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System-Level Airworthiness Tool

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One of the pillars of aviation safety is assuring sound engineering practices through airworthiness certification. As unmanned aircraft systems grow in popularity, the need for airworthiness standards and verification methods tailored for unmanned aircraft systems becomes critical. While airworthiness practices for large unmanned aircraft systems may be similar to manned aircraft, it is clear that small unmanned aircraft systems require a paradigm shift from the airworthiness practices of manned aircraft. Although small in comparison with manned aircraft these aircraft are not merely remote-controlled toys. Small unmanned aircraft systems may be complex aircraft flying in the national airspace system over populated areas for extended durations and beyond line of sight of the operators. A comprehensive systems engineering framework for certifying small unmanned aircraft systems at the system level is needed. This work presents a point-based tool that evaluates small unmanned aircraft systems by rewarding good engineering practices in design, analysis, and testing. The requirements scale with vehicle size and operational area, while allowing flexibility for new technologies and unique configurations.

I. Introduction

THE system-level airworthiness tool (SLAT) is a systems engineering framework designed to help civil and public certifying authorities (CA) as well as nontraditional aerospace manufacturers determine the requirements for fixed-wing small unmanned aircraft systems (UAS) flight over populated regions in the national airspace system (NAS). SLAT uses a concept of *safe* that is commensurate with the equivalent level of safety (ELS) that currently exists to third parties on the ground due to aircraft crashes, one fatality per ten million flight hours.§ For this research the risks to other airspace users due to small UAS flight (primarily midair collision concerns) were not considered.¶ The category of small UAS is defined as those UAS with a maximum takeoff weight (MTOW) between 2 and 350 lb. Airworthiness requirements (criteria, standards, and verification methods) scale based on the population density of the mission area and the threat of a vehicle crash to people on the ground. Methods for determining population density categories, UAS lethality and crash model have been incorporated such that SLAT prescribes very few requirements for flights over unpopulated areas to very stringent requirements for flight over open air assemblies such as sporting events or large outdoor celebrations. By bringing all of the different UAS domains into a comprehensive framework, SLAT allows a CA or project manager to easily determine a system's strengths and weaknesses, while also allowing CA to compare levels of airworthiness among dissimilar UAS. It is expected that this tool could be used by both project managers in industry and CA to determine the most cost effective manner to design, build and test small UAS by providing them a clear path toward certification with built-in flexibility for new technologies and techniques. SLAT easily adapts to various standards and verification methods, scaling the airworthiness requirements to reflect the threat of the UAS to people in the mission area.

The upper-bound on MTOW for SLAT is loosely based on the lower bound of 150 kg set by STANAG 4671: UAV Systems Airworthiness Requirements [2] that defines the minimum airworthiness requirements for larger UAS usage in the airspaces of NATO member states. The lower limit of 2 lb is based on crash lethality research (Chapter 3 of [3]) done at North Carolina State University that revealed UAS below 2 lb are unlikely to cause life-threatening injury in the event of an uncontrolled crash. SLAT limits its range to below the vehicles covered by STANAG 4761 and above the 2 lb lethal limit.

The goal for SLAT is to create a tool to help those CA and aircraft manufacturers that may not have significant airworthiness experience to be able to better address the unique difficulties of UAS certification. SLAT is not designed to replace engineering judgment by qualified engineers, but rather to provide a framework for evaluating the risk of small UAS operations in different environments in a quantitative way using system safety tools. No single tool can encapsulate every possible situation and so it is therefore imperative that qualitative engineering judgment be used in determining the final safety assessment of any UAS system. It is hoped that SLAT will be useful to public agencies such as police departments or state universities who must attest to the airworthiness of any small UAS that they operate in the NAS, but who have very little airworthiness experience. SLAT could also be useful for aerospace manufacturers, especially those that do not often produce manned aircraft, such that they could design a UAS with airworthiness certification in mind and be able to provide solid verification and validation documents to the appropriate CA when request certification for their systems.

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§This value is based on statistical analysis of fatalities due to aviation accidents to third parties (those people not actively involved in the flights). The number of fatalities were calculated from National Transportation Safety Board (NTSB) data by researchers at the University of Queensland [1] for general aviation and commercial flight data from 1985–2006. This data is freely available on the NTSB website (www.ntsb.gov).

¶An expansion of the current research effort is beginning to address these airspace integration concerns and expand SLAT to properly handle those issues. NAVAIR Public Release 10-858: Distribution Statement A: approved for public release; distribution is unlimited.

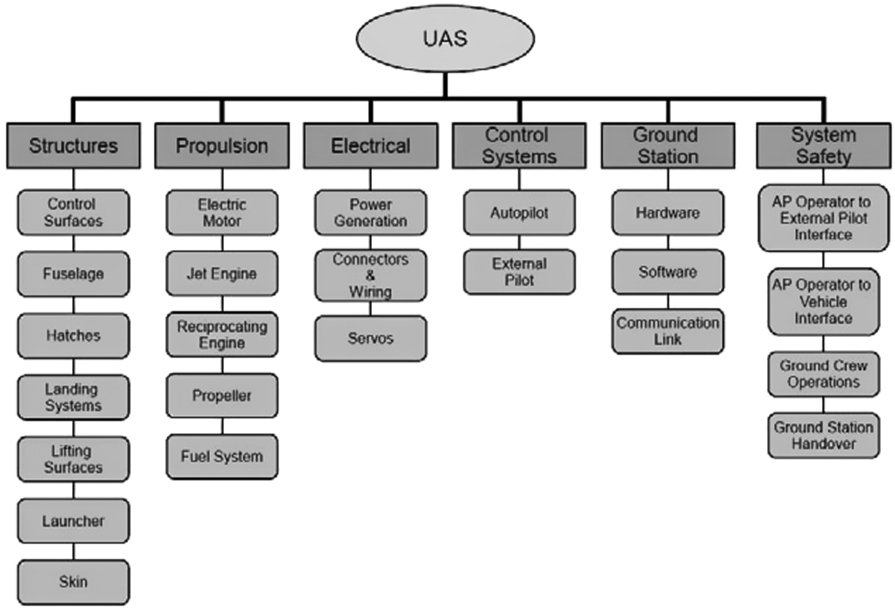

Fig. 1 SLAT overview showing domain breakdown.

Before any discussion of UAS airworthiness can be undertaken it is important to understand the airworthiness process for manned aircraft. The military definition of airworthiness is "the ability of an aircraft to obtain, sustain, and terminate flight in accordance with prescribed usage requirements" [4]. This covers all phases of flight and focuses on the aircraft's ability to fly. Safety of flight (SoF) is another term that is often used when discussing aircraft safety and is defined as the property of an air system configuration to safely attain, sustain, and terminate flight within prescribed and accepted limits for injury/death to personnel and damage to equipment, property and/or environment. In this way airworthiness captures those safety aspects related to the safe operation of the vehicle and SoF captures those safety concerns that could arise due to that operation. An example of a SoF concern would be a nonflight critical component inadvertently falling off an aircraft in flight (e.g. a missile falls off a fighter jet during maneuvers). The loss of the missile would not present an airworthiness concern since the aircraft would be able to continue flying without any problems, but it would pose a danger to people on the ground. Because UAS are uninhabited, the focus of safety processes to date for small UAS has been more to SoF considerations to third parties on the ground than to the airworthiness of the systems. Primarily this has been achieved through operational limitations to sparsely or unpopulated areas. These two aspects of aircraft safety are more closely linked to each other in the UAS context as improving the airworthiness (ability to fly safely) of the aircraft greatly reduces the risk that UAS pose to people on the ground. Since the commensurate level of safety is dependent on threat to people in the mission area a UAS could be considered airworthy for flights over sparsely populated area, but not airworthy for flights over a city. This differs from the typical view of airworthiness for manned aircraft where the focus is on ensuring that the aircraft is safe for the crew and passengers.

For U.S. military aircraft the guidelines for airworthiness are defined in MIL-HDBK-516B [5], while U.S. civil airworthiness standards are defined in the Federal Aviation Regulations (FARs) contained in Title 14 of the Code of Federal Regulations [6]. Subchapter C of [6] parts 21 through 49 contain detailed airworthiness and SoF requirements that vary depending on aircraft type, use, and some individual components.** The European Union has very similar legislation for civil airworthiness covered in CS parts of the same numbers (FAR Part 23, which defines airworthiness requirements for the small airplane category, is basically mirrored by CS Part 23) and enforced by the European Aviation Safety Agency (EASA). By necessity, military airworthiness guidance is typically more flexible in order to accommodate new technologies, challenging environments, and a variety of missions. While elements of U.S. Air Force, Army, and Navy/Marine Corps airworthiness processes vary, in general the military CA develops an airworthiness certification plan based on a tailoring of the MIL-HDBK-516. In this tailoring process, applicable criteria are chosen for the specific aircraft configuration being examined, standards are associated with each criterion, and a verification method is associated with each standard. The technical data product that documents the analysis, simulation, or test used to address the design issue is called an artifact. The final set of artifacts for each item is determined as part of the plan to certify airworthiness. In the end, this plan defines the requirements that the aircraft must meet to be considered airworthy. In many ways SLAT mimics the engineering/data requirement agreement plan (EDRAP)†† approach through the tailoring of the failure modes, effects, and criticality analysis (FMECA) sets, while providing a method for handling differing standards and verification methods. The airworthiness artifacts are what are presented to a CA to earn points in SLAT.

II. SLAT Overview

SLAT is a point-based tool where UAS earn points toward airworthiness based on good engineering practices. Points are earned as a UAS manufacturer shows design, testing, and mitigation artifacts to support the proposed operation of their vehicle. The foundation of SLAT is a tailored FMECA where all of the reasonable failure modes are detailed along with their causal modes and methods to mitigate each failure.‡‡ The FMECA is done at the component level for all of the domains except for System Safety, which is a functional FMECA. The FMECA is tailored to capture the configuration of each UAS. The supplemental document "SLAT FMECAs" that accompanies [3] provides a fairly extensive set of base FMECAs

**The US civil airworthiness standards are designed such that engines and propellers are certified separate from the aircraft. FAR Part 35 contains all of the airworthiness requirements for propellers. This differs from the standard military approach of certifying the airworthiness of the aircraft as a whole (if the engine is changed the airworthiness release would need to be modified to reflect the configuration change). SLAT follows the military model in its approach to configuration control.

††The EDRAP is the process of tailoring the airworthiness criteria presented in MIL-HDBK-516 to fit a specific aircraft configuration.

‡‡The term *reasonable failure modes* is used to ensure that effort is not wasted on unrealistic situations (e.g. wing spar failure due to micrometeorite impact). It is also important that when determining the outcome of a failure that the worst credible outcome be chosen over the worst conceivable outcome.

to facilitate in the tailoring: a few pages of one of those FMECA sets are provided in Appendix A of this paper to help illustrate the FMECA tailoring process. The applicant earns more points towards certification by addressing the most critical failures as identified by the FMECA. Unlike more rigid pass/fail requirements for airworthiness artifacts in manned aviation, the artifacts in SLAT are graded such that the number of points depends on the quality of the analysis/testing performed.

SLAT divides any UAS into six domains: structures, propulsion, electrical, control system, ground station, and system safety. The structures domain includes all physical structural members, the skin of the aircraft, control surfaces and components, hatches, and landing gear or launcher system if applicable to air vehicle-based launch/recovery gear or land-based launch/recovery systems as applicable. The propulsion domain comprises the engine or motor, propeller, fuel systems, and power generation as applicable. The electrical domain includes all of the wiring, connectors, and electronic servos in the aircraft. The control system domain is composed of two parts: external pilot and autopilot. The ground station domain includes all of the components used by the operators including all data links (e.g., command and control, voice communications, payload/sensor telemetry, etc.) as applicable to the vehicle configuration. The system safety domain captures those functional aspects of the aircraft that have not been captured by the individual domains. Specifically the system safety domain focuses on the interfaces between domains and operational aspects such as UAS handoff between two different control stations. Figure 1 shows the domain breakdown as it has been arranged for the base FMECA sets. Clearly there are some components that are mutually exclusive (such as electric motors and reciprocating engines) or items that may not be present in all configurations (such as power generation). The first step in SLAT is to tailor the FMECA sets to accurately reflect the specific UAS configuration being examined. The overlapping FMECA sets are supplied to provide a larger basis for a UAS designer to pull from for the initial configuration. By providing a sufficiently complete set of basis FMECA sets to draw from that the tailoring process will be more approachable by developers who may not be intimately familiar with the FMECA process.

The UAS must earn enough points on a domain by domain basis such that all of the domains reach a common target level of safety (TLS). The TLS is the goal that a UAS must reach to be considered safe to fly that particular mission. Each of the different domains has its own column and the goal is to earn points by showing good engineering practices to bring each domain to at least the TLS line. This is based on the concept that any UAS is only as safe as its weakest domain. The TLS algorithm was designed to scale with the threat of the vehicle to those people on the ground and is directly derived from the ELS discussed previously.[§§] The TLS was designed to vary as a function of the wingspan of the aircraft, the weight of the aircraft, and the population density of the mission area. The TLS was scaled such that a 350 lb UAS flying over the most crowded, least sheltered situation will be required to approximate the requirements for small manned aircraft. Figures 2 and 3 below shows a view of the top level break down of SLAT and how the TLS scales with the mission population area.

SLAT uses tailored FMECA sets as the foundation for the tool. A FMECA is a system safety tool that provides a framework for breaking down a complex system into subsystems, then assemblies, and finally down to its base components. At the component level all the reasonable failure modes are explored. An attempt is made to determine what causal factors could lead to each failure mode, what the result of the failure will be to that domain and the overall system, and how bad that failure is in comparison to other failures. One of the final results from a FMECA is a list of recommendations on how to avoid each failure mode on an individual causal mode basis.[¶¶] These recommendations provide valuable data that the CA wants to see during the airworthiness certification process.

[§§]Sec. IV of this paper details the derivation of the TLS algorithm.

[¶¶]The FMECA format often has a column for "Recommended Actions" [7] that can help avoid a particular failure mode. It is the entries from that column that is discussed as the final result of the FMECA that relates to the test creation in SLAT.

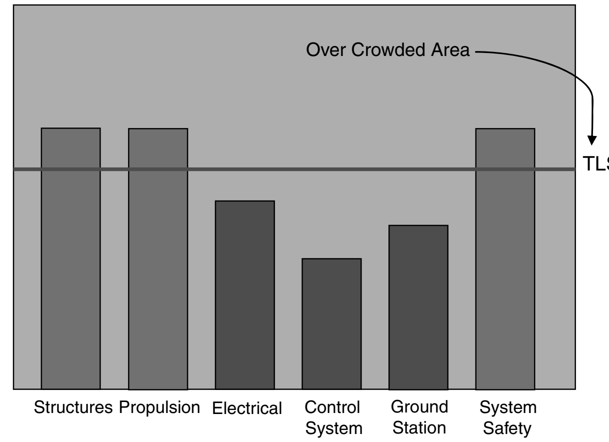

Fig. 2 Top-level view of SLAT showing TLS over populated area.

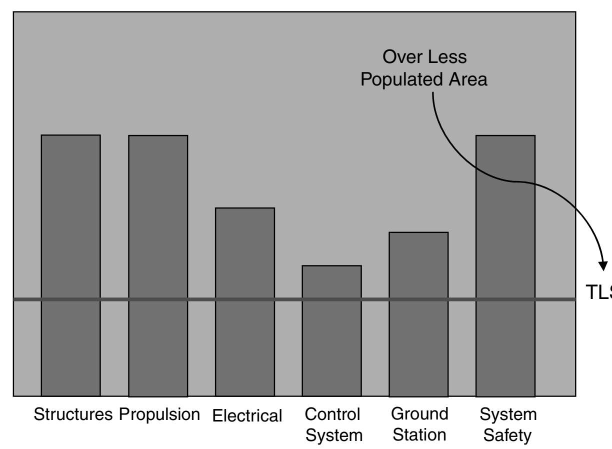

Fig. 3 Top-level view of SLAT showing TLS over less populated area.

To be able to characterize the severity of the failure, it is helpful to create failure categories. SLAT uses four failure categories: catastrophic, critical, major, and minor. These hazard categories are based on the format typically used by the military and FAA for hazard analysis. Catastrophic failures comprise those most-feared events including the uncontrolled crash of the UAS (where people on the ground are at risk) or permanent injury or fatality to the ground crew (such as the control station trailer catching fire or a crew member being severely injured by the vehicle launch system). During the initial FMECA research it was found that there were series of failures that dictated the creation of a subcategory of the catastrophic category called catastrophic fly-away. This subcategory of catastrophic captures those failures that result in an unmanned aircraft flying without supervision and with no way of recovering that supervision. The fly-away failure category, although not totally unique to unmanned systems, is much more of concern with the human crew removed from the aircraft. The critical failure category captures those failures that result in an inability to maintain flight, but where some control over the aircraft trajectory is still maintained (i.e. loss of propulsion, aircraft can still glide away from populated areas). The major and minor categories capture those failures that result in some reduction in safety margins, but are not a direct threat to the aircraft. Table 1 below shows the basic descriptions for each of the failure categories and their priority.

III. Risk Model

The TLS is designed to scale with the threat of the vehicle to people in the operation area. To accomplish this scaling a risk model was

Table 1 Failure categories

Hazard level	Description
Catastrophic	Complete loss of control of the aircraft or fatality to ground crew. The vehicle has had a failure where the crew cannot control where it crashes.
Catastrophic fly-away	The aircraft has gone "dumb" and is flying out of the mission area under some form of autopilot control with the operator unable to redirect the vehicle.
Critical	Loss of operator control over aircraft, inability to maintain flight trajectory or injury to ground crew. This includes lost link situations where the autopilot goes to a predetermined rally location as well as loss of propulsion where the crew still has control over the vehicle, but can no longer maintain altitude.
Major	Emergency situation, land as soon as practicable. This includes failures that significantly reduce safety margins or vehicle performance or significantly increase ground crew work load.
Minor	Little or no effect on vehicle performance or ground crew workload.

Table 2 Population density categories and representative values

Category	Description	People per square mile
Open air assembly	Any event of more than 1000 people in one location. (e.g. college football game)	99,000
Densely populated	Anywhere inside the yellow regions on the sectional charts	9900
Sparsely populated	Anywhere outside of the yellow regions on the sectional charts	500
Unpopulated	Areas where access control has been shown to guarantee unpopulated status (e.g. controlled test range)	50

Table 3 Example UAS mission: traffic monitoring

Mission stage	Population category	Total time spent	Percent of mission	Time-weighted average population density, ppl/mi^2
Launch	Sparsely populated	0.25 h	5%	25
Ingress	Densely populated	0.75 h	15%	1485
Loiter	Densely populated	3.0 h	60%	5940
Egress	Densely populated	0.75 h	15%	1485
Landing	Sparsely populated	0.25 h	5%	25
——	——	Total 5 h	Total 100%	Total 8960

developed to encapsulate the relative threat that any small UAS poses to people on the ground. There are three components to the risk model used in SLAT. First is the method for easily calculating an exposed population density in the mission area. Second, a crash model has been developed to represent how large of an area is affected by an UA crash and, third, a crash lethality model has been investigated to determine the probability of someone within the crash area sustaining a life-threatening injury. These three components allow for risk comparisons between dissimilar UAS and are used directly in the calculation of the TLS.

A. Population Density

During the development of SLAT the authors*** developed an easy to use method for modeling population density based on the marked urban regions on FAA sectional maps. The sectional maps for the continental US were pulled into a geographic information system (GIS) program along with current census data. A correlation of population density to these yellow regions on the sectional maps has been completed [8]. This research showed that population density can be divided into four categories: unpopulated, sparsely populated, densely populated, and open air assembly. Any areas inside the yellow regions on the sectional maps (those regions described as observable urban development) are considered to be densely populated. By default any area outside of the yellow regions should be considered sparsely populated. Any outdoor event of more than 1000 people is considered an open air assembly and only those areas where controls are in place to ensure that there are no people in the mission area (such as a controlled range) should be considered unpopulated. Table 2 below shows the results of the work from [8].

As an example let us examine a UAS mission to monitor traffic in a large city. In this mission the UAS launches from a sparsely populated area, ingresses and loiters over a congested urban area to report on the traffic situation, and then returns to the sparsely populated area for landing and recovery. Table 3 below shows how to calculate the population density for such a mission.

Table 3 shows that the equivalent risk profile for this mission could be represented as if the flight were to take place entirely over a population density of 8960 people per square mile. In this way the exposure times are taken into account across the entire flight.

B. Crash Model

Quantifying the threat that a UAS poses to people on the ground is a complicated problem because there are numerous different ways that an unmanned aircraft could crash. Having the main wing spar buckle under load will likely result in a very different descent profile than if the propulsion systems fails and the vehicle is in a gliding descent. To even further complicate this problem there are many failures, such as loss of autopilot, that could result in a crash profile that is somewhere in between a gliding descent and a plummeting crash. The EASA defined two different crash modes, unpremeditated descent and loss of control, in "Policy Statement Airworthiness Certification of Unmanned Aircraft Systems (UAS)" [9], which defines the European policy on civil UAS airworthiness as of 2009. The loss of control crash mode corresponds to the catastrophic failure in SLAT where the aircraft falls out of the sky with the operators

***John Southwell, a masters student with NC State Flight Research, performed most of the GIS software analysis for the population density component of SLAT. Jason Bishop also assisted in the initial work to determine the correlation between population density and the marked urban areas on the sectional maps. The authors would like to acknowledge their contributions to this aspect of SLAT.

Table 4 Example UAS crash areas (calculated using πb^2 crash model)

UAS	Crash area, ft^2
Typical hand-launched UAV (~5 lb, ~4 ft wingspan)	60
Typical short-range small UAV (~50 lb, ~10 ft wingspan)	350
Typical long-range small UAV (~300 lb, ~12 ft wingspan)	500

unable to modify its trajectory. This would include failures such as the main spar buckling under load, failure of all flight control systems, loss of a flight critical control surface, etc. The unpremeditated descent crash mode, on the other hand, encompasses those situations where the aircraft cannot maintain flight, but where the operators still have some control over the trajectory of the vehicle. This mode would include situations where the propulsion system has failed or where a failure has resulted in such a reduction of safety margins that it is more acceptable to purposefully crash the vehicle in some known safe location rather than risk transit over heavily populated areas. RCC-323-99 [10] has proposed two approaches for modeling the crash area as part of the casualty expectation (CE) equation discussed previously. The first method uses the frontal area of the vehicle as this corresponds to a vehicle crashing in a near vertical dive. This method though is not particularly conservative as the chance of a vehicle maintaining a vertical dive is not a likely type of failure. The more conservative approach presented in RCC-323-99 models the crash area as a rectangle swept by the wings as the aircraft descends along its most efficient glide slope from 6 ft to impact with the ground. This swept-path model tends to be overly conservative as it is reasonable to assume that the mostly likely crash trajectory will be something in between these two extremes.

For SLAT it was decided to focus on a crash model that exists in between the uncontrolled descent mode and the swept-path mode scenarios. It is expected that with the loss of propulsion scenario that the operators in the ground station still have some control over the aircraft and would be able to direct the vehicle to a safe area for a crash.[†††] In this way the swept-path model is not the failure profile of significant concern. Several different models were examined to determine the optimum approach. RCC-321-07, "Common Risk Criteria Standards for National Test Ranges" [12], has detailed methods for determining the affected area in the case of a missile failure. This approach is very thorough, but requires extensive simulation[‡‡‡] to model accurately. Since SLAT is trying to determine a generic crash model that is independent of the exact flight area it was determined that the approach presented in [12] would be overly cumbersome and/or would require numerous assumptions. The SLAT designers examined other methods of crash modeling and found an FAA Advisory Circular (AC-431.35-1) [13] that defines a method for determining the crash area of civil spacecraft. This approach models the impact area of a piece of debris, such as a rocket booster, as a circle with the radius being the longest dimension of the piece of debris.[§§§] It was decided to use this model such that the crash area would be defined as a circle with the wingspan of the aircraft as the radius. It assumes that the aircraft does not break up during flight. This approach would be both straightforward to calculate and be adequately conservative. This approach correlates to a swept-path mode crash where the box swept out is 3.14 times the wingspan long and the wingspan wide. This effectively simulates the area swept out from a steep angle approach.[¶¶¶] SLAT's final crash area model estimates a UAS crash area as a circle with the wingspan of the aircraft as the radius. Table 4 below shows some common UAS and how large their impact areas would be with this model.

C. Crash Lethality

UAS pose a unique challenge for regulatory agencies in regards to airworthiness standards for safety to people. The lack of onboard crew or passengers dictates that the main concern during a UAS crash is its striking people on the ground. A significant unknown is the likelihood of someone suffering life-threatening injuries if they are struck by a UAS. For large UAS it is very likely that anyone hit would sustain life-threatening injuries, but that may not be the case as the size of the aircraft and its impact velocity are reduced. Logically at some point a UAS will be light enough and moving slowly enough that it will be incapable of causing serious injury or death. The initial development of SLAT explored the various ways the lethality of small UAS could be determined. The result of Chapter 3 of [3] proposes a binary threshold above which any UAS should be considered capable of causing life-threatening injuries. This research effort leveraged several existing reports such as "Blunt Trauma Data Correlation" from Edgewood Arsenal [14] and an Army Research Lab study performed in 1999 (ARL-TR-1868) [15] that correlated lethality based on kinetic energy (KE) transfer into clay blocks for less-than-lethal munitions.

This research shows that the nonlethal range for UAS be considered below 2 lb of weight, less than 68 ft lb of KE (based on MTOW and maximum operating speed), and have a maximum operating speed of 100 ft/s.[****] This 2 lb limit corresponds well with a category of very small UAS called micro air vehicles (MAVs). This KE approach to modeling lethality would suggest that a 2 lb limit for MAVs would be reasonable. Furthermore, this research provides a foundation for a CA to safely say that any aircraft that falls into the nonlethal range may not need to go through a full airworthiness process because they pose very little threat to the people on the ground.

The KE approach appears to be a viable method for determining the lethality of small UAS. The separation between nonlethal and lethal energy thresholds is small enough that the lethality of small UAS can be modeled as a binary grouping instead of a continuous function. Any vehicle under 68 ft lb of energy and two pounds can be considered nonlethal, while anything outside of that range should be considered capable of causing life-threatening injuries during an uncontrolled crash. Based on this result SLAT will be limited to above the nonlethal range only and will assume any vehicle over 2 lb capable of causing life-threatening injuries.

[†††]Exactly what qualifies as a safe area for an emergency crash of the vehicle is beyond the scope of this research as it is an operations aspect of UAS integration into the NAS. It is assumed that the flight plan for any UAS operation will be required to have certain specified areas for emergency crashes of the aircraft. It is expected that the CA will provide guidance to the operational community on how these locations are determined as part of the operational flight planning. The FAA has already required such crash locations in the flight planning of the Ikhana flights [11] and it is assumed that some version of that requirement will likely become mandatory for UAS flights over populated areas.

[‡‡‡]Typically a Monte Carlo-type simulation of vehicle break up and debris dispersal.

[§§§]This crash model also included a factor of seven increase to the impact area to account for the high energy seen from debris falling from extremely high altitudes and to ensure that the approach was very conservative. For SLAT the assumptions justifying this factor of seven increase did not hold, but the base impact model seems to be a good approximation.

[¶¶¶]The effective approach angle would be ~50 deg for a 3 ft wingspan aircraft up to ~80 deg for a 15 ft wingspan aircraft. The equation for this approach angle is: $\theta = \cos^{-1}(\frac{6}{\pi b})$ where b is wingspan of aircraft. This is derived geometrically based on a UAS descending from six feet above the ground to impact.

[****]The maximum operating speed limit is in place because this research is based on blunt trauma only. Any micro air vehicle with an operating speed over 100 ft/s (59 knots) would need to be examined independently as its ability to cause penetrating injuries would be significantly high.

IV. TLS Algorithm Derivation

The TLS algorithm is derived from the CE equation in the Appendix D of [10]. The CE equation was derived from first principles based on multiplication of point estimates for the different risk variables. Equation (1) below shows the equation as it is found in [10]:

$$\mathrm{CE} = \mathrm{PF} \times \mathrm{PD} \times \mathrm{AL} \times \mathrm{PK} \times S \tag{1}$$

where PF is the probability of failure (failures per flight hour), PD is the population density of the mission area (people per square mile), AL is the lethal area (square feet), PK is the probability of killing someone if hit (dimensionless), and S is the shelter factor (dimensionless).

Unfortunately the units specified above (as they appear in [10]) make the original equation prone to a potential error due to multiplying the PD variable (in units of people per square mile) by the AL variable (in units of square feet). This error can be easily corrected by dividing the population density variable by the number of square feet in a square mile (roughly 27.8 million) as shown in Eq. (2) below. The PD variable has been replaced with ρ to denote the time weighted average of the mission area using the population density categories discussed in Sec. III.A. Also the AL variable has been replaced with the crash model discussed in Sec. III.B. Furthermore, since SLAT is limiting its scope to aircraft about 2 lb MTOW the PK (probability of fatality if struck) variable can be set to one as discussed in Sec. III.C:

$$\mathrm{CE} = \mathrm{PF} \times \frac{\rho}{27.9 \times 10^6} \times \pi b^2 \times 1 \times S \tag{2}$$

The PF variable represents the system-level probability of a failure that leads to the crash of the UAS. This can be a very difficult variable to define with any certainty for this category of aircraft. Because of the limited history and use of hobby grade components, very few UAS can estimate their top level failure rate with any degree of accuracy. The reliability data for many of the components simply does not exist and performing such in-depth reliability studies would push the cost of small UAS to that of manned aircraft making them economically infeasible.

The shelter factor variable (S) can be viewed as two distinct components: hard shelter and soft shelter. Hard shelter refers to those buildings and cover that will provide protection from even the heaviest of the aircraft in the small UAS category (e.g. multistory concrete wall buildings), while soft shelter includes the protection provided by items such as trees or being in a car. The hard shelter component is contained in the assumptions made during the creation of the population density categories. The primary assumption is that all yellow observable urban areas can be treated as having the same exposed population density of 9900 per square mile. By treating all of the yellow urban areas as the same this approach makes the assumption that as population density increases the amount of hard shelter increases proportionally (i.e. the only way to get really high population densities is to put people vertically in buildings that will provide protection from any aircraft in the small UAS category). Soft shelter may provide some shelter from the smallest UAS in the small UAS category, but may not provide much shelter at all as the aircraft size approaches 350 lb. If a 3 lb UAS were to crash into a car it is reasonable to expect that it would not injure the people inside, but if a 300 lb UAS were to crash into the same car it is not unreasonable to expect that anyone inside would have received life-threatening injuries. Quantifying this shelter factor though proves to be very difficult. In the original CE equation it can be varied between 0 (everyone is sheltered) to 1 (no one is sheltered), and the choice of this variable can have a huge effect on the overall result. The soft shelter component will be brought back into the TLS equation at a later step, but for now it will be set aside.

The acceptable casualty rate (the CE variable) can really be seen as the ELS or ELS mentioned earlier. This is the base risk to all people of being killed by a crashing conventional aircraft. Thankfully that probability is very low, 1×10^{-7} per flight hour. For UAS operations in the NAS to be acceptable it will have to be shown that they pose no greater risk to the people on the ground than that posed by conventional aircraft. Therefore, the CE variable in Eq. (2) can be replaced by the ELS value of 1×10^{-7} as shown in Eq. (3) below:

$$10^{-7} = \mathrm{PF} \times \frac{\rho}{2.79 \times 10^7} \times \pi b^2 \tag{3}$$

This can be rearranged to bring PF to the right hand side of the equation as shown in Eq. (4):

$$\frac{(1 \times 10^{-7})(2.79 \times 10^7)}{\rho} = \mathrm{PF} \times \pi b^2 \qquad \mathrm{PF} = \frac{2.79}{\rho \pi b^2} \tag{4}$$

The inverse of Eq. (4) [Eq. (5) below] gives the mean time between failures (MTBF) that meets the ELS of one fatality every ten million flight hours based on the population density of the mission area and the size of the aircraft. This shows that MTBF is proportional to the risk variables $\rho \pi b^2$:

$$\mathrm{MTBF} = \frac{\rho \pi b^2}{2.78} = k(\rho \pi b^2) \qquad \mathrm{MTBF} \propto \rho \pi b^2 \tag{5}$$

The next step is to take the log of those risk variables [see Eq. (6) below]:

$$\mathrm{TLS}' = \log_{10}(\rho \pi b^2) \tag{6}$$

The TLS equation is almost finished at this point except for the soft shelter component. Soft shelter can be viewed as a function of the KE of the crashing aircraft. Soft shelter will be proportionally less effective as the KE in the crashing UAS increases. There will clearly be some transfer of potential energy to KE during an aircraft's uncontrolled descent, but it is difficult to quantify exactly what that amount would be. SLAT makes a further assumption that all the UAS in the small UAS category are going to reach effectively the same terminal velocity during an uncontrolled crash. With this assumption the KE variation between the different aircraft is reduced to a function of its mass or weight. The soft shelter component is then taken into account by adding the variable W (aircraft weight) to the TLS algorithm as shown in Eq. (7) below. Without the weight scaling a 20 lb glider-type UAS with a 10 ft wingspan would require the same TLS as a 300 lb UAS that also had a 10 ft wingspan. Clearly the 300 lb aircraft poses more of a threat than the 20 lb aircraft:

$$\mathrm{TLS}' = W(\log_{10}(\rho \pi b^2)) \tag{7}$$

The final step in the TLS algorithm derivation is to adjust the top level situation of a 15 ft wingspan, 350 lb aircraft[††††] flying 100% of its mission over open air assembly to map to 10,000 points. This is done through a tuning variable k that is set to 3.642[‡‡‡‡]:

$$\mathrm{TLS} = kW(\log_{10}(\rho \pi b^2)) = 3.642W(\log_{10}(\rho \pi b^2)) \tag{8}$$

Equation (8) is the final form of the TLS algorithm. The final value is always rounded to the nearest whole number since SLAT does not use fractions of points. As an example assume that an 8 ft wingspan aircraft that has a MTOW of 55 lb is flying the example traffic monitoring mission described in Sec. III.A. The population density (ρ) from the example mission is 8960 people per square mile as shown in Table 3. Equation (9) below shows the TLS derivation for this example aircraft flying the traffic monitoring mission:

[††††] This top level aircraft is representative of an aircraft slightly larger than the largest current aircraft at the top of the 350 lb range. Aircraft larger than 15 ft wingspan could still use SLAT, but it may be difficult to reach TLS values above 10,000 points. The point allocation algorithm is designed to ensure that any aircraft can earn 10,000 points, but aircraft larger than the top level aircraft could require TLS above 10,000.

[‡‡‡‡] The tuning variable is used to set the TLS for the top level aircraft flying 100% of its mission over an open air assembly to 10,000 points. The value of 10,000 points was chosen to avoid dealing with fractions of points or hundreds of thousands of points while still maintaining sufficient resolution between different tests. The tuning variable is of units to make the TLS points nondimensional.

$$Points\ per\ Failure\ Mode = \frac{10{,}000}{6(N_{cat} + N_{crit})}(Criticality)(Quality)(Confidence)$$

$$Points\ per\ Test = \sum Points\ for\ each\ failure\ mode\ addressed$$

Failure Category	Criticality Scaling
Catastrophic	1.0
Critical	0.8
Major	0.4
Minor	0.2

Confidence=	1 for Analytical Tests
	2 for Physical Ground Tests
	3 for Flight Tests

Quality Scaling		
	Manned Eq. Verification Method	<Manned Eq. Verification Method
Manned Eq. Standard	1.0	0.7
< Manned Eq. Standard	0.85	0.5

Fig. 4 Point allocation algorithm.

$$\text{TLS} = 3.642(55)(\log_{10}(8960 \times \pi \times (8)^2)) = 1132 \quad (9)$$

This shows that this 8 ft wingspan, 55 lb aircraft would need to earn at least 1132 points in every domain to be considered airworthy. To contrast let us examine a UAS half the size of the first example flying the same mission. Equation (10) shows the TLS for this smaller UAS:

$$\text{TLS} = 3.642(27.5)(\log_{10}(8960 \times \pi \times (4)^2)) = 566 \quad (10)$$

This shows how a smaller UAS would be required to show fewer artifacts to be considered safe to fly the same mission.

V. Point Allocation Algorithm

The next key component of SLAT is how the points are earned for showing good engineering practices. The maximum points available for any one test, such as a wing load test or ground test of communication equipment, is based on the criticality of the failure modes addressed by that test derived directly from the tailored FMECA for a specific UAS. It is generally understood that testing of actual components greatly increases the confidence in the final product over purely analytical approaches or simulations, while even more confidence is gained through thorough engineering flight tests of the actual aircraft system. It is very difficult to quantify exactly how that confidence increases, but SLAT attempts to capture it by granting twice as many points for physical testing of components and three times as many points for flight testing of components as compared with pure analysis.

SLAT is designed to be very flexible for both varying standards and verification methods. An example of a standard for structures would be building structures to a 1.25 factor of safety versus the manned aviation standard of 1.5. For verification methods an example would be picking up an aircraft by the wing tips to test the wing's strength versus a static load test to failure of a flight article to determine the load at which the wings actually fail. Tests and/or verification methods that meet the manned aviation standard warrant the highest number of points, while tests that fall short of the manned requirements are penalized by receiving fewer possible points. The penalty for reducing the verification method is twice the penalty for reducing the standard. This is an attempt to capture the reduction in confidence as verification methods are reduced. It is preferable to know with a high degree of confidence that some component has actually met some lesser standard than to have a low confidence that it has met some higher standard. For example, an aircraft could be designed with the manned standard of a 1.5 factor of safety for all of the structures, but if the verification method is only a statement from the designer stating that it was designed to that level then the CA will likely have very little confidence that the aircraft actually has met that standard.

For each test the developer must first determine the confidence slot that it is fulfilling (analysis, physical, or flight test). Next, the developer creates a list of the failure modes from the tailored FMECA that are addressed by the test. The criticality of each failure mode being addressed determines the overall point total for the test. It is important to only have one domain's failure modes in each test. If a test covers more than one domain then a group of tests (one for each domain with addressed failure modes) should be created since the base number of points varies based on the number of catastrophic and critical failure modes in each domain. The third step is to determine if the standard and verification method are following the manned aviation equivalents. The final step is to sum the points granted for each failure mode to determine the final point value of the test. This algorithm[§§§§] is shown in Fig. 4. It is designed to ensure that if all of the catastrophic and critical failures modes are addressed through all three levels of testing that enough points are available to meet the worst-case TLS of 10,000 points.

For example, let us assume that the 55 lb UAS from the TLS example (Sec. IV) has four catastrophic failure modes ($N_{\text{cat}} = 4$) and 12 critical failure modes ($N_{\text{crit}} = 12$) in the tailored Structures domain. Furthermore, let us assume that a finite element analysis (FEA) of the aircraft structures addresses 1 of the catastrophic failure modes, three of the critical failure modes, five major failure modes, and no minor failure modes. For demonstrative purposes this example assumes that the standard is manned equivalent and the verification method is less-than-manned equivalent. Equations (11a–11e) shows the calculation of the points available from such a FEA artifact under SLAT:

$$\text{Points per catastrophic} = \frac{10{,}000}{6(4+12)}(1.0)(0.7)(1) = 73 \quad (11a)$$

$$\text{Points per critical} = \frac{10{,}000}{6(4+12)}(0.8)(0.7)(1) = 58 \quad (11b)$$

$$\text{Points per major} = \frac{10{,}000}{6(4+12)}(0.4)(0.7)(1) = 29 \quad (11c)$$

$$\text{Points per minor} = \frac{10{,}000}{6(4+12)}(0.2)(0.7)(1) = 15 \quad (11d)$$

$$\begin{aligned}&\text{Total points for test}\\ &\quad = (\text{\#cat. modes addressed})(73) + (\text{\#crit. modes addressed})(58)\\ &\quad + (\text{\#major modes addressed})(29)\\ &\quad + (\text{\#minor modes addressed})(15)\\ &\text{total points for test} = (1)(73) + (3)(58) + (5)(29)\\ &\quad + (0)(15) = 392\end{aligned} \quad (11e)$$

A. Grading Tests

There are several difficulties that cannot be addressed by this point allocation algorithm. One situation occurs when an artifact shows

[§§§§]One of the advantages of SLAT is that it has been built to be flexible. The values for this algorithm can be modified by the CA based on input from their subject matter experts.

that a test was poorly conducted. This could be due to inexperience working with a computer program (such as overconstraining a FEA model) or it could be that the system simply failed to pass the test. In the design of SLAT it was important to ensure that systems earn points in accordance with their performance on the test. It is unacceptable to perform a load test on a wing where the wing fails halfway through and still get full credit for the test. On the other hand, if the wing failed at 90% of the maximum load the CA would have high confidence on the wing strength although the flight envelope may need to be reduced. There is another situation where a standard or verification method has been reduced so far from the manned equivalent that it is questionable if the artifact gives any real confidence on the system's safety. For example, if one designer used a 1.4 factor of safety (less-than-manned equivalent standard) and another used a 1.01 factor of safety (also less-than-manned equivalent standard) SLAT's point allocation algorithm would assign the same amount of maximum possible points if they used the same verification method and had the same base FMECA. To capture these situations SLAT relies on an independent expert grader to provide a qualitative assessment of each artifact. In the airworthiness field technical area experts and subject matter experts are employed to review airworthiness artifacts in their field of expertise. SLAT leverages these experts as graders for the artifacts presented in SLAT to earn points. Each test is reviewed by an expert grader who assigns a qualitative assessment of their confidence in that particular test method from 0 to 100%. The final number of points awarded is this grade times the maximum number of points from the point allocation algorithm rounded to the highest integer value. This grading process allows the expert to decide if a verification method or standard has been relaxed too far. The grader also determines if the testing is appropriate for the failure modes being examined. Heavier emphasis should be placed on the high criticality items over lower criticality items during the grading process.[¶¶¶¶] It ensures that no system earns points from failing a test and allows for flexibility without overly complicating SLAT. It is hoped that SLAT will help streamline the airworthiness process by using the knowledge base and personnel that are already in place for manned aircraft airworthiness certification. It is expected that the experts in a CA would be involved in producing sets of guidelines for this grading for their offices such that the grading is consistent between experts and different applications of SLAT.

B. Confidence Slots

There are two primary control components to SLAT that affect how many points a component can grant. The first control is the introduction of three confidence slots. Any one failure mode can contribute points through only three test articles; one analytical slot, one physical testing slot, and one flight test slot. The points granted for Flight Testing are three times higher than the points granted for just analysis since flight testing is usually the gold standard in airworthiness.[*****]

These three confidence slots are most easily explained with an example. Assume that a small UAS is going through SLAT. In the structures domain there are numerous catastrophic failures so clearly keeping the wings attached to the aircraft is of high importance. The developer could perform a simulation of the structures using a FEA tool to fulfill the analysis slot. The developer could then build a physical wing and perform a wing load test to fulfill the physical slot. Finally, the developer could perform a flight test of the full system where the aircraft is pushed to the edges of the flight envelope to gain points for the flight test slot. The number of points available for flight testing is equal to the total amount from both analytical and physical ground testing.

The limit of three tests is put into place to avoid testing one component of a domain repeatedly to obtain all possible points for that domain. For instance, a company could build a UAS with an overbuilt wing and then perform eight different physical load tests of the wing to try to certify all of the structures. The implementation of three testing slots limits the developers to one analytical test, one physical test, and one flight test for any single failure mode. This algorithm grants points only for the highest point value test for each slot. A company could repeat a test with better equipment to gain extra points, but they would only get the higher grade not the sum of both tests.

The goal of weighting flight testing so heavily is to ensure that a UAS will have to show successful flights in a controlled environment before being certified for flights over populated areas. The analytical and physical testing should be sufficient to show that the system is safe to operate in a controlled area for initial flight testing.

C. Criticality Requirement

The second control is the criticality requirement. This requirement states that one must address the highest criticality failure modes before addressing the lower criticality modes. The criticality of a test is based on the highest criticality mode of the failure modes addressed in the test. As long as a test addresses a catastrophic mode then the whole test is considered to be catastrophic criticality. For instance, a FEA analysis of the structures might address one catastrophic failure mode (i.e. wing spar buckling due to poor design), three critical failure modes, and six major failure modes. Since the test addresses at least one catastrophic failure mode the test would be viewed as having a catastrophic criticality even though a nontrivial portion of the points granted by the test are from the lesser criticality failure modes that it addresses. A different test may only address four major failure modes in the structures domain. One could not get points for the second test since it is only of major criticality until all catastrophic and critical failures modes in the structures domain have been addressed at least once. This control helps to ensure that points are granted only for addressing the failure modes that are of the highest concern.

VI. Conclusions

SLAT brings all of the different UAS domains into a comprehensive framework that provides a tool for use by CA and project managers to help certify the airworthiness of small fixed-wing UAS. SLAT was designed to be very flexible by allowing different standards and verification methods to be used. Those standards and verification methods that would be acceptable for manned aviation receive the most points, while the point values are reduced as the standard and verification methods are relaxed from the manned equivalent. The number of points required is directly tied to the threat that particular UAS poses to people in the mission area and is commensurate with the threat of manned aircraft to people on the ground. The methodology for mission planning leverages the NACO sectional maps for population density and uses only basic vehicle information for the crash area such that SLAT is straightforward to apply. It is anticipated that SLAT will be useful in streamlining the certification process by allowing small fixed-wing UAS developers to tailor their design phase to produce the artifacts that can be used in airworthiness certification. SLAT can also be a starting point for those public agencies that wish to use small UAS to begin the airworthiness assessment of their UAS for operations of the NAS. It is recommended that further work be commissioned to expand SLAT for rotary-wing UAS.

[¶¶¶¶]The authors recognize that in a tool as flexible as SLAT it will be possible to create tests that, although correctly formatted, abuse the point allocation process. Part of the responsibly of the expert graders is to provide some oversight positions in the process to ensure that the tests conducted are appropriate for failure modes stated as being addressed. SLAT is developed as an assisting tool, not a rigid set of requirements. It is still expected that discussion will occur between the CA and the UAS developer. SLAT provides a framework for that discussion and the evaluation of the airworthiness artifacts.

[*****]In certain areas, such as electromagnetic interference testing and material fatigue testing, the ground tests are superior to any flight testing that could be performed to address those failure modes. One of the flexible aspects of SLAT is that a CA can adjust the weighting for those areas to better represent the confidence gained from each level of test.

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