Hazards of In-flight Icing on Unmanned Aircraft

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The last decade has shown great technological progress in the field of unmanned aircraft systems (UAS) and many new applications have seen the light of day. To facilitate this fast-paced progress and capitalize on the potential of the technology, it is critical that a comprehensive and standardized UAS traffic management (UTM) system is developed. One of the topics that will need to be included in a UTM system is the hazard of atmospheric in-flight icing. In-flight icing occurs when an aircraft encounters supercooled liquid droplets in the air. These droplets impinge and freeze on the aircraft resulting in large aerodynamic penalties, sometimes with catastrophic consequences. While already an established phenomenon in manned aviation, little work has been done in the UAS community so far. Due to the operational profiles, the sizes of the aircraft, and not having human decision makers in the loop, in-flight icing poses a severe threat to the UAS industry and should therefore be addressed with the same rigor as in manned aviation. This document attempts to give a brief overview of the problem and provide recommendations for necessary improvements to UTM in order to mitigate the industry threat of in-flight icing. These recommendations consist of raising awareness, improving atmospheric forecasting and nowcasting, developing icing envelopes and regulations, and to include in-flight icing in the UA certification process.

INTRODUCTION

With the technological advances of the past decade, accessibility and applicability of UA are rapidly increasing, where many of the most dangerous tasks could be supplemented, or even replaced by UA operations. As present technologies develop further and novel technologies emerge, UA will acquire abilities enabling them to perform increasingly complex tasks. Some of the services that are currently being developed include:

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- Emergency response,
- humanitarian aid and disaster relief,
- conservation,
- disease control,
- health care,
- agriculture,
- weather forecasting,
- waste management,
- energy production,
- mining forecasting,
- construction planning,
- infrastructure development, and
- insurance inspection.

All of these services have potentially substantial societal, economic, environmental, and climatic impacts, highlighted by the current COVID-19 outbreak, which emphasizes society's vulnerability to immobility. Unmanned aircraft can be a critical tool in future emergency response situations. Through the delivery of crucial medical supplies, operating as communication relays in networks, and performing associated disaster management tasks, unmanned aircraft can add immeasurable value. Regrettably, current UA lacks the weather-robust capabilities, particularly related to in-flight icing, to be a reliable tool in times of distress.

The in-flight icing phenomenon is one of the most significant weather hazards to aviation that is experienced in freezing conditions when liquid water droplets impinge exposed aircraft surfaces. Upon impact, the droplets freeze and drastically reduce aircraft capabilities with potentially devastating consequences. Icing is a global phenomenon that is typically encountered at altitudes ranging from ground level all the way up to 18,000 feet [1, 2]. First-hand interactions with some key operational stakeholders1 in the UAS industry have revealed that more than 50% of their critical UAS operations are cancelled due to the risk of icing conditions2.

UTM and in-flight icing

The development of a UTM system that provides safe operations for civilian UAS in low-altitude airspace is a complex and comprehensive task. While UTM system development can draw on experiences and lessons learned from existing air traffic management (ATM) systems, new issues have to be addressed, and many existing concepts need to be further developed. Among one of the most significant differentiators between ATM and UTM is in the paradigm shift from having operators and pilots monitoring every single vehicle continuously to having a system where humans only are involved in a subset of the decision making. Other differentiating elements include the substantial increase in the number of aircraft that will operate within a given area. Also, low-altitude urban airspaces will be the center for a large number of operations and services.

A small subset of the elements that a UTM system has to contain is route planning, airspace corridors, congestion control, and adverse weather forecasting and mitigation. An important weather phenomenon that needs to be addressed is in-flight icing. A common industry approach to mitigate the threat of in-flight icing is grounding the UA in case of visible moisture and delaying the operation until clear weather conditions are met. However, this is not a feasible approach once the UAS industry evolves and becomes a larger part of the critical infrastructure of society. At the same time, it is unsafe to continue operations when there is a risk of in-flight icing conditions. Operating without a pilot in the loop removes the intuition and feel for the state of the aircraft which results in one less level of safety in case of in-flight icing. Furthermore, if flying in potential icing conditions, the strain on the UTM for routing emergency landings might be quite comprehensive in scenarios where aircraft starts to be exposed to in-flight icing.

For manned aviation, regulations and mitigating technologies for in-flight icing have been in place for many years now. For the UA industry to continue growing, it is important to address the hazard of in-flight through both regulation and technology. A failure to do so could easily lead to crashes, a reduced public trust of the industry, not to mention potentially result in human casualties.

Unmanned aircraft icing accidents

The first mention of UA icing in the open literature dates back to 1990 in a comprehensive study by the US Naval Air Development Center describing the hazard of icing for military UA operations [3]. Further reports state that icing was responsible for UA crashes in Hungary, Afghanistan, Serbia, and Kosovo during the

[1] US Airforce pilots operating in the State of New York, and pilots and operators from the Norwegian Armed Forces and the Finnish Army Aviation.

[2] The risk of icing conditions is assessed in pre-flight meetings. Weather forecasts predicting freezing temperatures and cloud covers at operational altitudes and space constitute a risk of icing, where a consequence is typically canceling the flight.

1990s [4, 5]. Since then, very little information is openly available, which is likely related to the fact that – up until recently – most UA operations were performed by the military. One more recent incident, that became publicly known, happened in February 2017, when a British Army Watchkeeper UAS stalled after its pitot tube got blocked, most likely due to icing [6].

BACKGROUND

In-flight Icing

In-flight icing, also called atmospheric icing, occurs when an aircraft encounters supercooled liquid water in the atmosphere and that liquid water freezes onto the aircraft. The water occurs as cloud droplets or precipitation in liquid form with a temperature below the freezing point. When such supercooled droplets collide with an aircraft, they freeze on the surface and can grow into various ice shapes, see Fig. 1. Atmospheric icing conditions can be encountered all year round and all around the globe [1, 2]. The ice severity is characterized by the air temperature, size and velocity of the vehicle, but also by the liquid water content and the droplet size.

Icing Effects

Numerous wind-tunnel experiments, in-flight tests, and numerical simulations show that ice accumulated on the leading-edge of a lifting surface will lead to a degradation of its aerodynamic performance. The ice shapes modify the airfoil geometry and typically lead to a significant decrease in lift, increase in drag, change in pitch moments, and deterioration of the stall behaviour. Furthermore, icing negatively affects aircraft stability and control. The degree of performance degradation depends on the form of the ice shapes and the degree of disruption of the airflow. A numerical study on the icing penalties of a typical UA airfoil for a wide range of meteorological icing parameters showed that lift can be decreased by 35%, stall angles can be reduced by 33%, and drag can be increased by up to 400% in the linear region [7]. One study on a UA propeller shows that glaze ice conditions can lead to a thrust reduction of 75% coinciding with a required power increase of 250% after only 100 seconds of exposure to moderate icing conditions [8]. Icing on rotary-wing UA rotor blades has similar negative effects and can build up very quickly [9]. In addition, icing can introduce imbalances between the rotors, leading to control issues and loss of stability.

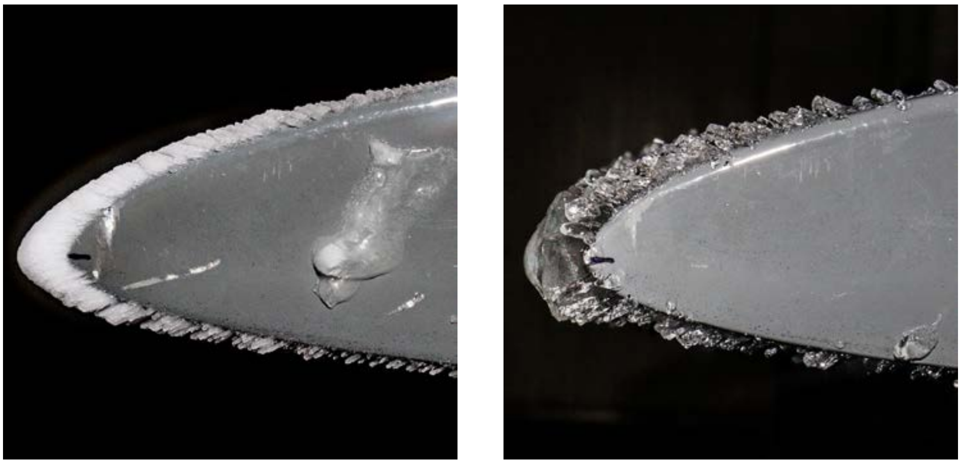

Fig. 1: Rime ice (left) and glaze ice (right) accretions on a UAV airfoil from an icing wind tunnel test.

Special Issues of UA Icing

The history of icing studies on manned aircraft dates back to the 1940s and 1950s, when the foundation for modern icing research was laid. Today, icing in manned aviation is generally a well-understood problem.

A large amount of research has been performed on the consequences of icing on aircraft. Commercial and military all-weather capable UASs are expected to be just as reliable as piloted aircraft. Therefore, the icing issue needs to be solved just the same, but there are different challenges to overcome for UAS. There are several differences between manned and unmanned aircraft that are relevant in the context of icing [10]. The comparison between the two types of aircraft is somewhat difficult, since UA come at a great variation of forms and sizes, ranging from hand-launched micro UA to large high-altitude military aircraft.

Generally, unmanned aircraft tend to fly at lower velocities compared to manned aircraft. The reason for this is that most UAS mission profiles are endurance-driven with the objective to loiter for extended durations above an area of interest. Due to the lower speed requirements, most UA utilize propellers for propulsion, with electrical, piston, or turbo engines instead of jet engines. UA tend to be significantly lighter than manned aircraft as their payload capacity is smaller too. The wingspans of the largest UA are comparable to small manned passenger aircraft – but the majority of UA have much smaller wings. Smaller airframes are also more sensitive to icing as they accrete larger ice horns relative to their size, which lead to substantially larger performance penalties compared to larger airframes.

The operational altitude is also largely varying for UA. On one end of the spectrum are large UA, used primarily for surveillance, that operate at altitudes higher than manned aircraft. On the other end are small UA that operate in limited areas, flying in close proximity to the ground level. The existing icing nowcasting and forecasting products are developed for manned aircraft and lack the spatial and temporal resolution for many UA applications, especially for near-ground operations.

Finally, the most obvious difference is that UA do not have a pilot onboard that can identify icing conditions but instead must rely completely on on-board instruments. Consequently, the overall degree of automation tends to be larger in UA than in manned aircraft. Therefore, there is a need for lightweight, accurate, and sensitive ice detection systems that can operate as primary automatic ice detection systems.

RECOMMENDATIONS

Atmospheric in-flight icing is a severe hazard and needs to be addressed for UA with the same rigor as for manned aircraft. First, awareness needs to be raised for the dangers of icing to UA for all UTM stakeholders. Second, icing nowcasting and forecasting products need to be developed to meet the needs of UA. The main challenge is that the vertical and horizontal resolution of the existing models are typically too coarse for UA applications. The existing nowcasting and forecasting models need to be improved with the objective to capture icing risks at the smaller scales and near ground conditions. Third, research is required to characterize the meteorological icing conditions that are typically encountered by UA. UA icing envelopes, especially for low altitudes, are a key element required to assess the icing hazards and to develop suitable regulations. Last but not least, in-flight icing risks need to be included in the certification process of UA. This includes the development of unified requirements for ice detection systems, ice protection systems, and general safe autonomous operation in icing conditions.

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