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A review of infrared thermography applications for ice detection and mitigation

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ABSTRACT

Ice accretion on various onshore and offshore infrastructures imparts hazardous effects sometimes beyond repair, which may be life-threatening. Therefore, it has become necessary to look for ways to detect and mitigate ice. Some ice mitigation techniques have been tested or in use in aviation and railway sectors, however, their applicability to other sectors/systems is still in the research phase. To make such systems autonomous, ice protection systems need to be accompanied by reliable ice detection systems, which include electronic, mechatronics, mechanical, and optical techniques. Comparing the benefits and limitations of all available methodologies, Infrared Thermography (IRT) appears to be one of the useful, non-destructive, and emerging techniques as it offers wide area monitoring instead of just point-based ice monitoring. This paper reviews the applications of IRT in the field of icing on various subject areas to provide valuable insights into the existing development of an intelligent and autonomous ice mitigation system for general applications.

1. Introduction

Cold regions across the globe, particularly the Arctic polar regions, are experiencing a steady growth in trade, logistics, and infrastructure development (Norwegian Shipowners' Association, 2021; Kenneth et al., 2008). This expansion encompasses diverse engineering projects both on land and in marine environments, including the construction of airports, seaports, dams, power transmission systems, offshore platforms, bridges, railways, and road networks (Shen, 2015). The Arctic region holds particular significance in the context of maritime transportation. It is due to the emergence of secure trade routes resulting after the gradual melting of polar ice caps reportedly at a rate of 12.6% per decade (NASA, n.d.; Schøyen and Bråthen, 2011; Hanaček et al., 2022; PAME, 2020). Notable examples include *Northern Sea Route (NSR)* by Russia (Sander and Mikkelsen, 2012), *Polar Silk Road* by China (Lanteigne, 2022; The State Council Information Office of the People's Republic of China, 2018; Nakano and Li, 2018), *Arctic Highway* by Norway, and other related projects (*Norway's Arctic Policy*, 2017; *The Norwegian Government's Arctic Policy*, 2021; Steed, 2021; Bambulyak et al., 2012; Zadorin et al., 2022). The development in Arctic regions is further spurred by the presence of extensive untapped reserves of both non-renewable and renewable energy resources, as well as fierce competition among stakeholders (*United States Coast Guard Arctic Strategy*, 2013). However, while the Arctic zones offer enticing prospects for businesses and research endeavors, they also present unique challenges; the key challenge being weather and icy conditions which make them risky for operation and exploration. In such environments, factors such as wind/ice conditions, operational time period, and ice-load-bearing capability become paramount considerations for successful endeavors (Ryerson, 2011).

1.1. The icing problem

Icing is an inherent and inescapable natural occurrence in cold regions, exerting a profound influence on their socio-economic progress. Its repercussions span a wide spectrum, encompassing aviation operations (Cao and Chen, 2016; Pulkkinen et al., 2019; Muhammed and Virk, 2022; Cebeci and Kafyeke, 2003), maritime trade (Zhou et al., 2022; Dehghani-Sanij et al., 2017) and the structural integrity of diverse infrastructure elements, including roads, dams, wind turbines, communication systems, gondola chairlifts (Azad and Virk, 2022), and power transmission cables and towers. Moreover, safety hazards are also associated with mass transit systems like railway and aviation in case of precipitation and in-flight icing, respectively (Lotfi and Virk, 2023). This study endeavors to explore the potential of infrared thermography in cold environments across various applications, where the accumulation

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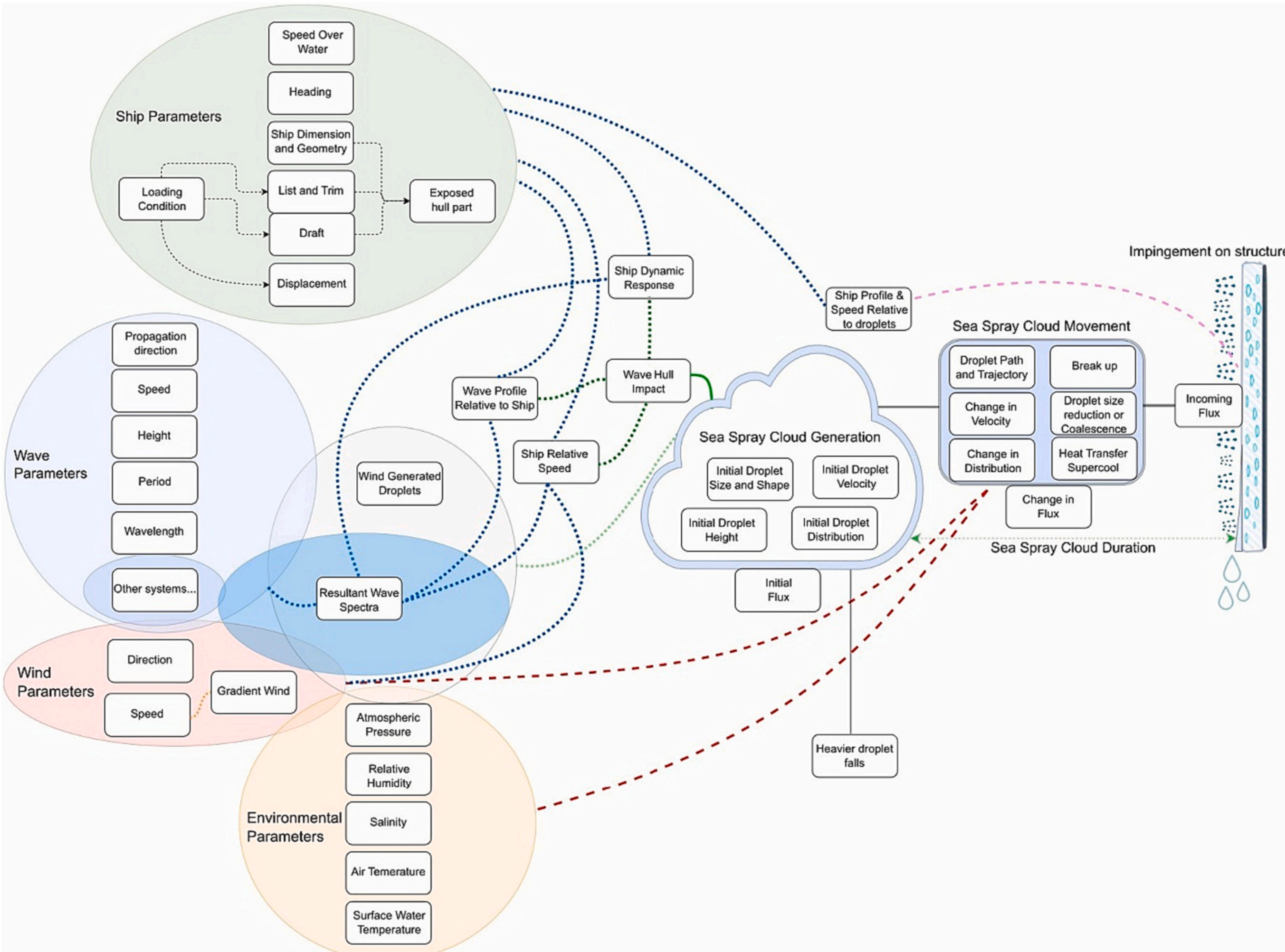

Fig. 1. Process of offshore icing. Environmental factors and vessel characteristics contribute to sea spray ice accreted on vessels. For towering structures atmospheric icing takes on multiple forms including in-cloud icing caused by supercooled water droplets, and precipitation in the form of freezing rain/snow, further exacerbating the icing challenge (Zhou et al., 2022; Mintu et al., 2016; Dhar and Khawaja, 2021).

of ice on assorted infrastructures poses not only safety hazards but also the risk of significant system failures.

There are essentially two primary types of icing (Homola et al., 2006): (i) Atmospheric Icing, which occurs when suspended supercooled water droplets freeze upon contact with structures, and (ii) Sea-Spray Icing, which accumulates on exposed offshore structures by saline, sea water droplets when air-temperature is below freezing. This phenomenon is influenced by environmental factors as well as by the vessel's characteristics (Guest, 2005). The presence of brine pockets depresses the freezing point of sea-spray well below 0 °C, making sea-spray ice weak and less robust than freshwater ice. However, it may have a strong deposition at the surface-liquid interface where no brine pockets are available (Minsk, 1980; Rashid et al., 2016a).

The consequences of icing can be evaluated in the context of specific applications within the aviation, offshore, and onshore sectors.

1.1.1. *Airborne icing problems*

In the aviation sector, in-flight icing resulting from supercooled liquid droplets has a significant impact on fixed wing aircrafts. This phenomenon affects critical components such as ailerons, tailplanes and jet engine parts, which causes the stalling angle to be reached at a much higher speed and low angle of attack (Cebeci and Kafyeke, 2003). Prolonged flight in these conditions may lead an aircraft to experience Ice Contaminated Tailplane Stall (ICTS) in which its pitch control becomes ineffective (Mingione and Barocco, 1997; Federal Aviation Administration (FAA), 2015). Crystal icing on engines results in power loss and flameouts (Yamazaki et al., 2021).

Rotorcrafts endure ice accretion on main rotor, tail rotor, cooling bay inlets, and vital engine parts (Cao and Chen, 2016). The icing dynamics observed in helicopters differ from those encountered by fixed-wing aircraft because of the additional centrifugal force exerted on iced blades, which can potentially facilitate ice shedding (Yamazaki et al., 2021). Pulkkinen et al. (Pulkkinen et al., 2019) examined the impact of icing conditions on patients transported by helicopters for emergency treatment in Northern Finland. Alarmingly, their findings revealed that 36% of the canceled High Emergency Medical Service (HEMS) missions were due to icing.

The impact of icing on fixed-wing drones or Unmanned Aerial Vehicles (UAV) is notably more pronounced than on aircrafts. This heightened susceptibility arises from their extended, low-velocity flight in concentrated Supercooled Liquid Droplets (SLD) zone (altitudes below 10 km) and their utilization of low Reynold's number airfoils, which are sensitive to minor aerodynamic alterations. Moreover, weight and power constraints restrict the use of a dedicated onboard ice mitigation system on UAVs (Muhammed and Virk, 2022; Muhammed and Virk, 2023a; Szilder and Yuan, 2017). In case of rotary wing UAVs ice accretion causes severe mass imbalance and vibrations in the airframe as the ice on blades sheds off due to centrifugal force (Muhammed and

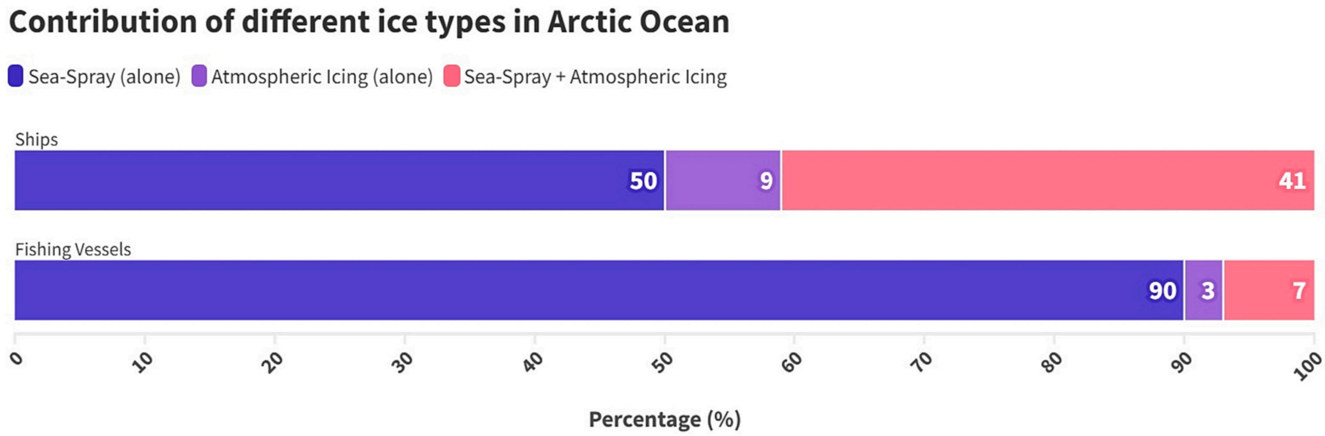

Fig. 2. Contribution of icing on fishing vessels and ships sailing in the Arctic Ocean (established from Lozowski (Lozowski, n.d.)).

Virk, 2023b).

1.1.2. Offshore icing problems

Offshore vessels with a height below 16 m predominantly contend with sea-spray icing (Minsk, 1980). However, oil rigs and lofty structures get impacted by both atmospheric icing and the icing resulting from wave- and wind-induced sea spray (Hansen, 2012) (see Figs. 1 and 2). In the context of offshore oil extraction, these frigid offshore regions necessitate drilling vessels capable of operating in severe climates and withstanding substantial ice loads (Adumene and Ikue-John, 2022). Moreover, their mooring and towing lines need to be kept ice-free. Similarly, emergency evacuation operations are also affected; lifeboats cannot be launched as the locks that attach them to the vessel get frozen (FutureBridge, 2019; Locke, n.d.). Adumene et al. (Adumene and Ikue-John, 2022) presented a detailed review of risks associated with icing on offshore structures in terms of environmental factors, offshore structural dynamics, operational risk, and logistics challenges. They also discussed roll, pitch, yaw, heave, sway, and surge motion effects on floating offshore structures when impacted by icing.

Wind turbines' operation in cold climates gets limited due to the heavy ice accretion, sometimes coupled with accessibility, non-availability of infrastructure, and related risks involved, like ice-shedding. In certain instances, icing-induced power losses in turbines can escalate to as high as 80% (Gao et al., 2019a; Gao et al., 2021; Homola et al., 2012). This predicament is further exacerbated in the case of offshore turbines, where despite the typically high wind speeds and low surface roughness, the same issues persist. Consequently, the development of offshore wind farms in the High North remains under-developed (Tahir et al., 2021).

Ice-jacking, ice sheet expansion, ice heave, and ice jamming are the typical phenomena encountered at streams, rivers, canals, and reservoirs/dams (Canadian Pond, 2023). The presence of ice impacts their hydraulic behavior, with direct implications for public safety, facility protection, and energy loss. Frazil ice causes clogging of water intakes and increases roughness incurring heavy economic losses in terms of maintenance. Manitoba Hydro (Canada) loses tens of millions of dollars per year due to ice effects. Similarly, a hydropower company in Norway lost around $125,000 for a complete blockage of brook water channel (Gebre et al., 2013).

1.1.3. Onshore icing problems

Overhead power lines in cold ice-prone regions endanger the safety and reliability of power transmission systems; prolonged icing can result in tower collapse. The accretion of ice on transmission lines adds weight to the overall tower structure. Simultaneously, it alters aerodynamic profile of power lines rendering them more vulnerable to wind-induced forces, which may induce oscillations in the cables. These combined factors exert excessive stress on various tower components, ultimately leading to structural fatigue and compromising the integrity of the transmission system (Solangi, 2018).

Development in civil engineering allows construction of bridges with longer spans which require lofty towers and longer cables in case of a cable-stayed bridge. However, this progress comes with an elevated risk of ice accumulation in cold regions, where falling ice from support cables and diaphragms poses a direct threat to traffic safety and, consequently, human lives. Icing incidents have been reported on different bridges in Europe, for example, Øresund Bridge (Sweden-Denmark), Uddevalla Bridge (Sweden), Severn Crossings (UK) (Virk et al., 2011; *The Local SE*, 2019; Kleissl and Georgakis, 2010), and similarly in USA on Veterans' Glass City Skyway (Henson, n.d.; Matejicka and Georgakis, 2022). Similarly, suspension bridges are also prone to atmospheric icing. 'Precipitation icing', characterized by freezing rain and wet-snow ice, is said to be a prominent contributor to cable-stayed bridge icing (Li et al., 2023; Szilder et al., 2021). Pipeline (suspension) bridges used to transport oil, natural gas, water or other resources experience glaze ice and snowstorms in certain regions and due to their lightweight structure, they are sensitive to wind action. Tragically, there have been reports of catastrophic incidents, such as bridge explosions in New Mexico and China which resulted in significant loss of life due to oil and gas leaks caused by extreme weather conditions (Yu et al., 2020; Wang et al., 2022).

In railways, precipitation icing may cause flashovers and derailment and hence disruption to rolling stock (Network Rail, 2022; Kandelin, 2021; Qi et al., 2022). Heavy icing in terrestrial environments affects railway transportation causing flashovers, disrupts electric power lines and telecommunication infrastructure by reducing the flashover/withstand voltage for insulators, and may cause equipment damage and loss of human life due to ice-shedding (Gao et al., 2019a; Gao et al., 2021; Statnett, 2018; Jin and Virk, 2019; Farzaneh, 2013; Farzaneh and Kiernic, 1995; Farzaneh and Melo, 1990; Yin et al., 2016; Hu et al., 2014). Secondly, railway tunnels in cold environments are homogenized with constant temperature and relative humidity, however at the openings of tunnels, cold air mixes with warm air resulting in rime ice deposition. Similar phenomenon happens on railway bridges, uphill elevated lines, and lines near the rivers (Blue Wire, 2023). Moreover, railway turnouts (track junctions) are greatly influenced by winter weather conditions and train traffic has to be stopped to avoid the risk of derailment or technical failure (Lotfi and Virk, 2023; Zelazny et al., 2021). Typically icing on the contact wires of tramlines and railways causes them to lose power, and heavy icing may collapse the whole catenary system (Blue Wire, 2023).

In short, ice accretion on structures is perceived as a safety hazard. It is also directly related to structures' integrity and their life span, and sometimes simply avoiding an icing event is not an option. To overcome

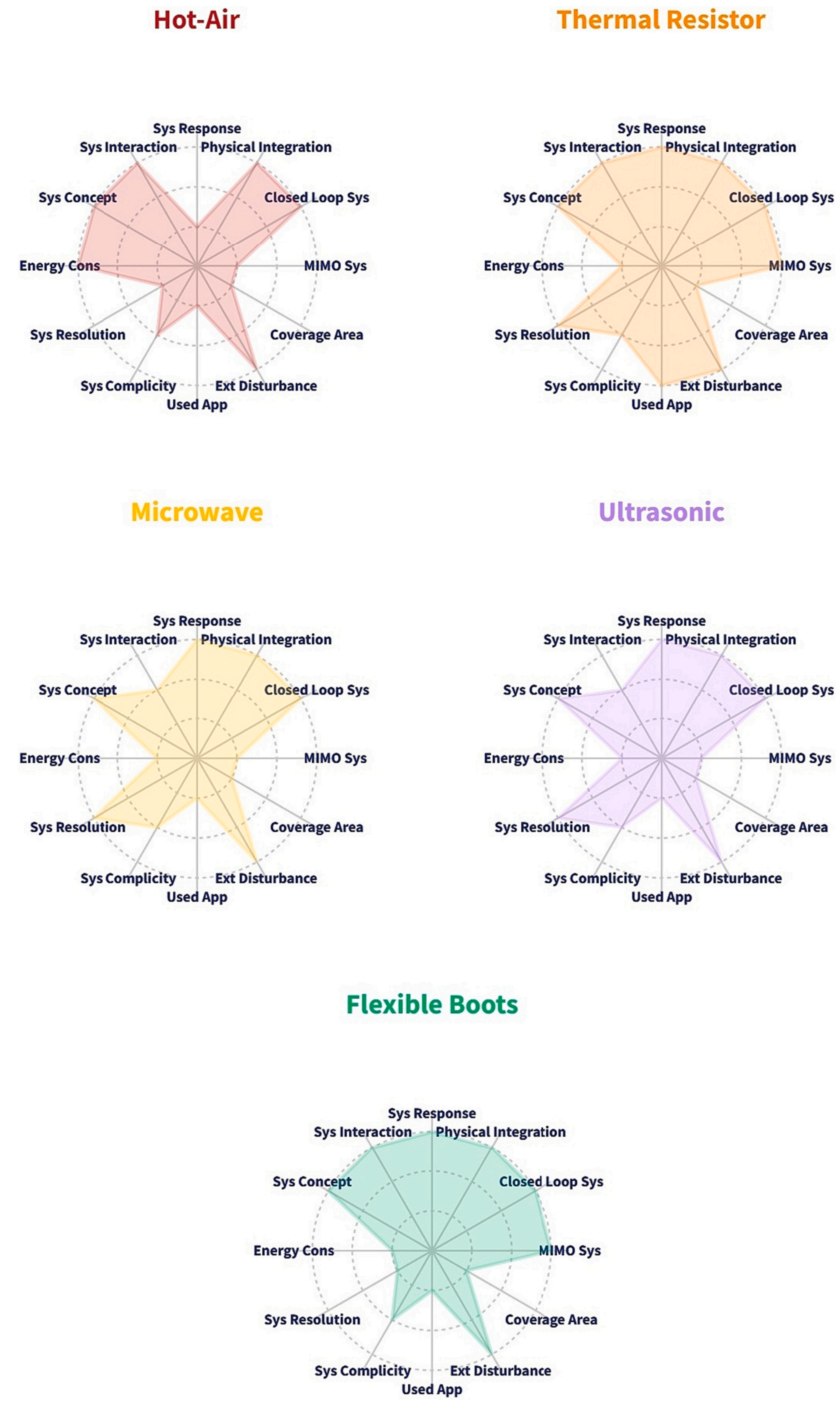

Fig. 3. Integration of Infrared Thermography as an ice detection technique along-with five different ice mitigation techniques for wind turbines (established from (Madi et al., 2019)). In the graphic, 'MIMO Sys' stands for Multiple Input Multiple Output System, which means whether multiple ice mitigation actuators can be addressed or controlled with corresponding ice detection technique. The inability of a particular ice mitigation technique to be integrated with an ice detection methodology makes it low resolution system sensitive to environmental disturbance.

icing hazards, ice detection and mitigation systems are developed depending on the application (aviation, railway, offshore structures, *etc.*).

2. Ice mitigation systems

Ice mitigation systems encompass a variety of methods, including *anti-icing* procedures like electrothermal, hot-air, pneumatic boots, microwave, coatings, chemical sprays, *etc.* or *de-icing* techniques like the creation of MAGnetic Slippery Surfaces – MAGSS, Electro Impulsive De-Icing – EIDI, Electro Expulsive De-Icing – EEDI, and others (Virk et al., 2011; Wei et al., 2020; Virk et al., 2011). Anti-icing systems are designed to prevent the formation and accumulation of ice on surfaces, thereby inhibiting its initial development. In contrast, de-icing systems are focused on removing ice that has already formed. A further distinction categorizes these systems as either active or passive, depending on their energy usage: Active systems require a dedicated energy source to function and convert the applied electrical or electromechanical energy. Passive methods incorporate materials engineering and take advantage of inherent physical, thermal, and chemical properties of the structural surface to eliminate or prevent ice.

The basic motivation behind the development of ice mitigation is accelerated from its usage in the aviation industry since second world war and onwards (Dawson, 1991). Today, there is a growing interest in applying these techniques to various related fields. The study of icing, or ice mitigation, typically unfolds through three distinct approaches: field analysis, laboratory experiments, and simulation results. Field analyses provide the most accurate insights into real-world icing scenarios but often demand significant budgets and extended timeframes. As an alternative, the research is initiated with simulation tools such as: FENSAP®, ANSYS®, TURBICE® and so on, and the results are compared with the laboratory experiments on downscaled models or samples (Kandelin, 2021; Jin, 2021).

Prior to deploying an ice mitigation system, it is essential to establish a robust ice detection strategy. While conventional ice detection often relies on visual inspections by human operators, this approach is not without its limitations, particularly in non-autonomous systems where the potential for human error exists. The risk of overlooking an icing event becomes more pronounced in the absence of human oversight. These factors underline the need to use efficient technology and develop reliable ice detectors in order to study and detect ice accretion at an early stage. These ice detectors can be coupled together with suitable ice mitigation techniques to develop an intelligent ice prevention system.

3. Ice detection techniques

Ice detection systems are classified as *ice condition monitors* and ice accretion detectors (Jackson and Goldberg, 2007). Ice condition monitors detect moisture, temperature, and related meteorological parameters that reflect the potential of meteorological icing conditions, however, ice may or may not be accreted on objects under observation. In contrast, ice accretion detectors measure the ice build-up on sensing surfaces and hence measure instrumental icing (Jackson and Goldberg, 2007). Homola et al. (Homola et al., 2006) segregated ice detection methods into *direct* and *indirect* detection and listed 29 such techniques. Direct detection usually refers to the measurement of physical properties of ice whereas indirect detection relates to numerically or statistically analyzing the meteorological conditions that lead to icing (Virk et al., 2011; Jackson and Goldberg, 2007).

Direct detection includes ultrasonic damping, microwave ice detection (Mughal and Virk, 2014; Madi et al., 2019) (Kabardin et al., 2021), pressure sensing (using piezo-electric sensors), vibration probe method (to record resonance frequency), vibration diaphragm (measuring change in capacitance), impedance sensor (measuring change in inductance), temperature change (using thermistors, resistance temperature detectors, thermocouples, hot-wire method (Jackson and Goldberg, 2007; Struk et al., 2014), dual wet-dry heated elements), ice load measurement (through load-cell) and optical measurement (infrared thermography, reflected light method, total internal reflection and LiDAR measurements) (Dhar and Khawaja, 2021; Wei et al., 2020). Indirect methods include dewpoint, RH, droplets MVD measurement (Wei et al., 2020; Madi et al., 2019), visibility of cloud base height, double anemometer technique (based on wind velocity measurement), noise detection (works for moving blades) (Virk et al., 2011; Wei et al., 2020; Madi et al., 2019).

Ideally, an intelligent, autonomous ice protection system should have ice detectors with a rapid response to presence of ice and must be able to pinpoint the location of ice on a surface. Optionally, it should be able to differentiate among different ice types. Its ice mitigation system should be characterized by no power loss, which means that all input power should be fully consumed as thermal energy without any loss. However, since real ice mitigation systems/coatings do not exhibit ideal characteristics, researchers propose different strategies for effectiveness to compensate for the loss in terms of reliability, cost, response time, and other similar factors.

An optimized intelligent ice protection system can be achieved by balancing cost and efficiency. For instance, Wei et al. (2020) proposed a hybrid strategy combining active and passive techniques to counter ice accretion on wind turbines. This approach integrates ultrasonic de-icing (active) with hydrophobic coatings (passive). For wind farms, some scientists also proposed indirect methods based on statistical data analysis to predict icing potential (Jin and Virk, 2019). However, a drawback of this approach is that meteorological masts or sensors for this technique are established at far-off locations apart from the actual target location, so accuracy is a concern. An alternate is the direct measurement technique which includes vibration diaphragms, ultrasonic/microwave transducers, capacitive/inductive sensors, infrared probes, or temperature sensors. However, it is worth noting that all of these are point-based sensors that measure a physical parameter affected by ice presence at a particular position and also require retrofitting over the target surface (Virk et al., 2011). Optical and infrared thermography, on the other hand, offer the characteristics of remote-sensing and area-based imagery. Optical technique based on true color, in some instances, confuses icing on the target surface (*e.g.,* overhead power lines) with the background (*e.g.,* icing on trees, white clouds) (Virk et al., 2011; Borkowski, 2002). (Active) infrared thermography appears as a non-destructive, non-invasive technique that creates a contrast for the object to be segmented out of the imagery based on temperature variation.

The use of infrared thermography for ice accretion studies has recently come into limelight and so most of the work is currently in research phase comprising simulation results and lab experiments. Madi et al. (Madi et al., 2019) concisely reviewed integrated ice protection systems with five ice mitigation systems (hot-air, electro-thermal, microwave, ultrasonic and flexible boots) and eight different ice sensing techniques including IRT. They deduced that IRT appears as the only ice detection technique with fast system response and applicable conceptual design for all five types of ice mitigation systems (see Fig. 3). However, since the real application is not available in literature or is redacted from general readers, qualitative assessment of its performance in practical scenarios cannot be made currently.

4. Infrared thermography

The use of imaging technology to capture heat energy in the infrared spectrum of electromagnetic radiation is called infrared thermography. This technique is employed for investigating various physical phenomena that occur within the invisible infrared region of the electromagnetic spectrum, ranging from 0.78 μm to 14 μm, with the primary objective of gathering thermal information. The data obtained from the IR spectral range is typically presented in the form of images that employ false colors and various color palettes, commonly known as thermograms. These thermograms serve as visual representations of temperature

Fig. 4. Technological evolution of thermal infrared technology: pictures on the left display AGA Thermovision-661 IR camera developed in 1969 in Sweden. This thermal IR camera with a Field of View (FOV) of 5°x5°, thermal sensitivity of 0.2 °C and mass of around 25 kg needed to be supported by oscilloscope (20 kg) and tripod stand (15 kg) and cooled using 10 l cryogenic cooler (liquified Nitrogen) powered by 220 VAC generator. Picture on the right shows a modern portable FLIR ONE Pro® thermal IR camera released in 2017. This handy camera weighing merely 36.5 g can be connected to smartphone and features 50°x43° FOV with thermal sensitivity of 0.1 °C (100 mK) (Gromicko and McKenna, 2022; AGA Thermovision, AGA Museum, Emmen, Netherlands, n.d.; Teledyne, 2023).

distributions over a wide surface area.

4.1. Physics of infrared thermography

All objects above absolute zero (0 K temperature) radiate heat in the form of infrared energy. The proportion of energy emitted, reflected, or transmitted by different bodies can be comprehensively understood by the concept of a black body which serves as an ideal theoretical reference that absorbs all types of radiation at all temperatures without any reflection or transmission. Practically, real objects emit thermal radiation based on their emissivity (ε) which is defined as the ratio of radiation emitted by that body to the radiation emitted by a blackbody at same temperature. The value of ε falls within a range of 0–1 (Rashid et al., 2019).

Infrared spectral band is divided into near, far, short wave, medium wave and long-wave infrared sub-bands. The wavelength band of radiated infrared energy is related to the body temperature and is defined by Wien's displacement law: $\lambda_{max} = b/T$ where 'T' is the body temperature in Kelvin, 'b' is proportionality constant ($2.897 \times 10^{-3}\ mK$), and λ_{max} is emitted wavelength of maximum intensity. Theoretically it states that as the temperature of an object rises it radiates energy in the low wavelength spectrum, and *vice versa*. Contemporary thermographic cameras operate in medium wave and long wave infrared range and their temperature measurement depends upon the intensity of photons striking the Focal Plane Array (FPA) of the cameras.

4.2. A brief history of infrared thermography

Infrared is invisible to the human eye and was discovered in 1800 by William Herschel (Swinburne University of Technology, n.d.; Rogalski, 2012; Gromicko and McKenna, 2022). The discovery led to the study of physical properties and formulation of laws of radiation by Kirchhoff, Stefan-Boltzmann, Wien and Planck (InfraTec GmbH, 2022). The technology was basically researched for military applications due to night-vision attributes (Rogalski, 2012; Gromicko and McKenna, 2022; Kylili et al., 2014; Gade and Moeslund, 2014). After its commercialization, high cost was the main hindrance for lack of applications, and moreover, the cumbersome, bulky apparatus including thermal camera, its mounting stand, and cryogenic cooler weighing more than 50 kg, restricted the use for many portable applications (Szajewska, 2017). The IR camera technology revolutionized after 1980 with the development of *uncooled* ferro-electric infrared detectors that used Barium Strontium Titanate (BST) and Vanadium Oxide (VOx) microbolometer. This development led to a substantial reduction in size, weight, and cost (Gromicko and McKenna, 2022). Today highly sensitive micro-bolometers with low temperature operation are used in Focal Plane

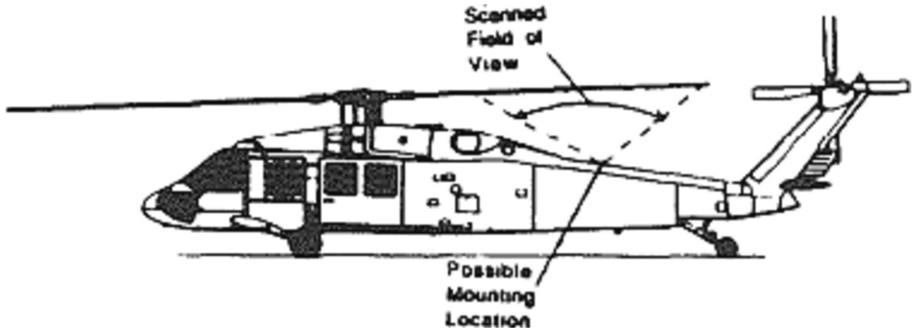

Fig. 5. Possible mounting location of passive IRT system for helicopter as proposed by Dershowitz (Dershowitz, 1991)/Dershowitz et al. (Dershowitz and Hansmm, 1991)

Arrays (FPAs) for infrared detectors and cameras. Fig. 4 provides a visual comparison of the technological evolution contrasting the legacy, bulky infrared camera (Thermovision-661) assembly *versus* modern portable, lightweight FLIR ONE® PRO for Android/iOS smartphones.

Industrial and technological revolution especially in semiconductor research and photolithography have widened the arena of thermal IR applications (Rogalski, 2012). Infrared thermography is today being used extensively in the fields of agriculture, aviation, buildings, electrical inspections, geology, marine, medicine, military, non-destructive testing (NDT), search and rescue (SAR) operations, and other applications involving recognizable thermal radiative dissipation. Since IRT provides 2D thermal images, it makes comparisons in a wide target area possible. This is advantageous against thermistors, pyrometers, and thermocouples, which provide temperature measurement at a single point (Usamentiaga et al., 2014). This also enables IRT to be used at locations beyond the human reach or where the installment of other detectors becomes risky or uneconomical.

5. Scope of infrared thermography in icing environments

5.1. Aviation

Ice on the aircraft is accreted on the exposed engine parts, ailerons, and horizontal/vertical stabilizers. Different studies have been conducted to study ice accretion under infrared thermography with integrated ice mitigation techniques. Hao et al. (Hao et al., 2020) used a similar way to introduce electro-impulse de-icing (EIDI) with cryogenically cooled mercury cadmium tellurium – MCT (or HgCdTe) thermal infrared camera operating in medium wave spectral range (2.0 μm −5.7 μm). The camera had a resolution of 640 × 512 pixels, and the target surface (pretreated aluminium with black acrylic resin sprayed) was electrically excited by a 2 × 2 lamp. Water was dropped on an aluminium plate and was allowed to freeze at ambient temperatures of −30 °C, −40 °C and − 50 °C. For preliminary ice detection they applied Principal Component Analysis (PCA) to infrared images and then Canny edge detection to obtain ice shape outline. The technique of PCA used in this experimentation eliminated the thermal field generated by the pulse coil on the surface of the aluminium plate (target), as well as decomposed the *non-uniform heating* components on the surface of the aluminium plate. In other words, it automatically compensated for the non-uniform heating issue. They also determined the ice shape obtained after PCA and measured its dimensions in pixels and millimeters using geometry and image processing tools. Once the EIDI system is actuated, a modified procedure was adopted to detect icing debris.

Liu et al. (Liu et al., 2019) conducted research on Dielectric Barrier Discharge (DBD) plasma as an anti-icing/de-icing technique for aircraft ice mitigation and used FLIR® A615 thermal IR camera (with FLIR® IR window: IRW—4C) to map the resulting surface temperature distribution when plasma is actuated. They performed a comparative study between duty-cycled and continuous actuation modes of DBD plasma inside icing wind tunnel to study their efficiency. Continuing with the work, Kolbakir et al. (Kolbakir et al., 2020) used setup based on infrared thermography to analyze the performance of DBD plasma based anti−/de-icing actuators for glaze ice mitigation on aircrafts and evaluated them based on their geometry and width of exposed electrodes.

Li et al. (Li et al., 2021) employed infrared thermography as a means to detect ice defects inside aluminium honeycomb samples sandwiched by carbon-fibers. They also qualitatively compared three different photothermal excitation techniques in this regard. For quantitative analysis they determined the extent and location of ice accretion using adaptive Canny edge detection technique based on morphological filtering and Otsu algorithm. In a subsequent work, they used the excitation of electromagnetic Electro-Impulse De-Icing (EIDI) mitigation coils to detect the ice shape and track the motion of residual ice fragments after de-icing effect (Li et al., 2022). In this work InfraTec® ImageIR 8300 with 0.02 °C temperature resolution was used for thermal imaging in a refrigerated environment for circular, square, and rectangular ice samples. Finite Element Method (FEM) was employed to study the effect of the discharge voltage, aluminium skin-coil gap and skin thickness on ice accretion temperature. During experiment they obtained thermal signature on a 2 mm thick aluminium substrate using 100 V - 200 V (with skin-coil separation of 4 mm) in *no ice condition.* For sequential image processing, first they used image difference method to identify coil pulse signal, and then employed Gaussian filter to reduce noise and smooth the image. Qualitative analysis indicated that increasing the coil discharge voltage and decreasing the coil-skin separation and substrate (skin) thickness considerably enhanced ice detection. Moreover, ice samples smaller than the inner diameter of the coil and larger than 1.5× outer diameter of coil were difficult to detect. For quantitative analysis they repeated the technique described in (Li et al., 2021) to get ice edges. Ice fragments (during de-icing process) were monitored using excitation voltage of 350 V and (sequential) inter-frame difference method. They also evaluated the de-icing ability of EIDI based on Euclidean distance of all ice fragments.

Girard et al. (Girard et al., 2010) used infrared thermography to explore temperature distribution of striking water droplets on heated solid substrates. They utilized FLIR ThermaCAM SC3000 supported by GaAs photon FPA detector with a resolution of 320 × 240 pixels. The experimental procedure involved deposition of water droplets at controlled temperature of 20 °C. These droplets were then directed to impact on a heated copper substrate at different temperatures (30, 40, 50 and 60 °C). High speed imaging and emissivity of water were used to measure temperature at droplet-substrate interface. The IR images reveal that after hitting the substrate and spreading over an area, the apex of droplets is colder than the overall contact area of droplets. An intuition can be drawn to use this technique to study runback water when electro-thermal de-icing system is activated.

Dershowitz (Dershowitz and Hansmm, 1991) and Dershowitz et al. (Dershowitz, 1991) used passive IR thermometry to study ice accretion on main-rotor helicopter blades. They tracked the latent heat of fusion

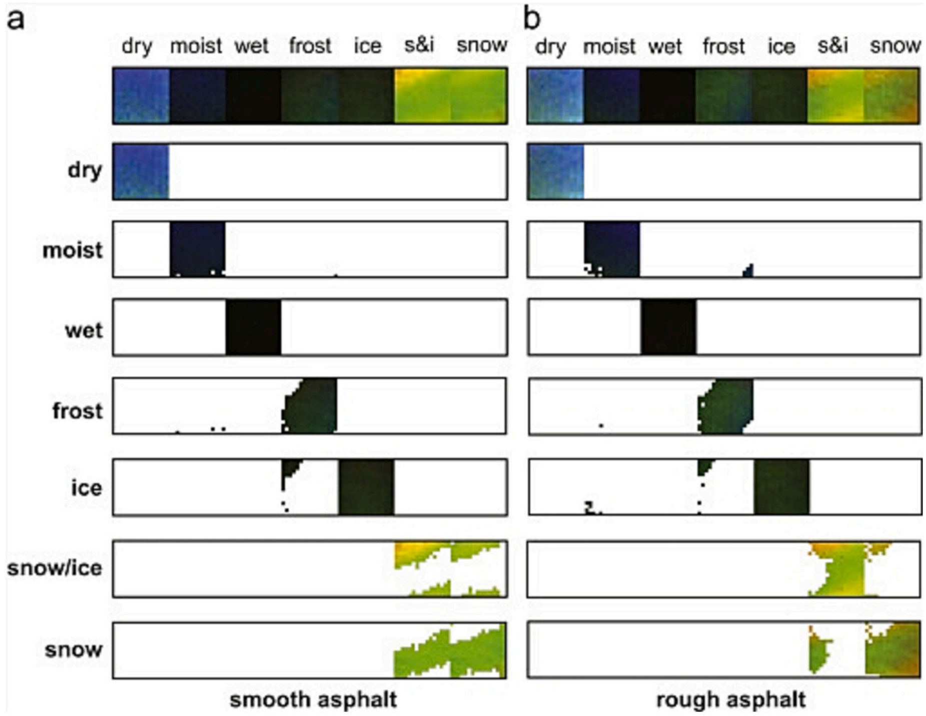

Fig. 6. Different roads conditions visualized after transforming the three NIR wavelength intensity-distribution into RGB values for (a) smooth and (b) rough asphalt. s&i stands for snow on ice (Casselgren et al., 2016).

emitted when supercooled water droplets hit the leading edges of blades. They also proposed a possible location to install infrared camera on helicopter body (Fig. 5). They ran two sets of experiments: In the first set, they experimented on a static, sub-scaled model inside NASA icing wind tunnel, while in the second one, they developed a rotor test rig to study dynamic icing during rotation. For that they used a single blade counter-balanced rotor with 22 cm span and 2 cm chord length. It was viewed by sensitive HgCdTe type cryogenic infrared detector (cooled by thermoelectric cooler). Blade's rotation speed could be varied between 0 Hz – 40 Hz however they conducted experiments at 22 Hz to allow good ice formation. Temperature profiles of uniced blade were measured followed by glaze iced blade profiles at different angles of attack and temperature conditions. Suitable placement of ice detector on helicopter, signal processing with high Signal-to-Noise Ratio (SNR), and blade flapping and bending are some peculiar implementation issues pointed out by them.

Richter et al. (Richter and Schulein, 2014; Richter et al., 2016) did not use IRT to detect icing however their insights regarding the use of High-Speed Infrared (HSIR) camera (IRCAM® EQUUS 327 k L – *MCT detector*) for transition detection on Mach-scaled Eurocopter BO105 and EC135 may be useful for planning icing studies. They recommended the use of cryogenically cooled thermal camera with photon detectors exhibiting shorter exposure time for HSIR thermography. In case of uncooled bolometric cameras, they need to be mounted on the same rotating shaft as the main rotor. The transition detection method they proposed allows the identification of defects, anomalies or laminar-turbulent boundary layer characteristics. They demonstrated that this transition detection is possible based on a single instantaneous thermal image of the rotating blade of helicopter. The results correlated well with numerical simulation results.

5.2. Transportation

Riehm et al. (Riehm et al., 2012) used Long Wave Infrared (LWIR) thermometer to detect ice formation on roads due to wet road surface or ice crystals deposition. They conducted experiments both in the cold climate laboratory (on a piece of asphalt road with embedded Peltier element), as well as in field. Casselgren et al. (Casselgren et al., 2016) modifies the work to distinguish between dry, moist, wet, frosty, icy and snowy road surfaces using NIR camera system (FLIR® SC7100). They performed lab experiments on asphalt road pieces by illuminating the scene with three NIR wavelengths (980 nm, 1310 nm, 1550 nm) and replicated the disturbance from sun using a 200 W halogen lamp. They transformed the calibrated intensity distribution values from these 3 wavelengths into RGB values to classify different road conditions in true colors. From these RGB values they calculated the average and standard deviation in R, G and B channels for each surface type, and then employed k-means clustering with Euclidean distance metric to segregate pixels for these seven environmental conditions on both smooth and rough asphalt. However, they faced the most difficulty in separating snowy surface from the surface with both snow on ice (s&i). The reason they mentioned is a striking resemblance between white color for snow and ice, due to which they appear close enough within Euclidean space (Fig. 6).

Severe icing on railway tracks can cause railway turnouts (junctions) to be blocked. Turnouts are the points where electric heating elements are installed to mitigate icing, however sometimes they malfunction while covered with ice and railway traffic has to be stopped for time-consuming inspection. Stypułkowski et al. (Stypulkowski et al., 2021) performed infrared thermographic analysis with CCTV thermal camera (FLIR SC660) from the perspective of manual analysis and early fault detection. The camera snapped images in both true-color and thermal IR mode, after which infrared images were subjected to temperature level normalization and isotherm mapping. Mapping the area of interest as an isotherm segregated the pixels information into *relevant* and *irrelevant data*. This allowed to decrease the image resolution by discarding the irrelevant data and only applying the assessment algorithm on useful pixels. The processed and downsized thermal images besides historic thermograms, expert analysis, historical inspection data, meteorological data and safety parameters were fed into a proposed machine learning framework (Support Vector Machine – SVM) for damage detection.

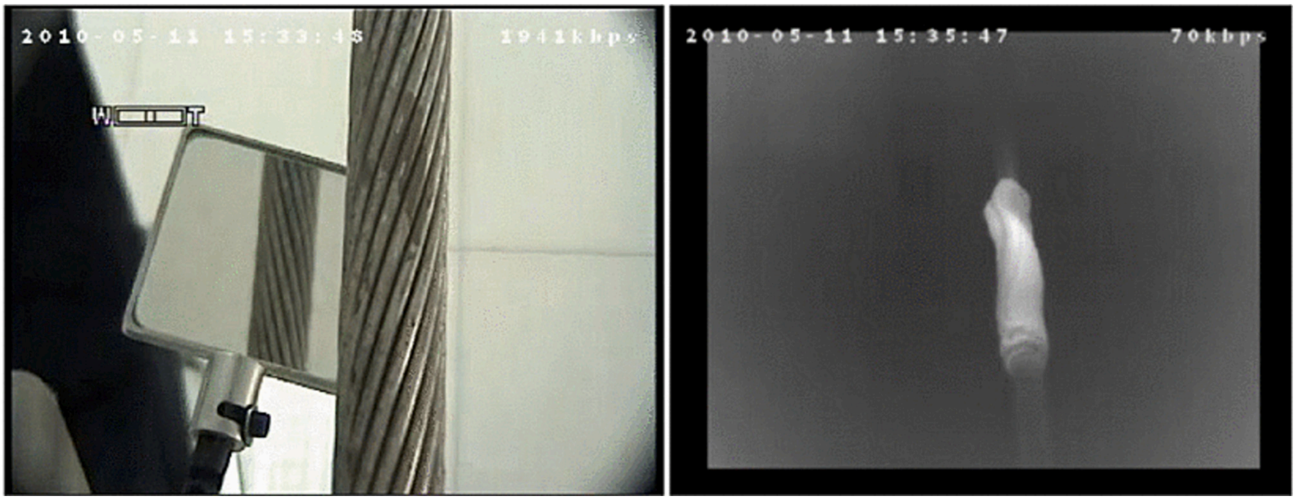

Fig. 7. True-color and infrared mages obtained during iced line inspection (Zhang et al., 2013).

5.3. Power lines

Zhang et al. (Zhang et al., 2013) presented the applications of remote-controlled mobile robot LineROVer for de-icing overhead power lines. The robot is supported by visual and infrared inspection and is installed at ice-prone networks (Fig. 7) (Li et al., 2016). They used Coded Orthogonal Frequency Division Multiplexing (COFDM) technology for wireless image transmission to ground station. The technology divides a single digital signal across multiple signal carriers simultaneously which are transmitted at right angles to each other using an omnidirectional antenna to prevent interference. Transmitted imagery allows operators to maneuver the robot as required. As a de-icing system, the robot employs a sharp ice cutting tool which crushes the ice into tiny pieces and clears the line passage for robot to move forward.

Overhead power lines are usually modelled with rotating or non-rotating cylinders assembly for laboratory experiments on analysis as per ISO-12494. Attempts have been made to study it using infrared thermography (alongside other techniques). Madi et al. (Madi et al., 2021) investigated the diameter of single and a group of frozen water droplets using image processing on thermal visuals. This way they determined the volume occupied by these droplets while impacting on a hydrophilic surface. They also proposed that sequential thermal images can help track the build-up of ice on the leading edge, and similarly trace the de-icing process if electro-thermal heating system is activated.

Veerakumar (Veerakumar, 2021) conducted a study on ice accretion on power lines using IRT in conjunction with plasma-based ice mitigation system. He prepared a model of power line conductor by first covering its surface by 100 μm thick copper film followed by dielectric insulation and then wrapped over by 3 mm wide copper tape as ground electrode. He used FLIR A615 thermal IR camera to instantaneously monitor surface temperatures when plasma was activated for 360 s and found the direct relation of temperature rise to plasma ON time.

5.4. Renewable energy (Wind Turbines)

Ice accumulation changes turbine's blade surface roughness, increase air resistance and hence affects the aerodynamic capacity of the blade (Wei et al., 2020). Most of the icing study performed with IRT on wind turbines includes lab experimentation. Mohseni et al. (Mohseni et al., 2012) examined icing with A320 thermal infrared camera on composite airfoils inserted in Aluminium NACA0021 frame with embedded electrothermal heating elements. They processed thermal IR video snapshots in Thermo Vision ExaminIR software and then on MATLAB® to remove noise using median filter and improved contrast with histogram equalization. In order to detect ice edges, they used Roberts, Canny and Sobel gradient operators and assessed that Sobel operator detects ice boundary much better in noisy IR images while Roberts operator being sensitive to noise, and the Canny operator detecting both the strong and weak edges, could not produce a clean edge from noisy IR images. They determined the major icing boundaries however small traces of ice were ignored.

Muñoz et al. (Muñoz et al., 2016) carried out experiments on a section of wind turbine blade using thermal infrared radiometry. They evaluated different scenarios of no ice, thin ice, thick ice and partial ice-covered regions on the white fiberglass turbine blade embedded with thermocouples. They also simulated the effect of surface dust accumulation on IRT measurements. Yousuf et al., 2021 studied ice accretion on wind turbine blades using FLIR® A615 thermal infrared camera to analyze the effect of liquid water content, angle of attack, temperature and blades profile geometry on ice formation.

Liu and Hu (Liu and Hu, 2018) studied the effect of *dynamic* dry-ice and wet ice with FLIR® A615 thermal IR camera (with FLIR-IRW-4C transmission window – efficiency 0.82) in an Icing Research Tunnel (IRT) for NACA0012 airfoil and deduced unsteady heat transfer equation in terms of convective heat transfer coefficient, impinging velocity and Liquid Water Content (LWC) for both the cases as a part of theoretical model. Gao et al. (Gao et al., 2019b) used FLIR® A615 thermal imaging camera on dynamic glaze, rime and mixed ice covered wind turbine blade DU96-W-180 for constant ambient temperature of −10 °C & three varying LWC (0.3 gm^{-3}; 1.1 gm^{3};3 gm^{3}) for corresponding ice type.

When it comes to fast rotating wind turbines, cooled thermal IR camera is proposed in literature for its advantages of high sensitivity; suitable for fast-moving objects. Another significant parameter to look for is shorter integration time (against a popular concept of camera 'framerate'). Knisely et al. (Knisely et al., 2021) performed a detailed literature review in this regard. They did not particularly study icing however they addressed the challenges faced by thermal IR detectors to analyze spatially resolved rotating blade temperatures in gas turbines for film cooling. They employed commercial Sofradir® MiTIE MARS LWIR camera with HgCdTe detector – a highly sensitive detector for fast-moving objects. They discussed the importance of shorter integration times for fast rotating gas turbine blades (11,000 rpm) and presented its effect on image quality. They performed tests at selected integration times between 1 μs - 10 μs and stated that trade off exists between motion blur and spatial noise. At shorter integration time, spatial noise becomes apparent in the form of granular pixels and if in order to improve it the number of averaged IR images is increased, vertical stripes appear in images snapped at low integration time due to camera's Noise Equivalent Thermal Difference (NETD). At higher integration

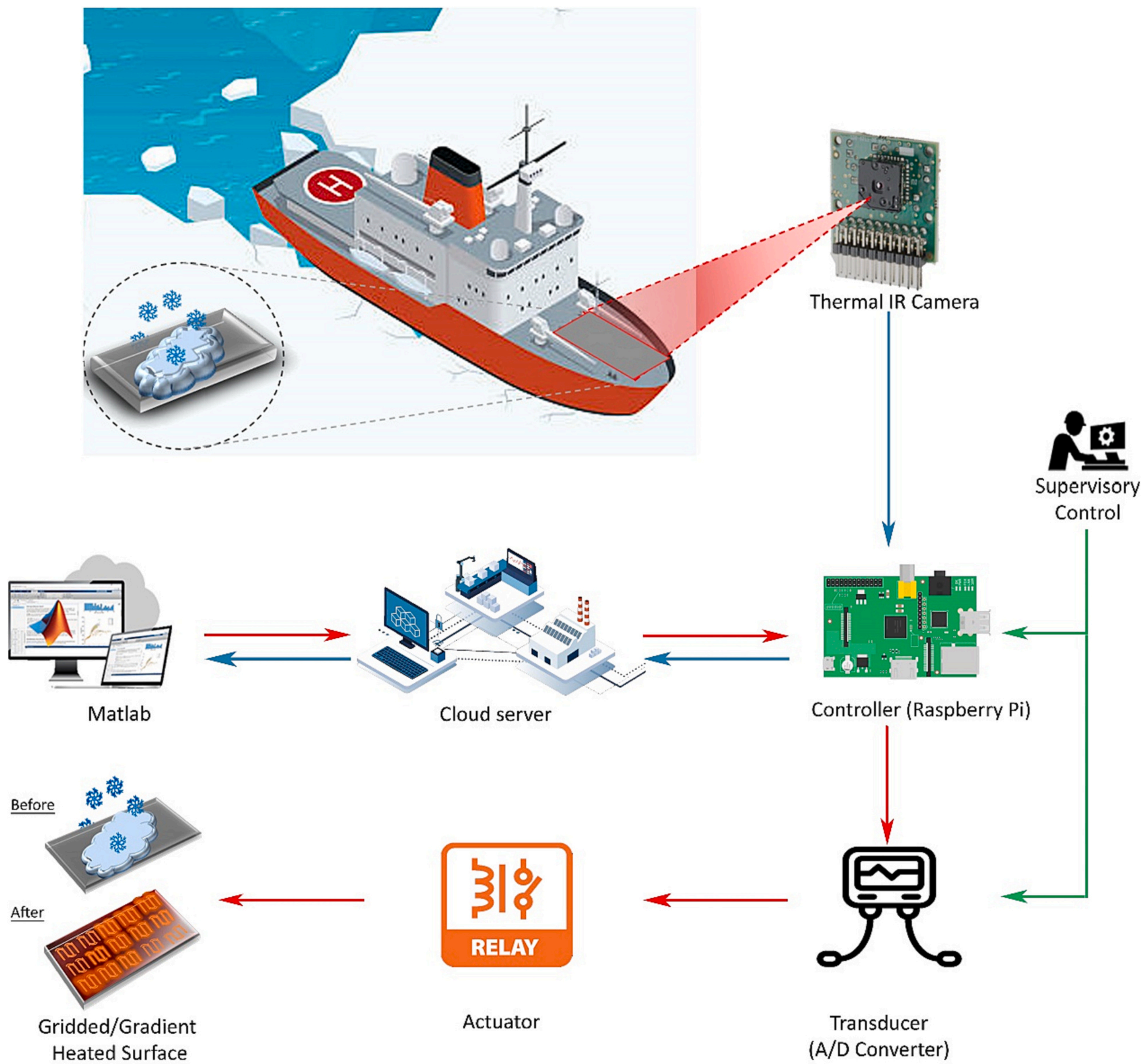

Fig. 8. Conceptual design of proposed ice detection and mitigation system (Yousuf et al., 2023).

times thermal IR images possess low noise but increased motion blur. An optimal integration time balances both the spatial noise and motion blur to achieve reduced local errors in temperature measurements.

5.5. Offshore operations

Light et al. (Light et al., 2012) used handheld FLIR® T640 camera to capture ice conditions around the lake side environment. They filtered noise in the images using multiple median filters and then clustered the image data with k-means. Same pixel values are grouped together which indicates the presence of ice for those pixel locations in filtered images.

Literature review also suggests that it is possible to differentiate between fresh water and marine ice through IRT (Andleeb et al., 2020; Rashid et al., 2016b). Experiments were conducted by Rashid et al. (Rashid et al., 2016b) to determine the thermal conductivity and overall heat-transfer coefficients of freshwater and marine ice-blocks using FLIR® A310 IR camera. Then these values were used as input within the Multiphysics simulation tool with surrounding temperature as boundary conditions to create and verify temperature profiles (Rashid et al., 2015; Rashid et al., 2016c; Rashid et al., 2016d). Marine ice thickness is determined using active thermography by Rashid et al. (Rashid et al., 2019). They determined that the rate of change in the surface temperature of ice, as measured from an LWIR camera, decreases with ice thickness. Moreover, it correlates with the initial temperature of ice. In another study Rashid et al. (Rashid, 2018; Rashid et al., 2021) also tested carbon nano-tubes (CNT) as an electrothermal coating material (*also called 'CNT ink'*) for marine applications during icing operation. They developed the film heater on poly-ethylene terephthalate (PET) sheet using roll-to-roll (R2R) slot-die process and examined qualitative and quantitative aspects (including heater's electrical resistance and thermal map) using FLIR® T1030SC IR camera. The analysis explained Ohmic conducting properties of film owing to its proportional voltage-current curve. They performed experiments both outdoors and inside cold room, and proposed that similar procedure can be replicated to anti-ice/deice ship deck, railings, pathways or other exposed surfaces. However, further research needs to be performed in this regards for feasibility studies (Rashid et al., 2021).

Fazelpour et al. (Fazelpour et al., 2016) proposed using both true color and thermal infrared cameras for measuring marine ice thickness. They compared the color and grayscale image output from both types of

Table 1
Ice detection and mitigation techniques under research/implementation on different infrastructure prone to icing in cold climates.

Field (Application)	Ice Detection Technique	Ice Mitigation Technique	Remarks
Aviation (Aircrafts)	Vibrating probe, ultrasonic, capacitive, impedance sensor, microwave absorption, optical fiber sensor (Ge et al., 2022), Polarized light reflection (Grishaev et al., 2022), Echo-pulse systems, Radio frequency ice detection	Electro-Impulse De-Icing (EIDI) (Hao et al., 2020; Henderson and Schrag, 1986), Infrared de-icing (Koenig and Ryerson, 2011), Plasma based actuators (Liu et al., 2019; Kolbakir et al., 2020), Pneumatic boots (Collins Aerospace, 2023), Pulse Electro Thermal De-icing (PETD) (Petrenko et al., 2011)	IRT has been only tested with EIDI system to study dynamic ice accretion on airfoil model. It has not been used in practice on commercial/declassified military planes.
Aviation (Helicopters)	Optical/particle beam occultation/occlusion (Jackson and Goldberg, 2007), Accelerometer (Villeneuve et al., 2021)	Hydrophobic/icephobic coatings with electrothermal anti-icing (Samad et al., 2021)	Passive IRT as an ice detection technique is applied to study the impingement of supercooled water droplets on static as well as rotating propeller rig (Dershowitz and Hansmm, 1991; Dershowitz, 1991). High Speed Infrared (HSIR) Thermography has been applied on rotating propellers of Eurocopter BO105 and EC135 but not studied for icing (Richter and Schulein, 2014; Richter et al., 2016). By combining the IR detection methodology used by them with hybrid approach adopted by (Villeneuve et al., 2021; Samad et al., 2021) for ice-mitigation, an IRT based ice protection system can be designed.
Aquaculture (Fish Farms)	Visual inspection	Ice melting aeration or Bubble Tubing® (Bubble Tubing, 2023), hitting with rubber/wooden mallets	Suitable literature could not be found to detect icing on fish-farms using IRT. Note that for marine life and health concerns, salts or hydrophobic sprays cannot be used on fish-farms.
Energy (Dams)	No data available	Ice melting aeration or Bubble Tubing® (Bubble Tubing, 2023)	
Energy (Power Lines)	Ultrasonic damping (Wei et al., 2020), Microwave (Mughal and Virk, 2014; Madi et al., 2019) (Kabardin et al., 2021), Visual imagery (Kreutza et al., 2020), Electro-thermally heated slip rings (MOOG, 2022), IR spectroscopy, Optical reflectometry, structured lightning, capacitance, impedance sensor (Kabardin et al., 2021; Roberge et al., 2018), piezo-electric, hot-wire method, thermistors (Jackson and Goldberg, 2007; Struk et al., 2014), dewpoint/RH/droplets MVD measurement (Wei et al., 2020; Madi et al., 2019), visibility of cloud base height, double anemometer technique (based on wind velocity measurement), noise detection (for moving blades) (Virk et al., 2011; Wei et al., 2020; Madi et al., 2019), IR thermography (Madi et al., 2021)	Power line ice-shedder (Nourai and Hayes, 2003), High frequency and high voltage excitation (Sullivan et al., 2003), Shockwave, Thermal methods (utilizing Joule heating and dielectric losses), Phase shifting transformer de-icing (Solangi, 2018)	Robotic systems supported by IR and visual cameras have been tested in the field.
Energy (Wind Turbines)	Mathematical model based ice detection (Shi, 2017), Electrostatic (capacitive) sensor array (Elzaidi et al., 2021), Ultrasonic sensors and blade based methods (Cattin and Heikkilä, 2016), RGB imagery combined with Convolutional Neural Networks (CNN) (Kreutza et al., 2020), Vibration sensors (Weijtjens et al., 2018)	Di-electric Barrier Discharge (DBD) plasma (Abdollahzadeh et al., 2020; Hu et al., 2022), Hot air circulation (Enercon, Vestas)/ Integrated electrothermal heating elements in the blades (Siemens, Nordex, VTT)/ Bladeshield anti-icing paint (Gamesa) (E. IQ, n.d.)	Laboratory based assessment regarding application of IRT for rotating wind turbine blades exist using cooled infrared camera. Experimentation on actual wind farm could not be found in literature.
Marine (Boats/ Ships)	Electrostatic (capacitive) sensor array (Elzaidi et al., 2021)	Rock Salt (NaCl), Calcium Chloride, Urea, Ethylene Glycol, Methanol and other alcohols (Guest, 2005), Magnesium Chloride, Calcium Magnesium Acetate, Potassium Acetate, Potassium Formate, Sodium Acetate and Sodium Formate (Rashid et al., 2016a), Ship's hydrodynamic and aerodynamic design to repel wave- and wind-induced sea spray (Zhou et al., 2022)	Since IRT is found to be useful in distinguishing marine ice (Rashid et al., 2015) provided that an excitation source is available, it can be accompanied with electrothermal system along-with conventional anti-icing/de-icing strategy.
Marine (Oil Rigs/Gas Platforms)	Visual inspection	Salts, acetates, formates (Rashid et al., 2016a)	*Same as for boats/ships*
Transport (Roads)	LWIR (Riehm et al., 2012) /NIR ice detection (Casselgren et al., 2016), Optical ice detection (Intelligent Vision Systems (IVS), 2023)	Salts and chemicals (Hatamzad et al., 2022a; Hatamzad et al., 2022b)	Using a mini optical camera such as 1MP Omnivision® OV10640 (as presented in (Intelligent Vision Systems (IVS), 2023)) alongwith mini portable FLIR® Lepton LWIR camera can improve the ice detection on roads. The cameras' imagery can be combined with machine-learning techniques expressed in (Hatamzad et al., 2022b) to predict amount of salts used on roads as an ice mitigation technique.
Transport (Bridges)	Ice thickness and other meteorological condition monitors	Electro-mechanical Expulsion De-icing Systems (EMEDS), Electro Impulsive De-Icing (EIDI), Hot air, chemical coatings, sprays and salts (Sodium chloride, calcium chloride, magnesium chloride,	Infrared thermography is currently being used as a non-destructive testing technique for delamination in bridges which is caused by freezing snow, corrosion, and interaction of chloride ions from de-

(*continued on next page*)

Table 1 (*continued*)

Field (Application)	Ice Detection Technique	Ice Mitigation Technique	Remarks
		potassium acetate) (Kleissl and Georgakis, 2010; Matejicka and Georgakis, 2022; Virginia Department of Transportation, n.d.; Selingo, 2001), Geothermal heating (for bridge decks) (Habibzadeh-Bigdarvish et al., 2021)	icing fluids with concrete bridges (Omer and Nehdi, 2016; Janků et al., 2019; Omar et al., 2018). However direct detection of ice on bridge decks or cables has not been studied through infrared cameras.
Transport (Railway)	Visual inspection, meteorological conditions, IR ice detection and machine learning on infrared images (Stypulkowski et al., 2021)	Electro-thermal resistive heating, inductive heating (Zelazny et al., 2021), Running 'ghost trains' – empty overnight train to keep tracks clear (a costly method) (Rail Safety and Standards Board (RSSB), 2022), Salts, acetates and formate (Association of Train Operating Companies (ATOC), 2006)	IR ice detection on Polish railway turnouts exists as a proof of concept (Stypulkowski et al., 2021). It may be combined with induction heating (Zelazny et al., 2021) or (pulsed) electrothermal

cameras and applied thresholding operations and morphological algorithms. Fazelpour (Fazelpour, 2017) studied the impact of marine ice droplets with 0%, 20% and 35% salinity, striking cold surfaces at −15 °C and − 25 °C and used recorded images and videos from FLIR® SC700 to analyze freezing point and freezing fraction of accreted droplets. The work also discusses thermal imaging results for an iced structure at different camera heights and angle of view with multiple known ice masses. With this, they estimated the quantity of ice accreted on structure through image processing and commented on the overestimation and underestimation of ice-mass when viewed from various angles.

For maritime applications IRT also provides an insight for ships, tugboats and other marine vessels, to check for the weakening spots in the wire strands of on-board cranes and mooring equipment arising due to adverse weather conditions in cold regions (Handlin).

One of the most significant challenges in IRT research is the expensive operational setup and equipment, particularly the infrared camera. The heavy cost hinders field study of icing on structures as it adds to the maintenance costs of camera in case of mishap or malfunction. Yousuf et al., 2023 addressed this issue by conducting laboratory experiment to detect ice *via* an expensive FLIR® T1030SC camera and a low-end FLIR® Lepton on-chip camera. The former one offers resolution of 1024×768 and is priced at approx. $50,000, whereas the later one has resolution of 80×60 costing around $250. Qualitative analysis revealed that although T1030SC excelled from accuracy point of view, however when it comes to ice detection, even the low-cost Lepton performed the job. These promising results paved a way to present a cost-effective design of an ice detection system for structures based on infrared thermography (Fig. 8). This design system comprises of FLIR® Lepton LWIR camera focusing the susceptible to atmospheric or marine ice formation. Snapped IR images shall be sent to controller for processing and based on the decision (ice/no ice), it will send signals to energize/de-energize the relays for heating only at the locations where ice is detected. For this, a gridded heating surface is proposed that can attain a gradient heating pattern. For research phase, remote image processing shall also be incorporated into the system. In this setup the controller shall send captured images to a cloud server from where they can be downloaded through an image processing software such as MathWorks® MATLAB. Additionally, the inclusion of supervisory control for emergency operations ensures the overall system's reliability and fail-safe operation.

6. Summary

The conducted literature review regarding infrared thermography applications can be combined with the available ice mitigation techniques and currently used ice detection methods.

Table 1 below summarizes them in tabular format. Since there are only a few instances of research work available in which IRT has been specifically applied as an ice detection technique against an ice mitigation method, comments and critical opinion is also added to mark research gaps.

7. Conclusion

Adverse weather conditions and prolonged icing in the cold regions raises a new set of challenges resulting in the malfunctioning of sophisticated equipment. Different ice mitigation techniques are used based upon application. Many researchers suggest using a hybrid approach in this regard *i.e.,* using both active and passive techniques. For the design of an autonomous system, there is a need to integrate ice detection methodology. Industrial and technological revolution especially in semiconductor research and photolithography have widened the arena of thermal IR applications. Since IRT provides 2D thermal images, it makes comparisons in a wide target area possible. This is advantageous against thermistor, pyrometers, thermocouples, capacitive, inductive and other thermal sensors which provide measurement at a single point on surface. Moreover, thermal detection does not involve any retrofitting in the current design of target surface, unlike some other techniques such as microwave or ultrasonic.

Infrared thermography can be used in a wide range of applications involving the study of static and dynamic icing, as reflected from literature review. It presents itself as an effective tool for risk assessment, component failure and device malfunction due to ice. A wide area coverage also enables infrared thermography to be used at locations beyond human reach or where the installment of other detectors becomes risky or uneconomical.

Based on the conclusive findings from the laboratory experiments detailed in this article, there is compelling evidence to support the deployment of an Ice Detection System utilizing infrared thermography for on-field analysis. Combining an ice detection system based on infrared thermography with an application-dependent suitable ice mitigation system has a potential to evolve into an automated, reliable, and economically feasible ice protection system. Such a system presents a valuable solution for addressing winterization challenges at remote locations where round the clock operator's presence cannot be made possible due to the associated risks or non-availability of permanent logistic support.

Declaration of Competing Interest

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Data availability

No data was used for the research described in the article.

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