ICE SENSING TECHNOLOGIES WITH APPLICATIONS IN AUGMENTED SITUATIONAL AWARENESS

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SUMMARY

This paper contains an overview of technologies employed in the scientific literature to provide data on ice severity to augment situational awareness of human operators (aboard a ship or in a remote control centre). As ships navigate in ice, masters use a wide source of information to assess the ice conditions along their planned route. This information is used to make ongoing assessments of the ice severity and to decide how to optimise the route to avoid damage to the ship and the ship becoming stuck in the ice. Typically, this assessment is made by the officers in charge of the ship based on observations, experience, and metocean publications such as weather forecasts and ice charts. Significant levels of experience are needed to safely assess and navigate in complex or severe ice conditions. A fundamental challenge in allowing autonomy or decision-support for navigation of ice-covered waters is providing accurate and relevant ice severity data that feeds decision-making. It is expected that this can be achieved with a carefully selected set of ship-mounted sensors.

1. INTRODUCTION

Much of the content of this paper was originally presented as two papers at the RINA Smart Ship Technology Conference, 2020.

The goal of this paper is to present a review of technologies that may be used to provide situational awareness for navigating ships in ice-covered waters. A suite of relevant sensors to achieve this situational awareness is also proposed. Such a sensor suite is envisioned as an integral part of a decision support system and eventual autonomous ship navigation in ice since assessing ice conditions and integrating that information into routing and navigational decisions is vital to safe and efficient operation. In order to fulfil this objective, the sensor suite must be able to provide both tactical-level information (to allow routing decisions on the scale of hours to days) and operational-level information (to allow navigational decisions on the scale of seconds to minutes). To do this, up-to-date information on the ice severity along a ship's routing options is needed, allowing the master or autonomous autopilot to plot a course that optimises ice severity and distance travelled to keep risk of damage or besetting within acceptable levels.

This paper is intended for readers who are not familiar with data sources used in ice forecasting, operational ice forecasting products, or arctic shipping risk assessment. The information in this paper will be already well understood by people trained in the relevant disciplines. I hope that the information will provide useful for people outside their regular discipline and potentially provide some insights.

2. PROBLEM DESCRIPTION

Navigating in ice-covered waters presents complications for ship navigation. In addition to the risks of structural damage and possible loss of the ship, ships mat become beset by ice and require rescue (Fu, et al., 2016; Montewka, et al., 2015; Kubat, et al., 2016; Turnbull, et al., 2019; Vanhalto, et al., 2021). In some cases, besetting can pose a risk to crew and cargo even if there is no structural damage to the ship, if the duration of the besetting exceeds the supplies aboard the ship. Despite these risks, there is increasing activity in ice-covered waters, driven by resource exploration and increased opportunities for trans-arctic shipping. Current practices rely on the training and experience of the ships' masters and an array of forecasting tools to avoid conditions that may result in damage to the ship or besetting (Veitch, et al., 2019). Even with increasing automation, humans are expected to be a vital part of navigational decision making for ships for the near future, particularly in areas of increased complexity and risk such as ice-covered waters (Parasurman & Wickens, 2008; Maritime Safety Committee, 2021). While full automation may come, human decision makers will benefit from information that allows them to make better, more informed decisions.

This paper contains an overview of current technologies described in the scientific literature but does not hope to discuss any one of them in technical detail. The goal is to provide enough description to understand the strengths of the various techniques and how they may fit together to provide a complete picture. Many diverse technologies have been used to measure and observe ice for scientific purposes. Taken together, the various techniques promise a formidable battery of ice observations that can assist mariners and eventually autonomous ships in forming an understanding of ice conditions along their route.

In order to estimate the severity of ice confronting a vessel, measurement of the following ice properties is desired: *Thickness*, *Strength*, *Concentration*, *Composition (snow, rubble, brash, ridging, refrozen rubble, first year, multi-year, etc.)*, *Piece size (dimensions and mass)*, and *Pressure*.

2.1 RISK ASSESSMENT & NAVIGATION

Several risk assessment tools exist for ships operating in ice-covered waters, including the Arctic Ice Regime Shipping System (AIRSS) published by Transport Canada and The Polar Operational Limit Assessment Risk Indexing System (POLARIS), published by IMO. Since POLARIS is internationally applicable, it will be discussed in more detail. POLARIS is not mandatory or prescriptive, intended rather as a decision support tool. Under POLARIS, ships are assessed based on their ice capability and assigned a Risk Index Value (RIV). Levels of ice capability, in descending order, include "Polar Class" 1 thru 7, "1A Super", "1A", "1B", and "1C", based on the IACS Polar Class and the Finnish-Swedish Ice Class. The ship category is compared to ice conditions defined according to the World Meteorological Organization nomenclature as used for international ice charts, ice regime, and state of decay. The RIV is compared to the ice conditions to compute a Risk Index Outcome (RIO), which is then used to assess risk as "Normal Operation", "Elevated Operational Risk", or "Operation Subject to Special Consideration" (lower RIOs indicating higher risk). The higher two risk assessments may result in restrictions to operation such as limited speed, more rigorous watchkeeping, or icebreaker support. Rather than a prohibition, ships' masters are given discretion to operate in the highest risk level. The result of a risk evaluation under AIRSS is the "Ice Numeral" which is analogous to the RIV. (Fedi, et al., 2018)

2.2 PROPOSED APPROACH TO SITUATIONAL AWARENESS

The proposed goal is to provide a map of ice severity covering the operational and tactical timescales. At its most basic, this map could be based on a simple numeric scale such as POLARIS, which would allow a comparison of options based on the expected risk of structural damage along a route. At the operational timescale, detail such as estimates of the properties of individual ice pieces is expected to be required. Ice severity overlaid on a marine chart for interpretation by mariners is in-line with current ice chart formats and can be converted into a set of regions of graded severity based on a metric such as the POLARIS RIV or AIRSS Ice Numeral, similar to that shown in Figure 1, from (Kubat, et al., 2017). In Figure 1, an alternate route has been identified (dashed line) that provides a lower ice severity (in this case, as estimated using AIRSS) but a longer transit distance. More sophisticated versions could include estimates of besetting risk, required propulsion power, fuel required, etc. This would allow better routing optimization. It would also be possible to include an optimization of risk, including vessel-centric risk as well as broader minimization of life safety, ecological, and socioeconomic risks using a framework similar to that proposed by (Browne, et al., 2020). This approach would account for the very different life safety risks posed by an accident involving a ship with a high number of persons on board compared to a ship with few persons on board. Similarly, the ecological impacts of an accident involving a ship with dangerous cargo would involve a different risk calculation than a ship with less potential to cause ecological damage. Under this type of framework, different types of ships could be routed differently given their different risk profiles. For instance, a ship with dangerous cargo would be routed further from ecologically sensitive areas and ships with high numbers of persons on board would be routed closer to areas with high Search and Rescue capacity.

To provide up-to-data information on current conditions and near- and long-term forecasts, a shared data platform is proposed where data from the various sources is maintained and updated. Multiple ships providing observations of their local conditions collected using an on board ice sensor suite could provide verification of forecasts with a larger number of contributing vessels strengthening the dataset. A proposed framework that includes aggregating data from multiple ships and other sources to be optimised against schedule requirements and the ship-specific risk assessment is shown in Figure 2.

This approach is not entirely novel. A range of data types including weather modelling and satellite observations have been used in previous work to optimise ship routing based on observed and forecast surface current and wind data (Eriksson, et al., 2018). A system with similar goals and principles has been described by (Zhang, et al., 2019).

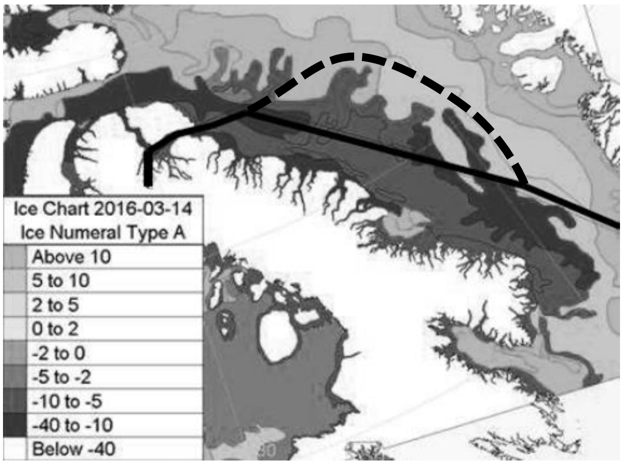

Figure 1. Regions of expected AIRSS Ice Number with proposed route overlaid, allowing along-route risk assessment. From Kubat et. al. (Canadian Arctic Shipping Risk Assessment System, 2017), with alternate (dashed) route added.

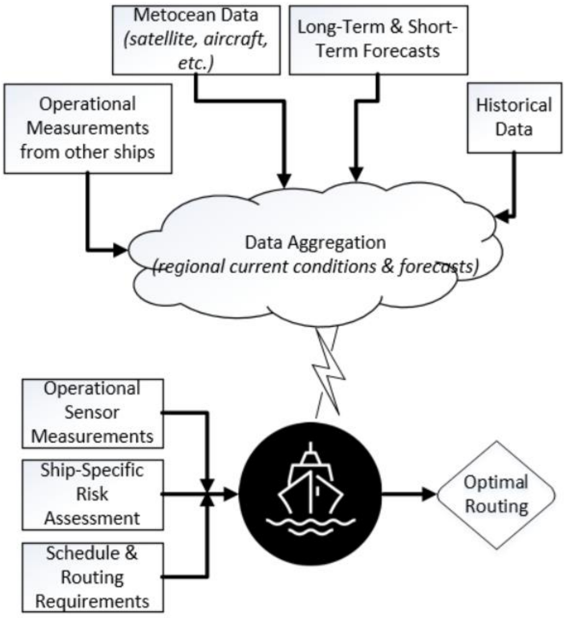

Figure 2. Proposed tactical information model.

3. TRADITIONAL ICE MEASUREMENTS

There is a significant body of literature concerning the measurement of ice properties. Largely, these measurements are labour intensive and require dedicated time and resources with the data analyzed after the fact. We must, therefore draw a clear distinction between measurements made for research purposes and those suitable for navigational decision making. The former may involve stopping the ship to retrieve samples and analyzing data after the fact with the goal of obtaining high-precision measurements. The latter must be made while the ship is under way with the data processed in a timeframe that preserves it relevance. For navigation, the precision of the measurements must be sufficient to allow accurate assessment of risk but may not involve precise measurement of individual ice properties. A discussion of the relevant scientific techniques, however, lays the foundation for automating and expediting these measurements.

3.1 THICKNESS MEASUREMENTS

The first category of thickness measurements typically involves stopping the ship and placing people and/or equipment on the ice to drill through the ice. Common methods include drilling a series of holes along the intended route for the ship to measure centreline thickness of the track. Another common technique involves sensors such as ground-penetrating radar dragged on sleds along specific patches of unbroken ice (ie, intended routes) to profile continuous ice thickness along a single path (Jones, et al., 2001).

Over the Side Video (OTSV) is a technique that involves nadir-oriented video cameras located at the bow shoulders of an icebreaking vessel. This location provides the cameras with a view of the edge of broken ice pieces as they surface edge-on alongside the ship. This technique has been used extensively and, recently, has been greatly aided by the proliferation of cheap, readily available GPS-enabled video cameras. In concept, it is similar to visual techniques used to assess ice thickness but adds the benefit of providing an ongoing record. In studies with comprehensive complimentary borehole thickness measurements, OTSV showed good correlation of ice thickness with the borehole measurements while having less success with snow thickness measurement. OTSV has been more successful in first-year ice and, notionally, is expected to be more successful when ice thickness is small compared to broken piece size. It has been used successfully in pack ice and in level ice. (Canadian Ice Service, 2005; Garvin, 2016)

3.2 STRENGTH MEASUREMENTS

Traditional icebreaking hull designs are shaped to break ice in flexure so much of the research on ice strength as it relates to ship navigation has focused on flexural strength. Modern ice-going hull forms tend to have bow shapes that promote flexural ice failure even while changes to allow incorporation of podded propulsion have necessitated changes to stern shapes that are less likely to promote flexural ice failure. For ships moving forwards (as opposed to operations such as tight manoeuvring, ice management, etc.), flexural strength will likely continue to be the most important component of ice strength for most ice-capable ship designs.

While not without its imperfections, the in-situ cantilever test is a widely used and reliable method of measuring ice flexural strength both in the field and in a laboratory environment. In the field, these tests present a significant logistical challenge as the beam sections must be sawn out of pieces of level ice and significant equipment must be placed on the ice to apply load and measure deflection. (Frederking & Hausler, 1978)

Ice strength can be estimated from core samples by applying empirical relationships between temperature, salinity, density, and flexural strength. Immediately following the retrieval of a core, the temperature in the center of the core can be measured at intervals along its length, giving a good indication of the temperature profile through the thickness of the ice. Density is measured by measuring the force required to submerge a piece of ice in fresh water. Puck-shaped pieces are normally cut from locations along the length of the core to provide measurements of density through the thickness of the ice. Lastly, samples from the core are melted and their salinity checked. Measuring salinity of samples from a range of locations within the core allows the assessment of salinity through the thickness of the ice. Brine volume is calculated from Temperature, Density, and Salinity, using the relationship in Cox & Weeks (1982). The flexural strength is then calculated using the relationship in Timco & O'Brien (1994).

3.3 CONCENTRATION & PIECE SIZE MEASUREMENTS

Operational shipboard concentration and piece size measurements are typically made visually from the bridge of the vessel. Where possible, this information is supplemented by aerial photography and radar data, either from independent aircraft flyovers or from balloons or drones accompanying the ship. Traditionally, these images and data have been interpreted by ice specialists or crew members aboard the ship. (Canadian Ice Service, 2005)

3.4 PRESSURE MEASUREMENTS

Pressure fields within high-concentration pack ice derive from environmental forces such as wind and current shear and thermal strain. Ice pressure fields result when environmental forces push sea ice against a fixed boundary such as a shoreline. Floes contact their neighbors and form a “lattice” that allows pressure to build, particularly in the ice field near the fixed boundary. If this pressure exceeds the ability of the weakest ice floes to withstand it, the pack ice can fail, resulting in ridging and/or rafting of floes until a sufficiently strong lattice is reestablished. These areas of rafting or ridging pose a threat to shipping as ridges are a major cause of besetting but they are not the only hazard from ice pressure. The forces within the pressured ice lattice can exert extreme forces on ships, leading to besetting and structural damage. A ship passing through an area of pressured ice may sufficiently disturb the lattice to initiate rafting, ridging, or ice pile-ups against the hull. (Kubat, et al., 2015; Kubat, et al., 2016; Turnbull, et al., 2019)

A widely-used operational assessment of relative pack ice pressure is to observe the lead of open water left in the wake of the ship. If the lead remains open, ice pressure is low but if the lead closes tightly behind the ship, ice pressure is high. Experimental evaluations of ice pressure involve mounting stress meters within large ice floes and monitoring them throughout an ice season to detect & measure pressure events. These experiments are difficult and few have been conducted. (Comfort & Ritch, 1990)

3.5 ICE AGE MEASUREMENTS

Since multi- year ice has the potential to be so much thicker and stronger than first-year ice, it is implicated in the vast majority (75%) of incidents involving ship damage in the Canadian Arctic, with severe incidents (“large hole” or “ship sank”) being nearly entirely attributed to multi-year ice (Kubat & Timco, 2003). In particular, small pieces of multi-year ice within larger areas of level or pack ice can be difficult to distinguish and present a hidden threat.

Core sampling allows for through-thickness profiling of salinity and microstructure which, together, form the basis to determine the age of the ice. At a granular level, first-year ice is composed of slender needle-like ice crystals with interspersed brine and air pockets and sometimes solid salt crystals. The entrained brine and salt are a result of the formation process of the ice; as the ice crystals grow, they cannot eliminate all of the salt, trapping pockets of brine and salt crystals between the crystals which are sufficient to prevent further freezing. As temperatures increase, these brine pockets grow, eventually joining and, eventually, allowing brine drainage. If the remaining ice survives until the next winter, new ice will form on the underside as temperatures fall, leading second-year ice to exhibit a structure with low-salinity ice formed in the previous season with higher-salinity new ice below. The old ice is characterized by little if any brine or salt inclusion, described as a columnar grain structure. Multi-year ice is classified by having several of these layers made up of ice that survives the summer with newer ice below. Brine drainage is progressive meaning that the older ice has the least brine and salt inclusion. The grain boundaries are also more rounded/smoothed in older ice. This leads to distinctions that can be made based on the colour of the ice with first-year ice being predominantly white and multi-year ice taking on a turquoise blue colour. Inferences about ice age can also be made by the surface appearance and roughness of floes. As the top surface of the ice is subjected to summer sunlight, melt pools form and, in many cases drain through the ice. This leads to multi-year ice exhibiting an increasing a “hill and dale” appearance with progressively interconnected drainage ponds and channels. The surface roughness of multi-year ice can be distinguished from ridging in first-year ice since the surface roughness is more rounded in multi-year floes. Multi-year floes can often be identified within a mixed ice field by their increased freeboard compared to surrounding younger ice. (Johnston & Timco, 2008; Canadian Ice Service, 2005)

4. TACTICAL ICE SENSING TECHNOLOGIES

Estimating ice conditions that a ship may encounter in the coming hours or days (“tactical ice sensing”) will largely rely on remote sensing since the sensing range of ship-based sensors is limited. Important technologies include a wide range of satellite-based sensors which provide large-area nowcasts, aerial-based sensors which provide more detailed nowcasts, and land and seabed-based sensors which can monitor areas of specific interest. These data sources are currently used in compiling ice charts which are a vital ice navigation tool in use around the world.

4.1 SATELLITE-BASED INFORMATION

Satellites provide an opportunity for large area, frequent monitoring of ice conditions and are ideally applicable to making regional ice measurements. A variety of satellite information that has been used in the scientific literature is described below. For satellites currently operating that provide publicly available data, a link is provided.

There are a number of satellite-based Synthetic Aperture Radar (“SAR”) systems, including The Canadian Space

Agency's RADARSAT series, the European Space Agency's ERS-2 (mission ended 2019), CryoSat-2, & Sentinel-1. CryoSat-2 carries a SAR, complimented by an interferometric radar altimeter which allows precise measurements of the sensor's height above surface (European Space Agency, n.d.). Sentinel-1 carries a c-band SAR with multiple swath widths up to 400 km and resolutions down to 5 m (European Space Agency, n.d.). RADARSAT Constellation is the latest in the range of RADARSAT missions but, launched in June 2019, it has not yet featured in the scientific literature. Its predecessor, RADARSAT-2, carries a SAR with a spatial resolution of 8 - 100 m (50 - 500 km swath widths) providing daily near-global coverage (Canadian Space Agency, 2019). RADARSAT Constellation offers higher resolution, down to 3 m on a 20 km swath. There is significant potential for RADARSAT Constellation's enhanced coverage and expected data on ice extent, density, strength, and age.

In general, SAR excels at providing relatively small-scale, detail information such as floe identification, areas of ridging, and even identification of ice types. RADARSAT-2 and ERS-2 have been used for navigation planning and ice surveillance in near real-time (Vachon, et al., 2000). High resolution images were used to identify ice-covered areas, individual large floes, areas of ridging, and ice age (new ice, nilas, first year ice, multi-year ice) in support of icebreaker-escorted navigation, allowing safer and faster navigation through ice-covered waters (Pettersson, et al., 2000). In this case, the interpretation of the images required human involvement in interpretation but the nature of the mission allowed ground-truthing of the information gathered from the satellite images, showing good agreement. Further work has developed a semi-supervised classification model in a move towards automated interpretation of SAR data from ERS-2, RADARSAT-2, and Sentinel-1. The semi-supervised method was able to identify the presence of sea ice with good reliability from different SAR data sources (Johansson, et al., 2020). Recent developments have suggested good results are possible when using RADARSAT-2 to classify pure multi-year and first-year ice (Komarov & Buehner, 2019).

The US Defense Meteorological Satellite Program ("DMSP") satellites orbit the earth every 101 minutes and provide twice-daily global coverage. While these satellites carry a variety of sensors, the Special Sensor Microwave Imager (SSM/I) is of particular interest. SSM/I is a multi-frequency polarized passive microwave radiometer system that measures microwave brightness temperatures. A more advanced Special Sensor Microwave Image Sounder ("SSMIS") has been put into service. SSM/I and SSMIS provide differentiation between open water, first year ice, and multi-year ice. This differentiation is based on the emissivity differences between types of ice and open water. From this information, it is possible to determine total ice concentration and concentrations of both first-year and multi-year ice with a resolution of 30 x 30 km. Similar data is collected from Advanced SCATerometer (ASCAT) sensors aboard EUMETSAT MetOp satellites and NASA's Advanced Microwave Scanning Radiometer. Compared to SAR, passive radiometers are better suited to providing large-scale ice information such as the identification of ice extent. (Sandven & Johannessen, 1993; NOAA Office of Satellite and Product Operations, 2018)

Polar Operational Environmental Satellites ("POES"), operated by NOAA, provide daily data by making 14 polar orbits daily which, combined with the rotation of the earth provide complete polar coverage. Of particular interest is the Advanced Very High Resolution Radiometer (AVHRR) that allows measurements of surface emissivity with approximately 1 km resolution in the absence of cloud cover. Combined with data from the DMSP SSM/I, POES AVHRR provides complete ice data for ice-covered navigable waters. (NOAA Office of Satellite and Product Operations, 2017; Sandven & Johannessen, 1993)

Many satellite missions also carry visual-spectrum cameras. A near-visible spectrum camera data from China's HJ-1A/B has been used to monitor sea ice coverage based on comparisons of reflectance between snow, sea ice, and open water but has not successfully been able to distinguish multi-year ice (Zheng, et al., 2014). Similar capabilities are offered by the MODerate-resolution Imaging Spectro-radiometer ("MODIS") instruments on NASA's Earth Observing satellites.

Satellite data is widely used by meteorologists but does have limitations. Atmospheric conditions can obscure measurements and sea temperature variations such as pooled melt water can result in misleading data. This potential ambiguity is a barrier to the widespread operational use of satellite data. To help make satellite data more complete and useful, techniques are available to interpolate gaps in the data. (Partington, 2000)

Work has been done to use satellite-based SAR and LIght Detection And Ranging ("LIDAR") data to estimate ice thickness. This is a very enticing prospect due to the large areas that can be covered. Ice, Cloud, and Land Elevation Satellite-2 (ICESat-2), following on from its predecessor ICESat, carries a laser-based precision height measurement instrument that can measure the height and profile of ice sheets, providing an estimate of thickness. Current methods rely on assumptions about ice density to translate freeboard into ice thickness (having difficulty distinguishing between ice and snow-cover, for example) and are difficult to ground-truth (Johnston & Timco, 2008). Satellite-based LIDAR from ICESat has been used to measure the freeboard of sea ice with uncertainties of 7 cm using "tiepoints" of open water to provide a sea-surface height reference (Kwok, et al., 2007). This highlights a limitation of satellite-based thickness measurement in that nearby open water tiepoints, within ±5 km where seas surface height can be assumed constant, are needed to provide a reference (Petty, et al., 2016). ICESat data has been combined with AMSR-E data (a similar technology to SSM/I that is no longer in service) to measure sea ice thickness with an uncertainty of up to ~58 cm (Yi, et al., 2011). This large uncertainty is attributed to measurement uncertainties of the two datasets and assumptions about snow and ice densities. The US National Snow & Ice Data Center provides a dataset of sea ice freeboard and thickness based on combined data from GLAS and the SSM/I but it is expected that the uncertainty in this data is quite high.

4.2 AERIAL INFORMATION

Aerial ice observation has a wide range of complexity. Even simple visual fly-overs can provide valuable information on the presence and location of leads, floe size, existence of areas of ridging, and information on the degradation and age of the ice (eg. by observation of ponding, drainage, floe shape, etc.) (Johnston & Timco, 2008). A trained observer can discern significant information from aerial photographs that is relevant to navigation and this type of observation is still used, particularly when conditions are not favourable for instrument-based observations. In terms of application, aerial observation is best suited for investigating specific areas of interest to be combined with larger-area satellite based data. Heavily-trafficked near-shore areas are also likely to be investigated using aerial observation which is often used to complement shipboard observations; most Canadian Coast Guard ships operating in ice can access data collected from aircraft to be interpreted by on-board ice specialists (Canadian Ice Service, 2005).

SAR has been used in a number of studies and shown to be capable of providing a wide range of high-resolution (on the order of 15 m) ice information including ice types (first-year, multi-year, Nilas, etc.), floe size, and concentration (Schuchman, et al., 1988; Sandven & Johannessen, 1993). While excellent information can be collected from aerial SAR, the spatial and temporal coverage of such techniques is limited to the swatch of visible from the aircraft as it flies over and the flight endurance of the aircraft. There is potential for this type of technology to be deployed aboard unmanned drones to increase the area that can be covered but this technology is best suited to areas near aircraft infrastructure.

LIDAR has been used in several studies to measure the surface roughness of ice and has been attempted as a method to estimate ice thickness. The applications of LIDAR typically involve measurements of surface topography, which are useful for detecting features such as isolated floes & ridge sails with accuracies of 5 to 25 cm. Rivas et. al. (Rivas, et al., 2006) used a LIDAR-based Airborne Topographical Mapper borne on an aircraft to distinguish between first-year ice and multi-year ice based on the differences in topography discussed above. LIDAR and Airborne Topographical Mapping (ATM) has been used in several studies to measure the surface roughness of ice and has, more recently, been attempted as a method to estimate sea ice thickness. Estimates of freeboard can be made using LIDAR if areas of open water are present to provide a sea level reference. This information is often used to provide an estimate of thickness subject to the large uncertainty driven by assumptions of ice density, etc. discussed above (Forsberg, et al., 2002). NASA’s Operation IceBridge involved an extensive set of aerial missions with a suite of sensors including an ATM (to measure freeboard), snow radar (to measure snow depth), and photogrammetry. This dataset allows for the differentiation between snow and ice cover since the snow depth is directly measured, reducing the uncertainty of the resulting ice freeboard estimates to a vertical accuracy of 6.6 cm and a vertical precision of 3 cm. Still, uncertainty in sea ice thickness (once sources such as ice density were included) ranged from 58 cm to 78 cm for estimated ice thicknesses of 1.77 m to 3.82 m. This includes uncertainties with sea surface height interpolation and unresolvable sensor pitch and roll errors. (Kurtz, et al., 2013; Petty, et al., 2016)

4.3 LAND & SEABED-BASED INFORMATION

In near-shore environments, ground-based radar systems have the ability to track icebergs over significant areas. (Khan, et al., 1994) demonstrated that a high frequency surface wave radar system can track objects including icebergs and sea ice over an area of 160,000 square kilometres. Shore-mounted X-band radar can provide sea ice observation with a shorter range (ice presence, movement, and ridging identification). This type of technology is mature and applicable for shipping routes that pass near shore-based infrastructure such as the St. Lawrence Seaway and the Grand Banks of Newfoundland.

A method of measuring ice, which has become increasingly popular is the use of moored, upward-looking Ice Profiling Sonars (“IPS”) or Upward-Looking Sonar (“ULS”) that measure ice draft as it passes overhead. This method provides a more accurate thickness estimate than above-surface techniques since it is not sensitive to the presence of snow, although accuracy can be affected by the presence of melt water on the ice surface. IPS is often deployed with an Acoustic Current Doppler Profiler (“ADCP”) to estimate velocity of the ice passing overhead, which is a critical measurement in estimating draft from IPS data. With care in the interpretation of the data, including correct estimates of depth-averaged speed of sound, correction of tilt and depth, and beam footprint effects, draft measurement precision of ±0.1 m or better can be achieved. (Shcherbina, et al., 2005; Mahoney, et al., 2015; Ross, et al., 2014)

For level ice, this allows an estimate of thickness in a similar manner to estimating thickness from freeboard and is subject to similar assumptions regarding ice density. Accuracy can be improved if the sensor is periodically presented with regions of open water which provide a confirmation of the “zero” reading. Absent periodic measurements of open water regions or another means of re-zeroing, offsets may be present in the data which is problematic in areas with consistent winter ice cover. Fall and spring periods of open water bounding times of continual ice cover can be used in post-processing data but are less useful for real-time measurement. Roughness of the bottom surface of the ice can also be measured using ADCP and is less impacted by signal drift making ADCPs suitable for detecting areas of ridging within level ice. Sensors combining IPS and ADCP are particularly suited to monitoring ice thickness, ridge keels, and ice movement in frequently travelled ice-covered shipping lanes. (Shcherbina, et al., 2005; Strass, 1998; Birch, et al., 2000)

4.4 FORECAST TOOLS & INFORMATION

A number of forecasting agencies around the world issue ice Charts. In North America, the Canadian Ice Service ("CIS") and the US National Ice Center ("NIC") issue Ice Charts for the ice-covered waters around the northern coasts of North America. A description of how the NIC incorporates Satellite, Aerial, and ground-truthing into their ice forecasts is provided by Partington (2000) but suffice to say that the agencies responsible for producing Ice Charts are active in incorporating the most current available techniques into their forecasts. As such, Ice Charts provide excellent overviews of ice conditions that a ship may encounter and are consequently invaluable tactical route-planning tools. Specifically, products such as satellite SAR imagery are used directly and in near real-time by members of the CIS aboard Canadian Coast Guard ships (Ramsay, et al., 1998). It is important to note, however, that Ice Charts are intended to provide regional forecasts and local conditions may differ; yielding the requirement for on-ship observations.

Ice Charts define regions of roughly consistent ice coverage according to: Total Concentration, Partial Concentration of different ice types present (shown according to their thickness), Stage of Development (eg. new ice, first-year ice, multi-year ice, etc.) of the ice types present, and the form (eg. brash ice, small floe, large floe, fast ice, etc.) of the ice types present. One or a combination of different methods conveys this information, depending on the agency, including the "Ice Egg", symbols, and colour coding overlaid on navigational charts. (Canadian Ice Service, 2016)

A numerical model for forecasting ice pressure developed by the National Research Council Canada is one of a number of models that forecasts ice deformation, ridging and pressure (compression). The model output provides information to ship captains and operators on the development of compressive ice along shipping routes as well as the drift of pack ice. The model may also be used to quantify parameters that lead to vessel besetting and assessing risk of vessel besetting. The model provides up to a 48-hour forecast with integrated risk assessment under AIRSS & POLARIS (discussed below). At this time, longer-term forecasts are not possible, as the input data for wind and ocean current information is not available on a time frame that would allow this type of longer-term forecast to be accurate. The Canadian Ice Service, the Canadian Meteorological Centre, and the Department of Fisheries and Oceans provide ice and environmental inputs. These standard input models have a number of limitations. Some considerations with respect to the pressured ice model's output include grid cell size limitations, initial ice information, wind and ocean current forecast model availability and accuracy constraints. The use of standard ice chart forecasts without accounting for local conditions will lead to discrepancies in model forecasts (Kubat, et al., 2011; Kubat, et al., 2009).

4.5 HISTORICAL DATA

There are publicly available datasets published which list historical ice properties and can be used to provide a probability-based estimate of future ice conditions at long time scales. This type of method is particularly strong at estimating milestone events such as ice formation and breakup but can also provide more nuanced data such as ice conditions, ice hazards, and physical properties. The Canadian Ice Service maintains a public-access database of ice thickness & snow depth measurements for 11 arctic locations (195 locations from 1947 to 2002) (Environment and Climate Change Canada, 2016). Since these datasets can be onerous to interpret, database tools that compile this data with other data relevant to mariners have proven useful. The Canadian Arctic Shipping Risk Assessment System ("CASRAS") pulls together historical datasets including "*marine weather, marine hydrography, physical oceanography, sea-ice conditions, ice hazards and physical properties, Marine Protected Areas, community information, and mariner knowledge including notes, charts, and digital media* " (Kubat, et al., 2017). Data can be displayed as visualization of historical conditions, reports on specific hazards, and as chart overlays where an intended route can be plotted with data of interest. CASRAS includes integrated route planning with AIRSS and POLARIS so expected Ice Number and RIO (discussed below) can be calculated and a probability of exceeding allowable ice conditions for the ship can be assessed based on historical conditions along the proposed route. (Kubat, et al., 2017)

Recent work has involved assessing historical data to assess besetting risk. This type of work assumes "*that the ship is proceeding with her full power and the speed changes, which are recorded, are the results of encountered ice conditions and ship's crew does not intentionally evoke them.*" (Montewka, et al., 2015) Based on analysis of a transit of the Northern Sea Route, a probabilistic model of ship besetting was generated to assess the impact of ice conditions (ice concentration and ice thickness) and environmental factors on the likelihood of besetting (Fu, et al., 2016). The results of this study are applicable to the specific ship tested, the range of conditions encountered, and the operational decisions made by the crew; this may not reflect the full capability of the ship. An earlier study (Montewka, et al., 2015) included a broader set of ice conditions, including level ice thickness and concentration, ice pressure (magnitude and direction), ridge thickness and concentration, and rafted ice thickness & concentration derived from a numerical ice model in a study of an ice going bulk carrier. In this study, besetting was predicted with an accuracy of up to 90%. A more recent study (Vanhalto, et al., 2021) used

AIS data for ships operating in the arctic region over a five-year period. Ice concentration was estimated from satellite imagery and used to build a statistical model of the likelihood of besetting. At a high level, this study found that besetting risk was closely related to ice class (higher ice class vessels are less likely to become beset) and ice concentration (higher ice concentration is more likely to cause besetting).

5. OPERATIONAL ICE SENSING TECHNOLOGIES

Predicting ice conditions that a ship may encounter in the coming seconds to minutes ("operational ice sensing") is expected to require a suite of ship-mounted sensors that are focused on measuring the ice within an area on the order of kilometers surrounding the ship. Applicable technologies include videography, photogrammetry, LIDAR, ground-penetrating radar, and electromagnetic induction sensors. Sensors that measure the interaction between the hull and the ice (propulsion power and hull acceleration/vibration) are also expected to be relevant. Ship-launched aerial and underwater vehicles have great potential to extend the reach of ship-based measurements.

5.1 VIDEOGRAPHY & PHOTOGRAMETRY

Visual techniques have been used to assess ice type, concentration, and piece size from images of the ice surrounding a ship as well as thickness using advances on Over-the-Side Video ("OTSV") techniques. One drawback that affects all techniques using visual data is their reliance on lighting to provide clear images. Low light or poor visibility due to fog, etc. degrades thee techniques, particularly for images of ice further from the vessel, beyond the range of ship-based lighting. To date, use of OTSV has involved interpretation of the video by researchers although some work has been undertaken to automate this process using machine vision techniques (Kulovesi & Lehtiranta, 2014). This work is promising, particularly in thick ice although further work is needed. Improving the image analysis process is expected to have potential to not only speed up the analysis but also yield improved insights into the composition of the ice by examining colour variations in the ice cross sections. (Garvin, 2016; Jones, et al., 2001)

There has been significant recent interest in analysis of image data of ice surrounding a ship to provide estimates of ice concentration and floe size, and to distinguish between level ice, ice floes, brash ice, bergy bits, and icebergs by interpreting the surface characteristics of the floes. It is also promising that some of this work has been completed using open-source image classification software. (Kim, et al., 2019; Heyn, et al., 2017) The main problem with obtaining detailed ice measurements from image-based data is that ice presents very low colour contrast and often limited features (simply put, image processing must differentiate between varying shades of white). Because of the relatively high colour contrast between ice and open water, ascertaining the presence of ice by differentiating between ice and open water is the best-developed use of image data to date.

Stereo cameras have been used to measure the surface topography and other surface features of sea ice. Building on image processing developments in other disciplines, multi-layered image processing techniques have been developed that show promise in processing ice image data in ways that allow surface topography to be measured in low-contrast images (Rohith, et al., 2009). Recent work (Sorensen, et al., 2020) has shown that automated stereo camera systems using machine learning and convoluted neural networks for image processing can provide promising measurements as a supplement to trained observers in detection of ice presence, ridges, melt pools, and more nuanced defined topographical features but cannot yet provide real-time ice information.

5.2 LIDAR

While there will be some challenges associated with the angle of incidence, it is expected that many techniques used for airborne LIDAR (discussed above) would be applicable to high-mounted ship-based LIDAR. LIDAR sensors emit pulsed light into the surrounding environment. These pulses bounce off objects and return to the sensor. The time taken to return to the sensor is used to calculate the distance from the sensor to the object. This process can be repeated millions of times per second at a range of orientations (within the sensor's horizontal and vertical fields of view) to build a 3D map of the environment. (Velodyne Lidar, 2021)

5.3 GROUND-PENETRATING RADAR & EM SENSORS

Ground-Penetrating Radar ("GPR") is sensor technology widely used for detecting objects or layers within quasihomogeneous media. The GPR emitting antenna emits high frequency radio waves which propagate through a material at a velocity determined by the permittivity of the material and are reflected of any dielectric singularity and reflected back to the receiving antenna. Reflections off multiple layers result in measurable peaks in the signal measured by the sensor. (Benedetto & Benedetto, 2014)

GPR has been used to measure snow and ice thickness with good resolution: within 8.3% of in-situ measurements for snow and 5.6% for sea ice (Galley, et al., 2009). In addition to providing basic thickness data, GPR has been used to measure the thickness of different layers within the ice, typically discerning between snow layers and ice layers and has been shown to work for ice over water of low salinity (Lalumiere, 2011). Radar signals (100s of MHz to GHz) reflect off the interfaces of contrasting dielectric constant (such as the snow-ice interface and the ice-water interface). In general, better results are achieved in level ice with signal quality degrading in formations such as ridges as signals are scattered by angled ice interfaces.

GPR has been shown to be capable of providing an estimate of the salinity of sea ice by estimating the dielectric properties of snow, fresh water ice, and sea ice. (Liu, et al., 2014) achieved good dielectric properties measurements using broadband GPR and a single pair of transmitting/receiving antennas achieving good correlation with in-situ measurements. In turn, the dielectric properties may be used as a measure of brine volume in sea ice according to the relationship in (Backstrom & Eicken, 2006), allowing an estimate of ice strength to be made according to the relationship in (Timco & O'Brien, 1994).

Electromagnetic Induction ("EM") is a mature technology that has been in use since the 1980s with ongoing improvements in data collection and processing (Kovacs, et al., 1987). A typical EM sensor consists of paired transmitting and receiving coils. The transmitter coil produces a primary magnetic field which induces eddy current flow in nearby conductors which, in turn, produce a secondary magnetic field. The receiving coil senses the primary and secondary magnetic fields. The primary magnetic field is cancelled out by the sensor's electronics, allowing calculation of the apparent conductivity and the sensor height above the conductive surface. EM measurements rely on the contrast in conductivity between ice and the underlying sea water; the transmitted EM field penetrates the low-conductivity sea ice but generates eddy currents in the higher-conductivity sea water which are measured by the sensor, providing a reliable measurement of the distance of the ice/water interface from the sensor. Combined with a measurement of the ice top surface, this technique provides good accuracy. Haas et. al. (2009) showed thickness measurement accuracy of 0.1 m (dependent on sensor height) with an EM sensor flown 10 to 20 m above the ice at 148 to 167 km/h. Since EM measurement relies on a contrast in conductivity, it has been demonstrated over salt water and brackish water ice.

Most frequently in studies of ice, the sensor is moved across the surface of the area of interest but there are well established methods of deploying GPR and EM sensors underneath a helicopter. While the details of these methods vary, they commonly involve deploying the sensor at between 3 m and 20 m above the ice (Lalumiere, 2011; Moore, et al., 2000; Haas, et al., 2009). These results are of interest since the distance above the ice surface is achievable for ship-mounted sensors.

5.4 ICE RADAR

Recent publishing on ice radar for discrimination between ice types is scarce but earlier work showed an ability to differentiate between first year ice, multi-year ice, and icebergs based on Bayesian classification of data collected from sideways-looking radar (Murthy & Haykin, 1987). Commercially available ice radars now offer ridge, berg, and lead detection and can differentiate between icebergs/bergy bits and low-freeboard multi-year ice embedded within first-year pack ice (Rutter Inc., n.d.). More commonly, radar is used to measure presence and movement of ice. Shore- or ship- mounting radar gives a low incidence angle meaning that it is most sensitive to areas of roughness or discontinuity (eg. ridges, rubble, and floe edges) often failing to recognise areas of level, uniform ice. (Mahoney, et al., 2015)

5.5 HULL LOADS

Several researchers have directly measured impact loads by retrofitting various styles of load sensing device to the outside of the ship's hull. These systems are generally welded directly to the hull structure and extensive effort is required to ensure they are not damaged during testing. Generally they are not suitable for prolonged operational use. Primarily, these types of sensor are useful for measuring pressure over a specific region of the hull, particularly due to impacts. Generally, they are less well suited to operational load measurement over a prolonged period. (Gagnon, et al., 2008; Gagnon, 2008)

Many studies have investigated the use of strain gauges bonded to the interior of the hull structure to monitor loading. FEA techniques help to define points of interest in the hull structure and are useful in interpreting the results (Ritch, et al., 2008; Wang, et al., 2017). This type of measurement is quite difficult to obtain since strain gauges must be applied to the difficult-to-access interior surfaces of the hull structure. Accessing the required areas to install or service such systems is often prohibitive and may be most easily achieved if the system is installed while the ship is being built. That said, it is possible to retrofit this type of sensor to many parts of the hull and in-situ calibrations are possible to increase confidence in the results. Similar to externally-mounted pressure panels, this technique is most suited to measuring local load in specific areas of the hull. For best results, detailed finite element analysis of the hull structure is necessary to identify optimal locations for strain gauge placement. Deployed on areas of specific interest, this type of sensor can form part of a decision-support system that allows masters to assess hull loading in near real-time (Wang, et al., 2001; Wang, et al., 2017; Bekker, et al., 2019).

5.6 HULL ACCELERATIONS & VIBRATION

Global hull impact loads have been measured by accelerometer-based systems which use acceleration measurements and calculated total mass (mass of ship + added mass) to estimate load as the ship decelerates when colliding with an object (Johnston, et al., 2003). This technique has been used on several studies to measure ramming loads generated when an icebreaker is breaking through ridges or colliding with ridges, bergy bits and even smaller impacts such as large late-season pack ice floes (Johnston, 2012; Garvin, 2016).

The concept of using hull vibration as an indicator of ice resistance is based on fundamental icebreaking theory but this method has been applied in more recent studies in near real-time to allow a ranking of the severity of ice conditions (Kouts, et al., 2014). The goal of this method is to allow estimation of ice resistance during continuous ice breaking (eg. level ice, brash ice channels) rather than looking at the loads generated by discrete impacts. This method has received significant attention in recent years with a focus on sophisticated data-processing methods that are required to interpret the data. Specifically, good results have been achieved whereby the measurement of accelerations in the bow has been able to assess encountered ice conditions and distinguish between different levels of ice coverage (Heyn, et al., 2019). This assessment uses two general methods: advanced statistical tools statistical tools or machine learning algorithms. While datasets including both direct ice severity measurement and acceleration data are required to develop or calibrate ship-specific relationships, statistical methods appear to be more robust and provide more reliable results (Heyn, et al., 2019). Given the recent acceleration of this topic, it is reasonable to expect that techniques may be possible that can provide more nuanced assessments of ice severity (Bekker, et al., 2019).

6. PROPOSED OPERATIONAL SENSOR SUITE

The proposed sensor suite is a critical first step in the process of providing accurate and actionable information to ships' masters through a decision support system or to an autonomous navigation system. This is envisioned as a process similar to that shown in Figure 3, building on that proposed by (Bekker, et al., 2019). In this process, data from multiple sensors is analysed to predict conditions in the immediate vicinity of the ship.

The sensor suite can be viewed as two sets of sensors. The first provides estimates of ice conditions prior to interaction with the ship and the second measures the interactions themselves. While sensors in the second category are not directly applicable to planning operational navigation, they have great potential to validate any predictions made using other sensors. This validation strategy allows refinement of ship-specific ice severity estimates by using measurements of the ship's response to ship-ice interactions (eg. delivered power and impact load) to refine a predictive model of the ship-specific local ice severity. Shipboard sensors can be used as verification for information in ice forecasts.

The sensor suite described in Table 1 is proposed. Sensors are classified as "Predict" (that they provide estimates of conditions prior to interaction with the ship, with sufficient time to adjust navigation) or "Response" (they measure the interaction of the ice with the ship and are used to improve estimates). "*Priority 1*" comprise the fundamental sensor package while "*Priority 2*" could be added to provide more complete data.

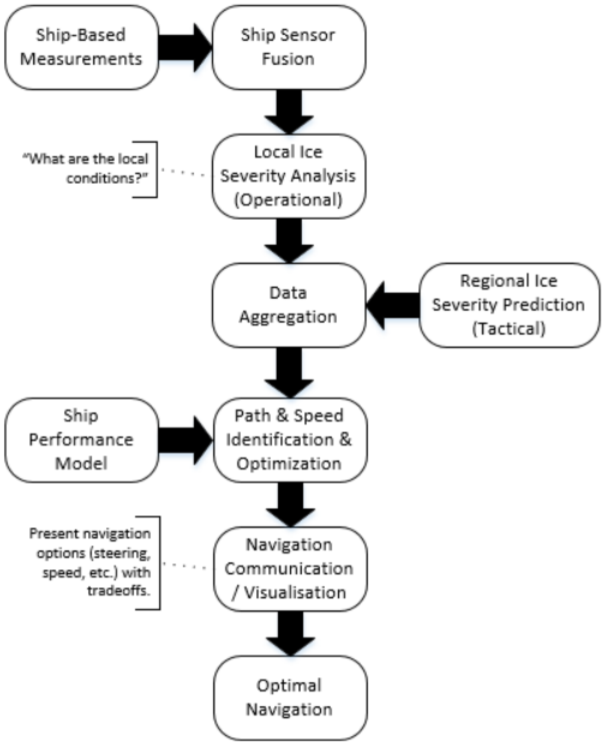

Figure 3. Process for converting data to actionable information.

While sensor technologies have been primarily envisioned to be deployed on the ship, underwater and aerial vehicles have potential to carry similar sensors ahead of the ship to measure and map ice conditions over a large area.

7. CONCLUSIONS

Many technologies exist at varying levels of maturity to assess ice severity in support of operational ship navigation. Nonetheless, there is considerable work to be done to make a reliable system similar to the one proposed. No one technology can provide a complete picture of ice severity and many technologies have overlapping capabilities. There is a significant sensor fusion effort required to combine the relevant measurements into an overall picture of ice severity. There are inevitable measurement uncertainties associated with even the most promising sensor types. Sensor fusion is expected to allow the system to overcome these uncertainties. This will improve the reliability of the system, allowing it to operate when measurements from one sensor are impaired by adverse weather, spurious measurements, sensor failure, etc. To provide robust, accurate data, it is proposed that ship responses (broken ice thickness, propulsion power, impact load, icebreaking load, etc.) be measured to provide ongoing calibration of the primary operational sensors.

Use	Sensor	Data
Predict	Ice Radar	Concentration Piece Size Identification of multi-year ice
Predict	LIDAR	Concentration Piece Size Ridge Identification Freeboard Ice Age
Predict	360º Camera	Piece Size Concentration
Predict / Response	Bow-mounted GPR	Thickness Composition Strength
Predict / Response	Bow-mounted EM	Thickness
Response	360º Camera	Pressure
Response	OTSV	Thickness Composition
Response	Whole Body Acceleration	Global Impact Load
Response	Propulsion Power	Total Ice Resistance
Response	Whole-body Vibration	Continuous Icebreaking Load
Response	Hull strain	Local Impact Load Structural “Health”
Priority 1 Sensors		Priority 2 Sensors

Table 1. Proposed Sensor Suite.

Two priority areas for real-time sensor development include more reliable methods of measuring ice thickness and enhanced methods of detecting ice strength.

There is a wealth of tactical ice data available from various sources. In order to make this data more useful for informing navigational decisions, a significant data aggregation / data fusion effort is needed. The goal of this task is to pull data from the various sources and make it available in a format that provides a nowcast, near-term forecast, and long-term forecast of ice conditions. This would allow ships' captains to assess the likely ice conditions along their route and adjust their route and speed accordingly. While it is acknowledged that there is significant nuance involved in aggregating diverse data sets and significant technical challenges associated with even compiling and storing this data, the following general principle is proposed: a snapshot of “current conditions” would be based on an aggregations of the most recent (last ~12 hours) data from satellites, aircraft flyovers of areas of interest, and shipboard observations from other ships. Currently-produced ice charts and ice pressure models typically provide several days' worth of forecast data at a regional level, and beyond the time window of current forecast models, tools built on historical data can provide probabilistic insight into what conditions may be expected.

Modern communications technologies are advancing at an unprecedented pace but there are still challenges associated with providing high-bandwidth, secure, and reliable data transfer to ships navigating around the globe. This is particularly true at high latitudes where coverage by common communications systems (eg. Marlink, Inmarsat) is limited (Inmarsat, 2020; Marlink, n.d.). If ships are to rely on data from outside sources for navigational decision-making, the delivery of this data must be very robust.

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