UAV FAILURE RATE CRITERIA
FOR EQUIVALENT LEVEL OF SAFETY

David W. King
Allen Bertapelle
Chad Moses
Bell Helicopter Textron, Inc.
Fort Worth, Texas

Presented at the International Helicopter Safety
Symposium, Montréal, Québec, Canada
September 26–29, 2005
ABSTRACT

The high mishap rate of UAV’s in operational service is frequently cited as a deterrent to more widespread deployment and one limiting factor towards utilization of Unmanned Air Vehicles (UAV) to operate in civil airspace. This paper presents an Equivalent Level of Safety (ELOS) analysis to determine a failure rate requirement for UAV critical systems to ensure civil airworthiness for various vertical-lift UAV applications and aircraft size. A safety level equivalent to the airworthiness standard for Normal Category airplanes is determined. The safety standards for manned aircraft are related to unmanned flight by defining a catastrophic condition as a UAV system failure that results in at least one third party casualty via midair collision or ground injury. ELOS analysis is based on a falling object model derived from commercial space transport safety assessment methodology and is validated through a comparison with airplane accident data. The analysis uses air traffic density data and population density data for various flight paths corresponding to potential applications. It is concluded that the existing UAV failure rate is unacceptable for operations over heavily populated areas for light or heavy UAV’s. The analysis yields a critical system failure rate criterion ranging from $6.5 \times 10^{-6}$ per flight hour for tiltrotor UAV’s on an inter-city ferry flight to $1.0 \times 10^{-7}$ per flight hour for UAV operations over densely populated urban areas. Airworthiness standards for UAV’s are needed to address safety concerns, and this paper demonstrates how ELOS methodology can be used as an interim approach until standards are published.

INTRODUCTION

Unmanned Air Vehicles (UAV’s) are currently being utilized throughout the world for specific military applications. Operational successes have proven the strategic advantages of UAV’s. These successes have led to a rapid development of vertical takeoff and landing (VTOL) UAV’s for limited applications, including naval surveillance, homeland security, and border patrol. However, the high mishap rate of UAV’s in operational service is frequently cited as a deterrent to more widespread military and civil use.

Once deployed, VTOL UAV’s will likely operate within the national airspace. Civil airspace will be utilized for UAV ferry flights, homeland security operations, or other potential civil applications, such as weather or environment monitoring, agricultural purposes, or police surveillance or incident response. As a result, public safety can only be guaranteed if the UAV designs are proven to be airworthy—a detailed effort currently being undertaken by both ASTM Committee F38 on Unmanned Air Vehicle Systems (www.astm.org/) and by RTCA Special Committee 203 Unmanned Aircraft Systems (www.rtca.org). A means to achieve this safety objective is to establish airworthiness standards for VTOL UAV’s that provide public confidence that the unmanned aircraft will present no greater risk to third parties than manned aircraft currently operating in National Airspace.

This paper presents an equivalent level of safety (ELOS) analysis, as an interim approach, to determine a failure rate requirement for UAV critical systems. A safety level equivalent to the airworthiness standard for manned aircraft is determined for flight profiles corresponding to three potential applications along with three typical VTOL UAV sizes. The safety standards for manned aircraft are related to unmanned flight by defining a catastrophic condition as a UAV system failure that results in at least one third party casualty via midair collision or ground injury. This paper derives ELOS criteria for UAV flight control system (FCS) failures resulting in uncontrolled descent. The paper does not address other UAV safety concerns such as air traffic control, see and avoid sensing, and controlled flight into terrain (CFIT). These other UAV safety concerns require additional discussion beyond the scope of this paper and are actively being discussed with industry committees.

BACKGROUND

Currently, the UAV mishap rate is 100 times higher than that of manned aircraft. There is approximately one mishap for every 1000 flight hours. Approximately half (between 33% and 67%) of these mishaps are attributed to aircraft failure (Ref. 1). The relatively high failure rate is likely caused by relaxed design assurance methods and system reliability. There is a general perception that this aircraft
failure rate—about one per 2000 hours—is unacceptable for operation in crowded civil airspace because of the risk to public safety on the ground and air traffic. Technical developments to improve the reliability of UAV’s are merited and should be preceded by published airworthiness standards. Unfortunately, there is currently no unified set of airworthiness standards for UAV system design, although the need has been identified and is in work through industry committees.

For manned platforms, the FAA Type Certification process is a means to ensure airworthiness of new aircraft designs. Civil certification of Class II Normal Category airplanes (i.e., airplanes capable of carrying no more than nine passengers and weighing less than 6,000 pounds) is accomplished in accordance with Title 14 Code of Federal Regulations (14 CFR) Part 23 (Ref. 2). New airplane designs and design modifications must demonstrate compliance to all applicable regulations prior to receiving FAA certification. These regulations ensure a minimum acceptable level of safety for aircraft design aspects, including systems airworthiness standards and failure rate criteria. Advisory Circulars (AC) accompany the rules and provide guidance on an acceptable means to show compliance. While these rules are designed to protect the crew and passengers, certification to these rules, along with operational rules, allow for aircraft flight over populated areas.

The Part 23 rule applicable to systems failure rate criteria is paragraph 23.1309. This paragraph states, “The occurrence of any failure condition that would prevent the continued safe flight and landing of the airplane must be extremely improbable.” A means to show compliance with this rule is defined in the corresponding AC (Refs. 3, 4) as a Safety Assessment process that uses quantifiable failure rate criteria for the term “extremely improbable.” Applying the manned aircraft failure rate criteria to a typical VTOL UAV, including single turbine engine aircraft with gross weight up to 6,000 pounds, the maximum acceptable probability of a failure condition that would prevent continued safe flight and landing is

\[ P_{CM} = 1 \times 10^{-7} \]  

where \( P_{CM} \) represents the maximum acceptable probability of manned aircraft loss of critical function.

There are currently no published civil airworthiness standards for unmanned aircraft. Recent history has shown that for complex issues the turnaround time for aviation authorities to derive and approve new Federal Aviation Regulations can last over five years. In the interim, an approach to establish airworthiness in the absence of applicable rules is to apply FAR Paragraph 21.17 (Ref. 5). This rule applies to civil certification of aircraft configurations without applicable design rules. Paragraph 21.17 states that special classes of aircraft for which airworthiness standards have not been issued can be certified by establishing new criteria that provide an equivalent level of safety to applicable published regulations, such as 23.1309.

**EQUIVALENT LEVEL OF SAFETY APPROACH**

The ELOS approach is used to define failure rate criteria for flight critical UAV systems. For manned aircraft, a catastrophic condition is defined as an event causing complete loss of aircraft plus fatalities to the flight crew and passengers. For example, a catastrophic condition can be defined as a loss of flight control leading to the inability to continue safe flight to a landing. However, UAV’s preclude any first party (i.e., flight crew) or second party (i.e., passengers) casualties from a loss-of-controls scenario. Therefore, a catastrophic condition for an unmanned aircraft is defined as a failure event that results in at least one third party casualty via midair collision or ground injury.

The ELOS approach equates the UAV failure rate criterion to the accepted loss-of-control criterion for manned aircraft, adjusted by the conditional probability that a loss of control scenario results in at least one third party casualty:

\[ L_{GC} \times P_{CF} = P_{CM} \]  

where \( L_{GC} \) = likelihood of third party casualties given loss of control

\( P_{CF} \) = maximum acceptable probability of UAV loss of critical function

\( P_{CM} \) = maximum acceptable probability of manned aircraft loss of critical function

Substituting Equation 1 into Equation 2 yields

\[ P_{CF} = \frac{1 \times 10^{-7}}{L_{GC}} \]  

It is apparent from Equation 3 that the key to establishing an ELOS criterion, \( P_{CF} \), is to calculate the likelihood of third party casualties given loss of control, \( L_{GC} \). The approach used to calculate \( L_{GC} \) consists of several steps:

1. Derive a stochastic model for a randomly falling uncontrolled object.
2. Calculate a casualty area for a VTOL UAV-sized object impacting the ground from a typical uncontrolled steep descent trajectory.

3. Determine the probability of ground casualties given loss of control by applying the casualty area to the population density for flight path.

4. Determine the probability of a midair collision by applying the falling object model with a typical VTOL UAV-sized footprint to typical air traffic density.

5. Validate the model by comparing the predicted probabilities to empirical accident data of third party casualties caused from a loss of control scenario.

**FALLING OBJECT STOCHASTIC MODEL**

The falling object stochastic model is derived from the methodology used by the FAA to approve commercial space launch licenses. This methodology is defined in Title 14 Code of Federal Regulations Parts 415, 417, and 420 (Refs. 6, 7) and is used to demonstrate that a guided expendable launch vehicle flight corridor satisfies an acceptable level of risk for third party casualties. A loss-of-control scenario for a UAV can be analyzed as a randomly falling object in the same manner as an expendable launch vehicle or debris from a space vehicle breakup during launch or recovery. The Columbia Accident Investigation Board (CAIB) (Ref. 8) utilized a similar methodology to analyze the third party casualty risk from the falling debris of the Space Shuttle Columbia on February 1, 2003.

**Ground Casualty Risk**

The ground casualty area for an out-of-control UAV is calculated by applying the CAIB simplified model (Ref. 8, page 488), which establishes a one-dimensional relationship between casualty area and falling object ballistic coefficient. Assuming that loss of control occurs at cruise altitudes, it is expected that the UAV impacts the ground at a steep angle. At steep angles, the casualty area is a function of the ballistic coefficient of the falling object:

\[
A_c = f(\beta_{uav})
\]  

(4)

where \( A_c \) = casualty area in ft\(^2\)

\( \beta_{uav} \) = ballistic coefficient of falling UAV in lb/ft\(^2\)

This functional relationship between casualty area and ballistic coefficient was derived empirically in Ref. 8, based on a more detailed analysis establishing casualty area for a terminal velocity falling object. This casualty area is based on multiple parameters including an average person’s size, impact velocity, impact angle, object surface area, object weight, kinetic energy, and ballistic coefficient. The simplified functional relationship of Equation 4 is quantified in Table 1 and accounts for the ground impact energy and dispersion characteristics, including skip, splatter, and bounce. A casualty is generally defined as a serious injury or worse, up to and including death.

The functional relationship is such that a heavy falling object (i.e., over 1,000 lb) will have a casualty area inversely proportional to ballistic coefficient, while lighter objects exhibit a proportional relationship. This inverse relationship for heavy objects is due to the increase in dispersion area of a heavy object as drag increases. Therefore, the UAV ballistic coefficient, \( \beta \), is calculated based on the worst-case flat plate drag for a flat spin descent:

\[
\text{Drag} = 0.9 \times \text{length} \times \text{width}
\]

(5)

\[
\beta = \frac{GW}{\text{drag}}
\]

(6)

For evaluation purposes, this calculation is applied to three typically sized VTOL UAV’s to provide a representative sample for UAV casualty area. To simplify the calculations, it is conservatively assumed that there are no protective benefits from sheltering. The “heavy UAV” calculation is representative of a Bell 407 size aircraft, the “light UAV” is representative of a Fire Scout size aircraft, and the “tiltrotor UAV” is representative of an Eagle Eye aircraft (Ref 9). Table 2 lists the data necessary to compute the ballistic coefficient of the three VTOL UAV’s.

<table>
<thead>
<tr>
<th>Ballistic coefficient (lb/ft(^2))</th>
<th>Total casualty area (ft(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.0</td>
<td>32,665</td>
</tr>
<tr>
<td>56.23</td>
<td>1,448</td>
</tr>
<tr>
<td>100.0</td>
<td>150</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2. UAV specification data.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Heavy</strong></td>
</tr>
<tr>
<td>UAV</td>
</tr>
<tr>
<td>Length (ft)</td>
</tr>
<tr>
<td>Width (ft)</td>
</tr>
<tr>
<td>Gross weight (lb)</td>
</tr>
<tr>
<td>Flat plate drag (ft(^2))</td>
</tr>
</tbody>
</table>
The ballistic coefficient and ground casualty area for a free falling UAV is calculated from Table 1 and using the values from Equation 5 and Equation 6 for the three vehicle sizes:

\[ \beta_{\text{Heavy}} = \frac{GW}{\text{drag}} = 54.93 \, \text{lb/ft}^2 \]
\[ A_{C, \text{Heavy}} = 3,000 \, \text{ft}^2 = 0.000108 \, \text{mi}^2 \]

\[ \beta_{\text{Light}} = \frac{GW}{\text{drag}} = 38.55 \, \text{lb/ft}^2 \]
\[ A_{C, \text{Light}} = 22,490.9 \, \text{ft}^2 = 0.00081 \, \text{mi}^2 \]

\[ \beta_{\text{Tiltrotor}} = \frac{GW}{\text{drag}} = 79.51 \, \text{lb/ft}^2 \]
\[ A_{C, \text{Tiltrotor}} = 757.53 \, \text{ft}^2 = 2.72 \times 10^{-5} \, \text{mi}^2 \]

Another observation is that the tiltrotor sized UAV has a significantly smaller casualty area than the other two sizes. The narrow fuselage of the tiltrotor-sized UAV results in a smaller drag and corresponding lower casualty area while in a flat descent.

Continuing with the ELOS calculation, the population density for the area being flown over must be determined. The time spent over the various population densities within a flight path provides mission specific data required for ELOS computation. Flight paths are largely dependent on the mission task(s) assigned to the vehicle. The following three different UAV applications were selected for this evaluation:

1. Homeland Security Border Patrol
2. Law Enforcement
3. Inter-city ferry flights

**Example Application No. 1: Homeland Security Border Patrol over Populated Areas**

The border patrol application may perform various tasks such as vehicle surveillance. A representative mission for this application is a flight path from San Diego airport to the Mexico border then back up to Los Angeles following Interstate 5, as illustrated in Figure 1. Profile data is provided in Table 3. The likelihood of a ground casualty...
from an out-of-control UAV, $L_{GC}$, is calculated from the casualty area for a given UAV size and the population density of the flight path. It is assumed that the flight is at constant speed, as follows:

$$L_{GC, \text{Heavy}} = \sum_{i=1}^{n} w_i N_i A_{C, \text{Heavy}} = 0.4268 \quad (8)$$

where $N_i$ = the population density of each city/county as determined from 2000 Census (Ref. 10)
$d_i$ = distance in miles over each city/county
$d_T$ = total distance of flight path (149 mi)
$w_i$ = weighting factor based on percentage of flight spent over a city/county

$$w_i = \frac{d_i}{d_T} \quad (9)$$

A similar calculation for light- and tiltrotor-sized VTOL UAV’s yields $L_{GC, \text{Light}} = 3.2$ and $L_{GC, \text{Tiltrotor}} = 0.11$. The light-sized vehicles produced a likelihood of ground casualty greater than one. As a result, a system integrity level equivalent to manned aircraft is necessary to ensure an equivalent level of safety for this UAV mission profile.

The ELOS failure rate criterion for the tiltrotor UAV is calculated from Equation 3:

$$P_{CF, \text{Heavy}} = 2.34 \times 10^{-7}$$
$$P_{CF, \text{Light}} = 1.0 \times 10^{-7}$$
$$P_{CF, \text{Tiltrotor}} = 1.0 \times 10^{-7} \frac{L_{GC}}{L_{GC}} = 9.279 \times 10^{-7} \quad (10)$$

Example Application No. 2: Law Enforcement over Populated Areas

Law enforcement agencies conduct many operations that are well suited for UAV usage. A generic mission was selected where the aircraft’s flight path was within New York City’s five counties (Fig. 2). Profile data is provided in Table 4. Once again, the heavy- and light-sized vehicles produced a likelihood of ground casualty greater than one. Therefore, a system integrity level equivalent to manned aircraft is necessary to ensure an equivalent level of safety for this UAV profile.

<table>
<thead>
<tr>
<th>City/County</th>
<th>Distance (mi)</th>
<th>Population density (people/mi$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Diego (city)</td>
<td>47.1</td>
<td>3,771.9</td>
</tr>
<tr>
<td>San Diego (county)</td>
<td>28.2</td>
<td>670</td>
</tr>
<tr>
<td>Encinitas</td>
<td>5.3</td>
<td>3,035.6</td>
</tr>
<tr>
<td>Oceanside</td>
<td>4.0</td>
<td>3,967.2</td>
</tr>
<tr>
<td>San Clemente</td>
<td>5.6</td>
<td>2,833.4</td>
</tr>
<tr>
<td>Orange (county)</td>
<td>10.2</td>
<td>3,605.6</td>
</tr>
<tr>
<td>San Juan Capistrano</td>
<td>3.5</td>
<td>2,381.2</td>
</tr>
<tr>
<td>Laguna Hills</td>
<td>2.0</td>
<td>4,911.1</td>
</tr>
<tr>
<td>Irvine</td>
<td>3.0</td>
<td>3,098</td>
</tr>
<tr>
<td>Tustin</td>
<td>3.4</td>
<td>5,921.4</td>
</tr>
<tr>
<td>Santa Ana</td>
<td>2.6</td>
<td>12,451.9</td>
</tr>
<tr>
<td>Orange (city)</td>
<td>1.6</td>
<td>5,506.4</td>
</tr>
<tr>
<td>Anaheim</td>
<td>5.8</td>
<td>6,702</td>
</tr>
<tr>
<td>Buena Park</td>
<td>1.7</td>
<td>7,403.1</td>
</tr>
<tr>
<td>Norwalk</td>
<td>2.5</td>
<td>10,667.6</td>
</tr>
<tr>
<td>Los Angeles (county)</td>
<td>6.2</td>
<td>2,344.2</td>
</tr>
<tr>
<td>Los Angeles (city)</td>
<td>16.3</td>
<td>7,876.8</td>
</tr>
<tr>
<td>Total</td>
<td>159</td>
<td>87,147.4</td>
</tr>
</tbody>
</table>

Table 3. Distance and population density per area for Example Application 1.

New York City counties | Population density (people/mi$^2$) |
------------------------|----------------------------------|
Richmond                | 7,587.9                          |
Kings                   | 34,916.6                         |
Queens                  | 20,409.3                         |
Bronx                   | 31,709.3                         |
New York                | 66,940.1                         |

Table 4. Population density of New York for Example Application 2.
In the calculations below, equal time and constant speed is considered over each county.

\[ n \] = number of counties in flight path \((n = 5)\)

\[ N_i \] = the population density of each county as determined from 2000 Census (Ref. 10)

\[ L_{GC, \text{Heavy}} = \frac{1}{n} \sum_{i=1}^{n} N_i A_{C, \text{UAV}} = 3.490 \]

\[ L_{GC, \text{Light}} = 26.3 \]

\[ L_{GC, \text{Tiltrotor}} = 0.88 \]

\[ P_{CF, \text{Heavy}} = 1.0 \times 10^{-7} \]

\[ P_{CF, \text{Light}} = 1.0 \times 10^{-7} \]

\[ P_{CF, \text{Tiltrotor}} = \frac{1.0 \times 10^{-7}}{L_{GC}} = 1.139 \times 10^{-7} \] (11)

Here one can see, by comparing the tiltrotor UAV \( P_{CF} \) of Example Applications 1 and 2 that as the population density of the over flight area increases, the acceptable probability of UAV loss of critical function decreases.

**Example Application No. 3: Inter-City Flights**

UAV missions may include the ferrying of the aircraft between assignment locations, or may perform surveillance flights/security missions over less populated areas. A flight path in Texas from Dallas to Houston is used as a representative flight path for this application (Fig. 3). The DFW to Houston flight path is a conservative inter-city ferry mission because 20% of the flight is over heavily populated Tarrant and Harris counties (Table 5 contains profile data). Assuming an equal amount of flight time of each of the counties and an evenly distributed population within each county, the ELOS failure rate criterion is calculated as follows:

\[ L_{GC, \text{Heavy}} = \frac{1}{n} \sum_{i=1}^{n} N_i A_{C, \text{Heavy}} = 0.0609 \] (12)

where \( n \) = number of counties in flight path \((n = 9)\)

\[ N_i \] = the population density of each county as determined from 2000 Census (Ref. 10)

\[ L_{GC, \text{Light}} = 0.455 \]

\[ L_{GC, \text{Tiltrotor}} = 0.0153 \]

\[ P_{CF, \text{Heavy}} = \frac{1 \times 10^{-7}}{L_{GC}} = 1.642 \times 10^{-6} \] (13)

\[ P_{CF, \text{Light}} = \frac{1 \times 10^{-7}}{L_{GC}} = 2.198 \times 10^{-7} \]

\[ P_{CF, \text{Tiltrotor}} = \frac{1 \times 10^{-7}}{L_{GC}} = 6.526 \times 10^{-6} \]

Here one can see the differences between acceptable probabilities of UAV loss of critical function, as is dependant on UAV size and weight.

**GROUND CASUALTY ANALYSIS SUMMARY**

As shown in Figure 4, the likelihood of a ground casualty from an out-of-control UAV depends primarily on the population density of the UAV flight path and the vehicle ballistic coefficient. Calculations using a falling object model show that the expected number of casualties for a heavy or light size VTOL UAV operating primarily over densely populated urban centers is greater than one. As a result, a system integrity level equivalent to manned aircraft

| Table 5. Population density for Texas counties for Example Application 3. |
|-----------------------------|------------------|
| Texas counties             | Population density (people/mi²) |
| Dallas                      | 2,522.6           |
| Ellis                       | 118.5             |
| Navarro                     | 44.8              |
| Freestone                   | 20.4              |
| Leon                        | 14.3              |
| Madison                     | 27.6              |
| Walker                      | 78.4              |
| Montgomery                  | 281.4             |
| Harris                      | 1,967.0           |
is necessary to ensure an equivalent level of safety for these UAV missions.

Lower levels of reliability can be allowed for flight paths that are mostly outside of densely populated metropolitan areas. An example is an inter-city ferry flight in Texas from Dallas-Fort Worth (DFW) International airport to Houston Intercontinental Airport. However, the reliability of UAV’s currently in service—approximately one loss from aircraft failure every 2,000 hours—is insufficient to provide an ELOS for a typical ferry flight for the range of UAV sizes considered. For example, combining the current UAV failure rate with the likelihood of a ground casualty given a failure for a tiltrotor UAV on a ferry flight (1.53%) yields one casualty event every 131-thousand flight hours. This safety level is far below the Part 23 manned flight standard of one catastrophic event from aircraft failure every 10-million flight hours.

**MIDAIR COLLISION RISK**

In addition to ground casualties, third party injuries can result from a midair collision between an out-of-control UAV and a manned aircraft. The likelihood of a midair collision for an out-of-control UAV depends on the dimensions of the two vehicles and the likelihood that the randomly falling UAV will impact the volume in space occupied by the manned aircraft. For simplicity, a two-dimensional planar area is used to calculate the probability of a midair collision as the collision area multiplied by the summation of expected number of aircraft per potential collision area at any given time:

\[
L_{MC} = \left( A_M + A_{UAV} \right) \sum_{j=1}^{\infty} E_i(A_i) \frac{1}{A_j} \tag{14}
\]

where \( L_{MC} \) = likelihood of a midair collision given loss of control UAV

\( A_M \) = planar area of manned aircraft

\( A_{UAV} \) = planar area of UAV

\( E_i(A_i) \) = expected number of manned aircraft is in any potential collision area, \( A_i \)

For simplicity, it is assumed that the out-of-control UAV falls vertically, while air traffic travels flies horizontally. It is conservatively assumed that UAV loss of control occurs at a high altitude such that its random descent traverses both high altitude occupied by commercial air traffic and low altitude occupied by general aviation traffic. Air traffic density was defined for two altitudes: large planes (747 size) at 25,000 feet, and small planes (Cessna 172 size) at 5,000 feet. It is assumed that all traffic is at one of these two altitudes. According to a study by Larson and Haber (Ref. 11), the large plane density at 25,000 feet is 0.0008 planes per square mile, with a large plane top area of 480 ft\(^2\), and the small plane density at 5,000 ft is 0.03 planes per square mile, with a small plane top area of 281 ft\(^2\). The air traffic density was derived from data in the Central Valley of California during daytime hours and is typical of air traffic adjacent to large urban areas.

The planar area of a heavy UAV is estimated for a 35-foot rotor diameter as

\[
A_{large} = \pi \left( \frac{d}{2} \right)^2 = 962 \text{ ft}^2 \tag{15}
\]

Equation 14 can be used to calculate the likelihood of a midair collision for each of these two air traffic altitudes by setting the expected number of aircraft per area equal to the air traffic density. Using the densities defined above and Equations 14 and 15 yields:

\[
L_{MC,25k} = 4.14 \times 10^{-8} \tag{16}
\]

\[
L_{MC,5k} = 1.34 \times 10^{-6} \tag{17}
\]

Adding these two together,

\[
L_{MC} = L_{MC,25k} + L_{MC,5k} = 1.38 \times 10^{-6} \tag{18}
\]

Since the likelihood of a midair collision given loss of control is four orders of magnitude smaller than the likelihood of a ground casualty given loss of control, the midair collision risk can be effectively ignored for the purpose of this analysis.
COMPARISON WITH AIRPLANE ACCIDENT DATA

To validate the falling object stochastic model, an empirical comparison with accident data is performed. The analytical prediction from Equation 13 implies that 1.5% of tiltrotor sized UAV critical failures are expected to cause a third party casualty when operated on an inter-airport ferry mission. This prediction is validated by an empirical assessment of airplane accident data. A study by Aiken in 2002 (Ref. 12) found that out of 20,122 general aviation accidents in the 1990’s, only fourteen resulted in ground injuries. Applying the FAA rule-of-thumb that one in ten accidents are caused by aircraft malfunction (Ref. 3) implies the empirical probability of a ground casualty given an aircraft malfunction for general aviation is

\[ L_{GC, GA} = \frac{14}{20,122} \times 10 = 0.007 \]  \hspace{1cm} (19)

where \( L_{GC, GA} \) = the empirical likelihood of a ground casualty given loss of control for general aviation.

Another study evaluated 1574 fatal airplane accidents between 1 January 2000 and 30 March 2004. Neglecting the terrorist activities of 11 September 2001, only two accidents in this time period resulted in ground fatalities (6/6/03 and 11/12/01) with 76 (5%) impacting a residential area (Ref. 14). Assuming that 10% of the airplane accidents were caused by malfunction, then the empirical probability that a ground casualty occurs given a malfunction for airplanes is

\[ L_{GC, AP} = \frac{2}{1,574} \times 10 = 0.013 \]  \hspace{1cm} (20)

where \( L_{GC, AP} \) = the empirical likelihood of a ground casualty given loss of control for airplanes.

The calculations of Equations 19 and 20 show an empirical probability of a failed aircraft causing a ground casualty of 0.7% and 1.3% and are very close to the analytical prediction of 1.5%. The analytical prediction is the same order of magnitude yet slightly conservative when compared to empirical data. Furthermore, an audit of the airplane accident database for midair collisions validates the analytical prediction of Equation 18. According to accident data, the general aviation midair collision rate between 1991 and 2002 was 0.51 per million flight hours (Ref. 14). Assuming one-hour flights, the empirical midair collision rate is approximately three times higher than the probability of a UAV midair collision given a random descent. The higher empirical collision rate is likely caused by the close proximity of aircraft during terminal airport operations that is not accounted in the midair collision model.

CONCLUSIONS

An approach to address safety concerns with VTOL UAV’s operating in civil airspace is to perform an equivalent level of safety (ELOS) analysis to establish UAV failure rate criteria to provide an equivalent level of public safety as manned aircraft. An ELOS analysis can be used as an interim approach to authorize VTOL UAV flight in civil airspace in accordance with FAR 21.17 until appropriate airworthiness standards are published. Since there are no passengers or flight crew at risk from a UAV failure, the ELOS analysis is based on equating a catastrophic manned aircraft failure to a UAV loss of control event that results in a third party casualty via ground injury or midair collision. Ground casualty risk is based on a falling object model derived from commercial space transport safety assessment methodology.

To illustrate this methodology, a sample analysis is provided for three generic VTOL UAV missions in civil airspace for three typically sized aircraft. The analysis uses air traffic density data and population density data for a flight path over heavily populated and moderately populated areas (Table 6).

<table>
<thead>
<tr>
<th>Homeland Security over Populated Areas (Example 1)</th>
<th>Law Enforcement over Populated Areas (Example 2)</th>
<th>Ferry Flight (Example 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_{GC} )</td>
<td>( P_{CF} )</td>
<td>( L_{GC} )</td>
</tr>
<tr>
<td>Heavy UAV</td>
<td>0.4268</td>
<td>( 2.34 \times 10^{-7} )</td>
</tr>
<tr>
<td>Light UAV</td>
<td>3.2</td>
<td>( 1.0 \times 10^{-7} )</td>
</tr>
<tr>
<td>Tiltrotor UAV</td>
<td>0.11</td>
<td>( 9.279 \times 10^{-7} )</td>
</tr>
</tbody>
</table>
The analysis yields the following specific conclusions:

1. FAA policy defines the accepted probability for loss of critical function, such as the flight control system, for a Part 23 airplane less than 6,000 pounds as $1.0 \times 10^{-7}$ per flight hour.

2. If the AC 23.1309 definition of “catastrophic” is applied to UCAR operations, then a “catastrophic” condition exists if a system failure results in at least one third party casualty.

3. A conservative estimate for the probability of a UAV operating over moderately to heavily populated commercial airspace causing third party casualties, given a loss of control malfunction, ranges from 1.5% to 100% depending on the flight path population density and vehicle size.

4. A system integrity level equivalent to manned aircraft is necessary to ensure ELOS for VTOL UAV operations over heavily populated urban centers.

5. The reliability of UAV’s currently in service—approximately one loss from aircraft failure every 2,000 hours—is insufficient to provide an ELOS for a typical ferry flight for the range of UAV sizes considered.

6. The likelihood of a failed UAV causing third party casualties via midair collision ($1.4 \times 10^{-4}$) is low compared to the likelihood of ground casualties (1.5% to 100%).

7. An empirical calculation of ground casualty risk using airplane accident data (0.7% to 1.3%) is similar to the analytical prediction for a tiltrotor UAV on an inter-airport ferry flight (1.5%).

REFERENCES

1. Williams, K.W., “A Summary of Unmanned Aircraft Accident/Incident Data: Human Factors Implications”, FAA Civil Aerospace Medical Institute, Oklahoma City, OK.


