Framework for Risk-Based Derivation of Performance and Interoperability Requirements for UTM Avionics

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***Abstract*— In order to define system requirements for avionics used for low-altitude, small, Unmanned Aircraft Systems (sUAS) operations, the functions those avionics must perform need to be identified. Since avionics are an important contributor to ensuring the safety of sUAS operations, one way to determine what functions are necessary is to identify the operational hazards Unmanned Traffic Management (UTM) avionics must help mitigate.**

SUAS operations have the potential to pose a risk to persons onboard other aircraft, as along with persons and property on the ground. Thus, the primary safety objectives are to prevent collisions between sUAS and manned aircraft, as well as collisions between sUAS and persons or property on the ground. Together with procedural and operational mitigations, UTM avionics would need to sufficiently mitigate operational hazards that could potentially lead to such collisions. However, depending on the operation, the type and level of exposure to such hazards will vary, and as a result the level and type of mitigations that UTM avionics need to provide will differ.

Three operational categories are proposed in this paper, each with a specific set of operational hazards that have the potential to negatively impact safety. Category 1 operational hazards consist of collisions with fixed, or nearly-fixed, ground-based obstacles, including humans. Other operational hazards are excluded by nature of the operation or the operational environment. For example, a Category 1 operation may be the within line-of-sight inspection of a cell tower, where the presence of manned aviation can be excluded due to the presence of the cell tower. Category 2 includes Category 1 hazards as well as moving (ground-based) vehicles and other sUAS. An example would be a Beyond-Line-of-Sight (BLOS) inspection of a power-line, where manned aviation can still be excluded, but where there is a potential of encountering another sUAS. Category 3 further includes manned aviation – air transport as well as "Low and Slow" aircraft – in addition to Category 1 and 2 hazards. An example of this type of operation would be a BLOS inspection of a pipeline; the operation could no longer "take credit" of any infrastructure to mitigate the possible hazard of manned aviation.

High-level system requirements for equipment that helps in the mitigation of operational hazards are derived for each operational category. Category 3 operations are of particular interest since they have the potential of interacting with manned aviation either within the UTM airspace, or during operations near the interface between the UTM airspace and the airspace immediately above it (usually Class G or E airspace). This introduces additional system requirements related to the interoperability of the two traffic management systems, which are explored in the last section of the paper. Specifically, if the sUAS is transmitting position and velocity information, that information must meet accuracy and integrity requirements in order for it to be used in separation assurance functions. If the sUAS uses position information received from another aircraft to execute collision avoidance maneuvers, those maneuvers must be coordinated with the maneuvers that are being executed onboard the manned aircraft. Similarly, if the sUAS uses a navigation system to ensure conformance to certain airspace and routes, this navigation system becomes a safety critical component, and must thus meet applicable performance standards.

The derivation of lower-level system requirements for specific operations within each category is left as future work.

Keywords*— *UTM, sUAS, System Requirements, Airspace Integration, ADS-B

I. Introduction

To enable the routine use of Unmanned Aircraft Systems (UAS) worldwide, their operations must be conducted so as not to impact the safety of other flight operations or persons and property on the ground negatively.

The level of safety present in today's aviation system is the result of years of technology maturation, research, and operational experience, much of which is codified in aviation regulations worldwide. A fundamental assumption for this aviation system is the presence of one or more human pilots onboard the aircraft to observe, respond, and interact with the operational environment [1]. In addition to the pilot, today's global aviation system also relies on a large number of complex sub-systems that together provide the redundancy and reliability necessary to ensure the safety of flight operations [5].

To ensure the safety of an operation, a pilot operating a manned aircraft executes a wide range of tasks with the primary goal of maintaining the safety of the onboard occupants. In the case of unmanned aircraft, this primary safety objective no longer applies – rather, avoiding injury or damage to property on the ground ("ground risk") and risks from midair collisions with manned aircraft ("midair collision risk") now dominate the hazard analysis and system design [4]. It follows that many of the tasks a pilot of an unmanned aircraft needs to execute will change as well; some will change criticality (e.g. communication and data links), others need to be replaced by an onboard capability (e.g. see and avoid), while others may remain mostly the same, with the exception that they are not executed by a pilot onboard the aircraft (e.g. navigation).

Thus, a change as significant as the removal of the human pilot from an aircraft has the potential not only to reduce the safety of a specific operation, but to cause system-wide effects that may not necessarily be contained to the task of piloting a particular aircraft. The absence of a pilot in the cockpit may propagate across the system, ultimately to result in effects only tangentially related to the original operation. Therefore, to ensure the safety of unmanned operations, the operation must be evaluated in the context of the larger system, not within the constraints of the specific operation or application.

A concept such as the Unmanned Traffic Management System (UTM) proposed by NASA looks at developing an air traffic management system specific to the operation of unmanned aircraft at altitudes generally below those used by manned aviation.[1]

The above-mentioned considerations must be taken into account during its design and evaluation; however, while the UTM can provide the infrastructure for a traffic management of sUAS[2], avionics onboard the aircraft will provide additional capabilities in support of maintaining the safety of an operation. Together, avionics and the UTM can provide significant mitigations against potential hazards. The present paper proposes a framework for how system requirements can be derived from what hazards are to be mitigated, and how avionics as well as the larger UTM system thus contribute to maintaining the safety of sUAS operations.

II. Operational Hazards and Their Mitigations

Low-altitude, UTM-enabled small UAS (sUAS) operations are defined here as operations beyond the visual line-of-sight of the operator, below 500 ft, with aircraft that weigh less than 55 lb. As shown in Figure 1, this operational environment is currently excluded from other efforts to develop regulations and standards. Specifically, RTCA's SC-228 is developing Minimum Operational Standards (MOPS) for sUAS operations above 500 ft, and the proposed Part 107 regulations ("sUAS Rule") govern operations up to 500 ft and within the line-of-sight of the operator.

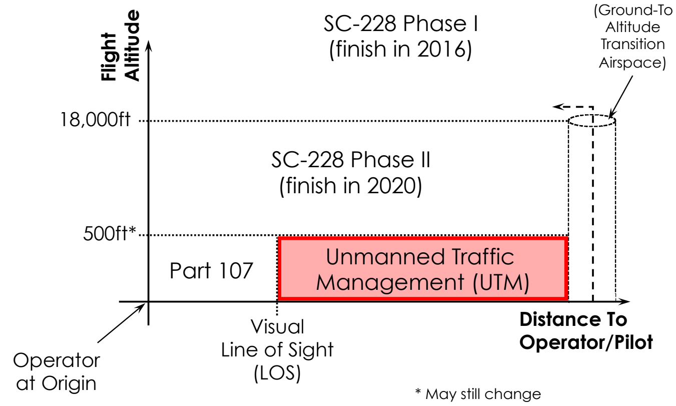

Figure 1: Mapping Between Operational Environments and Ongoing Standards or Regulatory Activities Related to small and large UAS Operations in U.S. Airspace

The types of hazards and the frequency with which they are encountered differ for each operational environment identified in Figure 1. To enable the safety objectives of minimizing midair collision risk and ground risk, those operational hazards must be mitigated properly. The list below highlights the primary operational hazards that a sUAS may encounter:

- **Persons:** Collisions with persons that may or may not be involved with the operation of the aircraft. A distinction must be made between "uninvolved" persons and persons that are "involved" with the operation of the sUAS; the operational hazard of interest is collisions with uninvolved persons.
- **Structures:** Collisions with buildings as well as other fixed, ground-based infrastructure. In addition to the damage that may be caused to the structure, falling debris may pose a hazard to persons on the ground.
- **Vehicles:** Collisions with ground-based, but moving obstacles. This may include cars, trains, trucks, etc. In addition to the damage that may be caused to the vehicle, falling debris may also pose a hazard to persons in or around the vehicle.
- **Other UTM sUAS:** Collisions with other aircraft that are participating in the UTM system. In addition to the damage that may be caused to the sUAS, falling debris may also pose a hazard to persons on the ground.
- **Non-UTM sUAS:** Collisions with sUAS that are not participating in the UTM system Such sUAS include those operated recreationally under Part 107 rules, as well as large UAS transitioning through the UTM airspace while climbing to higher altitudes. In addition to the damage that may be caused to the other UAS, falling debris also may pose a hazard to persons on the ground.
- **"Low and Slow" Aviation:** Collisions with manned aircraft that are intentionally operating at low altitudes for commercial or recreational purposes. This includes helicopters (e.g. police, news, EMS, transportation,

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[1] This paper will refer to an ATM system that is specific to sUAS operations at low altitude as "UTM." It is not intended to be focused solely on the NASA version of UTM, but could be extended beyond that. Additionally, it is currently unclear whether a UTM system would necessarily be distinct from the current ATM system or whether it could be an extension of today's manned aviation air traffic management system.

[2] While the topics discussed in the paper are not necessarily limited to small sUAS (sUAS), the paper will use the term sUAS.

general aviation) and fixed-wing aircraft (e.g. surveying aircraft, crop dusters, firefighting, general aviation). The number of occupants is generally limited to the flight crew. A mid-air collision with a manned aircraft poses significant risk to the onboard flight crew. Additionally, falling debris may pose a hazard to persons on the ground.

- **Transitioning Air Carrier:** Collisions with large, passenger-carrying aircraft. The probability of encountering such an aircraft is limited to areas near commercial airports. A mid-air collision with a manned aircraft poses significant risk to the onboard persons. Additionally, falling debris may pose a hazard to persons on the ground.
- **Equipment Failures:** Failures not due to collisions. The frequency of occurrence is dominated by mean time between failures of flight critical components. Such failures pose a hazard to persons on the ground.

The mitigation of these hazards is necessary in order to ensure safe sUAS operations. Historically, hazards have been mitigated by a combination of multiple safety layers, as shown in Figure 2, consisting primarily of ensuring that aircraft are airworthy (e.g. structurally sound design), that they are equipped with the necessary capabilities (e.g. navigation systems, collision avoidance systems, etc.), and by certifying the ability of pilots to safely operate such aircraft within the context of a complex air transportation system. This air transportation system itself serves as an additional, strategic layer of safety, while aircraft and pilot certifications serve as primarily tactical layers of protection.

This paper is primarily focused on the "Equipment/Rules of Operation" pillar, and how it can be adapted to avionics for sUAS. One concept of particular importance within that pillar is "Separation Assurance". Separation assurance itself consists of multiple independent layers that together minimize the probability of a midair collision. These safety layers can be de-composed into strategic and tactical de-confliction, as shown in Figure 3. Tactical de-confliction can further be broken down into "remaining well clear" (as defined by CFR 91.113), commonly associated with Detect and Avoid equipment within the context of sUAS, as well as "Collision Avoidance," which serves as a last resort in case all other safety layers fail. Depending on the mission and operational hazards, the different layers will be of varying importance.

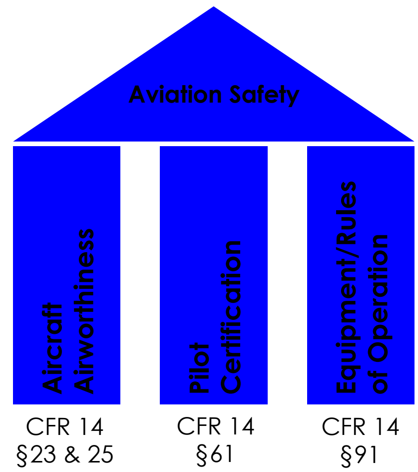

Figure 3: Aviation Safety as Codified in the Code of Federal Regulations (CFRs)

The existing paradigm of aviation safety, as discussed above, was developed and matured with the fundamental assumption of an onboard pilot, and therefore cannot be applied to operations of unmanned aircraft without modification. However, it provides a framework and represents a wealth of knowledge that is available for the development of a similar paradigm for unmanned aircraft.

Depending on the type of sUAS mission (and/or flight phase), certain operational hazards may be more or less likely to materialize. As will be shown later, in some cases a subset of the above hazards can be excluded entirely. It may be possible, therefore, to categorize sUAS operations based on their expected operational hazards; doing so provides the benefit of reducing which hazards would have to be mitigated during a specific operation, and thus may simplify system and certification requirements for aircraft, avionics, as well as reduce required operator training and certification.

A separation of sUAS operations into three categories based on expected operational hazards is proposed in the following sections, with a focus on Level 1 system requirements. A similar categorical grouping was using in a congressional hearing by Prof. John Hansman [2].

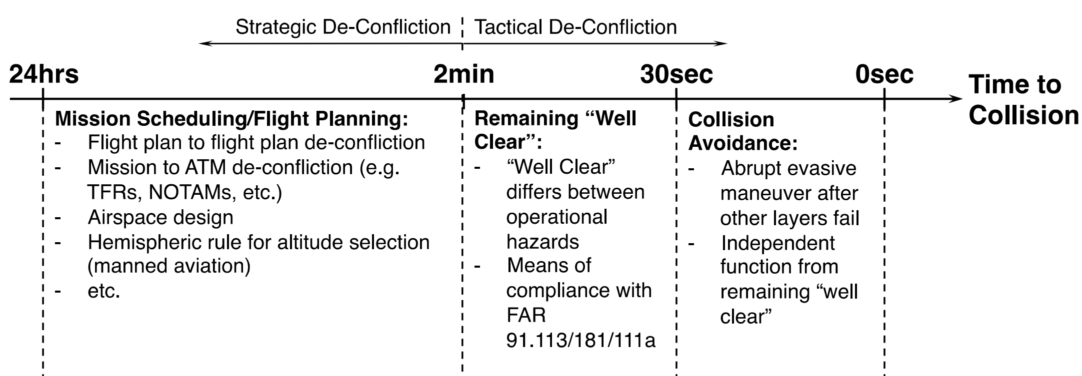

Figure 2: Mapping of Strategic and Tactical Layer of Separation Assurance to Collision Timeline

III. Operational Categories Based on Primary Operational Hazards

Table 1 shows a mapping between the three proposed mission categories and their primary operational hazards.

Table 1: Mapping Between Primary Operational Hazards and Mission Category

Operational Hazard:		Mission Category: Loitering, Partially BLOS	Mission Category: Constrained BLOS	Mission Category: Unconstrained BLOS
Ground	Persons	✓	✓	✓
Ground	Structures	✓	✓	✓
Ground	Vehicles		✓	✓
Airborne	Other UTM sUAS		✓	✓
Airborne	Non-UTM sUAS		✓	✓
Airborne	"Low and Slow" Aviation			✓
Airborne	Transitioning Air Carrier			✓

A. *Category 1: Loitering Operations, partially BLOS*

Category 1 missions occur in close proximity to physical infrastructure, and as a result tend to be at low operational velocities. Visual line-of-sight generally can be maintained, but is interrupted intermittently by the infrastructure. The sUAS poses a hazard to the structure itself, as well as any persons that might be in the vicinity. Other operational hazards are mitigated by virtue of the operational environment: manned aviation and other sUAS "… may not operate closer than 500 feet to any person, vessel, vehicle, or structure" (FAR 91.119c) and ground-based vehicles are not a concern for infrastructure other than roads and bridges (which could temporarily be closed if necessary)."

Figure 4: Category 1 Use-Case: Bridge Inspection. Most operational hazards are mitigated by virtue of the operational environment.

B. *Category 2: BLOS Operations in Constrained Environments*

Category 2 missions are Beyond Line-of- Sight (BLOS) of the operator but occur in an environment that affords some protections to the operation (e.g. power lines, over head wires, trees, etc.). Most of the mission consists of forward flight, and as a result, operational velocities are higher than those of Category 1. In addition to structures and persons, operational hazards include other sUAS that cannot be seen by the operator and must thus be detected by the sUAS or otherwise mitigated during operation. Manned aviation, however, still does not pose a hazard since these sUAS operations occur in close proximity to ground-based obstacles. From the perspective of the manned aircraft, the hazard is the structure around which the sUAS is operating, not the fact that there is a sUAS flying next to it.

Figure 5: Sample Category 2 Use-Case: Rail Track inspection. Manned aviation does not pose a hazard due to the protection afforded by the operational environment.

C. *Category 3: Unconstrained BLOS Operations below 500ft*

Category 3 missions are beyond the line-of-sight of the operator and occur in airspace that does not provide any inherent protection against certain operational hazards. As such, all operational hazards may materialize and must be properly mitigated. Manned aviation operating below 500 ft is limited to specific missions and types of aircraft (e.g. EMS, firefighting, etc.) and in the vicinity of airports.

Figure 6: Operational Hazards for Category 3 Use-Cases Include Manned Aviation.

IV. MITIGATION OF OPERATIONAL HAZARDS

The three pillars enabling aviation safety discussed in Section II must collectively mitigate the operational hazards that remain in each category. These hazards must be mitigated to such a level that they enable achieving the safety objectives of maintaining the safety of the flying public onboard manned aircraft, as well as the safety of persons and property on the ground. Operator Certification and Airworthiness are only considered superficially here, whereas the equipment pillar is considered in-depth.

Historically, the probability of occurrence for an event that leads to a fatality would be considered a "hazardous" event and must be mitigated to 10^{-7} per flight hour. If a large number of fatalities is probable, the event would be considered "catastrophic" and would need to be mitigated to a probability of 10^{-9} per flight hour. As conceptually depicted in Figure 7, the combination of mitigations employed for each operational hazard must together achieve the applicable probability of occurrence per flight hour.

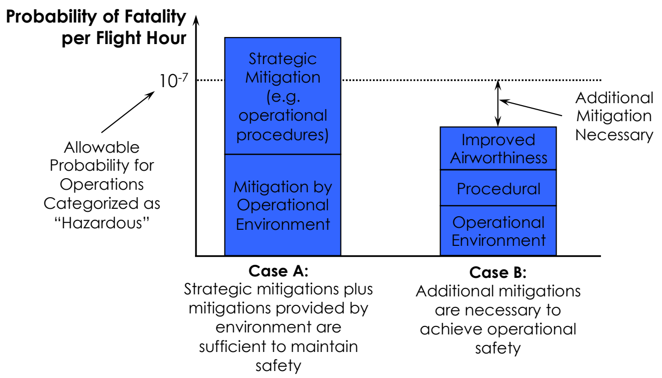

Figure 7: Conceptual Representation of How Multiple Layers of Mitigations Achieve Operational Safety

A. Aircraft Airworthiness

Compared to manned aviation, airworthiness for unmanned aircraft is not primarily to ensure the safety of onboard passengers, but rather for the safety of persons on the ground. As such, the required level of airworthiness for a sUAS should depend on the likelihood that a person would be injured.

In the case of Category 1 operations, the footprint of the operation is commonly small enough to ensure that no uninvolved persons are within the region where the aircraft could fall were a flight critical component to fail. Operations today under "333 Exemptions" already make use of this concept by requiring that a radius of at least 500 ft around to the operation be maintained free of uninvolved persons.

Once the footprint of an operation becomes sufficiently large – as would be the case for Category 2 or 3 operations – ensuring that no uninvolved persons are present becomes infeasible, and the probability of operating above an uninvolved person increases (e.g. a pedestrian during a railroad inspection mission). To offset this increased probability, additional mitigations will be necessary in the form of more stringent airworthiness requirements; i.e., reducing the probability of a component failure. The goal of ensuring that the probability of a fatality remains at the required level, however, remains the same; if the operation is taking place in a rural environment where the probability of encountering a person is very low, the increased airworthiness and equipment requirements will be less than if the flight is operated over a populated area.

When operations occur above populated areas, the probability that an uninvolved person is below the aircraft in the case of a part failure or malfunction approaches 100%. As a result, airworthiness requirements must increase to maintain the same level of safety, since there is a higher probability that a component failure would result in an injury or death. For some operations, it may even be necessary to introduce redundancy such that a failure would not negatively affect the operation of the aircraft; i.e. the performance of the aircraft should remain such that the flight can be terminated safely. Airworthiness requirements would then be derived such that at any point in the flight the aircraft can experience a failure, continue the operation, and reach a landing zone where the operation can be terminated safely while keeping the probability of a fatality at a minimum.

B. Operator Certification

The capability and certification of well-trained pilots or operators of sUAS is an additional layer of protection contributing to achieving the safety of a particular operation and the surrounding airspace. The operator serves two primary purposes: firstly to ensure that the aircraft remains in an operational environment that is representative of the specific category under which the operation is conducted. Secondly, the pilot is a last resort to ensure the safe operation of the aircraft in case of system failures. By way of example, a Global Positioning Systems (GPS) failure or outage may result in the aircraft deviating from a pre-programmed flight path, in which case the pilot can take over and land the aircraft safely.

Depending on operational category, operators will require different levels of capability and certification. Operations that fall into Category 1 may not require any additional training beyond what is required by the proposed sUAS rule (Part 107) operations. For operations that occur beyond the line-of-sight of the pilot, the FAA's "UAS Comprehensive Plan" currently requires that pilots be certified to operate aircraft under IFR flight rules and that one pilot control one aircraft .[3]

C. Hazard Mitigations Enabled by Aircraft Equipment

Operational procedures together with onboard and ground-based equipment provide one of the most important means for mitigating operational hazards. Referring back to Figure 7, risk that cannot be mitigated sufficiently by the operational environment or by improving operator capabilities and airworthiness is mitigated either strategically or, if necessary,

[3] While this requirement is likely going to remain for the near future, a future environment where pilots may be able to serve as supervisory controllers over multiple aircraft is conceivable. Such a paradigm is more likely for operations where the human pilot does not contribute significantly to mitigating the risk in the operation.

tactically by equipment that provides the ability for real-time hazard mitigation.

The type of required equipment and its required performance depend on the hazards that are to be mitigated and the level of mitigation that must be provided. The following sections break down the various strategic and tactical mitigations by operational category and translate them into high-level system requirements.

1) Required Equipment for Category 1 Missions

As proposed in the draft Part 107 rule, the pilot's visual observance of the operation is sufficient to ensure that aircraft remains safely separated from persons and property on the ground. To conduct Category 1 operations above uninvolved persons, however, additional mitigations are necessary; specifically, improved airworthiness contributes to reducing the likelihood of aircraft components falling and causing an injury. Additional strategic mitigations in the form of operational procedures or flight path adjustments also can reduce the probability of an encounter with an uninvolved person.

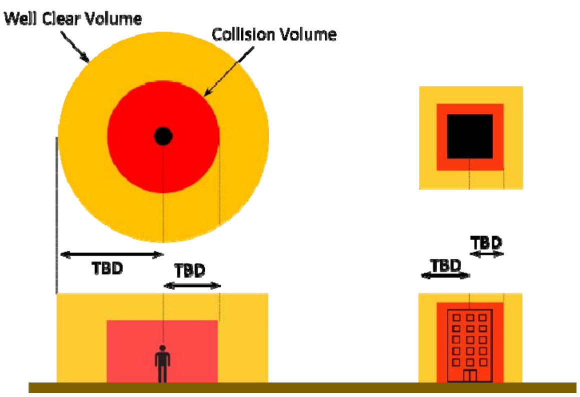

Figure 8: Well Clear and Collision Volumes for Persons and Structures

Tactically, the pilot operating the aircraft remains in control of the aircraft and can intervene in the event of an unexpected encounter with a persons or property. If the probability of an encounter is sufficiently large for situations where the direct line-of- sight to the aircraft is obscured, onboard sensing would be required to notify the pilot of an impending collision. If the pilot does not take action, or in situations where not enough time remains for pilot interaction, the onboard system would be required to abort the mission and remain "well clear" of the detected hazard. The FAA/DoD/NASA/DHS sUAS Science and Research Panel (SARP) is in the process of defining an objective standard for "well clear," and a final recommendation is expected by the end of 2016.

In order to ensure that the sUAS remains in an operational environment representative of Category 1 operations, the operation is assigned an airspace block in advance of the operation. The pilot is responsible for maintaining the operation within that airspace block. If the link to the sUAS is lost, a pre-determined response is automatically executed – namely, the aircraft would be required to land according to a specific flight path and at a specific, pre-programmed landing location. To reduce the likelihood of an intruder entering into the block of airspace, the operation is required to be announced via the UTM system beforehand, similar to how flight plans are filed today. Additionally, to ensure that the operation does not occur in a location where sUAS operations are not allowed, the UTM system can provide notification to the operator about such a potential airspace violation.

In summary, the required equipment for Category 1 operations consists of an automatic flight termination that can be activated by the pilot or is activated automatically when the link to the sUAS is lost or the sUAS has left its assigned airspace block.

Table 2: Method of Separation Assurance for Category 1 Missions (secondary hazards grayed out)

	Strategic De-Confliction	**Remaining Well Clear**	**Collision Avoidance**
Persons	Only above involved persons -or- Increase Required Airworthiness	Human-in-the-Loop -or- On-board Sensing	Human-in-the-Loop -or- On-board Sensing
Structures	Procedural		
Vehicles	Airspace Block/ Comparison against No-Fly Zones	Visual Scanning, Forced Landing inside Airspace Block on Loss of Link or Airspace Violation	
Non-UTM sUAS			
Other UTM sUAS			
"Low and Slow" Aviation			
Transitioning Air Carrier			

2) Approach to Separation Assurance for Category 2 Missions

In addition to the mitigations required for operational hazards in Category 1 operations, Category 2 operations need to mitigate against collisions with moving, ground-based vehicles, as well as other sUAS in the airspace. The closing speeds that can be expected for both those hazards are similar in magnitude, and as a result, their mitigations present similar technological challenges. Since the operation occurs beyond the line-of-sight of the operator, systems onboard the aircraft may be necessary to detect and mitigate the presence of hazards.

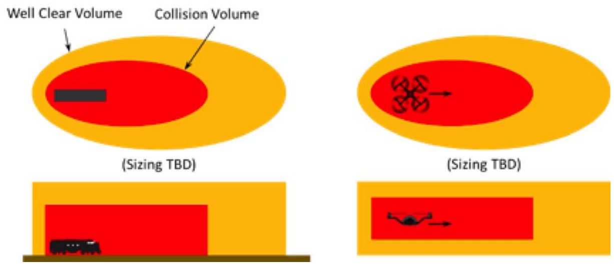

Figure 9: Well Clear and Collision Volumes for vehicles and UAS (notional).

For various operations in very low-density, rural regions, strategic de-confliction may be sufficient to achieve the necessary level of hazard mitigation. For example, if operations can be constrained to an altitude where no ground vehicles will be encountered, onboard sensing will not be necessary. If not, a loss of well clear or a collision must be mitigated tactically by the use of onboard sensors. The required sensing performance depends on the expected closing speeds (e.g. high-speed train vs. car in school zone), as well as the dynamic authority of the aircraft to get out of the way in time to remain “well clear.” No objective definition of ”well clear” or “collision volume” for Category 2 hazards exists. In the absence of a standard that is broadly accepted within the community, therefore, the operator would need to demonstrate that the aircraft has the necessary performance to mitigate the probability of collision sufficiently.[4]

For sUAS that are participating in the UTM system, a base-level of equipage can be assumed, which makes avoiding collisions with them more straight forward. The ownship aircraft can broadcast its own position to such sUAS while simultaneously receiving theirs using vehicle-to-vehicle (V2V) communication protocols.

Similar to Category 1, in order to ensure that missions of this type do not leave their operational environment, a block of airspace along the flight path is assigned to the operation an announced through the UTM system. However, for Category 2 operations, the aircraft will be required to monitor conformance to that airspace and initiate a lost-link or loss-of-GPS procedure rather than a pilot providing this function. As a result, the navigation system becomes a safety critical component of the operation. When using a Global Navigation Satellite Systems (GNSS) receiver for positioning and navigation, this translates to accuracy and integrity requirements; i.e. the position source must be capable of determining the aircraft’s position with an accuracy that is better than the size of the assigned airspace block, and do so with high reliability. Additionally, in order to ensure the navigation system detects degraded performance or failures in the GNSS constellation, integrity monitoring akin to Receiver Autonomous Integrity Monitoring (RAIM) used in manned aviation will be required. Similarly, if the measured position is transmitted to other sUAS for use in separation assurance functions, position accuracy and integrity requirements apply to the transmitted information.

Table 3: Method of Separation Assurance for Category 2 Missions (secondary hazards grayed out)

	Strategic De-Confliction	Remaining Well Clear	Collision Avoidance
Persons	Only above consenting persons -or- Increase Required Airworthiness	On-board Sensing	On-board Sensing
Structures	Procedural		
Vehicles	Procedural		
Non-UTM sUAS	Procedural		
Other UTM sUAS	De-confliction by UTM (Flight Plan Comparison)	V2V Coordination[5]	V2V Coordination
“Low and Slow” Aviation	Designated Route Airspace/ Comparison against No-Fly Zones	Forced Landing inside Designated Airspace on Loss of Link/GPS or Airspace Violation	
Transitioning Air Carrier			

In summary, Category 2 operations would be required to carry a flight termination system, a position source with appropriate accuracy and integrity monitoring, V2V communications equipment, as well as a navigation system capable of maintaining an operation within a predefined flight path with high reliability. Today’s aviation grade equipment meets and probably exceeds these requirements and could serve as a starting point.

3) Approach to Separation Assurance for Category 3 Missions

Unlike Category 1 and 2, Category 3 operations have the potential of interacting with manned aviation. Since manned aviation already operates within a well-defined air traffic management system (ATM), Category 3 operations must be conducted in a way that is interoperable with this existing system. This effectively introduces additional system requirements for UTM avionics, which may in some cases be

[4] It should also be noted that a collision between two sUAS is not the primary hazard to be avoided; instead, injury to persons on the ground from falling debris is the primary concern. A collision between sUAS would only be considered a causal factor.

[5] V2V is defined generically as Vehicle-to-Vehicle communication and does not imply a specific technology implementation. Potential solutions that have been proposed include ADS-B or V2V technology that has been developed by the Department of Transpiration under the “Smart Cities” initiative.

beyond what would be necessary to ensure safe mitigation of expected operational hazards.

Category 3 operations would be required to file an Instrument Flight Rules (IFR) flight plan[6], which will provide a means of strategic de-confliction with any operations for which a flight plan is filed in the same region. Additionally, while not currently required for manned IFR operations, issuing a Notice to Airmen (NOTAM) would provide notification to operators flying under visual flight rules in that same region. As was the case for Category 1 and 2 operation, in order to ensure that the sUAS remains in an environment that is representative of Category 3 operations, a block of airspace along the flight path is assigned to the operation. Much like Category 2 operations, the aircraft would be required to monitor that it remains within that airspace and terminate the flight automatically if it leaves the airspace or observes an onboard failure or system degradation that would prevent the aircraft from monitoring conformance to the airspace.

Tactically, in most cases, onboard sensing of non-cooperative aircraft, as well as cooperative aircraft, will be necessary in order to sufficiently mitigate the probability of collision with a manned aircraft. For operations in extremely remote environments, procedural separation to ensure that no manned aircraft are within the vicinity of the operation may be sufficient. This was the case during FAA approved sUAS operations in the Arctic in 2014.

The required sensing performance for avionics enabling Category 3 operations depends on the expected closing speeds as well as the dynamic authority of the aircraft to get out of the way in time to remain "well clear." Part 107 proposes a maximum operational velocity of 100 mph for line-of-sight operations below 500 ft; but no current definition of "well clear" and the collision volume currently exists. RTCA's SC-228 will derive a definition during its Phase II activity that could potentially translate to UTM operations. Alternatively, the SARP may consider a definition of well clear between sUAS and manned aircraft in the future as well.

To ensure reliable separation assurance between manned and unmanned aircraft, the onboard systems must be interoperable and coordinated. Current separation assurance systems such as the Traffic alert and Collision Avoidance System (TCAS) interrogate other aircraft to evaluate whether they are an immediate collision threat. For this to be possible, all other aircraft must be equipped such that they can respond to such interrogations, ensuring *interoperability*. Additionally, if TCAS determines that an aircraft is in fact a threat, the manner in which it avoids the other aircraft is determined according to a standardized algorithm so that it's maneuver is very predictable. This allows other aircraft to *coordinate* their avoidance maneuver accordingly.

Separation assurance systems for sUAS would need to be designed with these same requirements in mind. Specifically, V2V communication for the purposes of position reporting must be interoperable with existing systems used by manned aviation, while at the same time not introducing negative effects. Specifically, ADS-B provides a viable option, but if an airspace experiences high densities of aircraft, frequency congestion may result in a reduction of reception ranges, reducing the overall safety of the airspace. Additionally, in order to use aviation spectrum, ADS-B transmissions must meet existing performance standards on how "good the broadcast information must be" (e.g. maximum allowed position or velocity accuracy, altimetry performance, etc.). The introduction of a new system for exchanging this type of information between aircraft introduces additional challenges as the question of interoperability must be addressed as part of the introduction as well.

Interoperability with TCAS in particular, however, may be simplified. TCAS does not issue collision avoidance instructions below 700 ft; thus, if the sUAS remains below 500 ft, the ability to respond to TCAS interrogations may not be required, which could potentially remove the requirement for the sUAS to carry a transponder.

In order to ensure coordination in avoidance maneuvers between sUAS and manned aircraft, as well as between sUAS, the algorithms used by sUAS to determine the maneuver must be standardized across implementations. A significant amount of literature is available on the subject – the algorithm that is currently favored for use by unmanned aircraft (small or large) is ACAS X_u. A summary of the ACAS X-family of algorithms can be found in [3].

An additional consideration is whether a separation assurance algorithm must reside onboard the aircraft. Recent proposals under NASA's UTM program place this functionality in "the cloud," where increased computational resources allow solving for more optimal outcomes. This architecture, however, makes the communication and control link to the aircraft safety critical component. The probability that the data link to the aircraft may drop must now be taken into consideration when calculating the mitigation probabilities.

To protect against manned aircraft that are not equipped with any means of electronic identification, publishing a flight plan, as well as a Notice to Airmen (NOTAM), would be a strategic means for reducing the probability of encounter. If the operational environment coupled with strategic mitigation does not provide the necessary level of safety, onboard sensing to detect such aircraft will be necessary. There is a potential that some of these aircraft fly at high speeds – some crop dusters spray fields at 180 kts.

It should also be noted that for sUAS operations the driving system requirements will necessarily be the same as what it would be for manned aviation. Traditional aerospace considerations of data accuracy, data integrity, design assurance levels as well as overall system performance will drive avionics requirements for systems used on manned aviation. For UTM avionics, sUAS-specific limitations such as size weight and power will have a significant effect on achievable performance. Additionally, differences in aircraft performance, traffic density, the role of the human pilot, and even business objectives will result in avionics requirements

[6] As mentioned in Section IV.B, low-altitude, BLOS operations are expected to occur under Instrument Flight Rules for the foreseeable future.

that would not commonly be considered for avionics on manned aircraft.

Table 4: Method of Separation Assurance for Category 3 Missions

<table>
<tr><th></th><th>Strategic De-Confliction</th><th>Remaining Well Clear</th><th>Collision Avoidance</th></tr>
<tr><td>Persons</td><td>Only above consenting persons
-or-
Increase Required Airworthiness</td><td rowspan="4">On-board Sensing</td><td rowspan="4">On-board Sensing</td></tr>
<tr><td>Structures</td><td>Procedural</td></tr>
<tr><td>Vehicles</td><td>Procedural</td></tr>
<tr><td>Non-UTM sUAS</td><td>Procedural</td></tr>
<tr><td>Other UTM sUAS</td><td rowspan="3">Designated Airspace Block,
IFR Flight plan, NOTAM, De-confliction by UTM</td><td rowspan="3">On-board Sensing
and[7]
V2V Coordination</td><td rowspan="3">On-board Sensing
and
V2V Coordination</td></tr>
<tr><td>“Low and Slow” Aviation</td></tr>
<tr><td>Transitioning Air Carrier</td></tr>
</table>

In summary, Category 3 operations would require the same equipment as Category 2, as well as be required to use systems that are interoperable with manned aviation. This interoperability on one hand requires that the source used to derive the state data for the aircraft meets the requirements of manned aviation, but also that the information is transmitted such that manned aircraft can receive it. Additionally, any avoidance algorithms used by the sUAS must meet the requirements of the ACAS family of algorithms to allow for safe maneuver coordination between the two aircraft.

D. Operational Approval

The UTM system proposed by NASA includes a provision that requires all aircraft operated in the UTM system to be registered. As part of this registration process, the type of aircraft, owner, or operator, as well as the aircraft’s capabilities would be captured. For each aircraft, therefore, the UTM system could identify which operational category it can support, and thus provide clearance for a particular operation (analogous to the “cleared for departure” in manned ATC). While filing the flight plan, the operator identifies the aircraft that would be used for the mission, which allows the UTM system to compare the required onboard technology capability and airworthiness to the threshold for the proposed operational category.

[7] Cooperative and Non-Cooperative target detection is necessary.

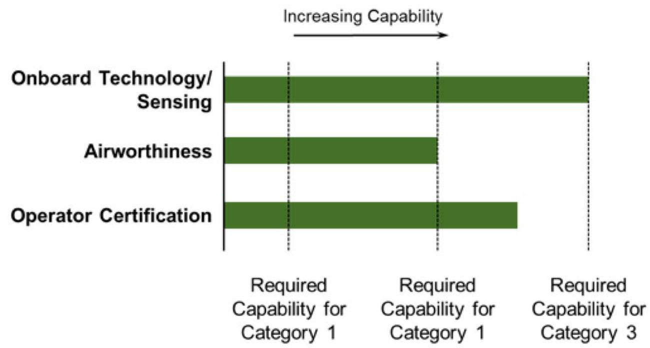

Figure 10: Notional Method of Determining Operational Approval for a Particular Mission

Figure 10 shows a conceptual approach to how this can be done within the UTM system. When an operator requests a particular mission, the operator must first log into the UTM system, which will allow for positive identification of the operator and his/her associated certifications. In order to receive operational approval, the onboard systems, airworthiness, and operator certification must all meet the minimum requirements listed for the operational category of the mission. In the case of Figure 10, missions of Category 1 and 2 would be approved, but Category 3 missions would be denied.

V. DISCUSSION AND CONCLUSION

While UTM provides a traffic management system that aids in strategic de-confliction, onboard equipment will be required in most cases to ensure that operational hazards are sufficiently mitigated. Dividing sUAS operations into different categories based on their operational hazards represents one approach that can be used to simplify system requirements and provides a framework that can be used to determine how and when an operation should receive operational approval.

In some situations, the proposed approach may not be as beneficial. One example would be operations where the benefit of the operation outweighs the potential risk of the operation, as may be the case in the delivery of urgently needed medication to villages without access, as was the case in Rwanda in early 2016. Another example where operational hazards may not be driving system requirement is a case where requirements levied by insurance agencies to as part of an operational insurance policy results in more stringent equipment implications. One example of such a case may a requirement that an antenna on a cell tower cannot be damaged during an inspection, thus requiring onboard sensing, even though there may not be any risk to human life.

A. Future Work

The derivation of functional and performance requirements is left as future work. Additionally, airworthiness requirements and the level of necessary pilot training will be evaluated in more depth. Lastly, applying the proposed methods to actual operations for evaluation in the filed would serve as a validation of the overall approach.

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