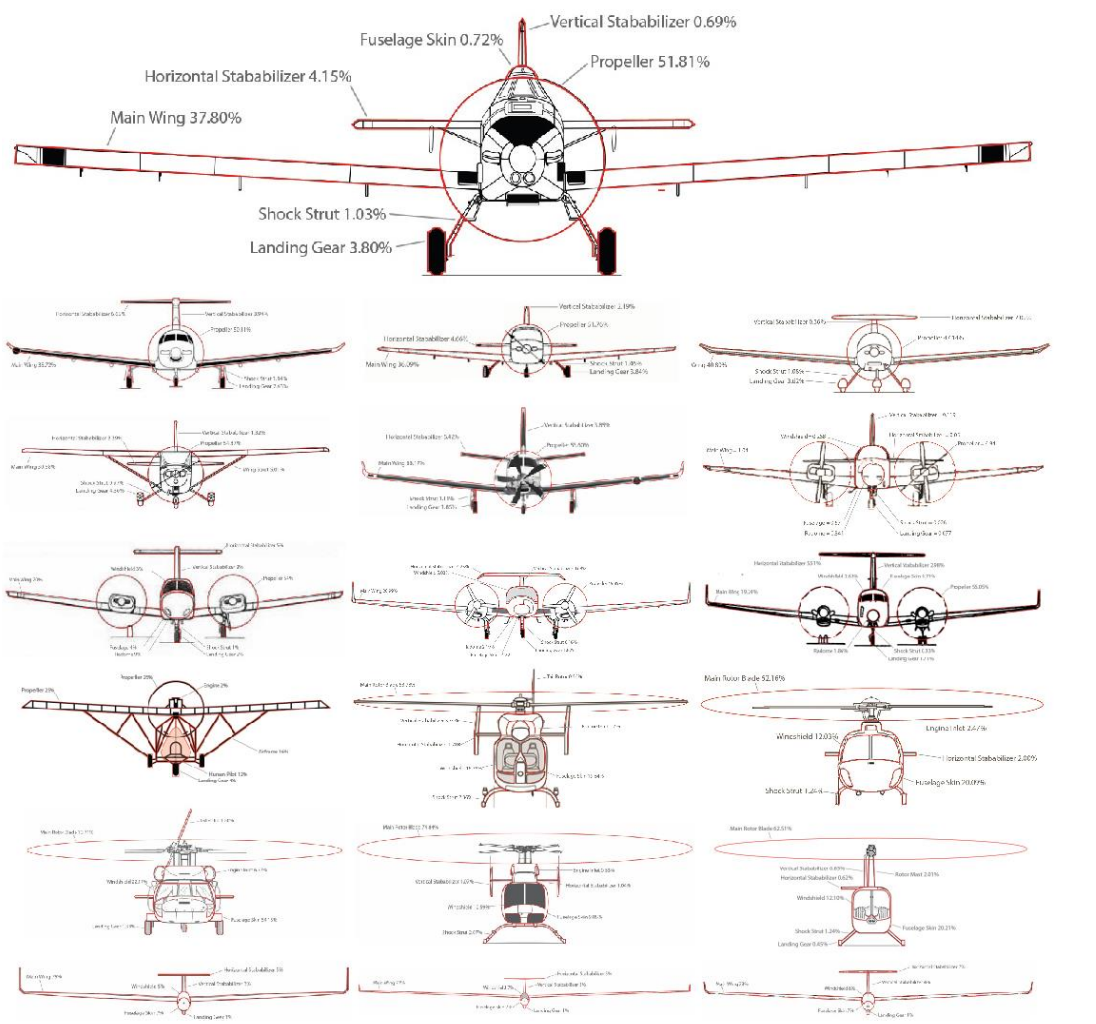

Figure 6. Zone of impact analysis diagrams of aircraft types in Table 5.

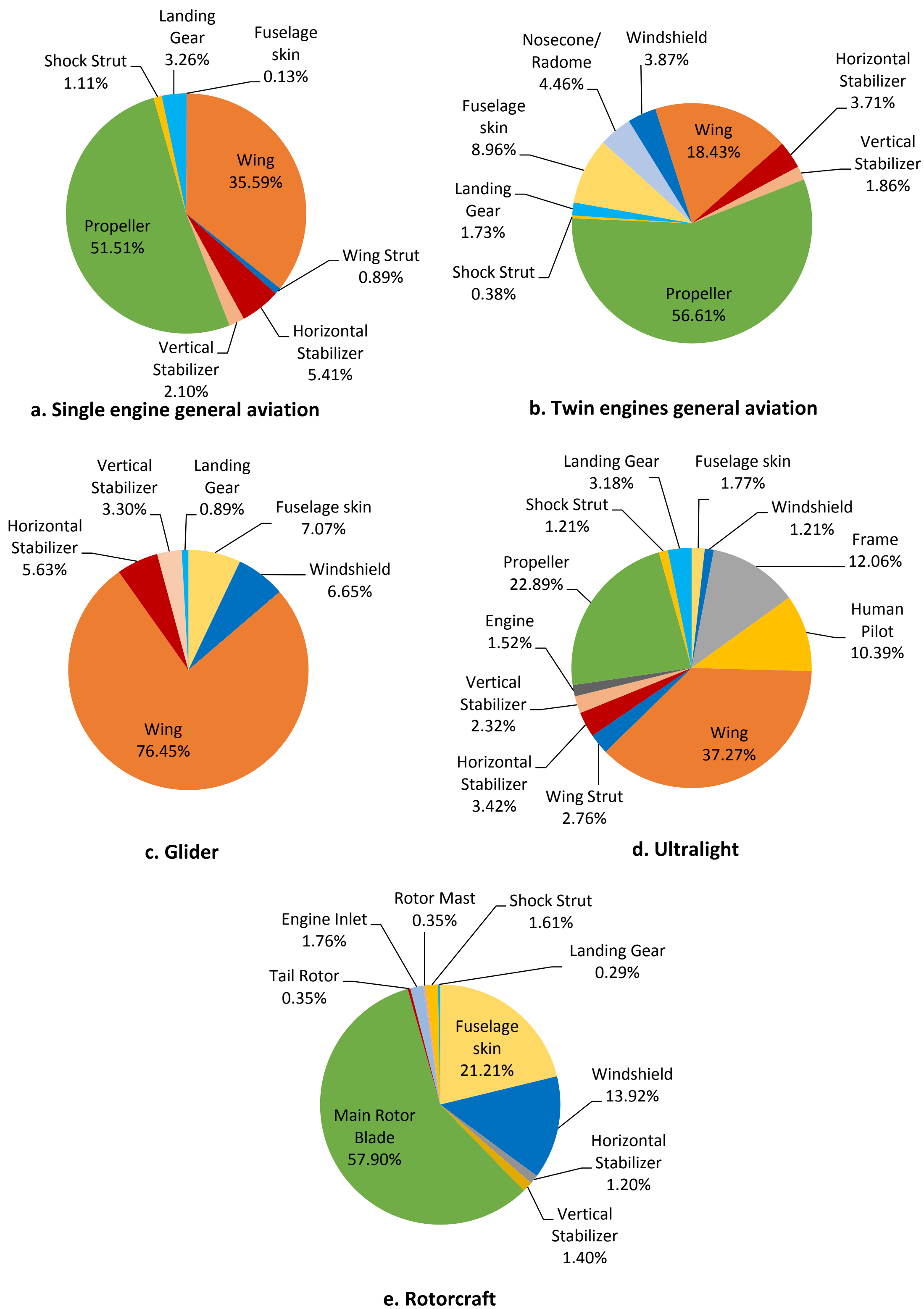

Figure 7. Pie-charts showing the composition of the different zone of impact of (a.) single engine general aviation, (b.) twin engines general aviation, (c.) glider, (d.) ultralight and (e.) rotorcraft

B. Zone of Impact Analysis for UAS

For small fixed-wing and multi-rotors UAS representative examples with various masses are selected for the zone of impact analysis; this is shown in Table 6. Similar to GA, frontal impact areas are analyzed and estimated in order to determine area composition of each model. Figure 8 shows the example of the zone of impact analysis of the representative UAS models where the red lines illustrate the different collision zones on the vehicle.

Table 6. Representative UAS examples selected for the zone of impact analysis

UAS Type	Weight Class	Representative Examples
Fixed-Wing	Small UAS	Parrot Disco (0.75 kg), Precision Hawk Lancaster (3.55 kg), AeroVironment Puma (6.3 kg), Insitu Scan Eagle (18 kg), UAV Factory Penguin B (21.5 kg)
Multi-rotors	Small UAS	Parrot Bebop 2 (0.5 kg), DJI Phantom 3 (1.39 kg), DJI Matrice 200 (3.8 kg), Yuneec Tornado H920 (4.99 kg), DJI Matrice 500 Pro (15.5 kg)

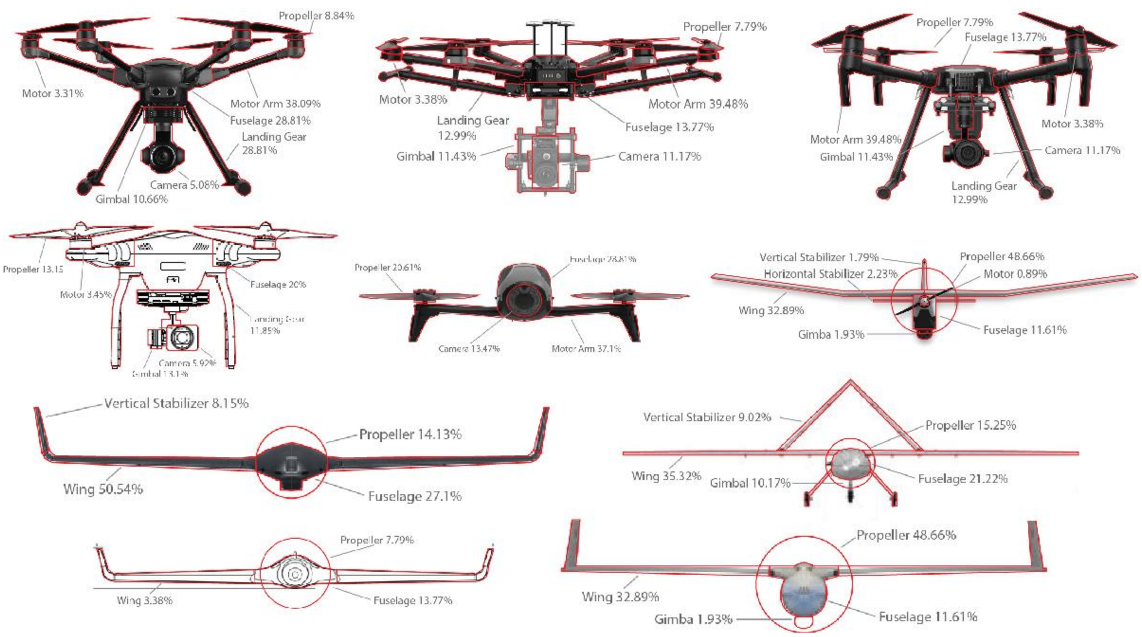

Figure 8. Zone of impact analysis diagrams for the types of UAS in Table 6.

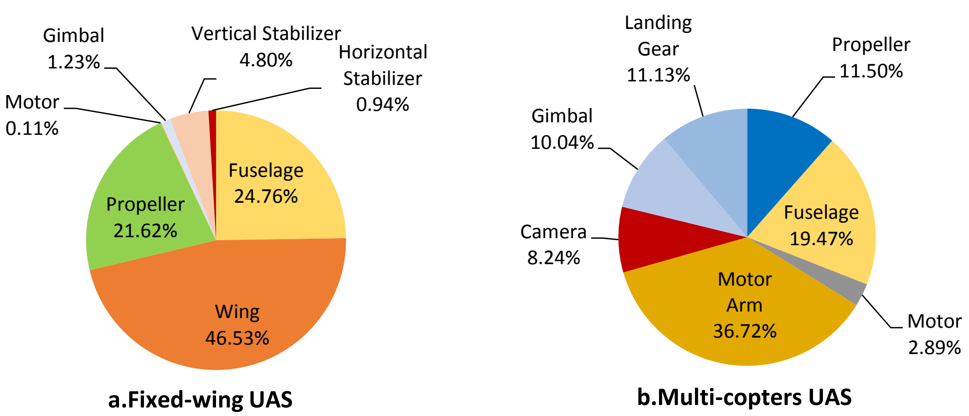

Figure 9. Composition of zones of impact of (a.) fixed-wing UAS and (b.) multi-copters UAS.

The area composition of fixed-wing UAS and multi-rotors UAS, which can be seen in Figure 9, are quite different due to distinct design. For fixed-wing UAS, about 47% of the whole frontal area is the wing area. The fuselage and propeller also cover a significant frontal area with percentages of 25% and 22% respectively. It should be noted that UAS models that are selected in this analysis only use propeller-driven propulsion systems, and not jet-engines. The vertical stabilizer is 5% of the overall area while horizontal stabilizer covers only 1% of the frontal area. Not all fixed-wing UASs are installed with gimbal which makes the averaged gimbal area for fixed-wing approximately equal to 1%.

V. Materials Identification and Classification

Next, commonly used materials for different zones of impact are identified and classified. The main aim of this characterization is twofold. Firstly, based on the identification of materials, the future analysis of collision consequence on particular materials type can then be used to speculate the possible outcomes of UAS collision on a particular zone of impact of certain objects. The prediction can also be done for each zone of impact by deducing from historical data or knowledge from other research on collision severity between materials. Secondly, the list of common materials will serve as a basis for any future investigation of UAS collision consequence severity analysis.

For general aviation and rotorcraft, the knowledge of the materials used is from literature studies.[32,33] Table 7 shows the list of common materials used in single-engine general aviation. As can be seen from the tables, many zones of impact use similar materials, and aluminum type is largely used for most parts. Based on this identification of materials, the future analysis of collision consequences on particular materials type can then be used to speculate on the possible outcomes of a UAS collision on a particular zone of impact of a certain object. See Appendix A for lists of common materials for the other four non-UAS objects (twin-engine GA, glider, ultralight, and rotorcraft).

Table 7. List of common materials of single-engine GA. See Appendix A for other objects.

Zone of Impact	Percentage	Common Materials
Propeller	51.5	Wood (cherry, mahogany, black walnut, oak, and birch), Aluminum, Fiber reinforced polymer (FRP) with foam core
Wing	35.5	Aluminum 2000 Series, Aluminum 7000 Series, Fiber reinforced polymer (FRP)
Horizontal Stabilizer	5.41	Aluminum 2000 Series, Fiber reinforced polymer (FRP)
Landing Gear	3.26	Steel, Titanium alloy, Rubber (for tire)
Vertical Stabilizer	2.10	Aluminum 2000 Series, Fiber reinforced polymer (FRP)
Shock Strut	1.11	Steel, Titanium alloy
Wing Strut	0.89	Aluminum 2000 Series
Fuselage	0.13	Aluminum 2000 Series, Aluminum 7000 Series, Fiber reinforced polymer (FRP)

Similarly, the common materials are identified for small fixed-wing and small multi-copter UAS as well. Table 8 and table 9 show the list of common materials for small fixed-wing UAS and small multi-copter UAS respectively. The types of materials used in the construction of small UAS are more diverse than in larger aircraft since these small UAS can often be made from light-weight, low strength structures. Polystyrene, wood, and plastic are widely used in small fixed-wing UAS for the ease of manufacturing, while FRP can be found in a larger size of small fixed-wing and multi-copter UAS.

Table 8. List of common materials for small fixed-wing UAS

Zone of Impact	Percentage	Common Materials
Wing	46.5	Polystyrene, Balsa wood, Light plywood, Plastic, Fiber reinforced polymer, Aluminum
Fuselage	24.8	Polystyrene, Balsa wood, Light plywood, Plastic, Fiber reinforced polymer, Aluminum
Propeller	21.6	Wood, Plastic, Fiber reinforced polymer (FRP)
Vertical Stabilizer	4.80	Polystyrene, Balsa wood, Light plywood, Plastic, Fiber reinforced polymer, Aluminum
Gimbal	1.23	Plastic, Fiber reinforced polymer (FRP), Aluminum
Horizontal Stabilizer	0.94	Polystyrene, Balsa wood, Light plywood, Plastic, Fiber reinforced polymer, Aluminum
Motor	0.11	Aluminum

Table 9. List of common materials for small multi-copter UAS

Zone of Impact	Percentage	Common Materials
Motor Arm	36.7	Plastic, Fiber reinforced polymer, Aluminum
Fuselage	19.5	Plastic, Fiber reinforced polymer, Aluminum
Propeller	11.5	Wood, Plastic, Fiber reinforced polymer (FRP)
Landing Gear	11.1	Plastic, Fiber reinforced polymer, Aluminum
Gimbal	10.0	Plastic, Fiber reinforced polymer (FRP), Aluminum
Camera	8.24	Plastic, Fiber reinforced polymer (FRP), Aluminum

VI. Collision Consequence Analysis

Next collision consequences due to UAS impact on each collision zone are identified. This stage aims to build a risk picture of the possible consequence and impact due to UAS collisions. In this paper, "consequence" describes the undesirable events (usually accidents or safety-related events).[34] However, severity, on the other hands, is the description of the level of loss or damage of a particular consequence. This paper considers only three levels of consequence severity; which are "damaged", "substantially damaged" and "destroyed". No damage and partially damaged severity levels are not addressed since they are not expected to directly lead to injuries. For human-related accidents, three injury levels are defined, namely; "minor injury", "serious injury" and "fatal". These severity and injury levels are based on ICAO Annex 13 severity definition[35].

Identification of collision consequence of UAS collision is done based on literature[15,16,19,36,37] on UAS collision analysis and the important findings are presented in this section. This literature addresses the collision effect on a general aviation aircraft, commercial aircraft, and human, inflicted by different UAS types with various weights, using both crash modeling and experimentation. Mid-air collision effect of small UAS on windshields and helicopter tail rotors are examined by the MAA[19] in collaboration with BALPA and UK's Department of Transport. It is found that non-birdstrike certified helicopter windshields proved to have a low resistance to drones collision and penetration through the windshield is very likely – the tests are done using 0.4, 1.2 and 4 kg classes of drone. These findings can also be applied to GA windshields since GA windshields do not have a requirement for birdstrike certification. The birdstrike certified helicopter windshield, however, shows better UAS collision resistance but penetration is still possible if aircraft fly at cruising speed. If the helicopter is stationary, both multi-copters UAS and fixed-wing UAS have less tendency to penetrate through certified windshields. The helicopter tail rotor is examined as well, and it is found that tail rotors are vulnerable to all types of drones due to the very high rotor rotating speed. Damage can be easily amplified if rotors become unbalanced resulting in uncontrolled rotor vibration which could jeopardize the whole tail structural integrity. Similar deduction for GA propeller impact severity can be done based on such study. Furthermore, the ASSURE research group[37] also conducted a series of impact severity analysis tests with multi-copters and fixed-wing UAS on business jet and commercial aircraft using both computational modelling and experimentation. It is found that 1.2 kg quadcopters UAS and 1.8 kg fixed-wing UAS at 250 knots can inflict various damage levels on different parts of commercial aircraft and business jet. Horizontal and vertical stabilizers can sustain medium-high damage severity levels which includes skin fracture, penetration into airframe and failure of parts of the primary structure. UAS can also leave permanent deformation on surface and structure, skin fracture and penetration into the airframe. Commercial aircraft windshields, however, shows permanent deformation, some fracture, but no penetration. These findings can be used to deduce the possible collision consequence outcomes of UAS to GA aircraft due to the fact that many parts of GA aircraft use similar materials on commercial aircraft and business aircraft, such as, leading edge or fuselage skin. In addition, the severity of jet engine ingesting UAS is investigated through computational modelling.[38] For typical turbofan engines on commercial aircraft, fan blades can be partially destroyed due to the hard components from the UAS such as the motor or the camera. The UAS can inflict even more damage as it moves closer to nosecone (or center) of the engine. In such case, both inner and outer blades are severely damaged and there is a larger chance for UAS debris to enter core engine which leads to a system shutdown.

Using the aforementioned understandings towards the effect of UAS collisions on different types of objects, collision consequences and subsequent event types have been identified for each zone of impact (or pass) for each of the non-UAS objects addressed in Section V; these results are shown in Appendix B.

VII. Conclusion

In order to safely integrate UAS operations into the airspace, UAS collision risks need to be well understood. For such a complex problem, there is a need to develop a systematic approach to characterize both frequency and consequence of various UAS collisions. This paper presented and followed a step-wise method for characterizing UAS collision consequences in future UTM system, focusing on only the VLL UAS operations which are below 500 ft. The proposed method first addressed the analysis of UTM dimensions by investigating the UTM ConOps, rules and regulations, and support infrastructure under consideration. These were analyzed and decomposed into several dimensions. The second step was the identification of the relevant objects within the airspace that was susceptible to UAS collision risk. Since UAS will operate very close to the ground, the objects sharing the airspace with the UAS then consist of both ground and airborne objects. For ground objects, different kinds of maps, such as land-use map, satellite map or land elevation map, were used in the identification process. Airborne objects were identified based on rules of the air which specified what types of aircraft were allowed to operate within the airspace. Additionally, opinions from aviation experts were incorporated during the identification of airborne objects as well. Next, the third step was to analyze the zones of impact for the identified objects. This was demonstrated for general aviation and rotorcraft. The aim of the zone of impact analysis was to decompose the overall area of an object into different impact zones that were exposed to the risk of colliding with a UAS. The areas of each zone were also estimated and represented in the form of percentages, which significantly influenced the collision probability of each impact zone. The fourth step was the materials identification and classification with the aim to characterize common materials for each zone of impact. Materials characterization is important for future research where impact analysis will be conducted for different materials. Lastly, collision consequence of the selected objects was done by identifying the possible collision outcomes for each zone of impact of each object. The collision consequence was identified based on literature which involved impact testing and simulation. Such analysis aimed to build a risk picture of the possible consequence and impact of a collision with a UAS.

The key added value of the approach developed in this paper is that the intermediate relations between the initiating events and the collision consequence outcomes are established through a systematic analysis and characterization process. Follow-up research can take advantage of this logical and well-structured decomposition that helps organizing the detailed quantitative modeling and analysis of collision consequences. Complementary follow-up research is to extend the step-wise approach proposed in this paper to a consequence analysis of primary collisions to secondary collisions, i.e. collisions that happen as a consequence of a primary collision.

Appendix A: Additional Materials Identification Results

Materials Identification Results – Twin-Engine General Aviation

Zone of Impact	Percentage	Common Materials
Propeller	56.6	Wood (cherry, mahogany, black walnut, oak, and birch), Aluminum, Fiber reinforced polymer (FRP) with foam core
Wing	18.4	Aluminum 2000 Series, Aluminum 7000 Series, Fiber reinforced polymer (FRP)
Fuselage	8.96	Aluminum 2000 Series, Aluminum 7000 Series, Fiber reinforced polymer (FRP)
Nosecone Radome	4.46	Fiber reinforced polymer (FRP)
Windshield	3.87	Acrylics, Polycarbonate
Horizontal Stabilizer	3.71	Aluminum 2000 Series, Fiber reinforced polymer (FRP)
Vertical Stabilizer	1.86	Aluminum 2000 Series, Fiber reinforced polymer (FRP)
Landing Gear	1.73	Steel, Titanium alloy, Rubber (for tire)
Shock Strut	0.38	Steel, Titanium alloy

Materials Identification Results – Glider

Zone of Impact	Percentage	Common Materials
Wing	76.5	Aluminum 2000 Series, Aluminum 7000 Series, Fiber reinforced polymer (FRP)
Fuselage Skin	7.07	Aluminum 2000 Series, Aluminum 7000 Series, Fiber reinforced polymer (FRP)
Windshield	6.65	Acrylics, Polycarbonate
Horizontal Stabilizer	5.63	Aluminum 2000 Series, Fiber reinforced polymer (FRP)
Vertical Stabilizer	3.30	Aluminum 2000 Series, Fiber reinforced polymer (FRP)
Landing Gear	0.89	Steel, Titanium alloy, Rubber (for tire)

Materials Identification Results – Ultralight

Zone of Impact	Percentage	Common Materials
Wing	37.2	Aluminum 2000 Series, Aluminum 7000 Series, Fiber reinforced polymer (FRP)
Propeller	22.8	Wood (cherry, mahogany, black walnut, oak, and birch), Aluminum, Fiber reinforced polymer (FRP) with foam core
Frame	12.1	Aluminum 2000 Series, Fiber reinforced polymer (FRP)
Human Pilot	10.4	Human flesh and skin
Horizontal Stabilizer	3.42	Aluminum 2000 Series, Fiber reinforced polymer (FRP)
Landing Gear	3.18	Steel, Titanium alloy, Rubber (for tire)
Wing Strut	2.76	Aluminum 2000 Series
Vertical Stabilizer	2.32	Aluminum 2000 Series, Fiber reinforced polymer (FRP)
Fuselage Skin	1.77	Aluminum 2000 Series, Aluminum 7000 Series, Fiber reinforced polymer (FRP)
Shock Strut	1.21	Steel, Titanium alloy

Materials Identification Results – Rotorcraft

Zone of Impact	Percentage	Common Materials
Main Rotor Blade	57.9	Aluminum 2000 Series, Titanium, Fiber reinforced polymer (FRP)
Fuselage Skin	21.2	Aluminum 2000 Series, Aluminum 7000 Series, Fiber reinforced polymer (FRP)
Windshield	13.9	Acrylics, Polycarbonate
Engine Inlet	1.76	Aluminum, Titanium
Shock Strut	1.61	Steel, Titanium alloy
Vertical Stabilizer	1.40	Aluminum 2000 Series, Fiber reinforced polymer (FRP)
Horizontal Stabilizer	1.20	Aluminum 2000 Series, Fiber reinforced polymer (FRP)
Tail Rotor	0.35	Aluminum 2000 Series, Titanium, Fiber reinforced polymer (FRP)
Rotor Mast	0.35	Steel, Titanium

Appendix B: Primary Consequences of UAS Collision with non-UAS Objects from Section V

Consequence Characterization of UAS Collision with Single-engine General Aviation

Impact/Pass Zone	**Primary Consequence(s)**
Near Miss	- Pilot distracted, critical during high-workload takeoff/landing phases
Propeller	- Propeller damaged with minor permanent deformation, UAS debris damage windshield, pilot distracted - Propeller substantially damaged with partial structural failure, risk of unbalanced propeller rotation leading to uncontrolled propeller vibration, debris of UAS collide onto windshield - Propeller destroyed, instance loss of thrust and risk of unbalaced propeller rotation leading to uncontrolled propeller vibration, debris of UAS collide onto windshield- UAS pass through propeller, collide and bounce off windshield, windshield damaged with minor fracture, leading to pilot distraction - UAS pass through propeller, collide and damage windshield, leading to pilot distraction and reduced visibility - UAS pass through propeller and penetrate through windshield, leading to injury/fatality of human pilot
Wing	- Wing damaged with minor permanent deformation - Wing substantially damaged with structural penetration, reduced structural integrity of primary structure, risk of structural failure - Wing destroyed, primary structure failed, leading to uncontrolled flight and injury/fatality of human onboard
Horizontal Stabilizer	- Horizontal stabilizer damaged with minor permanent deformation - Horizontal stabilizer substantially damaged with structural penetration, reduced structural integrity of primary structure, risk of structural failure, reduced control surface movement - Horizontal stabilizer destroyed, primary structure failed, leading to uncontrolled flight and injury/fatality of human onboard
Vertical Stabilizer	- Vertical stabilizer damaged with minor permanent deformation - Vertical stabilizer substantially damaged with structural penetration, reduced structural integrity of primary structure, risk of structural failure, reduced control surface movement and pilot distracted - Vertical stabilizer destroyed, permanent structure failed, leading to uncontrolled flight and injury/fatality of human onboard
Shock Strut	- Shock strut damaged with minor permanent deformation - Shock strut substantially damaged with partial structural failure, risk of structural failure during landing - Shock strut destroyed, risk of uncontrolled touch down leading to runway skid-off, resulting in damaged to aircraft and injury/fatality of human onboard
Wing Strut	- Wing strut damaged with minor permanent deformation - Wing strut substantially damaged with partial structural failure, reduced structural integrity and risked of structural failure, leading to unsupported main wing - Wing strut destroyed leading to unsupported wing, risk of main wing structural failure, leading to uncontrolled flight and injury/fatality of human onboard
Fuselage Skin	- Fuselage skin damaged with minor permanent deformation - Fuselage skin substantially damaged, UAS penetrates fuselage, leading to injury of onboard personals and immediate termination of flight - Fuselage skin destroyed, UAS penetrates fuselage and injuring onboard personnel, risk of fuselage structural failure, leading to uncontrolled flight and injury/fatality of human onboard
Landing Gears	- Landing gears damaged with minor permanent deformation - Landing gears substantially, risk of landing gears structural failure during landing, risk of uncontrolled touch down leading to runway skid-off, resulting in damaged to aircraft and injury/fatality of human onboard - Landing gears destroyed, risk of uncontrolled touch down leading to runway skid-off, resulting in damaged to aircraft and injury/fatality of human onboard

Consequence Characterization of UAS Collision with Twin-Engine General Aviation

Impact/Pass Zone	Collision Consequence
Near Miss	- Pilot distracted, critical during high-workload takeoff/landing phases
Propeller	- Propeller damaged with minor permanent deformation - Propeller substantially damaged with partial structural failure, risk of unbalanced propeller rotation, leading to uncontrolled propeller vibration - Propeller destroyed, instance loss of thrust and risk of unbalanced propeller rotation, leading to uncontrolled propeller vibration
Windshield	- Windshield damaged with minor fracture, pilot distracted - Windshield substantially damaged, UAS partially penetrate through, leading to pilot distraction and reduced visibility, risk of onboard injury - Windshield destroyed, UAS completely penetrate through, leading to pilot distraction and onboard injury/fatality
Wing	- Wing damaged with minor permanent deformation - Wing substantially damaged with structural penetration, reduced structural integrity of primary structure, risk of structural failure - Wing destroyed, primary structure failed, leading to uncontrolled flight and injury/fatality of human onboard
Horizontal Stabilizer	- Horizontal stabilizer damaged with minor permanent deformation - Horizontal stabilizer substantially damaged with structural penetration, reduced structural integrity of primary structure, risk of structural failure, reduced control surface movement - Horizontal stabilizer destroyed, primary structure failed, leading to uncontrolled flight and injury/fatality of human onboard
Vertical Stabilizer	- Vertical stabilizer damaged with minor permanent deformation - Vertical stabilizer substantially damaged with structural penetration, reduced structural integrity of primary structure, risk of structural failure, reduced control surface movement and pilot distracted - Vertical stabilizer destroyed, primary structure failed, leading to uncontrolled flight and injury/fatality of human onboard
Shock Strut	- Shock strut damaged with minor permanent deformation - Shock strut substantially damaged with partial structural failure, risk of structural failure during landing - Shock strut destroyed, risk of uncontrolled touch down leading to runway skid-off, resulting in damaged to aircraft and injury/fatality of human onboard
Fuselage Skin	- Fuselage skin damaged with minor permanent deformation - Fuselage skin substantially damaged, UAS penetrates fuselage, leading to injury of onboard personals and immediate termination of flight - Fuselage skin destroyed, UAS penetrates fuselage and injuring onboard personnel, risk of fuselage structural failure, leading to uncontrolled flight and injury/fatality of human onboard
Nosecone/ Radome	- Nosecone/Radome damaged with minor permanent deformation - Nosecone/Radome substantially damaged, UAS penetrates skin, radar component damaged - Nosecone/Radome destroyed, UAS penetrates skin, radar component and primary structure substantially damaged, risk of structural failure
Landing Gears	- Landing gears damaged with minor permanent deformation - Landing gears substantially, risk of landing gears structural failure during landing, risk of uncontrolled touch down leading to runway skid-off, resulting in damaged to aircraft and injury/fatality of human onboard - Landing gears destroyed, risk of uncontrolled touch down leading to runway skid-off, resulting in damaged to aircraft and injury/fatality of human onboard

Consequence Characterization of UAS Collision with Glider

Impact/Pass Zone	Collision Consequence
Near Miss	- Pilot distracted, critical during high-workload takeoff/landing phases
Wing	- Wing damaged minor permanent deformation - Wing substantially damaged with structural penetration, reduced structural integrity of primary structure, risk of structural failure - Wing destroyed, primary structure failed, leading to uncontrolled flight and injury/fatality of human onboard
Windshield	- Windshield damaged with minor fracture, pilot distracted - Windshield substantially damaged, UAS partially penetrate through, leading to pilot distraction and reduced visibility, risk of onboard injury - Windshield destroyed, UAS completely penetrate through, leading to pilot distraction and onboard injury/fatality
Horizontal Stabilizer	- Horizontal stabilizer damaged with minor permanent deformation - Horizontal stabilizer substantially damaged with structural penetration, reduced structural integrity of primary structure, risk of structural failure, reduced control surface movement - Horizontal stabilizer destroyed, primary structure failed, leading to uncontrolled flight and injury/fatality of human onboard
Vertical Stabilizer	- Vertical stabilizer damaged with minor permanent deformation - Vertical stabilizer substantially damaged with structural penetration, reduced structural integrity of primary structure, risk of structural failure, reduced control surface movement and pilot distracted - Vertical stabilizer destroyed, primary structure failed, leading to uncontrolled flight and injury/fatality of human onboard
Fuselage Skin	- Fuselage skin damaged with minor permanent deformation - Fuselage skin substantially damaged, UAS penetrates fuselage, leading to injury of onboard personals and immediate termination of flight - Fuselage skin destroyed, UAS penetrates fuselage and injuring onboard personnel, risk of fuselage structural failure, leading to uncontrolled flight and injury/fatality of human onboard
Landing Gears	- Landing gears damaged with minor permanent deformation - Landing gears substantially damaged, risk of landing gears structural failure during landing, risk of uncontrolled touch down leading to runway skid-off, resulting in damage to aircraft and injury/fatality of human onboard - Landing gears destroyed, risk of uncontrolled touchdown, leading to runway skid-off, resulting in damage to aircraft and injury/fatality of human onboard

Consequence Characterization of UAS Collision with Ultralight

Impact/Pass Zone	Collision Consequence
Near Miss	- Pilot distracted, critical during high-workload takeoff/landing phases
Propeller	- Propeller damaged minor with permanent deformation - Propeller substantially damaged with partial structural failure, risk of unbalanced propeller rotation, leading to uncontrolled propeller vibration - Propeller destroyed, instance loss of thrust and risk of unbalanced propeller rotation, leading to uncontrolled propeller vibration
Wing	- Wing damaged with minor permanent deformation - Wing substantially damaged with structural penetration, reduced structural integrity of primary structure, risk of structural failure - Wing destroyed, primary structure failed, leading to uncontrolled flight and injury/fatality of human onboard
Human Pilot	- Human pilot minorly injured, pilot distracted and reduced physical ability - Human pilot seriously injured, reduced physical ability to control aircraft, risk of uncontrolled aircraft - Human pilot fatally injured, resulting in uncontrolled aircraft
Windshield	- Windshield damaged with minor fracture, pilot distracted - Windshield substantially damaged, UAS partially penetrate through, leading to pilot distraction and reduced visibility, risk of onboard injury - Windshield destroyed, UAS completely penetrate through, leading to pilot distraction and onboard injury/fatality
Frame	- Frame damaged with minor permanent deformation - Frame substantially damaged with partial structural failure, reduced structural integrity and risked of structural failure - Frame destroyed leading to unsupported wing, risk of structural failure, leading to uncontrolled flight and injury/fatality of human onboard
Horizontal Stabilizer	- Horizontal stabilizer damaged with minor permanent deformation - Horizontal stabilizer substantially damaged, reduced structural integrity of primary structure, risk of structural failure, reduced control surface movement - Horizontal stabilizer destroyed, primary structure failed, leading to uncontrolled flight and injury/fatality of human onboard
Vertical Stabilizer	- Vertical stabilizer damaged with minor permanent deformation - Vertical stabilizer substantially damaged with structural penetration, reduced structural integrity of primary structure, risk of structural failure, reduced control surface movement and pilot distracted - Vertical stabilizer destroyed, primary structure failed, leading to uncontrolled flight and injury/fatality of human onboard
Shock Strut	- Shock strut damaged with minor permanent deformation - Shock strut substantially damaged with partial structural failure, risk of structural failure during landing - Shock strut destroyed, risk of uncontrolled touchdown, leading to runway skid-off, resulting in damage to aircraft and injury/fatality of human onboard
Wing Strut	- Wing strut damaged with minor permanent deformation - Wing strut substantially damaged with partial structural failure, reduced structural integrity and risked of structural failure, leading to unsupported main wing - Wing strut destroyed leading to unsupported wing, risk of main wing structural failure, leading to uncontrolled flight and injury/fatality of human onboard
Fuselage Skin	- Fuselage skin damaged with minor permanent deformation - Fuselage skin substantially damaged, UAS penetrates fuselage, leading to injury of onboard personals and immediate termination of flight - Fuselage skin destroyed, UAS penetrates fuselage and injuring onboard personnel, risk of fuselage structural failure, leading to uncontrolled flight and injury/fatality of human onboard
Landing Gears	- Landing gears damaged with minor permanent deformation - Landing gears substantially damaged, risk of landing gears structural failure during touch down leading to runway skid-off, resulting in damage to aircraft and injury/fatality of human onboard - Landing gears destroyed, risk of uncontrolled touch down leading to runway skid-off, resulting in damaged to aircraft and injury/fatality of human onboard

Consequence Characterization of UAS Collision with Rotorcraft

Impact/Pass Zone	Collision Consequence
Near Miss	- Pilot distracted, critical during high-workload takeoff/landing phases
Main Rotor Blade	- Rotor blade damaged with minor permanent deformation - Rotor blade substantially damaged with partial structural failure, risk of unbalanced propeller rotation leading to uncontrolled vibration - Rotor blade destroyed, instance loss of thrust and risk of uncontrolled vibration, leading to uncontrolled flight and onboard injury/fatality
Rotor Mast/Control Rod	- Rotor mast or control rod damaged with minor permanent deformation or surface damage - Rotor mast or control rod substantially damaged with partial structural failure, risk asymmetric rotation of rotor blades or loss of control over rotors - Rotor mast or control rod destroyed, loss of rotors and instance loss of thrust, leading to uncontrolled flight and onboard injury/fatality
Windshield	- Windshield damaged with minor fracture, pilot distracted - Windshield substantially damaged, UAS partially penetrate through, leading to pilot distraction and reduced visibility, risk of onboard injury - Windshield destroyed, UAS completely penetrate through, leading to pilot distraction and onboard injury/fatality
Tail Rotor	- Tail rotor damaged with minor permanent deformation - Tail rotor substantially damaged with partial structural failure, risk of unbalanced propeller rotation, leading to uncontrolled vibration and unstable/uncontrollable vehicle - Tail rotor destroyed, instance loss of stabilized thrust and risk of unbalanced propeller rotation, leading to uncontrollable vehicle which results in injury/fatality of human onboard
Engine Inlet	- Engine damaged, engine disrupted with significant reduction in power - Engine substantially damaged with complete loss of power, leading to vehicle uncontrolled descent, leading to uncontrolled flight and injury/fatality of human onboard - Engine destroyed with complete loss of power, engine catches on fire, risk of fire and explosion, leading to uncontrolled flight and injury/fatality of human onboard
Horizontal Stabilizer	- Horizontal stabilizer damaged minor permanent deformation - Horizontal stabilizer substantially damaged with structural penetration, reduced structural integrity of primary structure, risk of structural failure, reduced control surface movement - Horizontal stabilizer destroyed, permanent structure failed, leading to uncontrolled flight and injury/fatality of human onboard
Vertical Stabilizer	- Vertical stabilizer damaged with minor permanent deformation - Vertical stabilizer substantially damaged with structural penetration, reduced structural integrity of primary structure, risk of structural failure, reduced control surface movement and pilot distracted - Vertical stabilizer destroyed, permanent structure failed, leading to uncontrolled flight and injury/fatality of human onboard
Shock Strut	- Shock strut damaged with minor permanent deformation - Shock strut substantially damaged with partial structural failure, risk of structural failure during landing - Shock strut destroyed, risk of uncontrolled touch down leading to runway skid-off, resulting in damage to aircraft and injury/fatality of human onboard
Fuselage Skin	- Fuselage skin damaged with minor permanent deformation - Fuselage skin substantially damaged, UAS penetrates fuselage, leading to injury of onboard personals and immediate termination of flight - Fuselage skin destroyed, UAS penetrates fuselage and injuring onboard personnel, risk of fuselage structural failure, leading to uncontrolled flight and injury/fatality of human onboard
Landing Gears	- Landing gears damaged with minor permanent deformation - Landing gears substantially damaged, risk of landing gears structural failure during landing, risk of uncontrolled touch down leading to runway skid-off, resulting in damage to aircraft and injury/fatality of human onboard - Landing gears destroyed, risk of uncontrolled touch down leading to runway skid-off, resulting in damaged to aircraft and injury/fatality of human onboard

References

[1] Prevot, T., Rios, J., Kopardekar, P., Robinson III, J. E., Johnson, M., and Jung, J., "UAS Traffic Management (UTM) Concept of Operations to Safely Enable Low Altitude Flight Operations," *16th AIAA Aviation Technology, Integration, and Operations Conference*, 2016, pp. 1–16, doi: 10.2514/6.2016-3292, URL: http://arc.aiaa.org/doi/10.2514/6.2016-3292.

[2] Eurocontrol, "RPAS ATM Conops," 2017, URL: http://www.eurocontrol.int/sites/default/files/publication/files/rpas-atm-cocept-of-operations-2017.pdf.

[3] FAA, "Small Unmanned Aircraft Systems, Title 14 of the Code of Federal Regulations (14 C.F.R.), Part 107," 2017, URL: https://www.ecfr.gov/cgibin/retrieveECFR?gp=1&SID=dcf7ddb5f58f33726d33d7bc50a36d72&ty=HTML&h=L&mc=true &r=PART&n=pt14.2.107.

[4] European Aviation Safety Agency, "Notice of Proposed Amendment 2017-05 (A) - Introduction of a Regulatory Framework for the Operation of Drones," 2017, URL: https://www.easa.europa.eu/sites/default/files/dfu/NPA 2017-05 (A)_0.pdf.

[5] Burdett, H., Stoker, J., Strong, M., and Burdett, H., "Functional Hazard Assessment (FHA) Report for Unmanned Aircraft Systems," 2009, URL: https://www.eurocontrol.int/sites/default/files/content/documents/single-sky/uas/library/safety-uasfha-report-v2-ebeni.pdf.

[6] Belcastro, C. M., Newman, R. L., Evans, J., Klyde, D. H., Barr, L. C., and Ancel, E., "Hazards Identification and Analysis for Unmanned Aircraft System Operations," *17th AIAA Aviation Technology, Integration, and Operations Conference*, 2017, doi: 10.2514/6.2017-3269, URL: https://arc.aiaa.org/doi/10.2514/6.2017-3269.

[7] Barr, L. C., Newman, R., Ancel, E., Belcastro, C. M., Foster, J. V., Evans, J., and Klyde, D. H., "Preliminary Risk Assessment for Small Unmanned Aircraft Systems," *17th AIAA Aviation Technology, Integration, and Operations Conference*, 2017, doi: 10.2514/6.2017-3272, URL: https://arc.aiaa.org/doi/10.2514/6.2017-3272.

[8] Clothier, R. A., Williams, B. P., and Fulton, N. L., "Structuring the Safety Case for Unmanned Aircraft System Operations in Non-Segregated Airspace," *Safety Science*, vol. 79, 2015, pp. 213–228, doi: 10.1016/j.ssci.2015.06.007, URL: http://dx.doi.org/10.1016/j.ssci.2015.06.007.

[9] de Ruijter, A., and Guldenmund, F., "The Bowtie Method: A review," *Safety Science*, vol. 88, 2015, pp. 211–218, doi: 10.1016/j.ssci.2016.03.001, URL: http://dx.doi.org/10.1016/j.ssci.2016.03.001.

[10] Hong, E. S., Lee, I. M., Shin, H. S., Nam, S. W., and Kong, J. S., "Quantitative Risk Evaluation Based on Event Tree Analysis Technique: Application to the Design of Shield TBM," *Tunnelling and Underground Space Technology*, vol. 24, 2009, pp. 269–277, doi: 10.1016/j.tust.2008.09.004, URL: http://dx.doi.org/10.1016/j.tust.2008.09.004.

[11] Clothier, R. A., Williams, B. P., and Hayhurst, K. J., "Modelling the risks remotely piloted aircraft pose to people on the ground," *Safety Science*, vol. 101, 2018, pp. 33–47, doi: 10.1016/j.ssci.2017.08.008, URL: http://dx.doi.org/10.1016/j.ssci.2017.08.008.

[12] Tyagi, A., Zhang, Y., Toussaint, S., and Luxhoj, J. T., "Strategies to Model System Risk Using UAS Safety Analysis Model (USAM)," *16th AIAA Aviation Technology, Integration, and Operations Conference*, 2016, pp. 1–14, doi: 10.2514/6.2016-3597, URL: http://arc.aiaa.org/doi/10.2514/6.2016-3597.

[13] Lum, C. W., Gauksheim, K., and Kosel, T., "Assessing and Estimating Risk of Operating Unmanned Aerial Systems in Populated Areas," *11th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference*, Virginia Beach, VA: 2011, pp. 1–12, doi: 10.2514/6.2011-6918.

[14] European Aviation Safety Agency (EASA), "Drone Collision Task Force," 2016, URL: https://www.easa.europa.eu/system/files/dfu/TF Drone Collision_Report for Publication %28005%29.pdf.

[15] Arterburn, D., Ewing, M., Prabhu, R., Zhu, F., and Francis, D., "FAA UAS Center of Excellence Task A4 : UAS Ground Collision Severity Evaluation," 2017.

[16] Campolettano, E. T., Bland, M. L., Gellner, R. A., Sproule, D. W., Rowson, B., Tyson, A. M., Duma, S. M., and Rowson, S., "Ranges of Injury Risk Associated with Impact from Unmanned Aircraft Systems," *Annals of Biomedical Engineering*, 2017, doi: 10.1007/s10439-017-1921-6, URL: http://link.springer.com/10.1007/s10439-017-1921-6.

[17] Schroeder, K., Song, Y., Horton, B., and Bayandor, J., "Investigation of UAS Ingestion into High-Bypass Engines, Part I: Bird vs. Drone," *58th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Reston, Virginia: American Institute of Aeronautics and Astronautics, 2017, pp. 1–10, doi: 10.2514/6.2017-0187, URL: http://arc.aiaa.org/doi/10.2514/6.2017-0187.

[18] Schroeder, K., Song, Y., Horton, B., and Bayandor, J., "Investigation of UAS Ingestion into High-Bypass Engines, Part 2: Parametric Drone Study," *58th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Reston,

Virginia: American Institute of Aeronautics and Astronautics, 2017, pp. 1–10, doi: 10.2514/6.2017-0187, URL: http://arc.aiaa.org/doi/10.2514/6.2017-0187.

[19] Military Aviation Authority, "Small Remotely Piloted Aircraft Systems (drones) Mid-Air Collision Study," 2017, URL: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/628092/small-remotely-piloted-aircraft-systems-drones-mid-air-collision-study.pdf.

[20] European Aviation Safety Agency, "Prototype Commission Regulation on Unmanned Aircraft Operations," 2016, URL: https://www.easa.europa.eu/system/files/dfu/UAS Prototype Regulation final.pdf.

[21] SESAR Joint Undertaking, "U-Space Blueprint," 2017, doi: 10.2829/614891, URL: http://www.sesarju.eu/u-space-blueprint.

[22] ICAO, "Annex 11 - Air Traffic Services," 2001.

[23] FAA, "Instrument Flying Handbook," U.S. Department of Transportation Federal Aviation Administration, 2012, doi: 10.1186/s12986.

[24] Electronic Code of Federal Regulations (e-CFR), "Title 14 of Code of Federal Regulations (14 C.F.R.) - Part 107 Small Unmanned Aircraft Systems," 2018 URL https://www.ecfr.gov/cgi-bin/textidx?SID=8a0503d486fa747c92093b3853a20cc1&mc=true&node=pt14.2.107&rgn=div5.

[25] FAA, "Summary of Small Unmanned Aircraft Rule (Part 107)," 2016, URL: http://www.faa.gov/uas/media/Part_107_Summary.pdf.

[26] Kopardekar, P., "Unmanned Aerial System (UAS) Traffic Management (UTM): Enabling Low-Altitude Airspace and UAS Operations," California: 2018.

[27] City Population, "Population Statistics for Countries" URL https://www.citypopulation.de/.

[28] European Aviation Safety Agency, "Standardised European Rules of the Air," 2018 URL https://www.easa.europa.eu/regulation-groups/sera-standardised-european-rules-air.

[29] National Transportation Safety Board, "Aviation Incident Final Report," 2017 URL https://app.ntsb.gov/pdfgenerator/ReportGeneratorFile.ashx?EventID=20170922X54600&AKey=1&RType=HTML&IType=IA.

[30] Office of the Secretary of Department of Defense, "Unmanned Systems Roadmap 2007 - 2032," Washington: 2007.

[31] Association General Aviation Manufacturers, "2016 General Aviation Statistical Databook & 2017 Industry Outlook," Washington, DC: 2016, URL: www.gama.aero.

[32] Rambabu, P., Prasad, N. E., and Kutumbarao, V. V, "Aerospace Materials and Material Technologies," 2017, doi: 10.1007/978-981-10-2143-5, URL: http://link.springer.com/10.1007/978-981-10-2143-5.

[33] Pauliny, J., "The Overview of Propellers in General Aviation," Brno University of Technology, 2012.

[34] Civil Aviation Authority, "Bowtie Risk Assessment Models," 2015 URL https://www.caa.co.uk/Safety-initiatives-and-resources/Working-with-industry/Bowtie/Bowtie-elements/Consequences/.

[35] International Civil Aviation Organisation, "Annex 13 To the Convention on International Civil Aviation - Aircraft Accident And Incident Investigation," 2001, URL: http://www.emsa.europa.eu/retro/Docs/marine_casualties/annex_13.pdf.

[36] Civil Aviation Safety/Monash University, "Human Injury Model for Small Unmanned Aircraft Impacts," 2013.

[37] May, T. A., Texas, D., Gomez, L., and Cairns, D., "UAS Airborne Collision Severity Evaluation," 2017, URL: http://www.assureuas.org/projects/deliverables/a3/Volume I - UAS Airborne Collision Severity Evaluation - Structural Evaluation.pdf.

[38] D'Souza, K., Lyons, T., Lacy, T., and Kota, K., "Volume IV - UAS Airborne Collision Severity Evaluation – Engine Ingestion," 2017, URL: http://www.assureuas.org/projects/deliverables/a3/Volume IV - UAS Airborne Collision Severity Evaluation - Engine Ingestion.pdf.