Smart Icing Systems Project

M. Bragg, N. Sarter, W. Perkins, et al.
University of Illinois at Urbana-Champaign
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Introduction

Aircraft accidents continue to occur due to the formation of ice on aircraft in flight. The primary cause of these accidents is the effect of ice on aircraft control. Icing accidents can be prevented in two different ways: 1) Icing conditions can be avoided, or 2) the aircraft system can be designed and operated in an ice tolerant manner. For all aircraft, ice avoidance is a desirable goal for increased safety. However, for commercial aircraft, where revenue and schedules must be maintained, ice tolerance will continue to be the preferred method for all but the most severe icing conditions. Our approach is to conduct research to improve the safety of operations in icing conditions (ice tolerance) by developing the Smart Icing Systems concept through an interdisciplinary systems approach.

Successful ice tolerant concepts were first applied to aircraft in the 1930's with the installation of pneumatic boots on aircraft wings. Since that time, ice tolerant aircraft icing research has focused on sensing ice, improved ice removal methods, ice physics and other very specific research areas. Icing research has not focused on safety in terms of an overall systems view of the problem. Particularly lacking is the application of flight mechanics, aircraft control and human factors to the icing safety problem. Recent advances in digital control, cockpit instrumentation and computer-based automation make it possible to develop new approaches to ice tolerant aircraft design and operation.

The important effect of ice on an aircraft is its influence on the performance, stability and control of the aircraft system. Safety will be achieved in an ice tolerant aircraft if the pilot/aircraft system can continue to maintain the desired flight path, with an acceptable safety margin, regardless of atmospheric icing conditions. One scenario for a systems solution to ice tolerant aircraft safety is:

1. Sense the presence of ice accretion through its effect on measured aircraft performance, stability and control. Sense ice accretion and ice protection system performance. Provide the appropriate information to the flight crew.
2. Automatically activate and manage the ice protection systems, and provide the pilot with feedback on the system status and behavior of both the aircraft and the ice protection system.
3. Modify the aircraft flight envelope by use of the flight control system to avoid conditions where flight could potentially be uncontrollable. Notify the flight crew of this action and its implications for the flight envelope.
4. Adapt the aircraft control laws to maintain clean-aircraft-like flying qualities to enable the aircraft to be safely flown within the reduced flight envelope. Notify the flight crew of this action and maintain good pilot-automation coordination.

Objective

The objective of this research is to improve the safety of aircraft operating in atmospheric (including ground) icing conditions. The approach is to improve the ice tolerance of aircraft by developing autonomous systems which will sense changes in aircraft performance and handling qualities and respond in a human-centered fashion to enable the aircraft to maintain control and flight safety. We are conducting the fundamental research necessary to develop such a smart icing systems concept.

The Smart Icing System Concept

The new approach to aircraft icing safety, the Smart Icing System, that will be presented and discussed in this proposal, is principally a better way to manage the ice protection system and the operation of an aircraft in icing conditions where some degradation in performance and control can be anticipated. However, this safety system or concept is not intended to operate in a vacuum from other, well established icing safety procedures. In section 3.1.1 the current inflight-icing-safety systems are briefly explained and the proposed Smart Icing System is described. The Smart Icing Systems concept is developed and it's implementation in terms of the proposed Icing Management System, IMS, and its four primary functions are presented.

Current Icing Safety Systems

The safest way to operate when icing conditions exist in the atmosphere is, of course, to avoid these conditions. Whether through the use of strategic weather information in the preflight planning process or the use of new systems that are being developed to provide tactical weather information, ice avoidance is a viable safety strategy in many situations. Ice avoidance is certainly the safest icing strategy for small aircraft and other unprotected aircraft. It may also be the best strategy for larger aircraft when severe icing conditions, such as freezing rain and drizzle, are present.

Another well-developed safety strategy is ice protection. The ideal system would anti-ice the entire aircraft such that no ice would accrete anywhere on the airframe or propulsion system. This, of course, is not practical. However, many aircraft have excellent ice protection systems, IPS, which combine de-ice and anti-ice systems to provide overall aircraft protection. The concept proposed in this paper is intended to work in unison with the IPS to provide an additional level of safety beyond that provided by a simple IPS system alone. Since for a variety of reasons aircraft can not always avoid ice, and since during encounters situations arise which jeopardize safety, additional safety measures are required for a meaningful reduction in icing accidents beyond current levels.

The current model of an aircraft encountering icing conditions is depicted in Fig. 1. As ice accretes on the aircraft, ice accretion sensors relay this information to the pilot. This could include a variety of means, from simple visual detection by the flight crew to sophisticated electronic sensors. In most cases, this leads to the appropriate pilot response which is to activate the ice protection system, IPS. If the pilot activates the IPS, this is referred to as an advisory system. Less common is a primary system where the ice protection system is automatically activated. At any point in time, with or without the IPS on, the ice accretion on the aircraft affects the aircraft dynamics (performance, stability and control) through its impact on the propulsion system and aircraft aerodynamics. This may be relatively small for a well anti-iced aircraft, or quite large for an aircraft with no IPS operating. The pilot or the automation system (auto-pilot system) interacts through the usual flight control inputs to control the flight path of the aircraft. This is done without any situation-specific knowledge of the change in aircraft dynamics caused by the ice, except what is fed back through the pilot/automation's perception of the input/output response of the system. Simple envelope protection functions may be included, such as a change in stick-shaker angle of attack.

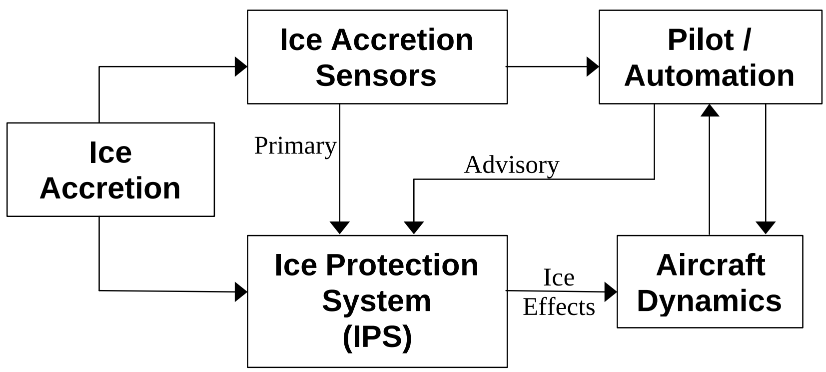

Fig. 1. Current aircraft icing encounter model

Proposed Smart Icing System

The new approach described below adds another level of safety. Assume that the icing conditions are not avoided and that flight through icing conditions is required. The aircraft is equipped with a state-of-the-art IPS, but now an additional level of safety is available through the Ice Management System, IMS, depicted in Fig. 2.

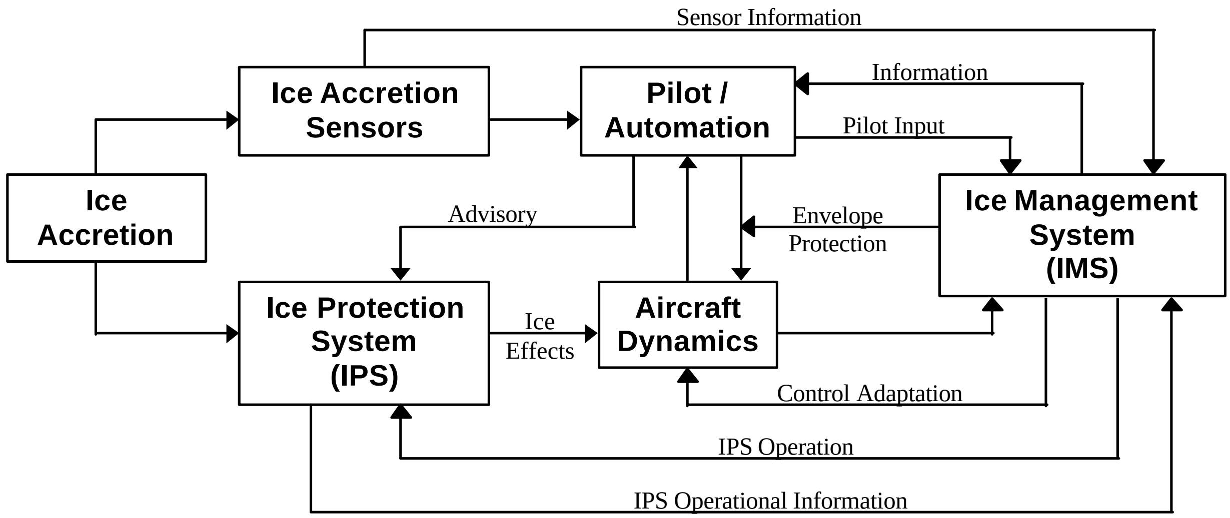

Fig. 2. Proposed new aircraft icing encounter model

The new model shown in Fig. 2 is similar to the current model, Fig. 1, with the addition of the Ice Management System, IMS, box on the right-hand side. The purpose of the IMS is to monitor the ice accretion and its effect, and assist the pilot/automation in the safe operation of the aircraft in the iced aircraft state. The operation of the IMS can be summarized by the four functions below:

1. **Icing Effects Characterization:** Sense the presence of ice accretion including its effect on measured aircraft performance, stability and control. Sense ice accretion and ice protection system performance and notify the pilot.
2. **Ice Protection System Operation and Monitoring:** Automatically activate and manage the ice protection systems, and provide the pilot with feedback on the system status and behavior of both the aircraft and the ice protection system.
3. **Envelope Protection:** If the performance and control degradation becomes significant, modify the aircraft flight envelope by use of the flight control system to avoid conditions where flight could potentially be uncontrollable. Notify the pilot of this action and its implications for the flight envelope.
4. **Control Adaptation:** Modify the aircraft control laws to maintain clean-aircraft-like flying qualities to enable the aircraft to be safely flown within the reduced flight envelope. Notify the pilot of this action and maintain good pilot-automation coordination.

The fundamental principle behind the IMS is that the important effect of ice on an aircraft is its influence on the performance, stability and control of the aircraft system. Safety will be achieved if the pilot/aircraft system can continue to maintain the desired flight path, with good flying qualities, and an acceptable safety margin, regardless of atmospheric icing conditions.

A functional diagram of the IMS is shown in Fig. 3. The primary IMS functions are the four items listed above and appear as the circles in Fig. 3. The square boxes are other aircraft/pilot components that must interact or communicate with the four primary IMS functions. For example the Icing Encounter box represents flight into an environmental icing condition. Here sensor information feeds data to the *Icing Effects Characterization* function and the Icing Encounter also changes the aircraft performance and control through the ice accretion and is represented as the arrow to the Aircraft Dynamics box. The *Icing Effects Characterization* function processes the icing sensor data and aircraft dynamics data to determine the iced aircraft characteristics. This information is then provided to the other three functions of the IMS. Also each of the four IMS functions is designed to interact with the pilot and the Flight Deck Automation.

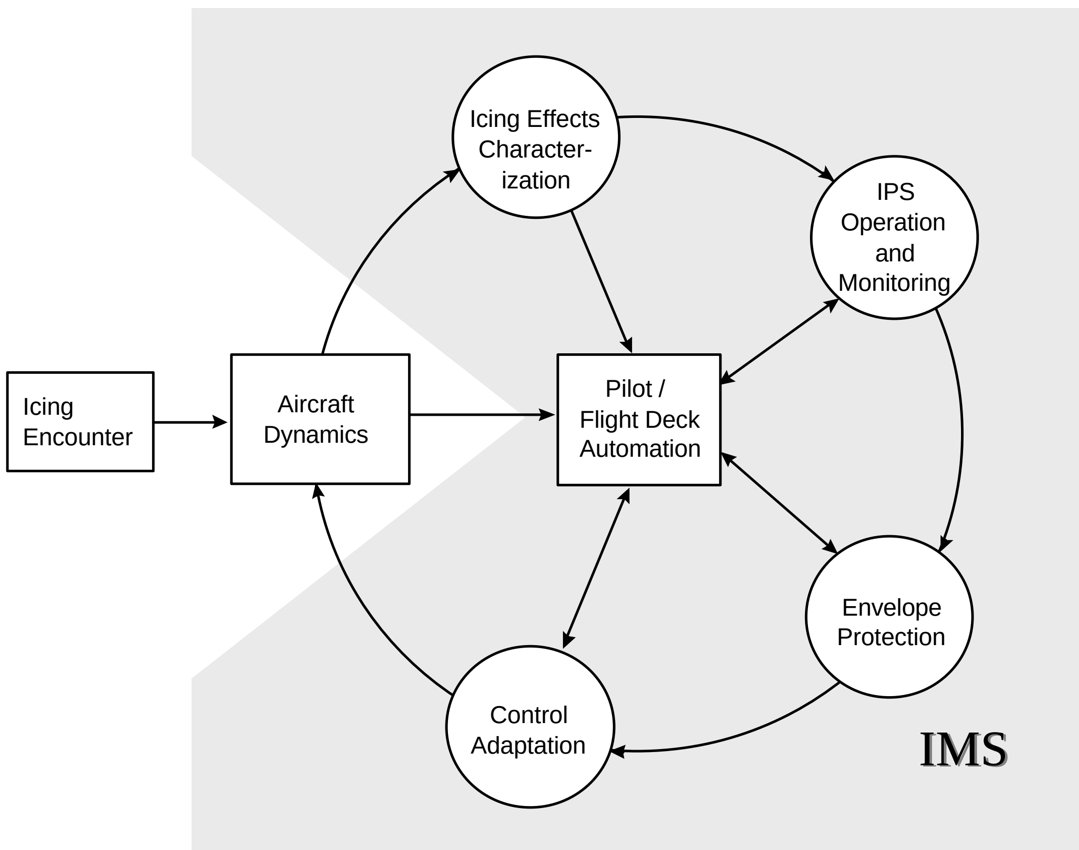

Fig. 3 Functional model of the Ice Management System, IMS.

Based on the continuously updated icing characterization information, the IMS would provide *IPS Operation and Monitoring* much as a primary ice protection system does now. This information would also be used to provide flight *Envelope Protection* based on the actual, real-time ice accretion experienced by the aircraft. This could include angle of attack protection through the stick shaker as is commonly done today; however, the angle of attack for stick shaker would be a variable determined by the IMS. Other envelope protection features could also be supplied through a digital flight control system. These might include limiting maximum g loads, bank angles, control deflections, flap deflections, pitch and roll rates, etc. As an additional level of safety, *Control Adaptation* is included. Control adaptation, or reconfigurable controls, would modify the control laws to maintain acceptable flying qualities in the presence of the effects of the ice accretion. This would be most useful in emergency situations where the aircraft had accreted significant ice. Reconfiguring the control laws would allow the pilot/automation to maintain control of the aircraft within some limited flight envelope until the icing conditions could be exited safely.

Figure 4 illustrates the concept underlying the proposed new icing safety system. We can think of this overall system as a series of defenses-in-depth where multiple layers of protective mechanisms are introduced to reduce the likelihood of mishaps. Each layer has gaps that may be penetrated as a result of failures, errors, or violations. However, a complete accident trajectory becomes possible only if all gaps are lined up precisely - a very unlikely event.

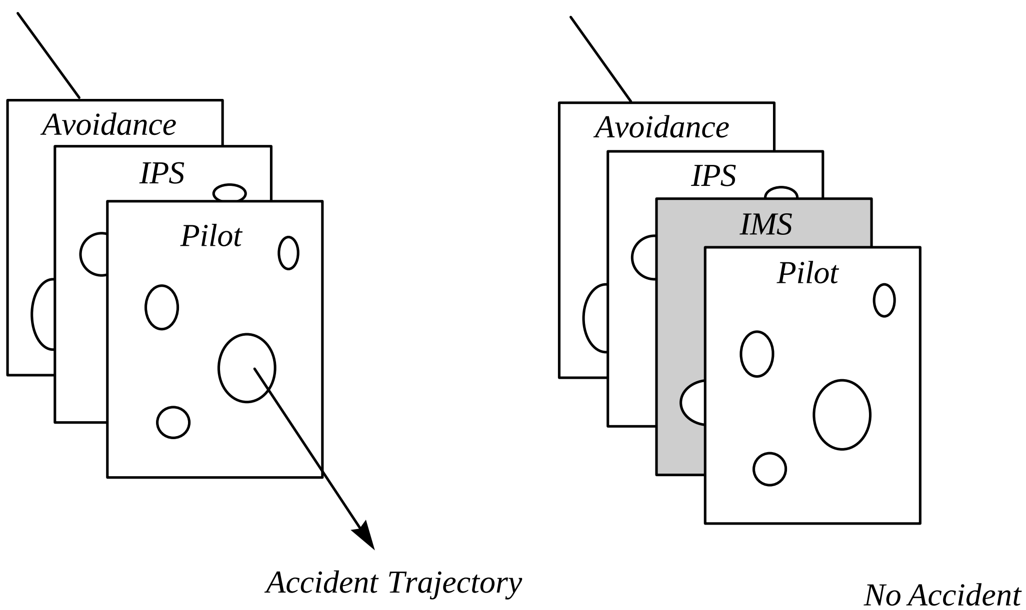

Fig. 4. "Defenses-in-depth" - An icing event penetrating the various layers of defense including the new IMS (adapted from Maurino et al.**Error! Bookmark not defined.**)

The first layer of protection in the current approach to icing safety is avoidance of icing conditions. If this step fails or is not feasible, the ice protection system (IPS) is engaged to prevent ice accretion. In the current model, the IPS is the last defense mechanism that, if unsuccessful, requires the pilot to take over in a potentially uncontrollable situation. In contrast, the proposed new system introduces yet another layer between the IPS and the pilot - the ice management system (IMS) - whose function is to compensate for the effects of icing on performance, stability, and control. These effects, if uncorrected, can lead, and actually have led, to aircraft accidents. Our goal is to develop the IMS to assess these effects in flight, to counteract them in appropriate ways, and to keep the pilot informed about the icing situation and the intentions, actions, and limitations of the system.

Summary

The proposed new icing safety system has been summarized in terms of the operation of a new Ice Management System, IMS. This approach assumes that regardless of the IPS, ice accretion can and will occur in some situations. The aircraft must then be protected from the changes in performance, stability and control which, if left uncorrected, can lead to aircraft accidents.

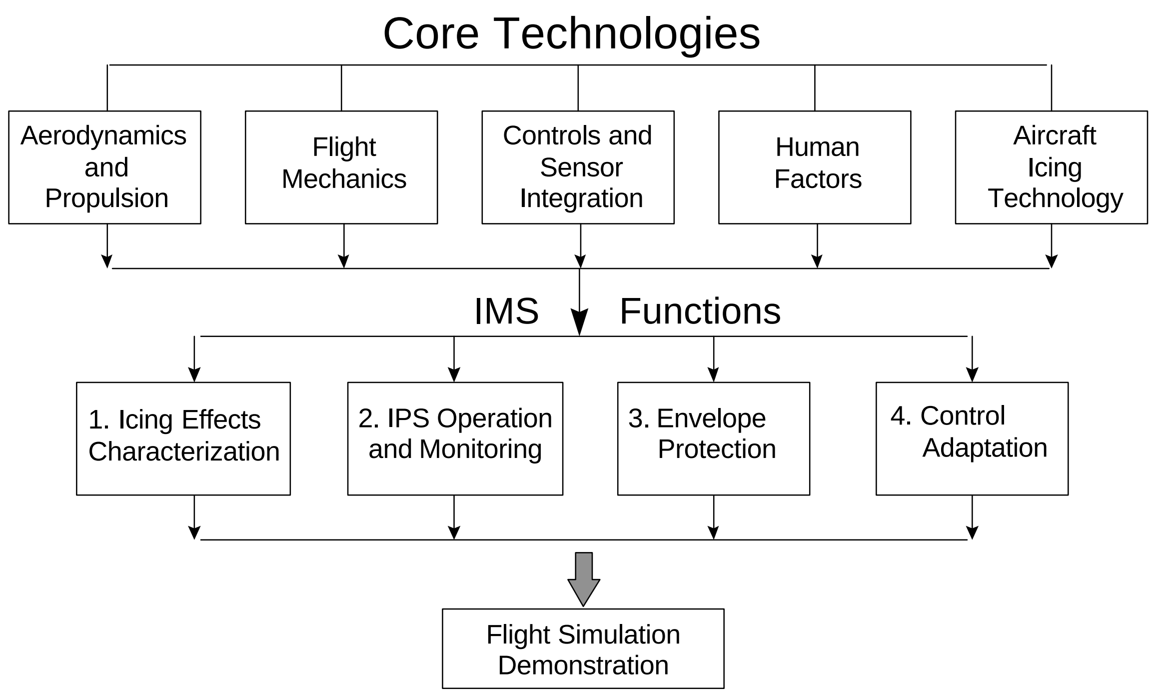

Fig. 6 Smart Icing Systems research organization.

Figure 6 depicts the organization of the research to develop the Smart Icing System and in particular the four functions of the Ice Management System. The five core technologies are shown in the top row of boxes and the four IMS functions are represented by the second row of boxes. Research will be organized by the five core technologies, but focused on developing the technologies required in each of these areas to perform the four IMS functions. For example, Flight Mechanics supported by Aerodynamics will develop a nonlinear model of the aircraft forces and moments including the effect of ice accretion. This will support the development of IMS functions 1, 2 and 4. Research in the other core technology areas will likewise support multiple IMS functions. In this proposal we do not propose to conduct original research in traditional Aircraft Icing Technology areas such as ice protection systems, etc. This research is being performed by other researchers and will primarily be useful during the

Application phase. Application is primarily an industry function where much of the aircraft icing technology expertise already resides. Likewise, the IMS function *IPS Operation and Monitoring* is primarily an Application phase task with the expertise in industry. We do not propose to conduct new research in this area although the function will, of course, be modeled in the Flight Simulation. The Flight Simulation will provide a research tool to integrate, develop and demonstrate the Smart Icing Systems technology and is shown at the bottom of Fig. 6.