Safety Assessment for Light Remotely Piloted Aircraft Systems

Safety Assessment for Light Remotely Piloted Aircraft Systems

Giorgio Guglieri
Dipartimento di Ingegneria Meccanica e Aerospaziale, Politecnico di Torino, Italy
giorgio.guglieri@polito.it

Gianluca Ristorto
Mavtech srl, Bozen, Italy
gianluca.ristorto@mavtech.eu

Abstract - **In the last years, Remotely Piloted Aircraft Systems (RPAS) have been developed for a variety of civil applications, such as agriculture, aerial photogrammetry and topographic mapping, environmental monitoring, search and rescue, prevent of fires and disasters, environmental research, monitoring of artistic heritage and general photography and videos. Multi-rotor and fixed-wing configurations are the most common platforms, but for the next years lighter-than-air vehicles (i.e. blimps) could represent an important niche market.**

In order to establish a set of rules to ensure the safety of RPAS operations, many countries have developed regulation for RPAS with a Maximum Take-Off Mass (MTOM) of less than 150 kg. In 2015, ENAC, the Italian aviation authority, has published the second edition of the regulatory issues for this kind of aircraft. This edition looks ahead to the forthcoming common EU regulation and further amendments will be considered based on (EASA, 2015) and further EASA reports. The reference rules introduce a distinction between RPAS with a MTOM equal to or larger than 25 kg and RPAS with MTOM of less than 25 kg. The operator must provide to ENAC a series of documents that demonstrate that the system is compliant with the regulatory restrictions, in particular the results of risk assessment in order to motivate the safety of the in-flight operations.

The aim of this paper is the presentation of a novel methodology for risk assessment applied to different RPAS with a MTOM lower than 25 kg, also including lighter-than-air configurations. This methodology concerns with ground impacts and does not cover the aspects of mid-air collisions. The results of this analysis provide a comprehensive insight for mission feasibility and operational implications in a set of realistic application cases. Practical solutions are proposed for risk mitigation of RPAS operations enforcing a concept of general validity, also compliant with forthcoming common EU regulations, applicable at continental level.

Index Terms - Remotely Piloted Aircraft Systems, Unmanned Aerial Vehicles, Certification procedures, Risk Assessment.

BACKGROUND

Unmanned Aircraft Systems (UAS) have been hugely developed in recent years. In particular small Unmanned Aerial Vehicles (UAVs) can be used in civil application such as agriculture, traffic monitoring, prevention of fires and disaster, search and rescue, environmental research, pollution, monitoring of the artistic heritage but also general photography and videos. Many countries have developed regulation to allow UAS integration in their National Airspace Systems (NAS). The regulations basic principle give to UAS an Equivalent Level of Safety (ELOS) to that of manned aviation.

In December 2013, the Italian Civil Aviation Authority (Ente Nazionale per l'Aviazione Civile, ENAC) published the regulation on RPAS with MTOM of less than 150 kg and the regulation came into force at the end of April 2014.

In 2015, the Italian Civil Aviation Authority (Ente Nazionale per l'Aviazione Civile, ENAC) has published the second edition of the regulatory issues for RPAS with MTOM of less than 150 kg. This edition looks ahead to the forthcoming common EU regulation and further amendments will be considered based on (EASA, 2015) and further EASA reports. The use of the term RPAS is to emphasize that, although not on board, the pilot is always present and has the capability to control anytime the RPAS flight.

The regulation makes a distinction between RPAS with MTOM equal to or more than 25 kg and RPAS with MTOM of less than 25 kg. For the latter simplified procedures are applied if the operations are not critical. Non-critical and critical operations are defined in (ENAC, 2013). Non-critical operations are those operations conducted in areas such that an impact on the ground does not cause fatal injuries to people on the ground or severe damage to third parties (buildings, infrastructures, …) on the ground. Non-critical operations are performed in the volume of space up to 150 m (500 ft) above the ground and up to 500 m radius. The operator must provide to ENAC a series of documents that state that the system is compliant with the regulation. The operator must provide to ENAC the results of risk assessment in order to motivate the safety of the planned operations, for both critical and non-critical specialized operation.

Several works have been made in assessment of risk for UAS operations. Clothier (2006) provided a discussion on the definition and application of safety objectives to ensure appropriate requirements for UAS operations. A simple ground fatality expectation model is also used to illustrate the influence of safety objectives variation on the design and operations of UAS. Lum and Waggoner (2011) proposed a risk model for both midair collision and ground collision. The same model is applied in (Lum et al, 2011) to assess the risk associated with operating an UAS in a populated area. Weibell (2005) introduced the concept of risk mitigation for small UAVs. Size of potential impact area, kinetic energy at impact and system design of small UAVs decrease the ground fatality risk.

The aim of this paper is the presentation of a novel methodology for risk assessment applied to different powered RPASs with a MTOM lower than 25 kg, also including lighter-than-air configurations, eventually tethered for critical operational environments. This methodology concerns with ground impacts and does not cover the aspects of mid-air collisions. The results of this analysis provide a comprehensive insight for mission feasibility and operational implications in a set of realistic application cases. Practical solutions are proposed for risk mitigation of RPAS operations enforcing a concept of general validity, also compliant with forthcoming common EU regulations, applicable at continental level.

The paper is organized as follows. Powered RPAS risk assessment is presented in section 2, while the case of a lighter than air unpowered vehicle (tethered blimp) is illustrated in section 3. The description of the RPAS and the blimp is given in Section 4 while the operative scenario is illustrated in Section 5. Section 6 provides the risk assessment results. The paper concludes with discussion of the results.

POWERED RPAS RISK ASSESSMENT

The buffer area

The buffer area is a safety distance between the area of operations and adjacent areas that are not subjected to overflight in normal operation. Adjacent areas may be involved in case of uncontrolled flight of the RPAS. The buffer area is computed considering the behavior of the aircraft during a failure. Typically for a multicopter is considered a ballistic trajectory, while for the fixed-wing aircraft a glide constant angle of 45 degrees is assumed during the falling phase.

Method for risk assessment

The methodology here proposed (Guglieri et al., 2014) concerns with ground impact and does not cover the aspect of mid-air collisions. The method considers:

- Casualty area of impacting debris (Ac).
- Population density (Dp).
- Probability of fatal injuries to people exposed to the crash (Pf).

RPAS dimensions (wingspan or propeller diameter for fixed-wing aircraft and diagonal wheelbase for multicopter), glide angle (γ) and height and width of an average human determine Ac. For further details see (FAA, 2000).

Pf is computed considering the kinetic energy at impact and sheltering. Sheltering is an important factor considered in this method. Indeed, trees, buildings, vehicles and other obstacles can shelter a person from the impact, reducing the probability of fatal injuries. The sheltering factor in Pf is an absolute real number. In (Guglieri et al., 2014) Pf is evaluated according to a qualitative estimation of the operative scenario (Table 1).

Table 1 Sheltering factor

Sheltering	Area
0 %	No obstacles
25 %	Sparse trees
50 %	Trees and low buildings
75 %	High buildings
100 %	Industrial area

The sheltering percentage (from 0% to 100%) is associated to the type of shelter that trees and/or buildings may provide to people on the ground. Sheltering percentage must be averaged over the area of operations, buffer zone included (indicatively for a 2km x 2km square) and weighted with the population density.

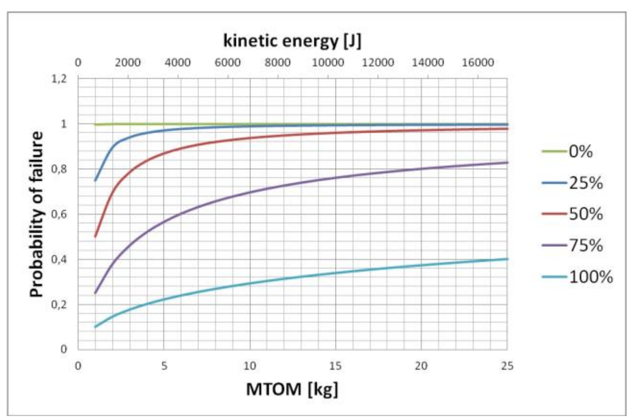

Figure 1 Probability of fatality as a function of RPAS MTOM and percentage of sheltering, @ V = 37 m/s

Probability of fatality as a function of the MTOM is presented in Figure 1. Sheltering percentage is the parameter. The graph is obtained starting from the kinetic energy at impact computed as

$$E_{CIN} = \frac{1}{2} M V^2 \qquad (1)$$

Where *M* is the MTOM and *V* is the velocity at impact. In this case *V* is set equal as the free fall velocity from an altitude of 70 m, that is approximately 37 m/s.

In this paper the maximum acceptable probability for on ground victims per fatal RPAS accident is computed as in (FAA, 2000) with the percentage sheltering factor proposed in (Guglieri et al., 2014):

$$P = \frac{N}{A_C \cdot D_P \cdot P_f} \qquad (2)$$

where N is the number of on ground victims per flight hour and it is set equal to 10^{-6} as safety objectives.

In case of nonhomogeneous population density areas, the introduction of a G probability factor considers that RPAS may crash in a specific area

$$P_i = \frac{N}{A_C \cdot G_i \cdot D_{P,i} \cdot P_{f,i}} \qquad (3)$$

The reciprocal of the maximum probability is then compared with the reliability of the RPAS. Because the components of this kind of aircraft derive from model aircrafts, it is impossible to evaluate the reliability of the overall system. (FAA, 2015) assumes an acceptable value for MTBF of 100 hours.

LIGHTER THAN AIR UNPOWERED VEHICLE RISK ASSESSMENT

The buffer area

In order to evaluate the buffer area some simplifying hypotheses are considered:

- The disengagement of the payload and its impact on people on the ground is considered lethal.
- The impact of the envelope is considered inoffensive because the kind of material.
- The height of the people is neglected.
- The model of impact is punctual.

The horizontal distance covered by the falling payload represents the buffer area. When there is no wind, the blimp will stay on the vertical of the anchoring point and the payload will fall inside a cone of semi-aperture α = 30° (Figure 2). In this condition, the buffer radius is

$$r_{xP} = L \cdot \tan \alpha \qquad (4)$$

where *L* is the height of the falling payload (length of the retention cable).

In windy conditions, the blimp assumes different position due to the aerodynamic drag that affect the envelope (Figure 3).

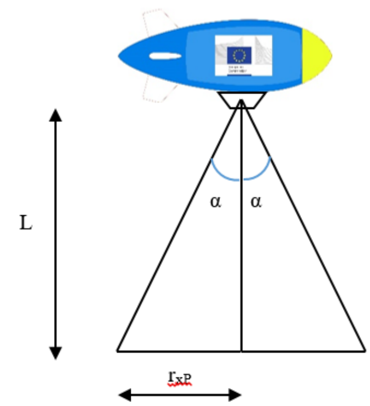

Figure 2 Blimp position in no wind condition.

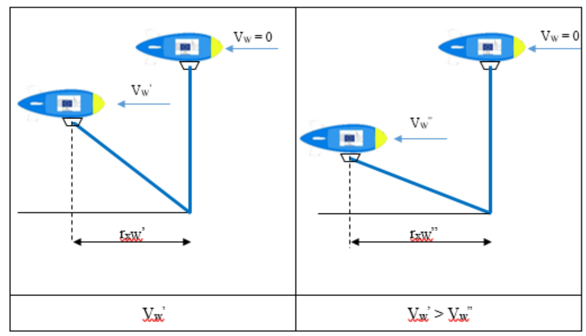

Figure 3 Blimp position in windy conditions.

The buffer radius is

$$r_B = r_{xP} + r_{xW} \qquad (5)$$

and it is measured on the vertical of the anchoring point. Furthermore, according to Figure 4 the horizontal distance covered by the falling payload in windy conditions is lower than the horizontal distance in still air.

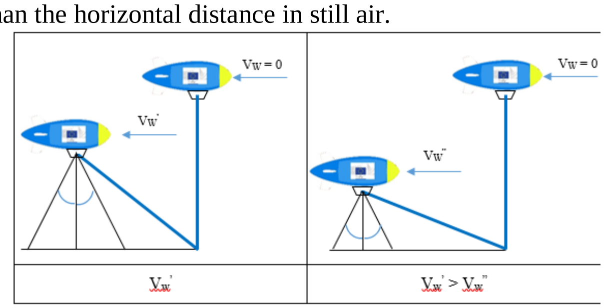

Figure 4 Effect of the wind on the horizontal projection of the falling payload.

Retention cable ultimate wind load

The wind speed for which the retention cable breaks is calculated by matching the aerodynamic drag and the ultimate load of the retention cable:

$$\frac{1}{2} \cdot \rho \cdot V_W^2 \cdot S \cdot C_D = R_C \qquad (6)$$

where

ρ	Air density	1.225 [kg/m^3]
V_w	Wind speed	[m/s]
S	Equivalent sphere frontal surface	[m^2]

C_D	Sphere drag coefficient	0.47 [-]
R_C	Ultimate load of the retention cable	3850 [N]

Reversing eq (6), we obtain the ultimate wind load:

$$V_W = \sqrt{\frac{2 \cdot R_C}{\rho \cdot S \cdot C_D}}$$

Wind limitations

It is assumed a maximum operator strength of

$$F_{\lim} = 30\,kg = 294.3\,N$$

According to equation (7), it is possible to operate in windy condition if the aerodynamic drag of the equivalent sphere is lower than the maximum operator muscular strength.

$$F_W = \frac{1}{2} \cdot \rho \cdot V_W^2 \cdot S \cdot C_D < F_{\lim} \qquad (7)$$

THE AERIAL VEHICLES

Four reference RPASs developed by MAVTech srl (www.mavtech.eu), a former spin-off of Politecnico di Torino, have been considered for the risk assessment. The MH850 is a fixed-wing aircraft, characterized by tailless wing-body configuration, two twins non-movable vertical fins at wing tips, electric propulsion in tractor configuration (Figure 5). Wings are made of EPP (Expanded Polypropilene) thus the aircraft is durable for damages. The wingspan is 872 mm, the fuselage length is 450 mm, the propeller diameter is 230 mm and it weighs 1 kg. The AGRI-2000 (Figure 6) has the same configuration of the MH850 except that the electric propulsion is in pusher configuration and the entire structure is in molded EPO. The wingspan is 2120 mm, the fuselage length is 770 mm, the propeller diameter is 330 mm and the Agri-2000 weighs 4 kg. The Q4-Rotor-Light (Q4L, Figure 7) is a multicopter characterized by four booms and four rotors. The diagonal wheelbase is 0.6 m and it weighs 1.8 kg. Finally, the Q4-Rotor-Power (Q4P, Figure 8) is the heavier version of the Q4L. The diagonal wheelbase is 1.880 m and it weighs 7.5 kg.

Figure 5 – The MH850

Figure 6 – The AGRI-2000

Figure 7 – The Q4L

Figure 8 – The Q4P

Figure 9 – Blimp ZNYL-900 (www.technofly2008.com).

The model of the tethered blimp is the ZNYL-900 (Figure 9) and it has a double envelope (inner envelope polyurethane, outer envelope nylon). The ZNYL-900 has inflatable stabilizers. The fuselage length is 9 m, while the maximum diameter is 3,38 m. The estimated volume is 45 m^3 and the ZNYL-900 has a maximum payload of 10 kg. The retention cable is in Dyneema® SK99 and its main features are summarized in Table 2.

Table 2 – Retention cable main features

Length (Max)	Diameter	Ultimate Load	Linear weight
[m]	[mm]	[N]	[g/m]
120	1.5	3850	1.6

A winch is used to stretch the retention cable. The winch has a maximum load capacity of 20 kg.

SCENARIO

Two types of scenarios have been considered for powered RPAS risk assessment: a non-critical scenario and a critical one. The non-critical scenario is characterized by uniform population density of 5 habitants per km^2 and a sheltering percentage of 25%. The critical scenario is a real case. The area considered is that of Torino Aeritalia Airport (I-LIMA). It is located in the North-West of the city, on the border between Torino and the town of Collegno. The area is depicted in Figure 10, while Figure 11 shows the area of operation (red circle, 400 m radius), the buffer area (green circle, 600 m radius) and the adjacent areas (yellow circle, 700 m radius). Torino Aeritalia Airport can be a promising site for RPAS experimental activities. Flight operations take place in the red circle. The site is characterized by different population density and offers different kind of shelter for people on ground. Agricultural lands (North) are characterized by low population density and few trees offer poor shelter. Whereas, industrial buildings (South and West) offer high population density but also high values of sheltering factor. In order to evaluate the average population density and sheltering factor, the area has been partitioned in 3 slices (Figure 12). For each area, population density (Dp,i) and sheltering percentage (P_s) are estimated and the average value has been evaluated (see Table 3).

Figure 10 – Torino-Aeritalia Airport

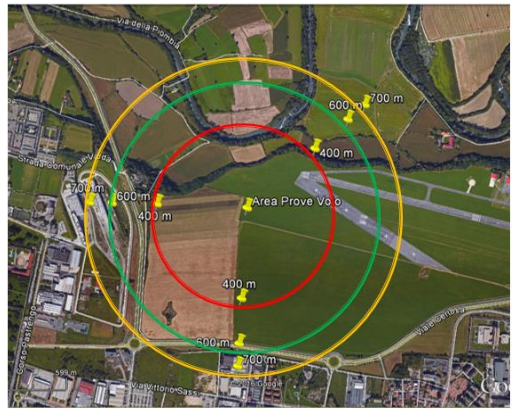

Figure 11 – Area of operations (RED), buffer area (GREEN) and adjacent area (YELLOW)

Figure 12 – Partition of the area

Table 3 - Estimation of population density and sheltering percentage for each slice of the scenario

Sector	Δα	Gi	S	Habitants	Dp,i	Sheltering %
[-]	[deg]	[-]	[km^2]	[people]	[people/km^2]	[%]
1	85	0.236	0.363	50	138	50
2	65	0.181	0.278	100	360	75
3	210	0.583	0.583	10	11	25

The probability of fatality is then estimated for each RPAS in each sector of the scenario.

RESULTS

Powered RPAS risk assessment results

Results for non critical scenario are shown in Table 4, while Table 5, Table 6, Table 7 and Table 8 illustrate the results for critical scenario of each aircraft considered in the risk analysis.

Table 4 – Results for non-critical scenario (Dp = 5 people/km^2)

	A_C	P_f	P	1/P
	[m^2]	[-]	[1/h]	[h]
MH850	2,247	0,559	0,159	6
AGRI-2000	2,924	0,876	0,078	13
Q4L	4,907	0,750	0,054	18
Q4P	15,957	0,950	0,013	76

Table 5 – MH850 results for critical scenario

Sect.	Ac	Dp	Gi	Ecin	Shelt.	Pf	P	1/P
[-]	[m^2]	[people/km^2]	[-]	[J]	[%]	[-]	[1/h]	[h]
1		138	0,236		50	0,514	0,027	38
2	2,247	360	0,181	1472	75	0,258	0,026	38
3		11	0,583		25	0,762	0,091	11

Table 6 – AGRI-2000 results for critical scenario

Sect.	Ac	Dp	Gi	Ecin	Shelt.	Pf	P	1/P
[-]	[m^2]	[people/km^2]	[-]	[J]	[%]	[-]	[1/h]	[h]
1		138	0,236		50	0,799	0,013	76
2	2,924	360	0,181	5886	75	0,477	0,011	91
3		11	0,583		25	0,947	0,056	18

Table 7 – Q4L results for critical scenario

Sect.	Ac	Dp	Gi	Ecin	Shelt.	Pf	P	1/P
[-]	[m^2]	[people/km^2]	[-]	[J]	[%]	[-]	[1/h]	[h]
1		138	0,236		50	0,659	0,010	98
2	4,579	360	0,181	2739	75	0,351	0,010	105
3		11	0,583		25	0,876	0,039	26

Table 8 – Q4P results for critical scenario

Sect.	Ac	Dp	Gi	Ecin	Shelt.	Pf	P	1/P
[-]	[m^2]	[people/km^2]	[-]	[J]	[%]	[-]	[1/h]	[h]
1		138	0,236		50	0,881	0,002	440
2	15,332	360	0,181	11411	75	0,587	0,002	587
3		11	0,583		25	0,976	0,010	96

Lighter than air vehicles risk assessment results

The following tables summarize the effect of wind on height of the blimp (h), horizontal projection of the falling payload (r_{xP}), horizontal distance of the blimp with respect the anchoring point and buffer radius (r_B) for three different lengths of the retention cable $L = \{20, 40, 100\}\ [m]$ and for a net thrust (F_N) of 10 kg.

Table 9 – Buffer radius (L = 20 m)

L = 20 m			FN = 10 kg	
V_w	h	rxP	rxW	rB
[kt]	[m]	[m]	[m]	[m]
0	20,00	10,00	0,00	10,00
5	19,32	9,66	5,18	14,84
10	13,63	6,82	14,63	21,45
15	7,66	3,83	18,48	22,30
20	4,54	2,27	19,48	21,75

Table 10 – Buffer radius (L = 40 m)

L = 40 m			FN = 10 kg	
Vw	h	rxP	rxW	rB
[kt]	[m]	[m]	[m]	[m]
0	40,00	20,00	0,00	20,00
5	38,63	19,32	10,37	29,69
10	27,25	13,63	29,28	42,91
15	15,30	7,65	36,96	44,61
20	9,08	4,54	38,96	43,50

Table 11 – Buffer radius (L = 100 m)

L = 100 m			FN = 10 kg	
Vw	h	rxP	rxW	rB
[kt]	[m]	[m]	[m]	[m]
0	100,00	50,00	0,00	50,00
5	96,54	48,27	26,08	74,35
10	67,93	33,96	73,39	107,35
15	38,10	19,05	92,46	111,51
20	22,61	11,30	97,41	108,72

Table 12 shows the parameter of the equivalent sphere and the retention cable ultimate wind load.

Table 12 – Retention cable ultimate wind load

F_N	ds	S	VW
[kg]	[m]	[m2]	[m/s]
10	4.20	13.92	31.0

The following table summarize the aerodynamic drag due to different wind conditions and for three different lengths of the retention cable $L = \{20, 40, 100\}\ [m]$ and for a net thrust (F_N) of 10 kg.

Table 13 – Aerodynamic drag of the equivalent sphere for different wind speed (L = 20 m)

L = 20 m		FN = 10 kg	
Vw	dS	S	FW
[kt]	[m]	[m]	[N]
0	4.21	13.92	0
5	4.21	13.92	32
10	4.21	13.92	130
15	4.21	13.92	292
20	4.21	13.92	519

Table 14 – Aerodynamic drag of the equivalent sphere for different wind speed (L = 40 m)

L = 40 m		FN = 10 kg	
Vw	dS	S	FW
[kt]	[m]	[m2]	[N]
0	4.21	13.92	0
5	4.21	13.92	32
10	4.21	13.92	130
15	4.21	13.92	292
20	4.69	17.28	520

Table 15 – Aerodynamic drag of the equivalent sphere for different wind speed (L = 100 m)

L = 100 m		FN = 10 kg	
Vw	dS	S	FW
[kt]	[m]	[m2]	[N]
0	4.21	13.92	0
5	4.21	13.92	33
10	4.21	13.92	131
15	4.21	13.92	295
20	4.69	17.28	524

COMMENTS AND CONCLUSIONS

According to Table 4, for the non-critical scenario, the reciprocal of the maximum acceptable probability is lower than the reliability accepted for this kind of aircraft. Thus, operations are allowed for every RPAS considered in this analysis.
The application of mitigation factors, such as probability of fatality and probability factor that RPAS may crash in a specific area, increase the maximum acceptable probability of the (FAA, 2000) method. According to Table 5, Table 6 and Table 7, the flight operations of MH850, AGRI-200 and Q4L are safety in that scenario, while for the Q4P (Table 8), sector 1 and 2 exceed the minimum reliability accepted for this kind of RPAS. Thus, a restriction of the area of operation has to be considered, as shown in Figure 13. Flight operation of Q4P are allowed only in the dashed red area.

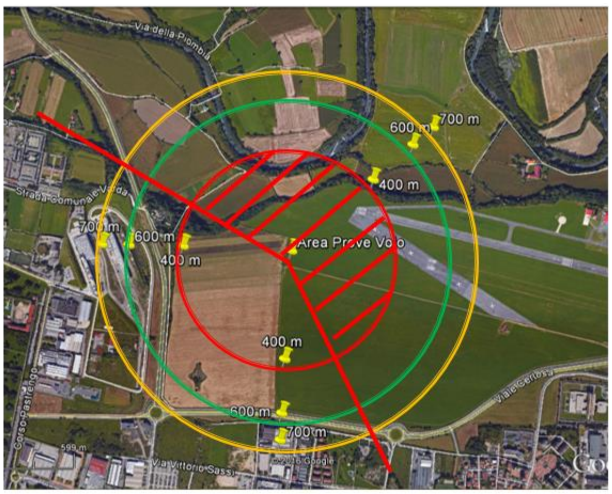

Figure 13 Restriction of the area of operation for the Q4P

In the lighter than air unpowered blimp exercise, a buffer radius that varies as a function of the length of the retention cable has been defined (cleared area):

- L = 20 m, buffer radius: rB = 23 m
- L = 50 m, buffer radius: rB = 46 m
- L= 100 m, buffer radius: rB = 114 m

Operations should be limited, according to the wind speed. In particular operations are allowed if the wind speed do not exceed 15 kt. As a comment, the present risk assessment methodology can be extended also to powered lighter than air vehicles where the tether is removed and a line of sight radial distance is considered for the definition of the cleared area.

ACKNOWLEDGMENT

The work here proposed is within the activities of the S-APR project, funded by the Autonomous Province of Bozen, Italy.

REFERENCES

Dalamagkidis K., Valavanis K.P., Piegl L.A., 2011. On Integrating Unmanned Aircraft Systems in to the National Airspace Systems, Springer, Mar. 2011

EC, 2008. Regulation (EC) No 216/2008 of the European Parliament and of the Council, 2008.

ENAC 2013. Regolamento Mezzi Aerei a Pilotaggio Remoto, 1st Edition, 16th December 2013.

ENAC, 2015. Remotely Piloted Aerial Vehicles Regulation - Issue No. 2, Rev. 1, 2015.

EASA, 2015. Introduction of a regulatory framework for the operation of unmanned aircraft.

EASA, 2016. Prototype Commission Regulation on Unmanned Aircraft Operations. 22th August 2016

FAA 2000. Expected Casualty Calculations for Commercial Space Launch and Reentry Missions, FAA-AC431.35.

FAA, 2015. Unmanned Aircraft Systems (UAS) Registration Task Force (RTF) Aviation Rulemaking Commitee (ARC), «Task Force Recommendations Final Report», November 21, 2015

G. Guglieri, A. Lombardi, G. Ristorto, 2015. "Operation Oriented Path Planning Strategies for RPAS". In American Journal of Science and Technology, vol. 2 n.6 pp. 1-8

G. Guglieri, F. Quagliotti, G. Ristorto, 2014. "Operational Issues and Assessment of Risk for Light UAVs", Journal of Unmanned Vehicle Systems, Canadian Science Publishing (NRC Research Press), pp 11, pagine 119-129, ISSN: 2291-3467.

Shelley, A. V., 2016. A Model of Human Harm from a Falling Unmanned Aircraft: Implications for UAS Regulation. International Journal of Aviation, Aeronautics, and Aerospace, 3(3). http://dx.doi.org/10.15394/ijaaa.2016.1120

AUTHOR INFORMATION

Giorgio Guglieri, Professor, Dipartimento di Ingegneria Meccanica e Aerospaziale, Politecnico di Torino, Italy.

Gianluca Ristorto, junior engineer technical specialist, Mavtech srl, Bozen, Italy