Small Unmanned Aircraft System (sUAS) Categorization Framework for Low Altitude Traffic Services

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***Abstract*—Within the context of unmanned aircraft system (UAS) traffic management (UTM), an small UAS (sUAS) categorization framework has been established for low altitude traffic services to enable safe and efficient sUAS operations. This is achieved on the foundation of understanding the existing manned aircraft, model aircraft, and UAS categorization methods, and the effects of sUAS design and operational characteristics on the trajectory of the sUAS itself and interactions the sUAS may have with the environment, other aerial vehicles, people, and structures on the ground. The framework includes categorization methods for each of the following aspects: aircraft configuration, type of flight, flight rules, performance-based navigation (PBN) capabilities, flight and operations control, and vehicle flight performance. Initial criteria for the categorization methods were discussed along with additional analysis needs to improve and refine the framework.**

Keywords—Small unmanned aircraft system, categorization, traffic services.

I. Introduction

For civilian operations in the United States, the term *small unmanned aircraft system* (sUAS) is defined as a system consisting of an unmanned aircraft or unmanned aerial vehicle (UAV) weighing less than 55 lb, and equipment necessary for the safe and efficient operation of that aircraft [9], [15]. Unmanned aircraft of this size have been flown as model aircraft for hobby, recreational, and sports use for many decades. The advancement, increased access by the public, and the reduced cost and size of technologies such as digital communications, digital controls, navigation, and autonomy have enabled fast growing capabilities of sUASs, including model aircraft, that were not imaginable decades ago.

In 2016, FAA added Part 107 to Title 14 of the Code of Federal Regulations (14 CFR) [14], which allows routine use of sUASs in the National Airspace System (NAS). Part 107 operations are limited to open airspace at or below 400 ft (122 m) above ground level (AGL) or within 400 ft (122 m) from fixed structures, to avoid interference with manned aircraft operations. Additionally, sUAS operations under this rule are restricted to the visual line-of-sight (VLOS) of the remote pilot in command (PIC) or a visual observer in effective communications with the PIC. Although the VLOS restriction may be waived under special conditions, routine beyond the visual line of sight (BVLOS) operations are expected in the future to fully realize the sUAS benefits. In its simplest form, the sUAS operational space can be summarized as shown in Fig. 1. In this figure, the green areas represent currently unregulated (model aircraft) and authorized routine operations (non-recreational VLOS). The light blue areas represent future expansion into routine BVLOS operations.

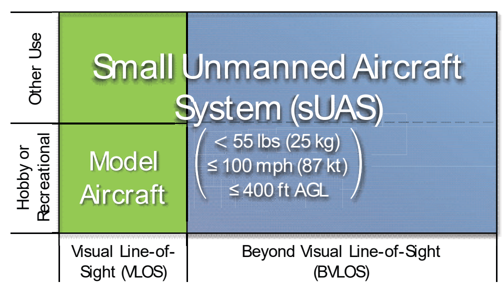

Fig. 1. Small UAS (sUAS) operational space defined

The UAS traffic management (UTM) is envisioned by the NASA to enable extensive safe and efficient VLOS operations and routine BVLOS operations in the future by providing various traffic services [26]. Trajectory modeling and prediction methods [32] are foundational capabilities in support of UTM to achieve its goals. Within this context, categorization of sUASs seeks to recognize, differentiate, and understand various sUASs from the perspectives of their design, operational, and safety characteristics. Categorization methods applied to manned aircraft and existing UAS categorization methods (including model aircraft) are reviewed first to provide a starting point for additional analysis of sUAS-specific characteristics. Results from this effort are documented in a detailed technical report [33]. This paper presents key results in the report, with a focus on the new proposed categorization framework. Readers are referred to the full-length report for additional details and analyses.

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Impact risks to other aircraft operating in the same airspace and risks to people and property on the ground have been the central concern for nearly all existing UAS categorization schemes. They are not directly considered in the new sUAS categorization framework presented here.

II. Existing Manned and Unmanned Aircraft Categorization Methods

A comprehensive review of existing categorization methods applied to manned aircraft, model aircraft and unmanned aircraft is carried out. Attention is given to design, operations, and safety aspects, and to the implications of these categorization methods; all are synthesized with necessary details presented in the form of tables, diagrams and analysis [33]. In the following subsections, key elements from each of the aircraft groups are highlighted.

A. Manned Aircraft Categorization

The review of manned aircraft categorization methods focuses on those adopted by the FAA and International Civil Aviation Organization (ICAO), which are believed to be representative of the state of the art.

Aircraft configuration is the most obvious categorization method. The FAA's aircraft configuration classification is given in 14 CFR Part 1 [14], which is a broad grouping of aircraft having similar characteristics in terms of propulsion, flight, or takeoff and landing. The FAA classification includes *balloon*, *airship*, *kite*, *glider*, *airplane*, *weight-shift control*, *powered parachute*, *gyroplane*, *gyrodyne*, *helicopter*, and *powered-lift*. ICAO Doc 8643 [24] defines an aircraft type description scheme to support air traffic service (ATS) and ATS automation. An aircraft type is described by the type of the aircraft (the type categorization), the number of engines, and the type of engines. The ICAO type of the aircraft categorization includes *landplane*, *seaplane*, *amphibian*, *helicopter*, *gyrocopter*, and *tilt-wing aircraft*. It is noted that the ICAO does not differentiate between a land-based conventional take-off and landing (CTOL) airplane, and a thrust deflection jet vertical take-off and landing (VTOL) airplane. The ICAO type of engine categorization include *piston*, *turboprop/turboshaft*, *jet*, and *electric*, while the FAA also considers *rocket* engine.

The most important aircraft categorization is by certification standards. A previous study provided a detailed review of specific classification factors considered in airworthiness standards [20]. At a system level, the FAA groups aircraft into standard certification, special certification, and certification not required, each further divided into a set of aircraft categories considering some or all of the design characteristics, intended use, or operating limitations aspects. Ultralight is the only manned aircraft in the certification not required group. One important observation from a review of the historical development is that the certification process for a given category may become more complex over time. Existing categories may be split or new categories may be introduced to serve different needs.

Several performance and equipage-based aircraft categorization methods are of reference value to the sUAS categorization for trajectory modeling purposes. The FAA transitioned to the new ICAO flight plan form on November 12, 2012 [17]. The new ICAO flight plan form [22] and the FAA's extensions provide specific details on how flight rules, type of flight, performance-based navigation (PBN) capabilities, wake turbulence category (WTC) shall be included in flight plan filing. The ICAO also defines an aircraft performance categorization using the approach speed as a criterion [23]. For airport planning and design purposes, the FAA [16] and the ICAO [21] also defined aircraft classification methods based on aircraft dimensions.

B. Model Aircraft Categorization

Model aircraft have been playing a vital role in aeronautics research, development, and education. Its development pioneered manned aircraft and modern UAS. Local, national, and international model flying communities have been playing an important role in developing, promoting, and administering safety programs that have helped maintain the safety record of model flying. Best practices, procedures, and lessons learned in model flying are valuable assets to the study of sUASs. As such, this section provides a review of existing model aircraft categorization methods.

The Fédération Aéronautique Internationale (FAI), the world governing body of all aviation sports activities, identifies model aircraft as Class F aircraft. The FAI model aircraft categorization is primarily based on the methods of remote control, propulsion, and airframe configuration [18]. At the top level, model aircraft are divided into *F1 Free Flight*, *F2 Control Line Flight*, *F3 Radio Control Flight*, *F4 Scale Model Aircraft*, *F5 Radio Control (RC) Electric Powered Aircraft*, *F7 Radio Control Aerostats*. The categorization is further refined based on the type of competition, and in some cases vehicle size, weight, and required pilot skill level. Specific design characteristics are imposed to limit and level set aircraft performance among competitors. Of interest to sUAS are various RC outdoor model aircraft categories.

For each of the model aircraft categories, the FAI's aeromodelling sporting code [18] defines model aircraft design characteristics, performance characteristics, allowable weather conditions, safety requirements, and noise limitations. Main model aircraft characteristics reviewed include: task to be completed, propulsion power source, total aerodynamic surface area or disk swept area in case of rotor craft, gross weight with or without fuel/battery/rubber band used for propulsion, aerodynamic surface or disk loading, and automation system. These characteristics determine model aircraft flight characteristics, thus are relevant to trajectory modeling.

Weather conditions are important factors. Specific factors considered by the FAI aeromodelling code include winds, visibility, the position of the sun (which may impact visual observation), and other atmospheric conditions. Except for winds, for which specific limits are specified for different model aircraft classed, weather conditions are subjectively evaluated by judges to determine if an interruption of the contest should be initiated.

The FAI has established a set of safety rules for model design, test, flying, and contest. Such safety rules may be adapted to a specific class; for example, the specification of flight site safety area and safety line are often class-specific. Subjective determination by judges is also applicable to the safe operations of many model aircraft classes. For some classes, specific requirements are in place to ensure safety or to mitigate safety risks. For some classes, particularly those reflecting the highest level of airframe design and piloting, unique safety rules in aircraft system design and operations are strictly enforced.

In addition to FAI classes, the Academy of Model Aeronautics (AMA)—the official national body for model aviation in the United States—also established national model classes. One unique AMA class is the Park Flyer model [3], [4]. These aircraft are situated towards the lower end of model aircraft in terms of weight and speed, and consequently have lower risks upon impact with properties or persons on ground. Under the AMA Large Model Airplane Program [2] and AMA Gas Turbine Regulations [1], strict safety rules and procedures have been established. These models are situated towards the upper end of model aircraft in terms of weight and speed, and thus have high risks upon impact with properties or persons on the ground. Under these rules and procedures, AMA pilot qualification and AMA aircraft certification are required.

C. Existing Unmanned Aircraft System (UAS) Categorization

Various unmanned aircraft categorization schemes have been developed by different regulatory, military, industry, and public organizations. Although many of these categorization schemes cover the broad spectrum of unmanned aircraft in terms of size, performance, and technology, recent fast growing developments in the sUAS arena have drawn attention from regulatory authorities, industry, and the research community to proposing new categorization schemes. Particularly, focus is given to the characterization of risk levels. This section provides a review of major unmanned aircraft categorization methods, including both existing ones (historical and current), and those still under development. This review is not intended to be a complete survey of all UAS categorization methods ever used or studied. Reviews of additional existing UAS categorization methods can also be found in [19], [28], and [31].

The simplest UAS categorization is by gross weight. Categorization by weight do reflect UAS performance and systems complexity in some way, but it does not provide a precise grouping of these two parameters, nor is it able to comprehensively capture differences in UAS operational characteristics.

FAA's existing UAS categorization methods reviewed include those presented in official FAA materials, and those considered by FAA chartered committees such as aviation rulemaking committees (ARCs) and Radio Technical Commission for Aeronautics (RTCA) committees. As a historical account, RTCA DO-304 [34], provided a notional categorization scheme for applying different requirements among the various operations and systems. Later, in RTCA DO-320, [35], a categorization was provided per grouping by UAS performance. Five manned aircraft performance categories were adopted: *turbojet fixed-wing*, *turboprop fixed-wing*, *reciprocating/electric fixed-wing*, *VTOL*, and *airship*. In 2016, the FAA chartered a micro small UAS (µUAS) ARC to develop a performance-based standard that would allow micro UAS to be operated over people [5]. The ARC identified four µUAS categories, defined primarily by level of risk of injury posed, for operations over people. The Department of Defense (DoD) has been using a UAS categorization that identifies UAS by attributes of weight, operating altitude, and airspeed into five groups [10].

In the United Kingdom (UK), the Ministry of Defence (MOD) had previously adopted the North Atlantic Treaty Organization (NATO) unmanned aircraft classification [30]. It uses maximum takeoff weight (MTOW) as a basic criterion to create 3 classes, each of which may be subdivided. In early 2015, MOD published a modified remotely piloted aircraft system (RPAS) categorization [27]. MTOW is no longer used as the sole determinant. It is considered alongside risk aggravating and mitigating factors of its operation and characteristics. The UK Civil Aviation Authority (CAA) currently uses a simple UAS classification with zero fuel mass (ZFM) as the main discriminant [6]. Using this classification, UASs are divided into small unmanned aircraft (SUA), light UAS, and regular UAS. An approach taken by the CAA [6] to determine the level of assurance and assessment required prior to the issuance of a permission categorizes UAS and the intended operations into either Category A, B, or C, which consider the *Technical Complexity* and the *Operating Environment Complexity*, along with aircraft mass.

For regulation purposes, the European Aviation Safety Agency (EASA) is proposing to establish three categories of operations and their associated regulatory regimes [11], [12]. This is the same categorization being adopted by the Joint Authorities for Rulemaking of Unmanned Systems (JARUS), except that categories *Open* (low risk), *Specific* (medium risk), and *Certified* (high risk) are codified by JARUS as Categories A, B, and C, respectively. Considering the different levels of risk within an Open category operation, this category is further divided into subcategories. For RPAS integration, EUROCONTROL is using a traffic classification [13] instead of aircraft classification for very low altitude (below 500 ft) operations.

In Civil Aviation Administration of China (CAAC) interim regulations for light and small UAS operations [7] and civil UAS pilot regulations [8], a UAS categorization is provided. This categorization is defined by a mix of specific weight, application domain (agriculture), configuration (airship), and operational requirements. Under CAAC interim regulations, BVLOS is also allowed for some categories, including UASs meets FAA's sUAS weight limit, agriculture no greater than 5700 kg, and airships no greater than 4600 m^3.

One previous NASA study looked at the question of how to group UASs of similar physical, performance, or other characteristics, such that appropriate airworthiness standards, ultimately including reliability and design assurance requirements, can be assigned [28], [20]. [29]. The study recognized the need to consider additional factors not considered in manned aircraft classification. A qualitative analysis was conducted to provide insights into the implications of different candidate UAS classification factors to safety risk, and potential use of these factors.

D. Lessons Learned

Through the comprehensive review of existing categorization methods and schemes for manned aircraft, model aircraft, and UAS, a few lessons could be learned.

There is no single widely accepted existing UAS categorization, nor there is a single existing categorization that serves all purposes. No prior efforts have been found in the context of UAS trajectory modeling and traffic services.

Manned aircraft categorization methods, although mostly a result of practical adaptation over time and not able to differentiate some aircraft configurations seen in sUASs, have also been tested over time. Additionally, through international harmonization efforts, common categorization methods have been more widely adopted by different countries and regions.

Model aircraft is the most relevant to sUAS in terms of size and performance. The FAI's well established model aircraft categorization, largely driven by international sports competitions through the charter of the FAI, is the most uniformly adopted categorization. The specific airframe configuration, design, and safety requirements for different model aircraft categories provide a start point for determining sUAS categorization criteria.

Most diverse categorization methods have been observed for UASs, compared with those for model aircraft and manned aircraft. The military is focused on mission capabilities. Civil aviation regulatory authorities are more focused on safety risks. The technology, market, and regulation for UASs, particularly civil ones, are evolving at a fast pace; and the development is not uniform across different countries and regions. Nonetheless, existing UAS categorization methods used by various countries and regions, and various organizations, provide insights into the major factors to be considered.

A recent trend is the proposed use of a more comprehensive risk assessment to replace simple single factor (e.g., weight) or two-factor or three-factor classification schemes. Trajectory-based analysis is expected to play a more important role in risk assessment and UAS categorization.

III. Small UAS Categorization Framework

The new sUAS categorization framework consists of categorizations from different aspects of the sUAS design and operations. In this section, requirements for an sUAS categorization framework is established first, followed by each of the aspects in a separate subsection. Additional details on the determination of initial criteria for each of the categorization methods can be found in [33].

A. Requirements for sUAS Categorization

In the context of sUAS trajectory management and traffic services, the categorization should recognize, differentiate, and understand various groups of sUASs from design, operational, and safety characteristics that influence significantly either the methods used in trajectory modeling, or the outcome of trajectory modeling, or both. At the high level, the sUAS categorization framework shall:

Req-1 Recognize and differentiate aircraft configurations with unique flight dynamics

Req-2 Recognize and differentiate power plants with unique performance characteristics

Req-3 Recognize and differentiate the type of flights and consider any special handling of the trajectory in the UTM ecosystem

Req-4 Recognize and differentiate flight rules for conducting sUAS operations

Req-5 Recognize and differentiate flight operations with different levels of trajectory tracking accuracy

Req-6 Consider the impact of different flight and operations control regimes

Req-7 Consider the impact of different environmental conditions, nominal and off-nominal

Req-8 Consider the impact of different system failures

Req-9 Be flexible, extendable, and scalable, while affordable in support of sUAS trajectory management and traffic services

B. Aircraft Configuration Classification

A small UAS aircraft configuration classification is an adaptation of manned aircraft classification. The purpose is to recognize and differentiate aircraft with unique flight dynamics and unique power plant performance characteristics (Req-1 and Req-2). Due to the diverse design and configurations of sUASs, compared to manned aircraft classification, new aircraft configuration classes may have to be added. To be flexible, scalable, and affordable at the same time (Req-9), the classification must avoid enumerating aircraft configurations seen and foreseen in the sUAS arena. A criterion used in this process is that if the flight dynamics and performance characteristics for a specific aircraft configuration can be numerically derived from classes that are already in place, then a new class won't be introduced. The resulting sUAS aircraft configuration classification is shown in TABLE I.

Compared to the manned aircraft classification [33], the *balloon* and the *kite* are eliminated because they are already managed outside the FAA's sUASs regulations.

The *airship* is retained because of its capabilities and economic value, and the fact that it is already authorized for BVLOS operations in countries such as China [7].

The *glider* is retained because it has always been part of the family of sUASs, and because of its unique flying procedures and trajectory characteristics.

The *weight-shift control* and the *powered parachute* are consolidated with the fixed wing airplane. Although their flight control mechanisms may be different from that of an airplane, for trajectory modeling purposes, they may be modeled as an airplane.

TABLE I. SMALL UAS AIRCRAFT CONFIGURATION CLASSIFICATION

Classification			Definition
Lighter than Air	Airship		Engine-driven lighter-than-air aircraft that can be steered.
Heavier than Air	Fixed Wing	Glider	Lift generated by wing, but not depending principally on an engine for sustained flight, including powered gliders.
		Airplane	Lift generated by wing, engine-driven propulsion, including weight-shift control and powered parachute aircraft, regardless of launch and recovery methods.
	Rotor-craft	Helicopter	Lift and propulsion generated by engine-driven rotor(s), principally depending on cyclic pitch for pitch and roll control, including compound helicopters with forward flight thrusters.
		Multirotor	Lift and propulsion generated by engine-driven rotors, principally depending on differential lift from multiple rotors (normally fixed pitch) for pitch and roll control,
	Powered-lift		Capable of vertical takeoff, vertical landing, and low speed flight that depends principally on engine-driven lift devices or engine thrust for lift; and cruise flight that depends principally on wing for lift. May include gyrodynes.
	Other		Any other heavier than air aircraft configurations that may not fit or may not be derived from defined classes, for example ornithopters, or gyroplanes.

In addition to *helicopter*, *multirotor* is introduced as a new rotorcraft class. The main difference between these two is that a helicopter uses cyclic pitch as the main flight control mechanism for pitch and roll control, while a multirotor uses differential rotor thrust as the main flight control mechanism. Thus, the flight dynamics model and flight controls are different, and consequently have different implications on trajectory modeling.

The *powered-lift* is retained with an expanded scope to include both jet and rotor powered-lift systems, or VTOLs. This class would represent the most diverse group of designs than any other explicitly defined classes.

The *gyroplane* and the *gyrodyne* are no longer considered separate classes because of the limited benefits that can be offered by these two configurations over the airplane and the helicopter for the size of sUASs. The gyroplane can either be modeled as an airplane with extraordinary stall characteristics, or it can be treated as a special class when it is necessary in some rare cases. The gyrodyne is essentially a powered-lift except that it becomes a gyroplane during cruise.

Compared with other design characteristics, weight is less significant in how the sUAS trajectory may be modeled. Weight is still a very important factor in safety-risk-based sUAS categorization, particularly for operations over people. The intention here is to leave the specific considerations of the weight factor in sUAS characterization to those studies that focus on impact safety risks.

The four standard engine types for manned aircraft are adopted without any changes, as shown in TABLE II. All four engine types have been seen in sUAS applications, with the electric motor dominating the number of installations in recent years.

TABLE II. SMALL UAS ENGINE TYPE CATEGORIZATION

Type Code	Engine Category	Propulsion
P	Piston	Propeller, ducted fan, or rotor(s)
T	Turboprop/Turboshaft	Propeller, ducted fan, or rotor(s)
J	Jet	Jet (including bypass fan jet)
E	Electric	Propeller, ducted fan, or rotor(s)

C. *Type of Flight*

For manned aircraft, simple and coarse categorization is used to group the type of flight into scheduled air service, non-scheduled air transport operation, general aviation, and military or others. A special handling code may be given as necessary to provide additional information about the type of flight, mostly for general aviation and military flights.

Most sUAS flights, including non-scheduled air transport such as package delivery, may correspond to the general aviation flight category. The diverse types of flights to be carried out by sUASs, the diverse operating environment for different sUAS applications, and their implications in sUAS trajectory require a different approach for categorizing the type of flight (Req-3).

The proposed categorization is based on the area where the sUAS flight is carried out, as shown in TABLE III. The operation areas as defined in the table have strong implications for the nominal or off-nominal trajectories. Under the same weather condition, each of the areas will impose unique environmental conditions to sUAS operations, such as localized wind field, temperature, pressure, and obstructions by manmade structures. The urban area is defined as the airspace volume near the boundary of or below the urban canopy. An sUAS flight well above the urban canopy is considered a populated area operation. Flight over open-air assembly of people is considered a separate category regardless of the geographic area. For this category, trajectory assessment must be performed for all possible scenarios and situations.

Analogous to the special handling information for manned aircraft flight, a mission objective categorization is also proposed to provide supplemental information about the flights, as shown in TABLE IV. This information may be valuable in aiding situation awareness for stakeholders that have an interest in the area where the sUAS flight is carried out. For example, a highway patrolling sUAS flight is of little concern to a crop dusting sUAS flight if the working field for the latter is well separated from the highway, while a package delivery sUAS flight may be a concern to the crop dusting sUAS flight if the package delivery destination is on the other side of the crop dusting working field.

TABLE III. SMALL UAS TYPE OF FLIGHT

Code	Category	Description
R	Rural Area	Open airspace, minimum probability of hitting people or property on ground.
P	Populated Area	Open airspace with moderate obstructions of manmade structures, medium probability of hitting people or property on ground.
U	Urban Area or Dense Industrial Complex	Near the boundary of or below the urban canopy with dense obstructions of manmade structures, high probability of hitting people or property on ground.
O	Over Open-air Assembly of People	Directly over assembly of people in a laterally confined open area, high probability of hitting people or property on ground, possibility of secondary impact.

TABLE IV. SMALL UAS MISSION OBJECTIVE SUPPLEMENT INFORMATION

Code	Category	Note
HUM	Humanitarian mission	To provide concise information aiding stakeholder situation awareness. Specific categories will be determined pending additional analysis.
MED	Life critical medical delivery	
NSP	Infrastructure inspection	
RPT	News and media report	
SAR	Search and rescue mission	
STA	Military, customs or police services	
SWM	Formation or swarming flight	

D. Flight Rules

For manned aircraft flights, there are two sets of flight rules, IFR and VFR. The distinction between the two is based on the pilot's use of outside visual reference. This distinction faces challenges for UAS flight operations because the pilot is not onboard the aircraft. For UASs, meteorological conditions are not the sole factor in determining the remote pilot's visual reference. Daylight-only operations are frequently specified in current VLOS sUAS regulations. Sometimes a distance limit such as 500 m (1640 ft) from the remote pilot is specified, as in the UK [6] and China [7]. Although sUAS VLOS flight rules are well established, such as those by the FAA [15], BVLOS flight rules are not yet well established.

The extended visual line of sight (EVLOS) operations as defined by the UK CAA [6], allow UAS operations either within or beyond 500 m lateral distance from the remote pilot, using alternative means to maintain direct visual contact with the unmanned aircraft. The remote pilot is still responsible for visually complying with collision avoidance, and maintaining positive control at all times. However, there are no established standards or rules on the alternative methods and procedures. It is up to the operator to submit a safety case, including a risk assessment that addresses the procedures for avoiding collisions, aircraft aids to observation, and the use of deployed observers, among other factors, before a permission is considered. If a visual observer is required for EVLOS, then it is still within the FAA's definition of VLOS.

Although the first person view (FPV) technology is not considered a means to meet current VLOS requirements, comments received in response to the FAA's notice of sUAS rulemaking argued the capability, field test, and the rapid development of the technology, as well as some of the limitations of FPV compared with direct human visual contact FAA [15]. Although some limitations would still exist in the foreseen future, the FPV technology is arguably significantly more mature and less complex than sense-and-avoid (SAA) technologies that target full UAS integration into the NAS. It is thus valid to consider using FPV as an intermediate step to full BVLOS operations.

The proposed flight rules (Req-4) for sUASs include three categories as listed in TABLE V. VLOS flight rules are considered the same as in Part 107. The FPV BVLOS, still conducted under visual meteorological conditions, is a set of flight rules bridging VLOS and full BVLOS that may be conducted under instrument meteorological conditions. It is envisioned that such a division will provide three unique sets of conditions for trajectory modeling.

TABLE V. SMALL UAS FLIGHT RULES

Category	Meteorological Condition	Description
VLOS	Visual	Rely on remote pilot maintaining direct visual contact (including via an observer) for collision avoidance and contingency.
FPV BVLOS	Visual	Rely on remote pilot utilizing FPV video feed, instrument telemetry, and potentially enhanced vision for collision avoidance and contingency; pilot positive control maintained at all times; geofencing may be required.
Instrument BVLOS	Visual or Instrument	Rely on instrument telemetry, potentially synthetic vision, and onboard autonomy for collision avoidance and contingency; geofencing required.

For the FPV BLOS, the FPV camera may be mounted on pan-tilt gimbals to enhance the scan of the airspace. Instrument telemetry is required under this set of flight rules to provide redundancy and real time system health information to the remote pilot. Instead of requiring full onboard autonomy, the remote pilot is required to maintain positive control of the aircraft at all times. The FPV and instrument telemetry may need to be subject to a regulatory or community consensus-based airworthiness certification process. A flight plan approval process may also need to be implemented to address potential communication link conditions in certain airspace areas. The onboard electronic target recognition and processing are not mandated for FPV BLOS.

The future full BVLOS is called Instrument BVLOS. FPV video feed may still be used by the operator, but it is not required, nor is it considered a means to meet sense-and-avoid requirements. Onboard electronic target recognition and processing are part of the sense-and-avoid requirements. Increased level of onboard autonomy may be required to address collision avoidance and contingency.

E. Performance-Based Navigation (PBN) Capabilities

For manned aircraft operations, the PBN concept specifies that aircraft area navigation (RNAV) or required navigation performance (RNP) system performance requirements shall be defined in terms of the accuracy, integrity, continuity, and functionality required for the proposed operations in the context of a particular airspace concept. The PBN concept can be easily applied to UASs that are intended to be operated in manned and unmanned mixed airspace environment, but it does not scale well for sUAS operations. On one hand, even the standard approach RNP 0.3 (556 m/1823 ft) and minimum RNP 0.1 (185 m/607 ft) are too large for sUASs considering their size and their intended applications. On the other hand, an sUAS is subject to the same navigation system error (NSE) as manned aircraft, if not worse. There have been discussions about PBN (or RNP in most cases) for sUASs at various occasions. In a recent NASA study [25], a quantitative framework to correlate operational risk with trajectory conformance requirements was developed. Additional research is needed before a standard is defined for sUAS operations. It would not be a simple undertaking.

Within this research, an attempt is carried out to define a framework for categorizing the total system error (TSE), or the accuracy aspect of sUAS PBN capabilities (Req-5), all assuming the same basic PBN concept for manned aircraft. The complete RNP requirements should be defined in terms of accuracy, integrity, continuity and functionality, including aircraft and pilot as a system, with significant adaptations to the specific characteristics of sUAS operations. For this reason, only the general term *PBN* is used for sUASs. The term *RNP* is not used in this discussion.

The proposed sUAS horizontal PBN capability categorization framework is shown in TABLE VI. The horizontal PBN specification is the accuracy in terms of TSE in meters in the lateral or longitudinal direction, which is expected to be achieved at least 95% of the flight time. The accuracy is measured from a desired path, if such a path is prescribed for the flight. Or it may be measured from a dynamically defined flight path, such as when the sUAS is conducting an infrastructure inspection flight. In the latter case, the flight path may be defined by a path that maintains an ideal distance from the infrastructure, which may not have a prescribed geometry that is known or accessible to the sUAS prior to the mission. Another example is obstacle avoidance against stationary objects. The horizontal PBN descriptors are chosen such to avoid confusion with existing ICAO PBN descriptors. Three descriptors are proposed to represent three levels of PBN specification. Additional levels may be added if justified by analysis.

The PBN concept includes specification of the navigational aid (NAVAID) required to meet the performance. For sUASs, Global Positioning System (GPS) and inertial measurement unit (IMU) have been the de facto standard systems. Various localized navigation systems employing radio frequency, laser, or vision sensors have been developed either as a complement to GPS or as a substitute in GPS challenged/denied environments. Miniaturized relative navigation systems have also been used by sUASs, often as part of an obstruction collision avoidance system. These two navigation systems will likely be incorporated in to the sUAS PBN specification when it is fully developed. TABLE VI to indicate the required NAVAID or specific procedure.

TABLE VI. SMALL UAS HORIZONTAL PBN CAPABILITY

Descriptor	PBN Specification	Description
X	60 m (200 ft)	Preliminary baseline PBN specification for sUAS operations.
Y	30 m (100 ft)	Tentatively given as 50 % of the baseline PBN specification, may be applied to sUASs en route or mission operations.
Z	Standard: 15 m (50 ft), Precision: 3 m (10 ft)	Minimum PBN specification, for precision mission tasks, departure and approach operations. The standard minimum is for general applications, and the precision minimum is for precision departure, approach, hovering, or other relative navigation-based mission tasks.

The lowest PBN specification for manned aircraft operations is RNAV 10 (RNP 10). RNAV 10 is designed for oceanic and remote operations and it does not require onboard performance monitoring and alerting. Thus, RNAV 10 can be considered the baseline PBN specification for manned aircraft operations. A challenge exists for defining the baseline sUAS horizontal PBN specification because no existing sUAS separation minima have been defined yet. It is an active topic of research.

Through years of continued practice and assessment, the FAI has defined minimum distances between the safety line and pilot, judges, or spectators for various RC model aircraft classes [18]. These numbers range from 25 m (82 ft) to 90 m (295 ft) for RC model aircraft, depending on their classes and their potential risks. AMA safety rules are generally in line with FAI safety rules. Based on a careful analysis of these guidelines [33], 60 m (200 ft) is selected as the baseline PBN specification for sUAS.

The FAI has also established landing rules for various RC model classes. The distance from the marked landing spot within which scores may be awarded ranges from 3 m (10 ft) to 15 m (50 ft). Related, for the F3U FPV racing, the air gates that the quadcopter must fly through have a maximum width of 3 m. These rules represent the highest lateral control precision required for a model aircraft. Based on the discussion about model aircraft landing precision rules, 50 ft (15 m) is selected as the preliminary standard minimum horizontal PBN specification for sUASs, and 10 ft (3 m) is selected as the preliminary precision minimum horizontal PBN specification.

For the intermediate level of horizontal PBN specification, 30 m (100 ft) is tentatively selected, which is half of the baseline horizontal PBN specification, and about 10 times the precision minimum horizontal specification.

To fully develop an sUAS horizontal PBN specification, additional analyses are required. Firstly, operational requirements must be well understood. Such understanding may be developed by a survey of the needs of various sUAS applications and missions, and an analysis of airspace and traffic management operational scenarios. The latter may include lateral obstacle clearance, separation minima, route spacing, and traffic flow management requirements. Secondly, what could be reasonably achieved needs to be carefully assessed. This could follow practices employed for manned flight operations; simulation studies with various navigation, guidance, and control capabilities; and vehicle performance similar to those recommended in [25]. The challenge is a lack of a sufficiently large volume of operational data. Trajectory modeling capability becomes an important foundation for this analysis.

For low altitude sUAS operations, the vertical PBN may be equally important, if not more. Confined within 400 ft (122 m) AGL, the altimeter setting, the equipage of radio or lidar altimeter, and the accuracy of GPS altitude represent a few challenges faced by sUAS operations, particularly Instrument BVLOS. For manned flight operations, vertical RNP is neither defined nor included in the PBN concept. Additional analysis is required to define a best path for sUAS vertical navigation performance. This could potentially include vertical PBN specifications, performance-based vertical separation minima (VSM) analogous to the reduced vertical separation minimum (RVSM) approval process, or community consensus-based airspace classification below 500 ft (152 m). A notional classification is provided in TABLE VII.

TABLE VII. SMALL UAS VERTICAL PBN CAPABILITY

Category	Vertical Separation Minimum	Note
Standard	30 m (100 ft)	E.g., utilizing a combination of GPS altitude and barometer.
Precision	15 m (50 ft)	E.g., with additional en route altimeter setting or localized navigation services. May also employ sUAS-sUAS SAA.

With the PBN capability categorization proposed above, one may avoid having to include specific navigation and control equipage information. This is particularly advantageous, because unlike manned aircraft, great variation in terms of performance exists for sUASs.

F. Flight and Operations Control Categorization

Much like manned aircraft, an sUAS flight may be carried out by the remote pilot completely manually, or utilizing different levels of automation. Additionally, an sUAS flight may be carried out autonomously, including generating flight path or flight intent during flight without human pilot intervention. For large manned commercial operators, there is a distinction between flight operations (pilot) and operations control (dispatcher or operations control specialist), and there is a joint flight safety responsibility. For sUASs (and light UASs as well), flight operations and operations control may be combined and may be difficult to distinguish from each other. As such, a single categorization is proposed for sUAS flight operations and operations control (Req-6), as shown in TABLE VIII.

Categories in the table are listed in the order of increased levels of system complexity, automation, and. A particular sUAS may allow mixed use of different categories in a given flight. As such, the categorization may be used to categorize the capability of an sUAS, a flight carried out by an sUAS, or different phases of a flight, in a way similar to the categorization of PBN capabilities. A more capable sUAS may be capable of all the less complex control categories. That is, an Autonomous Control (AC) capable sUAS may be operated in Flight Plan Control (PC), Mode Control (MC), and Direct Control (DC) modes. But this may not always be true, depending on the specific system design.

It should be noted that the flight and operations control categorization is not tied to the flight rules. For example, VLOS operations may be carried out in AC, PC, MC, or DC, as long as the remote pilot maintains positive control of the sUAS at all the times. This means that, if a flight is being conducted in AC, the pilot shall be able to switch to PC, MC, or DC at any moment during normal flight. Theoretically, BVLOS may also be carried out in DC with the remote pilot manually flying the sUAS during the entire flight.

TABLE VIII. SMALL UAS FLIGHT AND OPERATIONS CONTROL CATEGORIZATION

Category	Description	Note	
Direct Control (DC)	A broad category within which the remote pilot directly manipulates flight control surfaces via RC link to achieve desired attitude, speed, altitude, and lateral path. Electronic stability augmentation systems may be utilized to reduce pilot workload and enhance safety.	High pilot action variability impact on trajectory.	Ground control owns intended trajectory
Mode Control (MC)	The remote pilot provides high level control commands via RC link, such as turn rate (bank angle), climb rate, target altitude, etc., while the manipulation of control surfaces being carried out by autopilot functions.	Reduced pilot action variability impact on trajectory.	
Flight Plan Control (PC)	The remote pilot provides an initial flight plan, and subsequent flight plan amendments during the flight via data link, while the manipulation of control surfaces being carried out by autopilot functions following high level control commands generated by guidance functions.	Eliminated pilot action variability impact on trajectory.	
Autonomous Control (AC)	The remote pilot provides an initial flight plan and/or preprogramed or event driven uplink command to engage autonomous flight control logic that will generate flight intent or flight plan modifications based on sensor data to automatically carry out the flight utilizing guidance and autopilot functions.	Significant situation variability impact on trajectory.	Airborne system (partially) owns intended trajectory

G. Flight Performance Categorization

The FAA's sUAS final rule, 14 CFR Part 107, imposes an 87 kt (100 mph) limit on the groundspeed, rather than on the airspeed. This speed limit is determined based on the potential risk to person, property, and other aircraft in case of loss of positive control [15]. This also requires, for an operation with a planned maximum speed, the pilot taking precautions to ensure that the sUAS will remain within visual line of sight and the it will not pose an undue hazard to other aircraft, people, or property on the ground. Those precautions will likely be greater for an operation with a higher planned maximum speed. Additionally, within the imposed speed limit, winds and turbulence will have a disproportionately higher impact on sUASs than they would on larger manned aircraft flying at higher speeds. Due to atmospheric boundary layer effects, the wind speed at the cruise altitude, e.g., 350 ft AGL, could be twice the value, or more, of the wind speed indicated in weather forecasts and weather reports, which are normally the wind speed at 10 m (typically 33 ft or 27 ft in the U.S.) AGL. For the same airspeed, a strong tail wind will significantly increase the groundspeed, causing the sUAS to exceed the speed limit if it is flying fast enough. Conversely, a strong head wind will significantly decrease the groundspeed, causing difficulties for the sUAS to reach its destination or return to its base. It is thus necessary to establish a maximum speed categorization (Req-7).

The proposed sUAS speed categorization is shown in TABLE IX. This categorization is based on maximum CAS. For a powered sUAS, this is the maximum calibrated airspeed (CAS) that can be achieved during level flight. For an sUAS glider, this is the maximum never-exceed speed. As an initial proposal, four categories are defined. Each of the categories is expected to cover a reasonably large portion of operational regimes or a reasonably large portion of the sUAS fleet. The proposed category code consists of the letter A, which is the same as the ICAO aircraft category code for approach speed less than 91 kt (105 mph), and a numeric.

TABLE IX. SMALL UAS SPEED CATEGORIZATION

Category	Maximum CAS	Explanation
A1	< 22 kt (25 mph)	Intended to cover the slow flying sUAS fleet. Speed criterion to be determined by the ability to maintain safe flight in nominal wind and gust conditions.
A2	≥ 22 kt (25 mph), < 43 kt (50 mph)	Intended to cover the intermediate performance sUAS fleet, which are expected to comprise the largest portion of the entire sUAS fleet.
A3	≥ 43 kt (50 mph), < 65 kt (75 mph)	Intended to cover the more advanced performance sUAS fleet, which are expected to comprise a substantial portion of the BVLOS operations sUAS fleet and of the entire sUAS fleet as well.
A4	> 65 kt (75 mph)	Intended to cover the high performance sUAS fleet. Speed criterion to be determined by the requirement to conduct normal flight operations without exceeding the 87 kt (100 mph) groundspeed limit under normal tail wind conditions.

The *A1* category is intended to cover the slow flying sUAS fleet. This category may include a large portion of the lower-end sUAS fleet, both fixed wing and rotorcraft, that are intended for VLOS operations. The *A4* category is intended to cover the high performance sUAS fleet. These aircraft are most likely intended for BVLOS operations. The other two categories in between are intended to cover the intermediate performance sUAS fleet and the more advanced performance sUAS fleet, respectively. It is expected that these two categories will cover the majority of the overall commercial sUAS fleet.

The granularity and criteria of the fully developed sUAS speed categorization should be refined based on additional in-depth analyses. A survey of the sUAS products available in the market may be conducted to compare the maximum speed and the max wind speed under which the sUAS may be operated. For example, in sports mode, the DJI Phantom 4 quadcopter has a maximum speed of 20 m/s (39 kt/45 mph) and a maximum wind resistance speed of 10 m/s (19 kt/22 mph). A regression and clustering analysis may provide insights into the criteria used in the categorization. Trajectory simulation may also be conducted to provide quantitative results to support the justification. It is worthy to point out that the performance of flight controls is an important factor in determining the sUAS wind resistance capability. The analysis should be based on a nominal level flight control system to avoid the results being biased as overly optimistic.

Small UASs are also subject to up draft and down draft due to terrain, obstructions of manmade structures, trees, thermals, and breeze fronts etc. Vertical maneuvers may be required to avoid obstacles or yield the right of way in traffic situations. The maximum vertical rate is an important factor in maintaining or changing altitudes during flight. A proposed preliminary vertical rate categorization is shown in TABLE X.

TABLE X. SMALL UAS VERTICAL RATE CATEGORIZATION

Category	Maximum Vertical Rate	Note
N	±3 m/s (600 fpm)	Normal, nominal vertical maneuverability.
U	±7 m/s (1400 fpm)	Utility, intermediate vertical maneuverability.
H	±10 m/s (2,000 fpm)	High performance, agile vertical maneuverability.

Other flight performance factors to consider may include WTC. Additional analysis is required to consider lateral and vertical separation minima, wake turbulence, formation or swarming flying, ground effects, and effects of nearby structures in a holistic manner.

IV. SUMMARY

Through this effort, categorization methods applied to manned aircraft and existing UAS categorization methods (including model aircraft) were reviewed to provide a starting point for additional analyses of sUAS-specific characteristics. Based on that analysis, particularly implications of various factors on sUAS trajectories, an sUAS categorization framework was established to support trajectory management and traffic services. Unlike prior UAS categorization studies geared towards airworthiness certification that resulted in a single categorization in each case, the sUAS categorization framework proposed in this research includes categorization methods for each of the following aspects: aircraft configuration; type of flight; flight rules; PBN capabilities; flight and operations control; and flight performance.

Initial criteria for the categorization methods were selected based on either the limited data from the review of existing manned and unmanned aircraft categorization methods, or on a preliminary quantitative or qualitative analysis. The categorization framework is expected to be iteratively improved and refined as the understanding of sUAS-specific operational characteristics deepens and the trajectory modeling research progresses. Numerical analysis required to support the determination of various categorization criteria are identified and suggested for the final determination and incorporation of the categorization framework into UTM operations.

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