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# Integration of rule-based ‘Expert Systems’ on RPAS capable of Specific Category Operations within the U-space: an original mitigation strategy for operational safety risks

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**Abstract.** The use of RPAS for civil purposes is spreading across Europe and worldwide; Aviation Authorities are working to layout regulations to assure a safe and secure integration of RPAS with manned aircraft across both controlled and uncontrolled (below 500 Feet of altitude) airspace. Following the identification of a selection of safety risks potentially associated to RPAS Specific Category of operations, an original strategy of risks mitigation focused on rule-based ‘Expert Systems’, has been conceived and it is discussed in this work. The article recalls the main components of rule-based ‘Expert Systems’ that is the knowledge basis and the rules to instruct the ‘Expert system’. Then the work describes the implementation of the rules as statements derived from a safety risk matrix associated to RPAS capable of performing Specific Category operations within the U-space. Finally, the idea of integrating the ‘Expert System’ as a software module within RPAS functional architecture is presented and discussed. Such solution is deemed to be a valuable novelty for future implementations of advanced RPAS autopilots capable of recognizing and solving in flight/on ground operational safety risks in such a way to speed up the integration of RPAS into not segregated airspace and their market development.

## 1. Introduction

Remotely Piloted Aircraft Systems (RPAS) are a disruptive novelty within current civil aviation community. After many years of use for military purposes only, they started to be designed to accomplish civilian operational requirements. The added value, clear since the first applications, was the possibility to make RPAS fly for a higher number of hours (eventually with shifting crews) than manned aircraft with less risks for humans and more benefits from an economic perspective. Therefore, Aviation Authorities (ICAO, EASA), perfectly aware of these facts, started to layout regulations to allow in the next future gradual full integration of RPAS with manned aircraft into not segregated airspaces with a special focus on safety. In fact, RPAS operations move risks from on board (RPAS are remotely piloted from ground, with no humans on board) to third parties on ground (people, infrastructures, etc.). The RPAS, as new actors in the aerial scenario, must be absorbed by the global aviation system in such a way that the current level of safety of commercial airplane transport remains equal to the existing one or it is further increased [1], [2]. Worldwide Aviation Authorities are elaborating risk models on RPAS operations. Focusing on Europe, EASA defined three basic categories of RPAS operations according to their risk level: Open Category, characterized by a low level of risk by definition; Specific Category with a medium risk level and, finally, Certified Category of operations, with very high associated risk level. For the moment, this last category of RPAS operations is purely theoretical and it will be developed far in time due to very complex issues related to the certification of unmanned platforms capable of performing very risky flight operations. Considering Specific Category of RPAS operations, that will be the first ones to be ruled for commercial purposes within the subspace from ground up to 500 Ft. of altitude under the U-space service, a comprehensive risk assessment has been implemented in the form of a risk matrix [3], [4]. Then, after risks identification, an original mitigation strategy based on 'Expert Systems' has been conceived to maintain hazards consequences at or below an acceptable level [5], [6]. Such strategy is described and discussed in this work. The article is organized as follows: Section 2 recalls rule-based 'Expert Systems' definition and the main elements of a typical architecture; subsection 2.1 describes how the knowledge basis of the 'Expert System' object of this article has been associated to a given RPAS risk matrix and modelled from its content; Section 3 is about the results obtained from this study; subsection 3.1 focuses on the integration of 'Expert System' software module within RPAS autopilot for a more effective risk mitigation action; Section 4 is dedicated to the discussion of the work results and, finally, section 5 reports open points and research hints for future works.

## 2. 'Expert Systems', definition and main architectural elements

'Expert Systems' are computer systems based on Artificial Intelligence capable of solving problems in a given domain of knowledge emulating human expertise; they are designed to support human decision making processes [7]. There are many types of 'Expert Systems'; those considered in this work are said 'rule-based Expert Systems'; they were invented by NASA; the software coding is usually performed using the CLIP programming language [8].
Rule-based 'Expert System' (ES) functional architecture usually consists of: (Figure 1, [7] and [9]):

- A base of knowledge implemented using simple 'IF-THEN' statements
- An inference engine, that is the reasoning part of the 'Expert System'; it can be based upon a forward chaining technique [3], a backward chaining technique [3] or, in the most optimized 'Expert Systems', upon a flexible combination of both of the two strategies [10]
- An interface with a human user, to query the 'Expert System' about a problem to be solved

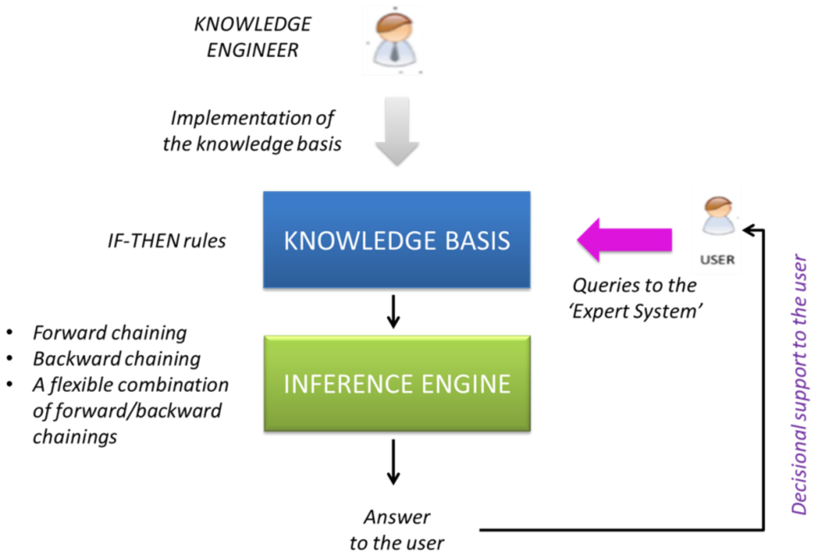


**Figure 1.** Typical 'Expert Systems' functional architecture [7] and [9]

'Expert Systems' (ESs) main criticalities depend on the level of knowledge in a given domain, knowledge basis size and software code maintenance [11]; ESs cannot recognized errors eventually introduced by the knowledge engineer and neither they cannot do anything that has not been previously programmed to be done.

Errors in the base of knowledge can affect the conclusions output by the ES itself [11]. ESs upkeep consists of code updating/debugging, knowledge basis upgrading or addiction of new interfaces with other information systems if necessary [10].
ESs main advantages are that they work like humans' mind without ageing, or being influenced by the psyche or by mental fatigue, etc.; finally, 'Expert Systems' software codes can be installed into robots and machines to work within dangerous environments (affected by pollution, nuclear radiations, etc.).

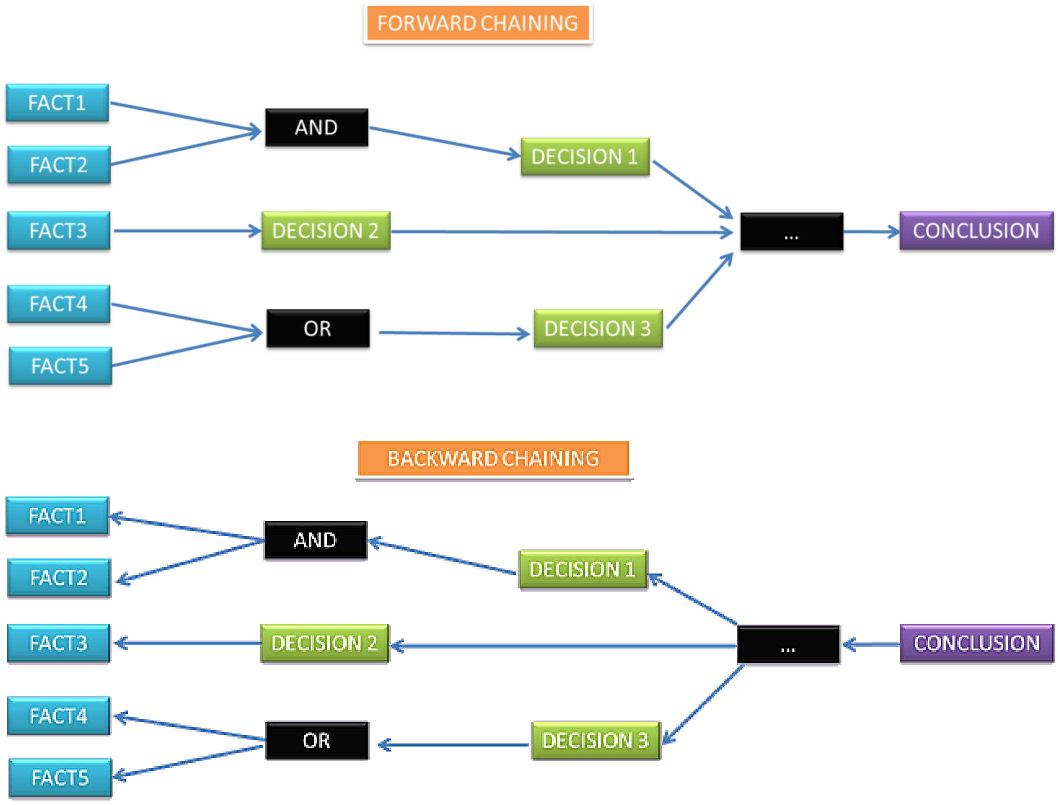


**Figure 2.** Forward/backward chaining techniques [3]

*2.1. Development of an 'ES' knowledge basis architecture from the RPAS 'U-space risk matrix'*
Figure 3 [3], shows the 'Expert System' functional architecture tailored for RPAS systems. the first obvious difference with a general ES architecture is that the ES user is represented by the RPAS remote operator. The second most significant element to be highlighted is that the knowledge basis has been built starting from the 'U-space risk matrix' reported in [3], [4] and Appendix A (which contains an extract of the matrix, where hazards of interest for this work are reported). As described in [3] and [4], the U-Space matrix was implemented for a selection of hazards identified for RPAS capable of performing Specific Category operations. Each assessed hazard of the matrix was singularly reconsidered and transposed into an 'IF-THEN' statement when possible; such process was judged not feasible for the following hazards ([3], [4]): Hazards H33, H34 and H35, related to unintentional radio link interference, hazards from H48 to H52, on human factor and hazards from H53 to H69 focused on adverse weather conditions. In these cases, the direct application of a workaround operational procedure was deemed to be the most proper mitigation provision against the risk associated to the considered hazard, instead of 'Expert Systems'.
All the other hazards were changed into an 'IF-THEN' statement thus building up the knowledge basis of the 'Expert System tailored on an RPAS system capable of Specific Category operations. The RPAS operator as user of the 'ES' will query the 'ES' to get support to solve on ground/in flight contingent hazards. The 'ES' will receive the request from the RPAS operator about the occurring

hazard ('IF' statement), it will process it through the inference engine and it will provide the remote operator with the solution of the hazard, that is the most proper mitigation provision to be applied to contain the effects of the consequences associated to the identified contingent hazard.
Two rules derived from U-space safety risk matrix from [3] are reported hereinafter to show their detailed implementation for example.

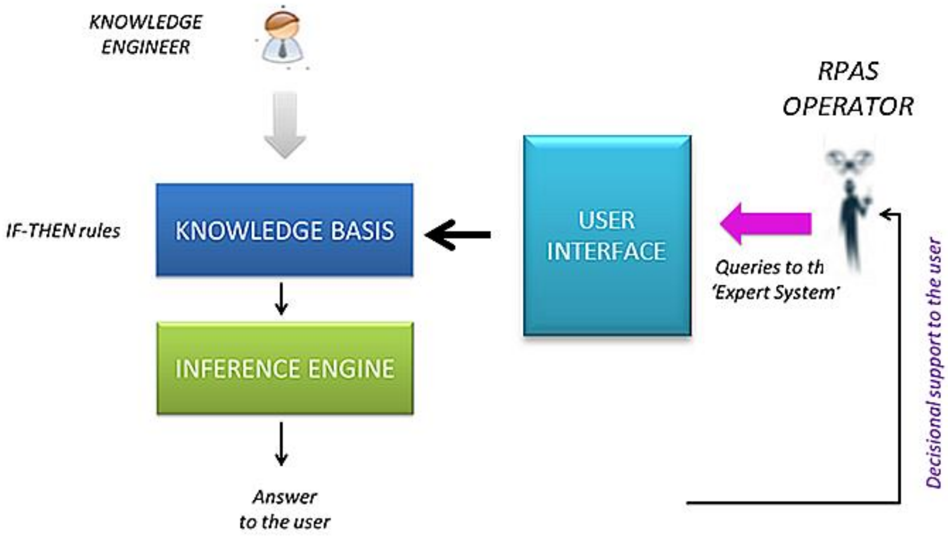


**Figure 3.** 'Expert Systems' functional architecture tailored for RPAS systems [3]

*2.1.1. Example 1.* Reference Hazard: H16 – Presence of man-made manufactures.
Risk range description: High Risk.

```
IF RPAS_LIDAR_SENSOR_OUTPUT IS 'OBSTACLE'
AND IF RPAS_DISTANCE_FROM_OBSTACLE IS SMALLER THAN THRESHOLD_DISTANCE
AND IF RPAS_DISTANCE_FROM_OBSTACLE IS GREATER THAN MINIMAL_DISTANCE
   Printout 'OBSTACLE HIGH RISK'
THEN SET AUTOPILOT TO PERFORM EVASIVE MANOUVER
   Printout 'OBSTACLE MODERATE RISK'
```

*2.1.2. Example 2.* Reference Hazard: H17 – Mid-air collision with other aircraft.
Risk range description: High Risk.

```
Rule number 1: Case of mid-air collision risk with cooperative traffic
IF RPAS_DAA_OUTPUT IS 'TRAFFIC'
AND IF RPAS_DISTANCE_FROM_OBSTACLE IS SMALLER THAN THRESHOLD_DISTANCE
AND IF RPAS_DISTANCE_FROM_OBSTACLE IS GREATER THAN MINIMAL_DISTANCE
   Printout 'TRAFFIC HIGH RISK'
THEN SET AUTOPILOT TO PERFORM EVASIVE MANOUVER
   Printout 'TRAFFIC MODERATE RISK'

Rule number 2: Case of mid-air collision risk with not cooperative traffic
IF RPAS_LIDAR_SENSOR_OUTPUT IS 'OBSTACLE'
AND IF RPAS_DISTANCE_FROM_OBSTACLE IS SMALLER THAN THRESHOLD_DISTANCE
AND IF RPAS_DISTANCE_FROM_OBSTACLE IS GREATER THAN MINIMAL_DISTANCE
   Printout 'TRAFFIC HIGH RISK'
THEN SET AUTOPILOT TO PERFORM EVASIVE MANOUVER
   Printout 'TRAFFIC MODERATE RISK'
```

## 3. Results

The full list of rules is reported in [3], Appendix F; it is preceded by the definition of a ground risk parameter derived from the JARUS SORA [12] ground risk index and by the definition of all the variables used in the rules. The rules were designed under for Light RPASs with maximum take-off weight between 25 and 150 kilograms, powered by rotor engines supplied by hydrogen fuel cells and backed up by a Lithium Polymer battery.

### *3.1. Integration with RPAS Autopilot*

Figures 4 and 5 (see [3]) show two of levels of functional integration of an RPAS with 'Expert System' software that have been conceived.
The aerial platform shall be equipped with on board monitoring sensors and safety sensors; the monitoring sensors recognize RPAS status parameters (flight altitude, speed, attitude, FTS or parachute health status, etc.); the safety sensors detect arising hazards conditions.
All these signals are routed to an interface module towards the 'ES'; the 'ES' will process these signals and it will output a conclusion; the conclusion is the mitigation strategy chosen from the 'U-space matrix' (Appendix A) to solve the contingent hazard. Hence, the rules constituting the 'ES' (in particular its knowledge basis) are the bridge between the 'ES' and the original 'U-space matrix' containing the information about the assessment of risks for the given RPAS capable of performing Specific Category of operations. More precisely, this is due to the fact that each rule of the 'Expert System' knowledge basis is a direct transposition of the associated hazard of the 'U-space matrix' into an 'IF-THEN' statement.

The two levels of implementation of the mitigation strategy based on 'ES' are conceived as follows:

- A basic level of functional integration where the remote operator maintains manual control of the RPAS in solving the hazard; he/she uses the 'Expert System' for decisional support only (Figure 4 from [3])

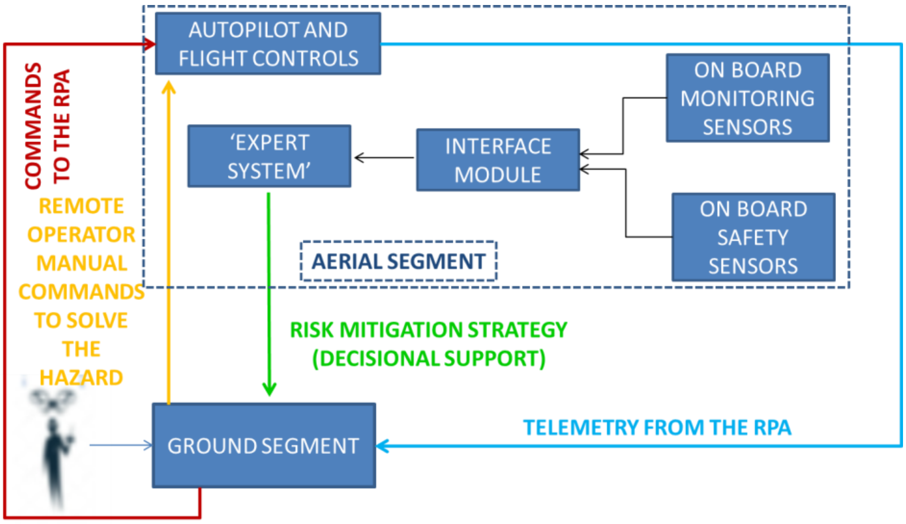


**Figure 4.** Basic functional integration of RPAS and 'Expert Systems' software modules [3]

- A more advanced level of functional integration where the 'ES' is fully integrated with the RPAS Flight Control System and Autopilot routines in such a way that the RPAS can autonomously mitigate/solve the detected arising hazard; the human operator monitors the operational scenario maintaining a supervisor role over the aircraft system as required by ICAO [1] (Figure 5 from [3])

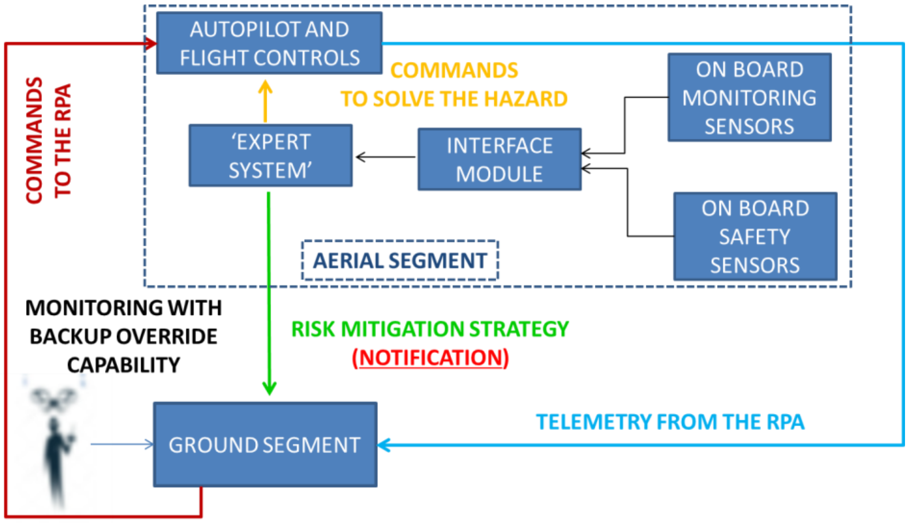


**Figure 5.** Advanced functional integration of RPAS and 'Expert Systems' software modules [3]

## 4. Discussions

The study has defined the main features of a rule-based 'Expert System' knowledge basis.
The 'ES' is the core of a new original mitigation strategy designed for RPAS capable of performing Specific Category operations between Ground and 500 Ft. of altitude with the support of the U-space service/infrastructure.
The 'ES' software code was not written; attention has been focused on the following other concerns:

- The verification of coverage, correctness and consistency of the knowledge basis with the hazards reported in the 'U-space matrix' [3]
- Further, the analysis of the requirements to properly layout the ES functional architecture has been privileged to the 'ES' software coding following [13], according to which, before writing a software used to control complex systems, it is better to analyse the given complex system to identify and avoid a priori errors that, if neglected, could generate hazards under unexpected combinations of critical conditions

The basic and advanced levels of functional integration of RPAS with 'Expert Systems' can be associated with Specific and Certified Categories of RPAS operations respectively; the two levels of integrations reflect a progressive capability of mitigating hazards increasing in number and risk level. In the most complex case (advanced level of integration), the role of the RPAS remote pilot as a supervisor of the whole sortie is foreseen to be kept, as a minimum, to accomplish Aviation Authorities basic guidelines [1]. The 'Expert System' inference engine has been supposed to be based on a forward chaining strategy. Each rule starts with the arising hazard conditions and ends with the conclusion/proposed mitigation strategy.
The most critical point is the level of autonomy to be applied to RPAS called to perform from Specific to Certified Category of operations. A proper level of autonomy against human manual capabilities is deemed significant from the Authors to assure more safety between manned and unmanned aircraft merged together with increasing levels of complexity and risk of operational scenarios. The further intelligence added by the 'Expert System' to RPAS autopilot software modules is expected to ease and speed up the reaction of RPAS platforms to an arising hazard in the airspace among other unmanned and manned traffic. Another equally important aspect is the set of monitoring and safety sensors to be installed on the RPAS to make effective the action of the 'Expert System' as an operational safety risk mitigation provision.

## 5. Conclusions

The architecture of a novel mitigation strategy has been presented and discussed: it has been implemented using rule-based 'Expert Systems' with the associated knowledge basis derived from the

'U-space risk matrix' described in [3], [4] with examples of hazards of interest for this work reported in Appendix A. In addition, a network of monitoring and safety sensors has been added to make this mitigation provision as much as possible effective in solving contingent operational hazards of RPAS capable of performing Specific Category operations. The work aims to introduce 'ES' and more in general techniques based on artificial intelligence as a possible category of support systems to manage Light RPAS operational hazards. This is encouraged by the possibility for software systems to process arising hazards conditions without errors and quicker than human operators. This novelty is expected to acquire more added value the more complex and safety critical the future not segregated aerial traffic scenario will be during daily operations of RPAS. The most important open points for next investigations are deemed to be the following ones: the best level of autonomy of the new systems composed of RPASs and 'Expert Systems' physically and functionally integrated; the quality and effectiveness of the preliminary safety analysis the 'Expert System' basis of knowledge is based on; the design requirements of the network of monitoring and safety sensors that will equip the RPAS system. In conclusion, the novel mitigation strategy proposed in this article together with a comprehensive RPAS system safety analysis can constitute a promising idea to maintain RPAS operational risks within not segregated airspaces at or below an acceptable level, provided that critical points about the use of artificial intelligence on board unmanned aircraft is carefully considered and deeply investigated.

## Appendix A

The following table contains some examples of the hazards contained in the 'U-space matrix' of [3] and [4]. Note: Hazards H16 and H17 are reported as direct reference for the two examples of 'ES' rules reported in 2.1.1 and 2.1.2. H34, H50 and H59 are reported as examples of each of the three kinds of hazards that were deemed not to be transposed into an ES rule, that is: hazards related to unintentional radio link interference, hazards due to human factor and hazards caused by adverse weather conditions.

**Excerpt of the 'U-space Risk Matrix' content ([3], [4])**

| Hazard | Definition | Description | Safety risk probability | Safety risk severity | Safety risk assessment | Tolerance | Risk range description | Recommended action | Mitigation factors | Residual risk | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| H16 | Presence of man-made manufactures | Flight operations in presence of man-made manufactures like buildings, bridges, electrical lines, etc. | Frequent - 5 | Catastrophic - A | 5A | Unacceptable | High risk | Cease or cut back operation promptly if necessary. Perform priority risk mitigation to bring down the risk index to moderate or low range | Provision of LIDAR/ SONAR sensors/ Provision of terrain profile data from mapping services (Google Map)/ Provision of geofence software | 5E | Moderate risk<br>Acceptable based on risk mitigation |
| H17 | Mid-air collision with other aircraft | Mid-air collision with other manned or unmanned aircraft | Occasional - 4 | Catastrophic - A | 4A | Unacceptable | High risk | Cease or cut back operation promptly if necessary. Perform priority risk mitigation to bring down the risk index to moderate or low range | Provision of onboard DAA (cooperative traffic)/Provision of LIDAR/SONAR (not cooperative traffic) | 4E | Moderate risk<br>Acceptable based on risk mitigation |
| H34 | Malicious radio link jamming | Intentional unlawful RF interference of RPAS radio - link | Occasional - 4 | Catastrophic - A | 4A | Unacceptable | High risk | Cease or cut back operation promptly if necessary. Perform priority risk mitigation to bring down the risk index to moderate or low range | Provision of redundant radio/Stop mission (FTS/Parachute) | 3D | Moderate risk<br>Acceptable based on risk mitigation |

| Excerpt of the 'U-space Risk Matrix' content ([3], [4]) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Hazard** | **Definition** | **Description** | **Safety risk probability** | **Safety risk severity** | **Safety risk assessment** | **Tolerance** | **Risk range description** | **Recommended action** | **Mitigation factors** | **Residual risk** | |
| H50 | Remote pilot loss of situational awareness | Loss of remote pilot situational awareness | Frequent - 5 | Hazardous - B | 5B | Unacceptable | High risk | Cease or cut back operation promptly if necessary. Perform priority risk mitigation to bring down the risk index to moderate or low range | Increase remote pilot training | 3D | Moderate risk<br>Acceptable based on risk mitigation |
| H59 | Ice | Weather hazard | Occasional - 4 | Hazardous - B | 4B | Unacceptable | High risk | Cease or cut back operation promptly if necessary. Perform priority risk mitigation to bring down the risk index to moderate or low range | Flight activity not to be performed due to less than optimal operational conditions | 4E | Moderate risk<br>Acceptable based on risk mitigation |

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