University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018

Project Definition Document (PDD)

UAV Wing De-icing Project

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1.0 Problem Statement

In today's world, Unmanned Air Vehicles (UAVs) are becoming abundant with their versatility for commercial, military, and even personal use. As the prevalence of these vehicles grows, the importance for both power and aerodynamic efficiency among UAVs is critical, especially when considering long-duration flights. The need for these efficiencies is predominant in regard to one problem in particular: the icing of an aircrafts' wings during flight. When ice forms and accumulates on the leading edge of a wing, lift is decreased and drag is increased.[4] In addition to this negative impact on efficiency, the control surfaces on a UAV can lock up and consequently terminate the flight. While engineers have researched multiple solutions to this costly de-icing problem for years, the universal goal remains consistent for all techniques; de-ice the wings of a UAV at low expense of additional power consumption as well as minimal effects on aerodynamic drag (specifically for long-duration flights).

The purpose of this project is to research, design, build, implement, and test a small-scale de-icing system that can be scaled to full size and implemented on the wing of the Orion UAV manufactured by Aurora Flight Sciences (AFS). For research, modeling, and testing purposes, the test sections' material/aerodynamic properties will resemble those of a carbon fiber composite sandwich laminate honeycomb core wing with a DAE11 airfoil. The overall de-icing system for this project will consist of a de-icing mechanism with the capability of turning the system on/off via customer-provided command. In addition to constructing and implementing this system on a wing test section, the de-icing system will also be characterized by a combination of testing and modeling to verify functionality and efficiency.

The major experimental test focuses only on the functional aspect of the mechanism; turning the de-icing mechanism on/off. The next experimental test will measure the power required to operate the de-icing mechanism for TBD amount of time; this value must be less than the maximum power consumption value of TBD if the mechanism were to be scaled to full-size.

In addition to conducting the physical test, a virtual model will also be created to examine the energy consumption and aerodynamic (lift-to-drag ratio) effects (depending on the chosen de-icing technique). The energy consumption model will examine the amount of energy provided to the system by the power distribution unit, as well as the amount of energy required by the system to de-ice the test-section to an ice-thickness level of TBD inches over an area of TBD square inches.

As for virtual metrics pertaining to the lift-to-drag ratio (L/D), these only need to be considered should an exterior solution be eventually implemented on a test section. In this case, the model will consist of aerodynamic analyses (in nominal conditions) for two separate infinite wings: one with the exterior mechanism in place on the test section, and one without the mechanism. The purpose of this simulation is to examine the aerodynamic effects of the mechanism during non-icing flight conditions to ensure the mechanism does not have a significant impact on the L/D. Both simulations will model nominal flight conditions with a velocity of 65 knots indicated airspeed at a cruising altitude of 20,000 ft. Upon analyzing both instances, the modeled test section with the mechanism in place shall experience no more than a TBD% decrease in L/D thus meeting the efficiency requirement with respect to aerodynamics.

By conducting numerous trade studies as well as thorough research in regard to all disciplines pertaining this project, this team aims to contribute to the success of the Orion UAV with the delivery of an effective and efficient small-scale de-icing mechanism.

2.0 Previous Work

In-flight ice protection systems (IPS) on aircraft fall into two major categories: anti-icing and de-icing. Anti-icing systems prevent ice from forming on the aircraft and are designed to be deployed before icing conditions are encountered. De-icing systems go through a cycle where they allow ice to build up before activating, at which point they remove the ice. Many types of ice protection systems are able to function as either anti- or de-icing although they are usually designed to be one or the other.

One common type of IPS is electro-thermal. This method typically uses resistive heating elements embedded in the structure of the aircraft to heat the skin of the aircraft. The system can either be run continuously to maintain the aircraft skin at a temperature too high for ice to form (anti-ice), or it can run intermittently to melt accreted ice (de-ice). De-icing operations are usually preferable because they require less power. The Boeing 787 Dreamliner uses an electro-thermal IPS on its wings in which heating blankets are embedded in the interior of the leading edge of the wing.[1]

Another type of IPS is referred to as electro-mechanical. These systems use a mechanical force to physically separate the ice from the aircraft. Actuators embedded under the skin of the aircraft are the most common example of this category. Electro-mechanical systems are only capable of de-ice operations. Some aircraft combine electro-mechanical systems with electro-thermal elements to create hybrid systems. One example of this is the Northrop Grumman Triton MQ-4C, a naval surveillance UAV, which uses a Thermo-Mechanical Expulsion Deicing System (TMEDS) on its wings and stabilizers.[2]

Chemical systems are often used for ice protection, with the most common being the Tecalemit-Kilfrost-Sheepbridge Stokes (TKS) system, which was developed during WWII. This system can be operated in anti-icing and de-icing applications although it is usually optimized for anti-ice. The system, which is sometimes referred to as a "weeping wing", involves pumping an antifreeze fluid through a fine mesh or porous plate on the leading edge of the wing. The fluid coats the wing and depresses the freezing point of the ice, causing it to melt. A TKS system has been implemented on the wings of the IAI Heron, which is a medium-altitude long-endurance UAV.[3]

Pneumatic Systems are another option for de-icing. Most involve a rubber "boot" at the leading edge of the wing that is inflated with pressurized air. Such systems are only capable of de-icing operations. Sometimes heated air, such as engine exhaust, is used to inflate the boot in order to improve de-icing performance. This method of de-icing was invented in 1923 and is the most widely used IPS. [5]

3.0 Specific Objectives

To successfully complete this project, the levels of success have been separated into modular-style increments. Starting with the baseline of success at level 1, the small-scale de-icing mechanism shall be manufactured and meet the power requirement as designated. In addition, the energy consumption shall be modeled along with the possible L/D depending on the chosen solution. For level 2 success, the mechanism constructed in level 1 shall be implemented on a test section to then be tested in a static (speed = 0 ft/s) yet cold environment (temperature range depicted in Table 1). Again, an exterior solution would also yield an additional performance objective of meeting the L/D requirement, however through experiment at this level (using a wind tunnel). For level 3 success, the mechanism shall be implemented on a test section with specified materials and undergo the same performance requirements as listed in level 2. Finally, level 4 tests the system (manufactured in level 3) in an icing wind tunnel; however access to such a facility is dependent on budget and resources, and hence is a top tier objective.

Table 1. Project objectives and levels of success

Criteria	Manufacturing	Performance	Icing	Software Modeling
Level 1 *(Minimum Success)*	Manufacture the small-scale de-icing mechanism to be less than TBD by AFS mass/span and less than an area of 7.26 in^2 per unit span	**Power** Mechanism stays within power requirement (Max power for small-scale mechanism = TBD)	Can consistently ice a representative wing leading edge surface to a minimum thickness of TBD over an area of TBD.	**Aerodynamic L/D Model** (Assuming exterior solution) Using infinite wing with DAE11 airfoil shape, compare and model L/D with and without mechanism

				implemented. Implemented system shall not decrease L/D by more than TBD%. Both models shall use wind speed = 65 knots indicated airspeed (IAS) at an altitude of 20,000 ft. **Energy Consumption Model** Model will take into account the amount of energy required to operate the system.
Level 2 *(Meet requirements of level 1 as well as…)*	Implement mechanism on test section with DAE11 airfoil shape*. Test section shall have an area per unit span equal to 26.23 in^2. *Note: materials of test section will mimic surface and shape of Orion wing (may not match actual materials)	**De-icing** De-ice (to TBD level) the pre-iced wing test section using implemented de-ice mechanism with wind speed = 0 ft/s and temperatures between -4°F and 32°F for 1 cycle (1 cycle = pre-ice + de-ice). **Lift/Drag** (Assuming exterior implementation) Use wind tunnel with infinite DAE11 airfoil shaped wing to compare and model L/D with and without mechanism implemented. Implemented system shall not decrease L/D by more than TBD%.		
Level 3 *(Meet requirements of level 2 as well as…)*	Implement Mechanism in/on carbon fiber composite DAE11 airfoil wing section.	**De-icing** Repeat level 2 performance objectives with level 3 manufactured system		**Aerodynamic Model** Model L/D with finite wing under simulated icing conditions.
Level 4 *(Meet requirements of level 3 as well as…)*		**De-icing** De-ice (to TBD level) the system manufactured in Level 3 in an icing wind tunnel.		

4.0 Functional Requirements

The Concept of Operations (ConOps, as shown in Fig. (1)) illustrates the function of the de-icing mechanism within the entire mission. As depicted, the figure is to be followed in chronological order from step 1 through step 7. In addition, the legend in the bottom left corner depicts the deliverables between the customer (AFS) and the engineering team (CU Boulder). The cycle begins with a UAV (Orion) flying into a storm with known icing and accretion. Next, the operator (or automated sensor) activates the deicing mechanism. Following activation, power is drawn from the UAV (Orion) and CU Boulder's de-icing mechanism is activated; meanwhile, ice is removed from the wing during flight. Next, a sensor and data acquisition system confirms the ice is removed to the desired level. Upon reaching this level, the de-icing mechanism is then powered off to conserve power. Thus, the UAV (Orion) continues flying without the adverse effects of ice accretion. For the scope of this project, the manufactured de-icing mechanism will only be fit to a small-scale wing test section.

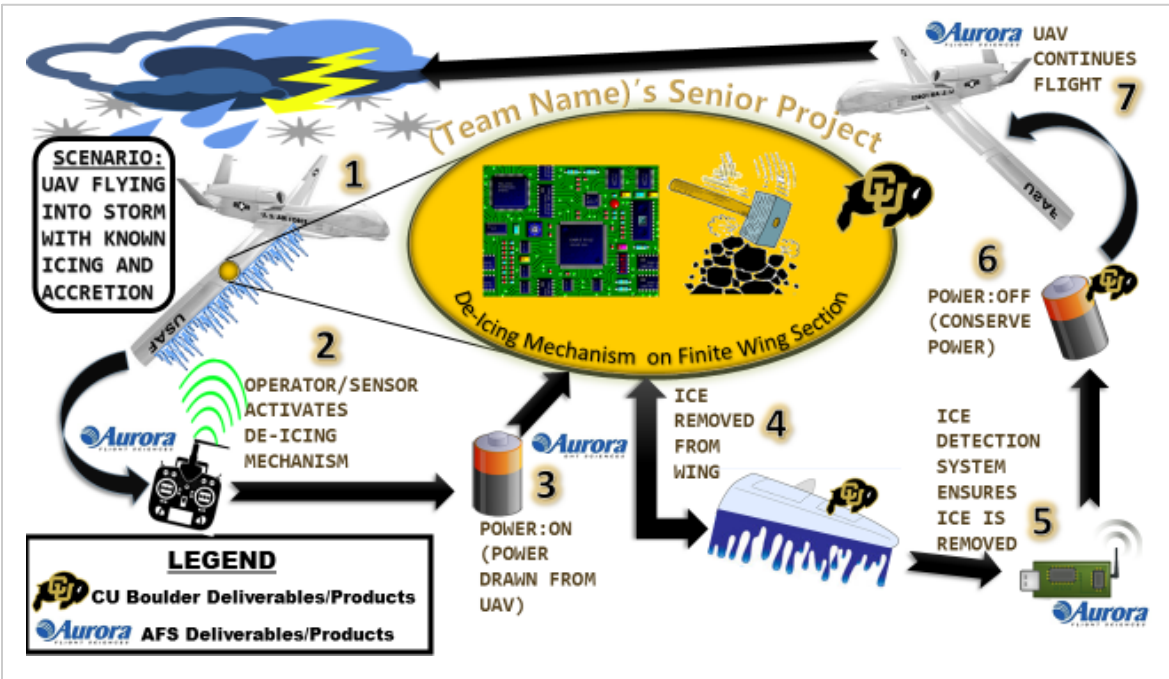

Figure 1. UAV Wing De-Icing Concept of Operations (ConOps)

The Functional Block Diagram (FBD) for the wing de-icing system, shown in Fig. (2), consists of three major sections—customer interface, internal components, and surface components. On the left side of Fig. (2) is the interface with the customer. The project will simulate these sections using a computer for commanding, and a lab power supply to power the system. These blocks are colored grey to indicate that while necessary inputs for testing, are not part of the system being developed. The middle portion of the diagram shows the sections of the system that will be located internal to the UAV including electrical and power systems. On the left part of Fig. (2), the de-icing mechanism will be positioned at, or on, the surface of the wing. Blocks are connected via green arrows for data transfer lines or orange arrows for power flow. Moving from left to right, the power supply will provide power to the power system, which will in turn power the processor. The computer will issue on/off commands to the processor. When the processor is commanded to turn on the de-icing mechanism, the processor will send a command to the power system to close the switch and provide power to the mechanism. Once the processor receives a command to cease de-icing, the processor will then command the power system to stop power flow to the de-icing mechanism. As per customer request, no feedback from the system to the commanding computer is required.

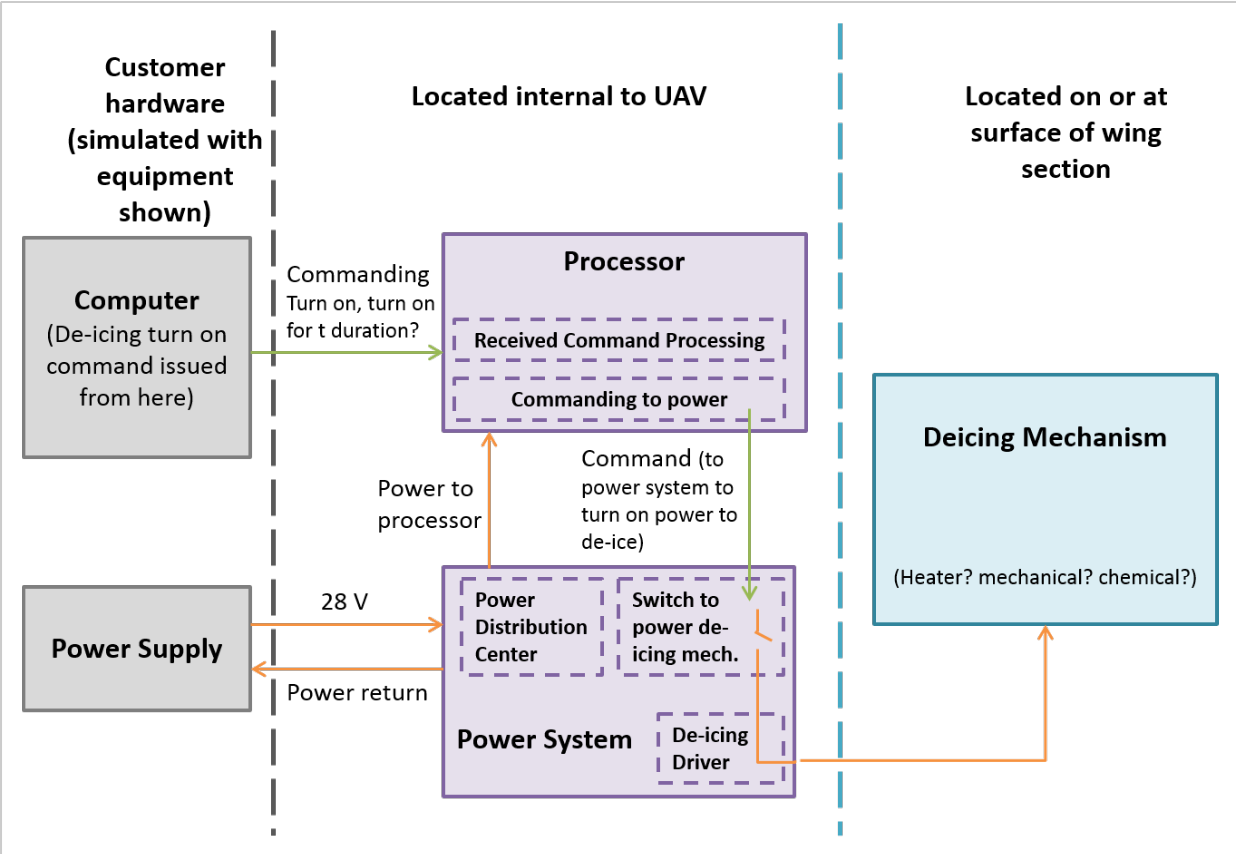

Figure 2. Functional Block Diagram (FBD)

5.0 Critical Project Elements

5.1 Defining Requirements

This project does not have well-defined parameters in regard to testing conditions, provided materials, and constraints. The lack of these values brings complications in regard to both customer feedback as well as a significant amount of preliminary research.

5.2 De-icing Techniques

The system must be able to remove enough of the type of ice that will be present in the expected flight environment. Choosing a method that is compatible with the composite material of the wing and satisfies the power and L/D requirements will involve a significant amount of research and trade studies, which will require a large time commitment.

5.3 Testing Methods (Simulating Conditions)/Accessibility to Testing Facilities

Through testing, it must be shown that the system performs as expected. It is believed that the type of ice and manner in which ice accumulates are important aspects that must be controlled to simulate the flight conditions. The LeClerc Icing Research Laboratory (LIRL) will possibly donate some time in their facilities for this purpose. However, a method for ice accumulation by hand will need to be developed for short-term testing in Boulder. This will require significant research and testing to produce consistent results. The University of Colorado at Boulder offers two wind tunnels; one currently operational for low speed wind, and a second currently under construction (available for testing in the spring semester), which will offer a higher wind speed.

To reach the top-level objectives the system must be dynamically tested in a wind tunnel while removing ice. Assuming that the schedule will allow time at LIRL, there is still a great financial obstacle that will need to be overcome. It is unlikely that there will be enough funds in the budget to account for the travel and lodging expenses for all members of the team. A fair amount of time will have to be spent fundraising and looking for sponsors if this trip is to be feasible.

5.4 Limiting Power Consumption

One component of the level 1 objective is to limit the power consumption of the de-icing system. This is a critical component and must be met at all levels of implementation of the system. This could be one of the most limiting constraints on the system that will drive the rest of the design. In addition, the system must be modeled to determine whether the solution will remove the necessary amount of ice using the selected method. As the solution is not yet known, it is unclear what model will be most useful. However, despite the solution, it can be inferred that a general energy balance model will be helpful in showing how energy is being used to power the system, and if there is sufficient energy being added to the ice for removal.

5.5 Integrating De-icing Mechanism with Manufactured Wing Section

It is critical that the system developed can be integrated onto/into an actual carbon fiber wing section. As the solution is not yet known, it is unclear what this implementation will entail. Depending on the solution, this might prove to be a challenge; this will have to be considered when initially thinking about methods and their viability. Additionally, this will require that an actual test section be manufactured, particularly if no materials are provided by AFS. As only a couple students have relevant experience in working with carbon fiber, this could prove to be challenge.

6.0 Team Skills and Interests

This team is comprised of dedicated and skilled students who, with a broad spectrum of experiences and interests, span all aspects of this project. These experiences and interests are depicted below along with corresponding CPEs.

Kelly Allred - Kelly was previously a Flight Engineer aboard the P-3C Orion while in the United States Navy. He has experience operating the P-3C's wing de-icing systems, and experience with icing conditions. His background also includes aviation electronics. He has interests in aviation electrical systems, systems engineering, and aerodynamics.

Jonathan (Jon) Eble - Jon has three years of experience designing and manufacturing; this experience was focused on composite high-power rockets. His interests include flow simulation, manufacturing, and aircraft design.

Nicole Ela - Nicole was the project manager of a CubeSat and through this gained extensive experience in systems engineering, testing, and integration. On other projects, she has also run and maintained a satellite tracking ground station, worked on a thermal model, and gained some experience with electronics and manufacturing. She spent the past summer interning for Northrop Grumman on the James Webb Space Telescope attitude control team, which gave her solid practice at software modeling. For the future, her interests reside mainly with designing and executing integration and testing plans.

Jacqueline (Jacquie) Godina - Jacquie has experience with thermodynamics as well as software, particularly with Matlab. In addition, she has CubeSat research experience incorporating this software to track satellite positioning. For this project, she hopes to further her experiences in manufacturing and testing.

Andre Litinksy - Andre excels in thermodynamics and aerodynamics and has a great deal of experience with Matlab software. During this project, he hopes to gain experience in aerodynamic airfoil modeling, manufacturing, and hardware test and integration.

Runnan Lou – Runnan has two years of nano-material research experience in a lab as well as Arduino and laser pulse picker electronics experience. In addition, he has a great deal of programming experience including C++, Matlab, Python, VBA, and LabView as well as experience with instrumentation (Raman, SHG, AFM, CMM). For this project, he hopes to expand his knowledge and experience with thermal systems, aerodynamics, manufacturing, software, and electronics.

Andrew (Drew) Moorman - Drew used to work on jet engines in the Navy and is a certified A&P mechanic. In addition, he has built his own jet engine and interned in the research and development department of Safe Flight Instrument Corporation, along with three years in Design Build Fly (with one year as project manager and another as propulsions lead). Over the course of these experiences he has learned an immense amount about the manufacturing of metal as well as working with mechanical systems, electrical systems, remote control systems, batteries, and management. His interests lie in aerodynamics, propulsion, thermodynamics, and mechanical design.

Elizabeth (Libby) Thomas – Libby had a summer internship for two seasons with a great deal of circuit-board construction as well as circuit-implementation for renewable energy systems. Through another internship at VMware, she also learned VBA and implemented this knowledge to assess company-worth and future growth. She is currently taking Finite Element Analysis to better her understanding of structures and modeling for structural analysis. She is interested in structures, thermal modeling, aerodynamics, and manufacturing.

Colin Zohoori - Colin was the manufacturing lead on the Design-Build-Fly team and gained experience with a variety of techniques and materials, including carbon fiber. He was also a software engineering intern at Aurora Flight Sciences and a systems engineering intern at Textron Unmanned Systems. While he is open to gaining experience in many fields, he is primarily interested in exploring structures, manufacturing, and testing.

Critical Project Elements	**Team Members and Associated Skills (S) and Interests (I)**
Defining Requirements	Nicole(S), Libby(I), Andre(I), Drew(I)
De-icing Techniques	Drew(I), Kelly(I), Jon(I), Nicole(I), Colin(I)
Testing Methods (Simulating Conditions)/Accessibility to Testing Facilities	Jon(S), Nicole(S), Andre(I), Drew(S), Jacquie(I)
Limiting Power Consumption	Runnan(S), Andre(S), Kelly(S), Libby(I&S)
Integrating De-Icing Mechanism with Representative Wing Section	Libby(I), Andre(I), Jacquie(S&I), Colin(S), Runnan(I), Nicole(S&I)

7.0 Resources

Critical Project Elements	**Resources/Sources**
Defining Requirements	Finding exact constraints for requirements will involve: • Trade studies (literature, research, etc.) – Benson library, the internet, Norlin library, scholarly articles, etc. • Direct information from AFS (specified parameters)
De-icing Techniques	Research the following modern techniques: • Electro-Mechanical Expulsion • Thermo-Mechanical Expulsion • Ultrasonic • Hydrophobic/Ice-Phobic Coating

	Mr. Joseph Tanner can provide insight to the different techniques currently in the market based on his previous experience. Trade studies will allow for the comparison of techniques currently available.
Testing Methods (Simulating Conditions)/Accessibility to Testing Facilities	Dry Testing: • Wind Tunnel available at CU. The team will have to get in contact with Dr. John Farnsworth about using the new wind tunnel. Dr. Eric Frew also had some ideas of other tunnels we could use for this type of testing. Dynamic Testing: • Aurora Flight Sciences is working on getting the team testing time in the LeClerc icing wind tunnel. Freezing the wing: • Research will allow us to see methods that are used for applying ice to the wing without the need for an iced wind tunnel. • The LeClerc icing wind tunnel can allow for the dynamic testing and freezing of the wing in a controlled simulated environment. • Trudy's Fan can be turned into a wind chamber for dynamic testing.
Limiting Power Consumption	• Dr. Jelliffe Jackson and Dr. Jeffrey Thayer can provide useful information on how to minimize power consumption. • Research on current and modern methods to see which method already has the lowest power consumption and how we can modify it.
Integrating De-Icing Mechanism with Representative Wing Section	• Mr. Matt Rhode can provide help in using the machine shop if it is necessary to implement the mechanism. • Mr. Bobby Hodgkinson can be a great benefit as he has worked on many aerospace labs implementing equipment together. • CNC machine in Flemming

8.0 References

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[5] UTC Aerospace Systems, and Dave Sweet. "Giving Ice the Boot: Understanding Pneumatic De-icing." (n.d.): n. pag. June 2015. Web.