Enhancing Drone Endurance in Sub-Zero Environments via Multi-Modal Bio-Chemical Approaches

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1 Project Abstract

Unmanned aerial vehicles operating in sub-zero environments face two major challenges that limit their mission endurance: ice accumulation on propeller surfaces [1, 2] and battery performance degradation[3]. While active heating systems can address these issues, they impose significant weight and power penalties that reduce i operational ability. This study presents an integrated approach combining a penguin-feather inspired propeller design [4, 5] with phase-change material thermal management [6, 7, 8] to enhance drone endurance in extremely cold conditions.

We have developed two coupled surrogate models: one that captures propeller icing dynamics through impingement(of ice) and freezing behavior [9, 10], and another that models battery thermal response with embedded phase-change materials. Unlike previous studies that examine aerodynamic or thermal performance separately, our model calibrates both parameters together under realistic flight conditions through a Monte-Carlo simulation. The penguin-inspired surface modification uses natural ice-shedding mechanisms observed in *Spheniscus humboldti* (penguin) [4], while strategically placed phase-change materials delay temperature caused battery degradation.

Monte-Carlo Simulation results across five hundred randomized scenarios demonstrated a mission success probability of 0.89 for the bio-inspired configuration, compared to a substantially lower baseline performance. Battery thermal simulations showcased a clear performance hierarchy, with the hybrid phase-change material and chemical heater configuration providing optimal endurance. Computational fluid dynamics validation in ANSYS confirmed reduced ice adhesion on the modified propeller surface, with ice mass accumulation visibly lower than conventional propellers. These findings establish a practical, lightweight framework for cold-weather drone deployment in rescue, delivery, and scientific applications [11, 12].

2 Introduction & Objective

2.1 Background

Drones in sub-zero environments accumulate ice on rotors, battery, and the fuselage, negatively affecting their performance and endurance. Both ice on rotors and the degradation of battery endurance in such environments are well-documented problems [1, 2, 3]. As we observe in further sections, ice on rotors depends upon droplet impingement, freezing fraction, adhered ice mass, etc. [9, 10]. The ice mass reduces thrust as observed via a simple surrogate mapping [10].

2.2 Research gap

Active heaters are effective but are expensive and add to the weight of the aircraft. Thus, our study aims to optimally combine penguin-feather inspired propellers and a phase-change material (PCM) in an integrated Monte-Carlo framework for realistic ranges to solve the aforementioned problems [4, 7].

2.3 Objective

This study will evaluate a drone's thermal endurance and icing performance by assessing battery-temperature curves and propeller thrust-loss. We hypothesize that combining a penguin-inspired propeller with a chemical heater and PCM will increase mission success, validated via simulation [1, 2].

3 Innovation

3.1 Novelty

This project develops two surrogate-based models: one for rotor icing and another for battery thermal endurance [10, 2, 3]. Unlike other studies that may evaluate either aerodynamics or energy storage as separate elements, these two parameters are calibrated simultaneously in our model to realistic UAV flight conditions [2, 1, 3]. The rotor model accounts for adhesion and shedding behavior inspired by penguin feathers [4, 5], and the thermal model accounts for the thermal effects of an embedded PCM [6, 7].

3.2 Impact

These models establish how bio-inspired propellers and PCM-based thermal heating can enhance UAV survival in sub-zero environments [10, 2]. Since these models reduce energy cost and mass penalties, they create a practical method for deploying drones in rescue, delivery, and scientific missions in frigid environments [6, 7].

4 Methodology

4.1 Overview

The overall workflow of the model is shown in the flowchart (Figure 1). The project follows two main tracks: a battery thermal model and a rotor icing model. Both of them use a common set of environmental and design inputs, such as Liquid Water Content (LWC), relative velocity, ambient temperature, and material parameters [11]. The outputs of these models are combined through a Monte-Carlo aggregation framework to evaluate mission reliability under sub-zero environments.

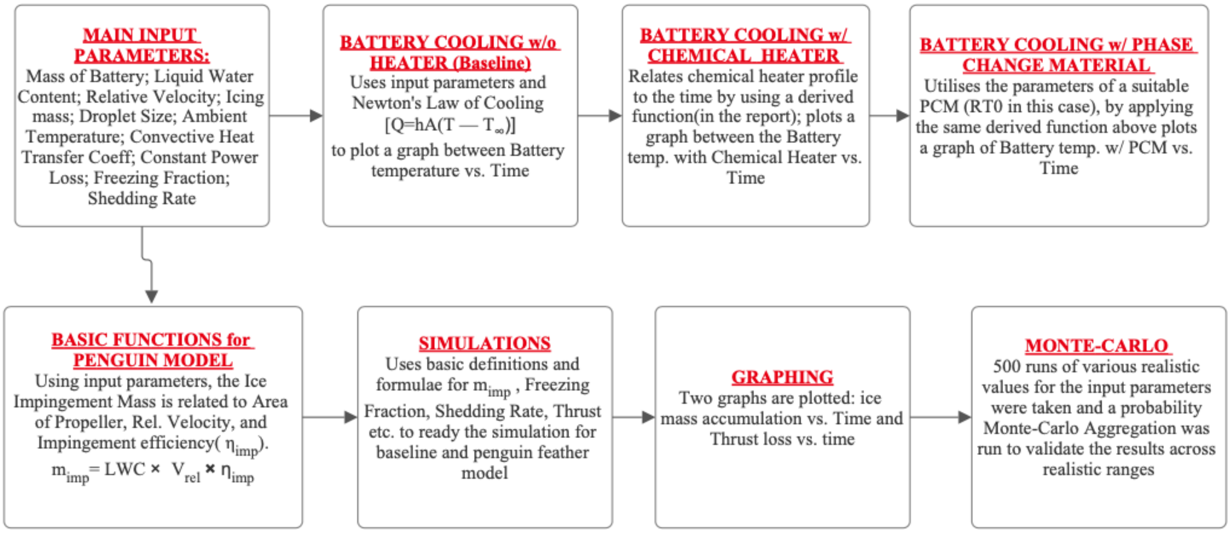

Figure 1: Methodology flowchart showing the modelling steps for battery cooling, penguin-inspired propeller icing, and Monte-Carlo aggregation.

4.2 Model formulation

For the thermal model, battery temperature is determined by a lumped energy balance:

$$\frac{dT}{dt} = \frac{P_{\text{elec}} + Q_{\text{chem}}(t) - hA(T - T_\infty)}{mc_p}.$$

Here, P_{elec} refers to the steady internal power loss, $Q_{\text{chem}}(t)$ is the heat released by a chemical heater [13], and the last term represents convective cooling to the environment (using Newton's Law of Cooling). The mass of the battery m and heat capacity c_p determine its thermal inertia. When PCM is added, its latent heat is included by using an effective c_p near its melting point [6, 7, 8]. The model is numerically integrated using a 1 second time step to predict temperature for the baseline, chemical heater only, PCM-only, and combined configurations.

The icing surrogate model predicts the adhered ice mass $m_{\text{ice}}(t)$ through impingement and freezing relations [9]. Thrust loss is calculated using a surrogate mapping $T(t) = T_0 f(m_{\text{ice}})$ adjusted to experimental ranges [10, 12]. Two configurations are simulated: a baseline rotor and a rotor inspired by penguin feathers [4, 5].

4.3 Simulation and analysis

Each model was tested over realistic ranges of parameters [11]. A Monte-Carlo, using a fixed-random seed (42) to ensure reproducibility, run of 500 samples was executed to predict mission-success probability, defined by maintaining $T \geq T_{\min}$ and thrust $\geq 0.75 T_0$ for atleast 95% of the total time. Thrust–velocity characteristics for both the baseline and penguin-inspired rotors were additionally obtained using ANSYS CFD to check surrogate predictions [10]. Key metrics checked include thrust output, ice thickness and ice-mass caught for both propellers.

5 Results and Conclusions

5.1 Model Results

The combined surrogate model produced quantitative predictions for battery temperature, ice accumulation, and thrust decay under sub-zero conditions. The battery-thermal simulation showed a clear endurance order: baseline $<$ PCM-assisted $<$ chemical-heater $<$ hybrid PCM + heater configuration.

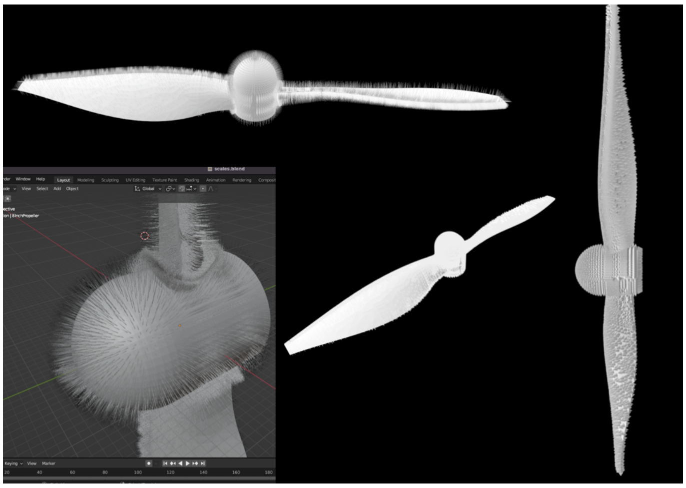

Figure 2: The various designs of penguin propellers that we modelled on various softwares including Fusion360, Blender and Onshape to try and best emulate the real feather on the propeller.

For the rotor-icing model, the impinged mass and freezing rate showed distinct ice-growth curves for both baseline and penguin-inspired propellers. The surrogate mapping $T(t) = T_0\, f(m_{\text{ice}})$ reproduced expected thrust-loss behavior, and Monte-Carlo aggregation of over 500 random input sets showcased a mission-success probability of 0.89 for the penguin-inspired rotor, indicating improved reliability.

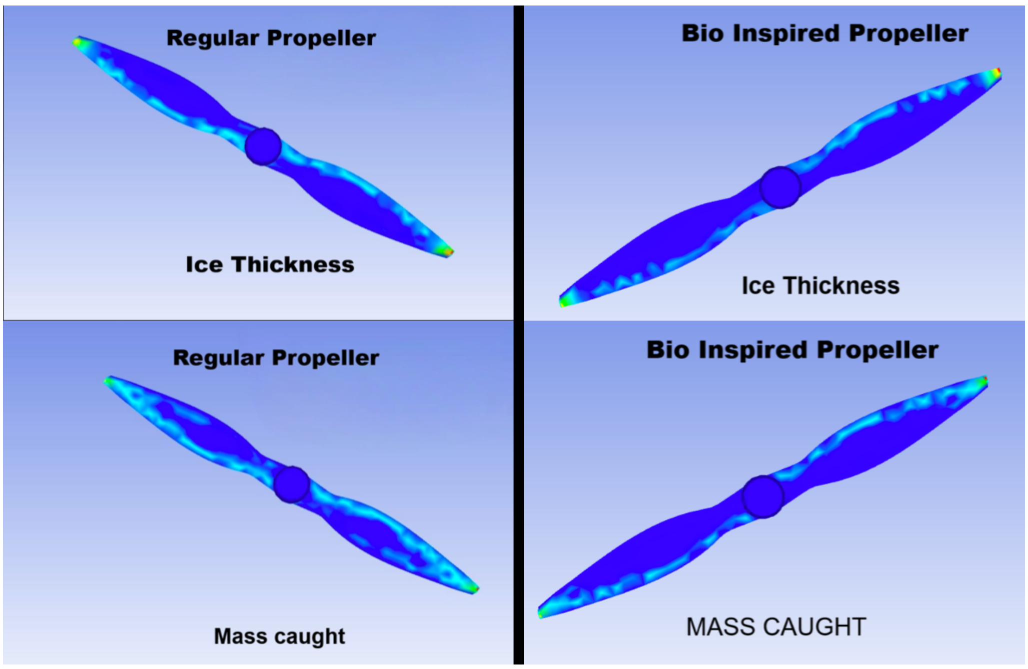

Figure 3: Ice mass accumulation comparison. The penguin-inspired propeller visibly shows reduced mass accumulation

ANSYS CFD confirmed these results too. Although various 3D designs of penguin-inspired propellers were designed by us (Figure 2), they were too complex to be run on ANSYS; we used a roughened propeller(similar in texture [4]) to simulate the penguin feathers, which accumulated visibly less ice (Figure 3) and exhibited smoother velocity and pressure contours , coming with a small loss of thrust due to lack of an aerodynamic structure (Figure 4). Quantitatively speaking, peak thrust reached 4.22 N for the regular propeller and 4.00 N for the bio-inspired one. The simulation therefore supports the surrogate assumption that surface modification reduces ice adhesion with a marginal aerodynamic penalty.

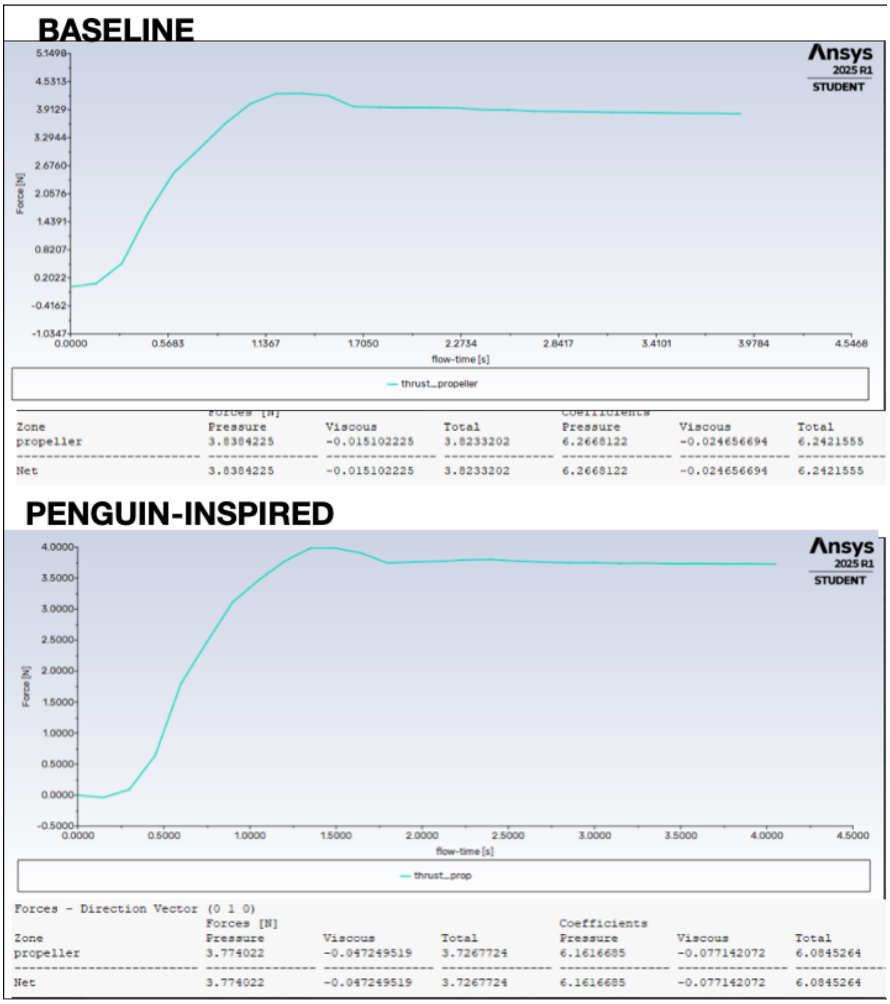

Figure 4: Thrust/force comparison. The penguin-inspired propeller incurs a minor loss of thrust due to simulated non-aerodynamic roughness on it to best emulate ice-shedding properties.

5.2 Interpretation

These results showcase the dual benefit of the integrated model: thermal stability from PCM enhanced batteries and delayed aerodynamic decay from surface roughness/penguin-inspired structure. The model's probabilistic structure captures this trade-off realistically: mission endurance improves mainly through slower temperature decay and reduced icing rate, while aerodynamic efficiency remains nearly unaffected. The ANSYS runs validate that the simplified physics of the Python model remain physically plausible.

5.3 Conclusion

The study showcases that integrating a penguin-inspired rotor design with PCM-based thermal heating yields a lightweight, low-power strategy for cold-weather UAV/drone operation. Our integrated surrogate framework quantifies these effects and provides a foundation for later hardware testing and optimization. Future work will involve refining the penguin-inspired rotor and extending the thermal model with real PCM testing in sub-zero conditions.

6 Acknowledgement and Reference Links

6.1 Acknowledgements

The modelling and simulation work was carried out using Google Colab for Python-based numerical modelling and ANSYS Fluent for aerodynamic simulation. Majority of the references used were from open-access journals including MDPI and NASA reports. Majority of the justifications and explanations lie in the Supplementary Material provided. AI tools were used strictly for code explanation, debugging, and documentation structuring, not for generating research data or conclusions. All experimental design decisions, modelling, analysis, and interpretations were performed independently by the authors. Paper structuring was done in Overleaf.

6.2 Reference Links

- Our main python model: https://colab.research.google.com/drive/1jaCqgw3P2neT9OhGBiTMw2P4TcI9C3n2?usp=sharing
- Tutorial guide for ANSYS Ice simulation: https://youtu.be/mSiUp8MR31U
- ANSYS Files: https://drive.google.com/drive/folders/1m45jYMepzoRO9UjRxRdc145PuNgFMo6o?usp=sharing

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