Technical Requirements for RPAS Operations in Cold Climates

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Abstract— **Remotely piloted aerial systems (RPAS) face significant challenges from atmospheric in-flight icing, which can drastically impair their safety and functionality. The objective of this document is to describe the effects of icing on RPAS and to suggest comprehensive operational and technical requirements for the safe operations of RPAS in icing conditions. This holistic approach is designed to inform and guide aircraft designers, operators, and policymakers in addressing the challenges posed by icing in uncrewed aerial operations.**

Keywords— ***icing, ice protection systems, RPAS, UAV, UAS, drone, technical requirements, specifications, certification***

I. Introduction

Remotely piloted aerial systems (RPAS)[1], have become increasingly important for commercial and defence applications. A major concern for these aerial systems is atmospheric in-flight icing, a hazard encountered in environments with supercooled clouds or freezing precipitation. Flight in icing conditions presents a substantial safety hazard that limits the operational availability, flyability, range, and functionality of RPAS in cold weather [1].

Atmospheric in-flight icing is a meteorological phenomenon critical to safety and occurs when aircraft encounter supercooled liquid water in the atmosphere. This supercooled water, present as cloud droplets or precipitation (rain/drizzle), remains in a liquid state even below the freezing point. Upon colliding with an aircraft, these supercooled droplets freeze upon impingement. This leads to ice accretion on the aircraft's surfaces, building into various ice shapes. Atmospheric icing can occur globally, at any latitude, and at any time of the year – but is substantially more frequent at higher latitudes, in cold climate regions, and during cold seasons [2,3].

The accumulated ice can take several different ice shapes or ice morphologies, see examples in Fig. 1. Rime ice occurs at lower temperatures when droplets freeze instantly upon impact. Glaze ice forms in temperatures near freezing, where not all droplets freeze immediately. Mixed ice is a combination of glaze and rime ice, resulting from partial freezing of droplets and the formation of a liquid film.

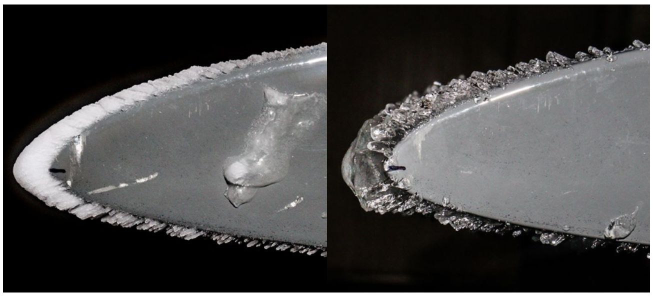

Figure 1: Rime ice (left) and glaze ice (right) ice shapes on a RPAS wing from icing wind tunnel experiments.

[1] Also called uncrewed aerial vehicles (UAVs), unmanned aerial vehicles, unmanned aerial systems (UAS), or drones.

II. Icing Effects

A growing body of research proves that icing severely impairs RPAS, e.g. [4–12]. Ice affects a larger number of components and, without suitable ice protection systems, can lead to a loss of the aircraft within minutes, see Tab 1.

A. Critical Effects

The following represents an assessment of negative icing effects on critical components, ranked by sensitiveness.

- **Airspeed sensor/pitot tube:** Ice accretion on the pitot tube, see Fig. 2, leads to blocked airspeed readings, resulting in erroneous data provided to the autopilot. This could cause inappropriate autopilot responses, such as stalls or nose-diving. Because of the exposed location and small size of the pressure holes, airspeed sensors are extremely sensitive to icing and can get blocked within seconds.
- **Propellers:** Icing on propellers rapidly and severely reduces thrust and increases power requirements. Experiments have shown a reduction of thrust by 75% percent and a power increase by 250% percent after only 100 seconds in moderate icing conditions [10]. Ice shedding due to centrifugal forces, see Fig. 3, can cause excessive vibrations and imbalances exceeding 10G, which can damage the propulsion system.

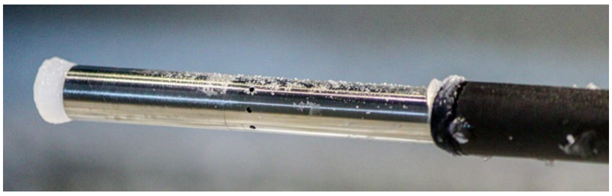

Figure 2: Ice accretion on a RPAS pitot tube.

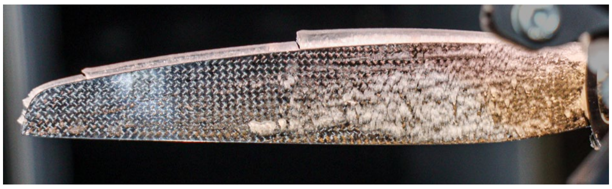

Figure 3: Ice accretion on a RPAS propeller after several ice-shedding events, creating “steps” on the leading edge.

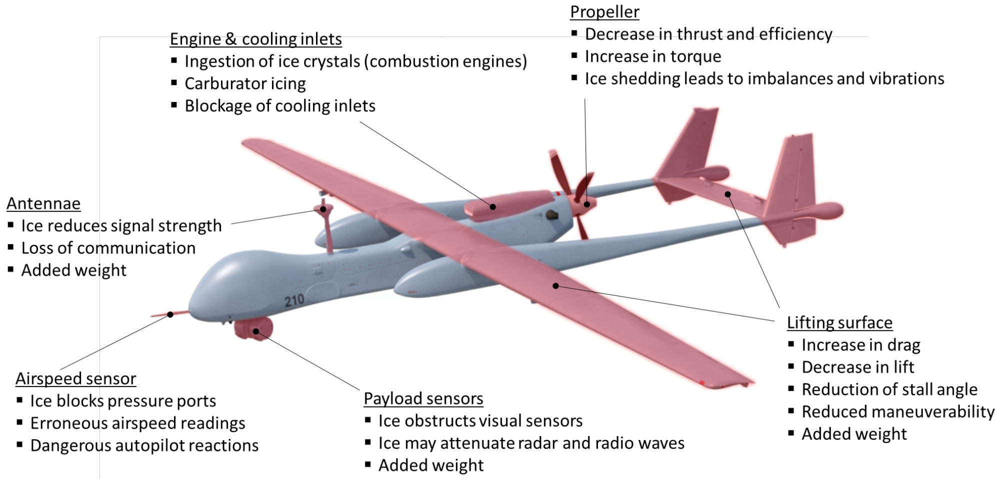

Figure 4: An overview of icing effects on different components of a typical tactical fixed-wing RPAS.

- **Lifting surfaces:** Ice accretion on wings and vertical/horizontal stabilizers alters the airfoil geometry and profile. This substantially increases drag, decreases lift, and reduces the stall margins. Simulations have shown a reduction of lift by 37%, an increase in drag by 107%, and a stall angle reduction of 4 degrees in severe icing conditions [7]. Also, ice reduces the effectiveness of control surfaces and thereby reduces manoeuvrability.
- **Autopilot:** Atmospheric icing can mislead the autopilot by altering the RPAS's flight performance, stability, and control. The autopilot system may struggle to accurately identify and adapt to these changes, increasing the risk of flight errors.
- **Antennae:** Icing on antennae can attenuate electro-magnetic and degrade signal quality and lead to communication loss. This is particularly critical for remotely-piloted RPAS, where reliable communication is essential for safe operation.

B. *Secondary Effects*

- **Carburetor icing:** In RPAS with piston engines, the carburetor can experience icing as the vaporization of fuel causes a drop in temperature, which, combined with high humidity, leads to ice formation inside the engine. This can obstruct the fuel/air mixture, resulting in engine power loss or shutdown.
- **Engine & cooling inlets:** Ice accretion on engine and cooling inlets can restrict critical airflow, leading to reduced combustion efficiency, potential engine stall, or mechanical failure due to overheating from inadequate heat dissipation.
- **Payload sensors:** Icing on payload sensors, such as cameras or radar domes, can obscure lenses and surfaces, leading to compromised data quality and reduced sensor accuracy.

Figure 4 gives an visual summery of all systems and components on a typical RPAS that can be affected by icing.

III. Ice Protection Systems

Ice protection systems (IPS) in aviation are categorized as anti-icing or de-icing systems. Anti-icing systems continuously prevent any ice accretion on critical aircraft surfaces. De-icing systems allow for an uncritical amount of ice to accumulate, which is then removed periodically. Today, there are several concepts that can be used for ice protection [1]; most common are electro-thermal systems, which use electrical heat; pneumatic boots that mechanically break ice through inflatable membranes (e.g. rubber); freezing point depressant systems ("weeping wings") that disperse a de-icing fluid; and piccolo tubes that channel hot, high-pressure engine bleed air into critical areas (most commonly found on airliners). Furthermore, there are more advanced ice protection concepts that have low maturity but may be promising in the future. For example, icephobic coatings passively change material properties such that ice cannot form on surfaces or reduce ice adhesion. Also, electro-mechanical systems are under development which induce forces in form of displacement, generated by electric motors, to break and shed ice from aircraft with low energy requirements.

For RPAS, the absence of a pilot necessitates reliable ice detection systems to activate and deactivate ice protection systems as needed. It is crucial that these systems are lightweight, energy-efficient, and rapid at detecting an icing encounter. In addition, for continuous flight in icing conditions, detection systems need to be able to indicate the severity of icing and when the aircraft exists icing conditions.

IV. Icing Environments

Icing environments describe icing conditions that aircraft can expect to encounter and are used for design and certification. Icing environments describe expected combinations of liquid water content, droplet sizes, and exposure times. In manned aviation, the civil aviation authorities have developed icing environments to be used for certification. These icing envelopes are described in several appendices of the certification standards [13,14]. For RPAS, typically, the following icing envelopes are considered relevant.

- **Appendix C, in-cloud icing:** There are two envelopes that describe typical icing conditions in two different types of clouds, see Fig. 5. The continuous maximum (CM) envelope describes icing in stratus clouds with liquid water contents 0.2-0.8 g/m³ and droplet sizes 15-40 microns over a 17.4 nm (32.2 km) extent. The intermittent maximum (IM) envelope describes icing in isolated cumulus clouds with liquid water contents 1.1-2.9 g/m³ and droplet sizes 15-50 microns in diameter over a 2.6 nm (4.8 km) extent.

Component	Criticality	Effects	Duration till critical effects
Airspeed sensor	Very high	Ice blocks the sensor, leading to erroneous airspeed readings and dangerous autopilot responses.	< 1 min
Propeller	High	Ice accretion leads to rapid and significant performance degradation, thrust reduction, and power requirement increase. Ice shedding causes vibrations exceeding 10G.	< 4 min
Lifting surfaces (wings, etc.)	Moderate to high	Ice changes wing geometry, leading to decreased lift, increased drag, and reduced stall angles. Also, adds weight and reduces maneuverability.	< 10 min
Autopilot	Moderate	Autopilots must adapt to icing-induced changes in flight performance, stability, and control. This includes identifying icing conditions and adjusting flight parameters accordingly.	< 10 min
Antennae	Low to moderate	Ice accretion on antennae increases weight and drag of the airframe. Ice can decrease signal strength and lead to communication loss.	< 10min

Table 1: Overview of component criticality and duration till effects reach a critical level.

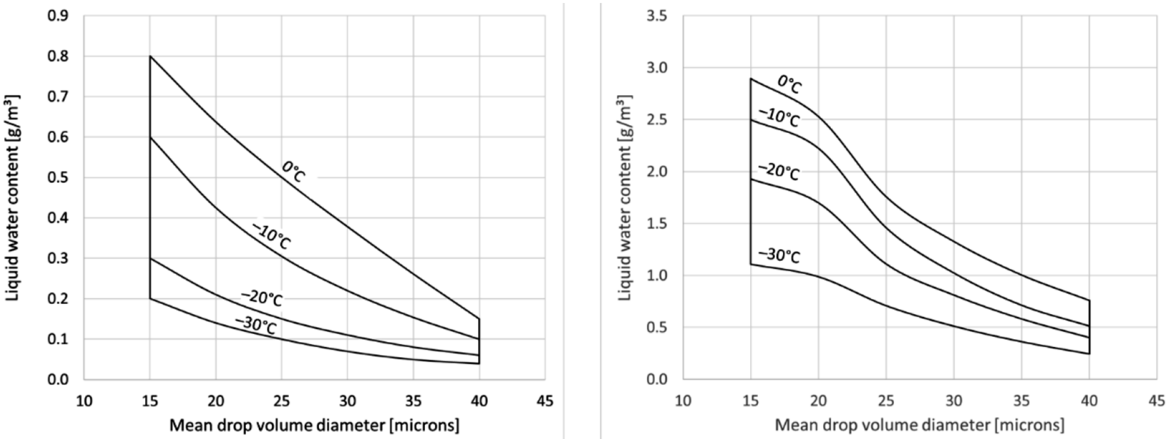

Figure 5: Meteorological icing environments as defined by the civil aviation authorities for Appendix C in-cloud icing. Continuous maximum icing in stratus clouds (left) and intermittent maximum icing in cumulus clouds (right), adapted from [14,15].

- **Appendix O, SLD icing:** More recently, two envelopes have been developed to account for supercooled large droplet icing (freezing precipitation), a very severe form of icing. There are two envelopes that describe freezing drizzle (FZDZ) and freezing rain (FZRA). These conditions are typically very severe and challenging to design for.

Note that these envelopes represent averages over a set distance, and actual conditions may fall outside these predefined ranges. Further research is essential to determine the most appropriate icing envelopes suited for different RPAS, tailored to their specific operational needs.

V. Ice Protection Systems

When addressing the operational and technical requirements for RPAS intended for operating in icing conditions, it is necessary to consider three distinct scenarios based on the aircraft's ice protection capabilities:

- **No ice protection system:** Aircraft without ice protection systems cannot operate in icing conditions, as ice accretions quickly com-promise performance and system integrity, potentially leading to loss of the aircraft. Operations must strictly avoid areas with any forecasted icing and avoid flight into visible moisture (e.g. clouds, fog, rain) in cold weather. This essentially translates to no flight beyond visual line of sight (BVLOS) in cold weather.
- **Inadvertent icing:** Aircraft are equipped with basic ice protection systems to handle unexpected, short-term icing. These systems provide a safety margin for exiting icing conditions inadvertently (unintentionally) encountered but are not intended for prolonged exposure to such environments.
- **Flight into known icing (FIKI):** Aircraft equipped with advanced ice protection systems, allowing for safe and continuous operations in known (forecasted) icing conditions. Such sophisticated systems enable the RPAS to handle a wide range of icing situations, thereby significantly broadening their operational capabilities and flexibility. Some severe icing conditions may still be outside the envelope for continuous operation.

In the following, two tables offer an overview of requirements for RPAS operating in these three icing scenarios. Table 2, outlines each case's risks, operational implications, and the required ice protection system components. Table 2, translates these aspects into recom-mendations for both operational and technical requirements. Applying the requirements from Tab. 2 in a design or an acquisition process ensures an outcome where RPAS capabilities match the desired operational requirements.

	No ice protection system	Basic ice protection system	Advanced ice protection system
Description	Aircraft have no ice protection capabilities and cannot operate in conditions with any risk of icing. Any icing encounter has a high likelihood of leading to a loss of aircraft.	Aircraft have a basic ice protection system that allows take-off in conditions that could result in an icing encounter. The basic protection system ensures the safe exit of any inadvertent icing encounters.	Aircraft have an advanced ice protection system that allows safe, continuous flight into known icing conditions.
Level of icing impact	High	Moderate	Low
Operational implications	▪ No flight beyond visual line of sight (BVLOS) when static ground air temperatures are below +5°C. ▪ Aircraft must avoid icing conditions entirely. ▪ Flight planning relies heavily on weather forecasts. ▪ Restrictions on operating in certain climates or seasons.	▪ Take off in conditions where icing could be present. ▪ Aircraft must immediately exit icing conditions if encountered. ▪ No sustained operations in icing environments.	▪ Continuous operations in a wide range of icing conditions, including moderate to severe icing. ▪ Limited operations into most severe conditions like freezing rain/drizzle (SLD).
Required ice protection elements	▪ None	▪ Ice detection system ▪ Protected pitot tube ▪ Protected propeller	▪ Ice detection system ▪ Protected pitot tube ▪ Protected propeller ▪ Protected lifting surfaces (wings, empennage) ▪ Protected antennae (optional) ▪ Protected payloads (optional)

Table 2: Summary of operational limitations of RPAS operating in icing environments depending on their ice protection system capabilities.

VI. Summary

For RPAS operations in cold weather environments, the importance of adequate operational and technical requirements to ensure safe operation cannot be overstated. Suitable ice protection systems are crucial for guaranteeing the operational readiness and effectiveness of military and commercial RPAS in diverse and challenging conditions. Suitable ice protection systems enable key aspects of RPAS operations.

- **Mission readiness and safety:** Operations often require RPAS to operate in harsh, cold-weather environments where icing is a common hazard. Suitable ice protection systems ensures that aircraft can perform their missions in any cold weather without the risk of ice-related failures, which can compromise mission objectives and safety.
- **Operational flexibility and extended range:** Robust ice protection systems allow to operate across a wider range of environments and weather conditions. This flexibility allows for greater strategic and tactical options, ensuring that critical missions can be carried out under various circumstances without being limited by weather constraints.
- **Enhanced performance and reliability:** Advanced ice protection systems ensure that RPAS maintain optimal aerodynamic performance and system functionality even in icy conditions. This reliability is essential for critical missions where performance can directly impact mission success and the safety of ground forces relying on RPAS support.
- **Autonomy in operations:** Given the unmanned nature of RPAS, autonomous ice detection and protection capabilities are crucial. They enable RPAS to independently manage icing threats, reducing the need for ground intervention and allowing for more autonomous operation profiles.

In summary, the integration of effective ice protection systems in RPAS is a key factor in enhancing their operational effectiveness, safety, and reliability in cold weather conditions. This capability is essential not only for the successful execution of missions but also for maintaining the integrity and longevity of these valuable assets. A key factor in acquiring RPAS that provide value is setting the right requirements that reflect the operational requirements.

Acknowledgment

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Topic	Technical requirement	Scenario
General	The RPAS shall maintain performance and safety for the duration of an icing encounters. This duration is defined as the time from initial ice accumulation to the point where the UAV successfully exits the icing conditions.	All
General	The duration of an inadvertent icing encounter should be at least 5 min.	Inadvertent icing
General	The duration of an flight into known icing encounter should be at least 20 min.	Flight into known icing
General	The effectiveness of the ice protection system shall be demonstrated during flight tests into natural icing conditions.	All
General	The performance of an ice protection system (propeller or airframe) shall be demonstrated for critical design cases in icing wind tunnel tests.	All
General	Critical icing design cases should be identified from Appendix C (continuous maximum and intermittent maximum) for the airframe and propeller separately by means of simulation.	All
Ice detection	The RPAS shall be able to accurately detect the onset and presence of icing conditions. The time between entering icing conditions and detection shall be sufficient to allow the RPAS to safely exit the icing conditions. Detection duration should be less than 1 minute.	Inadvertent icing
Ice detection	The RPAS shall be able to accurately detect the onset and presence of icing conditions. The time between entering icing conditions and detection shall be sufficient to allow the RPAS to activate suitable ice protection systems. The detection duration should be less than 1 minute. In addition, the RPAS shall detect when icing conditions have been exited and estimate icing severity (ice accretion rate).	Flight into known icing
Airspeed sensor	The static pressure port shall always provide a data reading not affected by ice or air moisture condensation, which can form even flying outside clouds.	All
Airspeed sensor	Pitot tubes, which provide airspeed indication through the total pressure reading, shall be heated.	All
Propulsion	Ice accretions on propeller or rotor shall not result in hazardous vibrations, which can damage the propulsion system.	All
Propulsion	The propulsion system shall be protected against excessive performance loss due to icing for the duration of the icing encounter. Sufficient thrust and torque shall be are maintained to keep the RPAS airborne and manoeuvrable.	All
Propulsion	Ice shedding from an heated or unheated propeller shall not lead to excessive vibrations to damage the propulsion system.	All
Airframe	Ice accretions on the airframe shall not results in hazardous aerodynamic performance degradation during the duration of the icing encounter. This includes effects on li[, drag, moment, stall, and control surface effectiveness.	All
Airframe	For a de-icing system, it shall be shown that intercycle ice shapes are not resulting in hazardous aerodynamic performance degradation.	Flight into known icing
Airframe	The total weight of ice accretions accumulated during an icing encounter shall not result in hazardous weight changes.	All

Table 3: Recommendations for technical requirements of RPAS operating in icing conditions.