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Executive summary

It is clear that autonomous underwater vehicles (AUVs) play a pivotal role in the monitoring and exploration of the under-ice environment primarily because they can explore areas that are too dangerous or too costly for manned systems to remain in for any productive length of time. With the impending impacts of climate change on the horizon, their role becomes increasingly imperative in predicting the environmental consequences for not only polar environments but global systems as a whole.
AUVs can potentially be equipped with several sensor payload, however their main limiting factors when operating in dynamic ice-covered habitats, is primarily due to difficulties in obtaining accurate position and adapting to events outside their preprogramed mission.

This report compiles an inventory of commercial and scientific AUVs that have been used under ice in the Arctic Ocean and/or regional seas around Antarctica. A large range of internal and external sensors have been demonstrated in those applications. In particular CTD, optical backscatter sensors and O_2 sensors appears to be common sensors necessary in all cases, while acoustic Doppler current profiler (ADCP) is often required in those polar missions. Applications include bathymetric mapping, resource exploration and inspections of hydrothermal vents, mapping ice structure and monitoring of phytoplankton dynamics. Those operations are challenged by the difficulties in operating under the ice including problems in the navigation, obstacle avoidance and long endurance missions.

Despite these challenges, with the rapid advances in computing power and machine learning, the research on autonomous operations under the ice is progressing at an unprecedented rate. It is conceivable that AUV technologies including adaptive sampling and cooperative robotics will play in the future a significant role for high-resolution mapping and inspection in Arctic environments.

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1. Under the ice exploration

An estimated 12% of the world's oceans are covered by ice. Ice shelves are one of the most inaccessible and most poorly understood environments on earth. Over the last three decades, exploration of under-ice environments has increased in importance for society. Reasons for this range from political (extension of the exclusive economic zone) to scientific (researching climate change, marine biology). Knowledge of these regions is fundamentally paramount to the understanding of issues such as the role of the Ocean in climate change, physical processes, mixing dynamics, ecosystem structure, ice melting, and the biology beneath the ice shelf (Loeb et al., 1997; Spenneberg et al., 2005; Screen and Simmonds, 2010).

Satellites have documented trends in polar region sea-ice variability for decades, however estimating sea-ice thickness using remote sensing data remains challenging. *In situ* observations needed for validation of remote sensing data and sea-ice models are limited as the majority have been restricted to visual shipboard estimates or sparse point measurements on selected ice floes (G. Williams et al. 2014). Autonomous Underwater Vehicles (AUVs) play a major role in the potential exploration/monitoring of these water systems due to the challenges of human access and relatively high associated risk when operating in this environment (Bandara et al., 2016).

Extensive scientific researches have been conducted in the Arctic and Antarctic focussing on different aspects of marine ecology, including climate change (e.g. Schofield et al., 2010), biological processes such as recruitment of artic invertebrates (Meyer-Kaiser et al., 2019), to outer limit of the continental shelf according to United Nations Convention on the Law of the Sea (UNCLOS) (Kaminski et al., 2010) and to characterize deep sea hydrothermal vents (Jakuba et al., 2008). In the context of ice-covered regions, different types of platforms have been used including AUVs (Banks et al., 2006), Remotely Operated Vehicles (ROV) (Bono et al., 1999), moorings (e.g. Fissel et al., 2013), Argo floats (Kikuchi et al., 2007), Unmanned Surface Vehicles (USV) (Cokelet et al., 2015), Unmanned Aerial Vehicles (UAV) (Bash et al., 2018) and satellites (Nghiem et al., 2014). See Figure 1 for an example of the systems used to collect data both above and under the ice.

The advantage of AUVs relative to other platforms is that they can operate tetherless for extended periods at sea and manoeuvre according to a pre-programmed mission plan at depths of up to several thousand meters without any external operator or reference input. The record of deepest underwater vehicle diving is at 10,903 metres deep with the hybrid underwater robotic vehicle Nereus (Bowen et al., 20009). They can be equipped with virtually any sensor platform required for environmental monitoring. They are generally silent which allow for minimal disturbance to marine organisms/habitats and can cover vast areas whilst navigating with high precision. This provides the potential for the acquisition of high-resolution data of any desired parameters, in wide spatial and temporal ranges (Norgren and Skjetne, 2014).

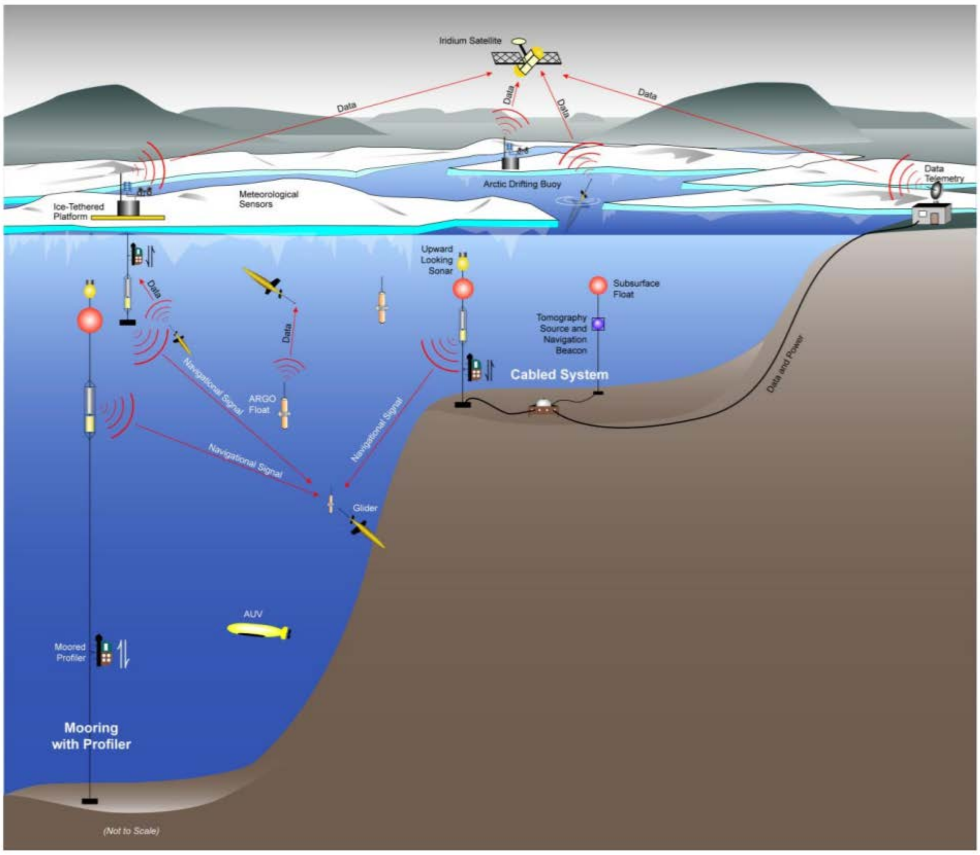


Figure 1. Some of the autonomous platforms used to investigate ice-covered areas. From Lee et al., 2010.

2. Autonomous underwater vehicles for under-ice missions

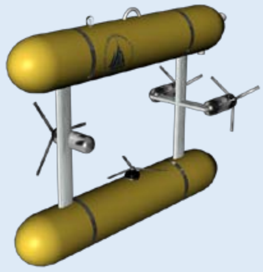
Table 1 presents a summary of AUVs that have been or are capable of under-ice missions. We focused on the spatial capabilities of each AUV in terms of depth, and the sensor payload that has been deployed on them. Other authors (e.g., Podder et al., 2004), have attempted to list the necessary equipment for AUVs scientific operations and identified the environmental parameters to observe and potential sensors to use.

Table 1 Autonomous Underwater Vehicles (AUVs) capable of being deployed under-ice with respective depth ratings and scientific payloads.

Model	Operating Organization	Maximum Depth (m)	Sensors
Bluefin 21 	Bluefin Robotics	4500	EdgeTech 2200-M 120/410 kHz side scan sonar (or EdgeTech 230/850 kHz); EdgeTech DW-216 sub-bottom profiler; Reson 7125 400 kHz multibeam echosounder, optional hydrophone array
PAUL	Bluefin Robotics; Alfred Wegener Institute for Polar	3000	Teledyne RDI: Workhorse Navigator DVL, Paroscientific Inc. Digiquartz

	and Marine Research		pressure sensor Thales, SBE 49 FastCat CTD, Satlantic SUNA deep Nitrate sensor, Contros HydroC CO_2 Sensor, Dissolved Oxygen SBE43, fluorometer Turner Designs C7 "U", Turner Designs C7 "C", Photosynthetically Active Radiation Satlantic PAR Sensor
ALTEX 	Monterey Bay Aquarium Research Institute	6000	3 configurations: (1) upper water column (CTD SBE3F and SBE4; Oxygen: SBE43; *In Situ* Ultraviolet Spectrophotometer (ISUS) (Satlantic); Laser In Situ Spectrometer and Transmissometer (LISST) Sequoia Scientific, Inc.; A Laser Optical Plankton Counter (LOPC) Brooke Ocean Technology; Bathyphotometer: UCSB Jim Case Life Science Lab; A HydroScat-2 Backscattering Sensor and fluorometer Hobi Labs; OCR-507 Satlantic (2) seafloor mapping (200 kHz multibeam sonar, 110/410 kHz sidescan sonar, and a 2-16 kHz subbottom profiler) (3) imaging AUV (high-resolution still camera, two xenon strobe lights, an acoustic modem).
ISE Explorer 	ISE International Submarine Engineering Ltd	6000	It can be equipped with any sensor designed for use on an AUV. These include: Multibeam Echosounder (MBES); Synthetic Aperture Sonar (SAS); Magnetometer; CTD, pH, pCO2, CH4, DO, Turbidity, Nitrate, and other chemical sensors; Laser Scanner; HD Still and Video Camera; Sidescan Sonar (SSS); Sub-Bottom Profiler (SBP)
Nupiri muka	ISE International Submarine Engineering Ltd	5000	SeaBird CTD, an Ocean Floor Geophysics magnetometer, an Edgetech combined sidescan, bathymetry, and sub-bottom sonar
Arctic Explorer	ISE International Submarine Engineering Ltd	5000	Knudsen 118 kHz single beam echosounder, Kongsberg Simrad EM2000 Multibeam Echosounder, CTD Seabed SBE-49, depth sensor

			paroscientific
Memorial Explorer	ISE International Submarine Engineering Ltd	3000	R2 Sonics 2024 Multibeam echosounder System, Edgetech 2200M Side Scan Sonar System/Subbottom Profiler, Valeport MiniSVS Sound Velocity Sensor.
Gavia AUV 	Teledyne marine	500 - 1000	Swath bathymetry module, Side scan sonar and camera, Sub-bottom profiler and sound velocity meter
Slocum G3 Glider 	Teledyne marine	4 to 150 m / 40 to 1000	ADCP, Acoustic Mammal Detection, beam attenuation meter, CTD, echosounder, fish tag detection, hydrophones, nitrate sensor, Spectrophotometer for Harmful Algal Blooms, turbulence sensor
REMUS 	Kongsberg Maritime	100, 600, 3000, 6000	ADCP, EK-80 Fish Sonar system, YSI Conductivity and Temperature Sensor, Aanderaa Oxygen Optode sensor
Seaglider 	Kongsberg Maritime	1000	Oxygen Sensor, fluorometer, passive acoustic monitoring, turbulence sensor, ADCP, single-beam echosounder, turbidity sensor, ARGOS tag
Hugin 1000 	Kongsberg Maritime	1000, 3000 or 4500	Multibeam echosounder (EM 2040), intereremetric synthetic aperture sonar (HISAS 1030), sidescan sonar, sub-bottom profiler, still image camera
Autosub6000 	National Oceanographic Centre	6000	EM2000 Multibeam, ADCP (RDI 300 kHz), CTD Seabird SBE 52MP
Autosub long range 	National Oceanographic Centre	6000	Upward and downward looking ADCP, CTD, chlorophyll fluorescence sensor, turbidity sensor and turbulence micro-structure probe

Seabed AUV 	Seabed Technologies Inc	2000 or 5000	Multibeam Imagenex Delta-T, camera 1,4,11 megapixel, CTD Seabed SBE-49,
Jaguar	WHOI	6000	Multibeam Delta-T Imagenex, downward-facing optical camera and strobe, imaging sonar, Eh sensor, magnetometer, CTD Seabed SBE-49
Puma	WHOI	6000	Multibeam Delta-T Imagenex, camera, Eh sensor, optical backscatter system, CTD Seabed SBE-49, LROBS (for hydrothermal plume detection)
LAUV Harald 	OceanScan	100	CTD Seabed SBE-49, dissolved oxygen Aanderaa Optode 4831F, fluorometer WetLabs EcoPuck Triplet
LAUV Fridtjof	OceanScan	100	High definition downward looking camera Lumenera Le165 and LED lighting, Sidescan sonar Deepvision OSM2, Doppler velocity logger Nortek DVL 1MHz
AquaExplorer2000a (AE2000a) 	Mitsui Engineering and Shipbuilding	2000	MBES, CTD, pH-meter
Hybrid AUV/ROV Icefin  Source: Spears et al., 2016	Georgia Tech Research Institute	1500	Kongsberg Light Ring forward-looking camera, BlueView P900-45 forward looking sonar sensor, Neil Brown Instrument Systems CTD
Artemis AUV 	Stone Aerospace	1000	Protein fluorescence spectrometer, Inlet port for water sample, Inlet port for flow-through sensing of pH, dissolved oxygen, and CTD, Optical triplet for dissolved organic matter, chlorophyll-a, and scattering

Source: Stone Aerospace, 2020			Up- and rear-looking HD video, 5 MP still cameras, and LED lighting
ENDURANCE AUV  Source: Richmond et al., 2011	Stone Aerospace	1000	Multibeam, wide field camera

3. AUVs' sensors

AUVs are equipped with an array of internal and external sensors and some of the most common are described below.

3.1. Internal Sensors

There are numerous internal sensors deployed on AUVs for under-ice navigation and localization such as Inertial Navigation Systems (INS), Doppler Velocity Log (DVLs) and pressure sensors. Internal sensors do not rely on measuring position but instead ascertain its location, through integrating real-time vehicle accelerations or velocities, while external sensors determine positions relative to the properties or features of the environment and state estimators represent the algorithms used for underwater localization and mapping (Bandara et al., 2016).

INS: These units navigate relative to the initial position. They require accurate knowledge of the vehicle state which is dependent on sensors to provide measurements of the derivatives of the states. This is an advanced form of dead reckoning that comprises of an accelerometer gyroscope, compass, and onboard computer to continuously calculate the velocity, orientation, and position of a moving object without the need for external references (Di Massa, 1997).

DVL: This system uses acoustic measurements to capture bottom tracking and determine the velocity vector of an AUV moving across the seabed. It determines the AUV surge, sway and heave velocity by transmitting acoustic pulses and measuring the Doppler shifted return from these pulses off the seabed. DVLs will typically consist of 4 or more beams with 3 needed to determine 3D velocity vector (Paull et al., 2014).

Pressure sensor: Pressure sensor provides a more reliable depth measurement and is used to aid during inertial navigation (Norgren and Skjetne, 2014).

3.2. External Sensors

Acoustic Transponders: These measure positions relative to a framework of baseline stations. They are broadly categorized into two types

1. Ultra Short Baseline System (USBL)
2. Long Baseline System (LBL)

USBL navigation allows an AUV to localize itself relative to a surface ship/buoy and does not require an sea floor mounted system making it relatively easy to deploy, however its position accuracy is much less in comparison to LBL systems which are generally mounted on the seafloor (Bandara et al., 2016). LBL and GPS intelligent buoys (GIBs) beacons are placed over a wide mission area with AUV position determined via triangulation of acoustic signals (Paull et al. 2014). This method consistently provides accuracies in the order of decimetres over large areas, independent of depth.

Side Scan Sonar and multi-beam Sonar: Sonar sensors are based on acoustic signals and allow AUVs to navigate using image processing techniques to generate a map of the surrounding geophysical characteristics (Stalder et al., 2008).

There are generally two types of sonars used (Chen et al., 2013).

1. Multi-beam sonars
2. Side-scan sonars

Side-scan sonar images can provide a clear view of objects in 2D with a relative higher resolution than multibeam sonar (Hongmeiet al., 2010). The resolution is however inversely proportional to range whilst in multibeam arrays, is inversely proportional to frequency (Stalder et al., 2008). These detector and descriptors have been demonstrated to work well in complex geophysical environments, however this task increases in complexity in under-ice operations due to the often featureless environment (Paull et al., 2014).

3.3 Oceanographic systems

A broad range of oceanographic instruments are routinely used as part of under-ice AUV sensor payload, these include:

- CTD (Conductivity, temperature and density) measurements are essential in oceanography and is therefore a crucial sensor onboard the AUV. Numerous properties can be extrapolated from these measurements, both directly and as a proxy for other parameters (Norgren and Skjetne, 2014). For example, Forrest and collaborators (Forrest et al., 2008) obtained the under ice thermal structure using moored vertical profiler.
- ADCP (Acoustic Doppler Current Profiler). AUVs equipped with downward looking ADCP are capable of collecting data on under-ice ocean currents (Wadhams et al., 2006). This data plays in essential role in predicting seasonal melt as well as the impacts of climate change (Zwally et al., 2002; Williams et al., 1998; Heimbach and Losch, 2012).
- pCO_2 sensor. Partial pressure of carbon dioxide can be measured with a pCO_2 sensor such as Contros HydroC CO_2 Sensor. Argo floats together with other observational datasets were used to understand the variability and change in subpolar Southern Ocean pCO_2 (Fay et al., 2018).
- *In situ* Ultraviolet spectrophotometer (ISUS). Nitrate can be measured with an ISUS, such as the “Deep SUNA Ocean Nitrate” sensor.

4. AUVs Applications

4.1. Bathymetric Mapping

Multibeam echosounders have generally been used for creating bathymetry and 3D digital maps of the ocean floor (Anderson, 1999) and is an established technology in AUVs. Continual developments in this area are opening possibilities for operating closer to the seafloor and in more variable/complex bathymetric conditions (Xinqian et al., 2010; Bush et al., 2016).

4.2. Geophysical

Tsingas et al. (2018) demonstrated an automatic seafloor acquisition system using AUVs as seismic sensors, primarily for oil exploration activities. This is predicted to drastically decrease cost and scope of the when compared to the current ship to equivalent.

4.3. Geochemical

Hydrothermal vents under the Arctic Ice cap have been studied in the Arctic Gakkel Vents (AGAVE) Expeditions through conductions of AUV missions at 4200 meters deep in order to understand hydrothermal processes (Reves-Sohn et al., 2007).

4.4. Ice Mapping

Using upward facing sonar allows AUV to map in high resolution the three-dimensional structure of the underside of ice using multi-beam sonar. Such missions have resulted in the underside topography of ice over a 450 km tract and was able to identify first and multiyear ice, including old hummocks young ridges, and undeformed melting ice (Forrest et al., 2008; Williams et al. 2014; Wadhams et al. 2004; Wadhams et al. 2006).

Forrest et al. (2012) stated that one of the biggest obstacles facing AUVs during these operations is navigation and mapping under a drifting and rotating reference frame such as free flowing ice, and the ability to plan the missions accordingly.

An important development by (Kimball and Rock, 2015) recently presented a technique for mapping a free-floating iceberg with an AUV using previously acquired terrain bottom maps as a reference for navigation (TRN). The major technical achievement of this was a method for estimating simultaneously the translation, shape and rotation of an iceberg during a typical mapping data collection mission. In addition, upward looking ADCP allows for estimates in sea ice thickness and topography to be obtained, although in lower resolution compared to sonar (Wadhams et al., 2006; Banks et al., 2006)

4.5. Phytoplankton distribution

Under-ice blooms might represent a significant component that is missing when studying the total production regime of the Arctic Ocean (Johnsen et al., 2018). A study gathering different multiple observational platforms, including an AUV deployed under-ice, was conducted in Chukchi Sea, Arctic Ocean to obtain more information about the under-ice bloom, being able to examine the composition, magnitude and origin of the bloom detected beneath the ice (Johnsen et al., 2018).

5. AUV challenges in under the ice operations

It has been found that AUVs operations are still heavily constrained by many technological, environmental and other issues (Podder et al., 2004). Some of the issues include: limited sensor capabilities (range, update, accuracy, availability) and limited adaptation to changing physical parameters (temperature, conductivity y, pressure, visibility, current, drag); Challenges in corrosion, marine growth, harsh conditions and uncertainties; Conflicts in the use of ocean areas between research and industrial activities.

AUVs use a suite of sensors (summarised in Figure 2) to determine their heading and location without human input during the autonomous component of the mission. In order to achieve this, AUVs need to address two critical problems:

1. Determining its position and orientation relative to world frame coordinates
2. Obstacle avoidance and path finding

Above water, the first task is overcome using GPS. Due to the rapid attenuation of radio signals through water, AUVs cannot rely on this method when submerged (Paull et al., 2014). Furthermore, the majority of state-of-the-art underwater localization systems frequently use surface or baseline acoustic transponders to triangulate the AUVs position (Ferreira et al., 2010). These acoustic approaches have limitations in under-ice environments, due to the logistic and time-consuming difficulties associated with placing acoustic baseline moorings in areas with line-of-sight to the AUV (Medagoda et al., 2016), and the large mission ranges often required (Bandara et al., 2016). Typically, an AUV in an under-ice mission will quickly lose direct acoustic communication with the operators, which means that the AUV must rely primarily upon its Inertial Navigation System (INS) to perform dead-reckoning estimation of its speed and position. Dead-reckoning position estimates grow in error (“drift”) as they are based on the integration of noisy velocity and acceleration data from the INS, and so need external on-board sensors such as pressure, sonar and Doppler Velocity Log to compensate (Webster et al. 2015). However, these sensors are prone to their own challenges, for example sonar and Doppler Velocity Log data are prone to error from navigating near or under translating and rotating surfaces such as ice (McFarland et al., 2015). Additionally, simultaneous localization and mapping algorithms that use features obtained from sonar or camera images to navigate are challenged by under-ice environments being largely featureless and low contrast (Spears et al., 2015).
Other issues related to navigation in Arctic includes limited processing power, inability to surface (due to glacier and ice floes), gyrocompass errors due the effect of high latitude and water currents, which might be the primary source of estimated errors (Salavasidis et al., 2018).

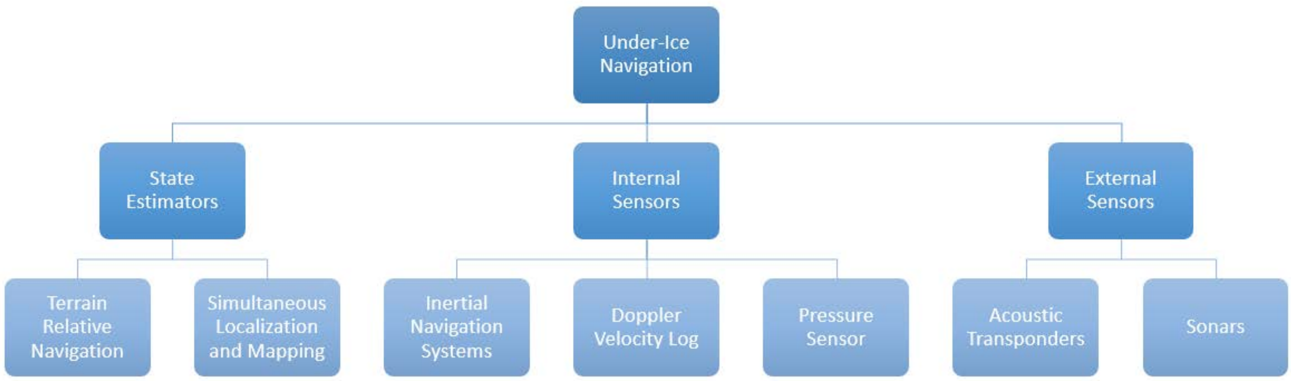


Figure 2. Overview of AUV under-ice navigation (adapted from Bandara et al., 2016).

6. Estimators for Under-Ice Localization and Mapping

To overcome some of the problem in navigation under the ice, different solutions have been suggested including those based on terrain relative navigation (TRN) and simultaneous localisation and mapping (SLAM).

6.1. Terrain Relative Navigation (TRN)

TRN can provide a drift free navigation tool for underwater vehicles, creating a powerful alternative to current navigation methods including, deploying transponder arrays or using high-accuracy inertial sensors. TRN generates vehicle position estimates by correlating terrain measurements collected by sonor, with offline stored topography maps (Meduna et al., 2008). In regard to under-ice missions, TRN must first overcome the major obstacle of access to accurate terrain/ice maps in addition to the development of high confidence matching algorithms (Bandara et al., 2016).

6.2. Simultaneous Localisation and Mapping (SLAM)

Using the same principles as TRN, SLAM is further extension of this system, requiring no prior knowledge of the environment navigated. Simultaneous Localisation and Mapping (SLAM) is the process of concurrently building a feature based map of the environment, from real-time accurate terrain senor data collection and using this map to obtain estimates of the location of the vehicle (Mahon and Williams, 2004). Despite its potential, limited work has been conducted using underwater SLAM for under-ice navigation but has yet to see broad application (Doran et al., 2010).

7. Future developments

7.1 AUV – Sensors and Endurance

We presented the sensors found in AUV deployed under-ice (see section 2) but other sensors can be deployed and water sample can be analysed for different purposes. An Environmental Sample Processor (ESP) coupled to an AUV have been used to estimate Environmental DNA from Monterey Bay (Yamara et al., 2019). Environmental DNA can be used to monitor invasive species or rare organisms of conservative concern (Yamara et al., 2019), these areas can be applied in the Arctic context. AUVs´ endurance is also an area that can be developed further. Current AUV use Silver-Zinc batteries or with Lead-Acid composition, however better batteries containing NiMH are available commercially which provides energy better (Mondal et al., 2019).

7.2 Adaptive sampling

Continual improvements in computer processing power has allowed for development of data-driven sampling with AUVs, giving them the ability to adjust execution of mission based on sensory information. Using these advanced control strategies opens the potential for more complex surveys, track dynamic environmental gradients such as temperature fronts, optimized data collection, reduced mission duration, and the amount of redundant data collected (Fossum, 2016).

A recent study by (Berget et al. 2018) demonstrated the effectiveness of this technique, through AUV tracking of suspended material plumes in relation to oil and mining activities. Furthermore, Jadaliha and Choi (2013) proposed an optimal sampling strategy using multiple AUVs in conjunction with adaptive sampling to maximize the area covered and resolution of data.

7.3 Cooperative Robotics

Cooperative robotics allows AUV teams to share sensor information, aiding in navigation and communication as well aiding completion of any mission parameters or tasks required. Although not yet carried out in under-ice environments, it is conceivable that these developments will play a role in future AUV missions. A new seismic acquisition approach (Essaouari and Turetta, 2016) uses a swarm of AUVs leading to more flexible and area-specific surveys. Sydney and Pauley (2014) presented a multivehicle trajectory generator for non-uniform coverage of a non-stationary spatio-temporal field that may vary in space and time. In addition, Roumeliotis and Rekleitis (2004) showed that in regard to cooperative localization, position uncertainty is negatively proportional to the size of the robot team.

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