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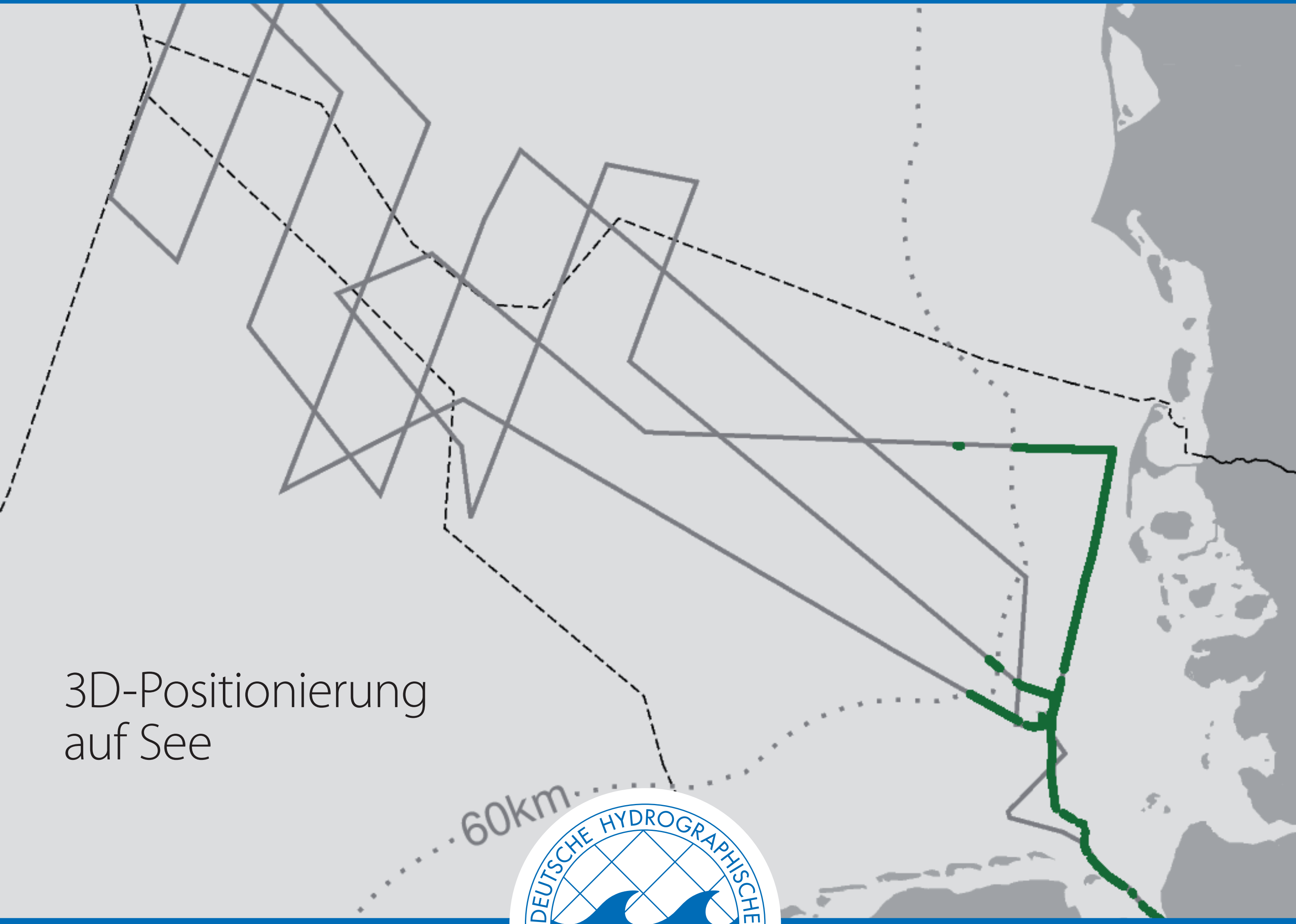

3D-Positionierung auf See

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Positioning robotic systems under ice

A summary of challenges and potential ways forward

An article by CHRISTIAN KATLEIN

Determining the position of underwater vehicles is crucial to any operation underneath the water. But when remotely operated vehicles (ROV) and autonomous underwater vehicles (AUV) venture underneath the frozen surface of polar waters, the knowledge of their position becomes absolutely crucial. Not only because any observation is only worth half as much if you do not know where it was taken, but particularly because underneath ice cover knowing its position is crucial for a robotic vehicle to be able to travel back to a spot where it can get recovered from underneath the icy blanket. However, in the under-ice environment, many factors make position estimation significantly more difficult. These challenges and potential solutions will be summarised in the following.

autonomous vehicles | under-ice operation | acoustics | positioning | vehicle navigation
autonome Fahrzeuge | Unter-Eis-Einsatz | Akustik | Positionierung | Fahrzeugnavigation

Die Bestimmung der Position von Unter-Wasser-Fahrzeugen ist für jeden Einsatz unter Wasser entscheidend. Aber wenn sich ferngesteuerte Fahrzeuge (ROV) und autonome Unter-Wasser-Fahrzeuge (AUV) unter die gefrorene Oberfläche der polaren Gewässer wagen, ist die Kenntnis ihrer Position absolut entscheidend. Nicht nur, weil jede Beobachtung nur halb so viel wert ist, wenn man nicht weiß, wo sie gemacht wurde, sondern vor allem, weil unter der Eisdecke die Kenntnis der Position entscheidend dafür ist, dass ein Roboterfahrzeug zu einer Stelle zurückkehren kann, an der es aus der Eisdecke geborgen werden kann. Unter der Eisdecke erschweren jedoch viele Faktoren die Positionsbestimmung erheblich. Diese Herausforderungen und mögliche Lösungen werden im Folgenden zusammengefasst.

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When talking about robotic exploration under ice on planet earth, a few possible scenarios come to mind. The most benign is often used as a test case during development programmes and consists of a lake with frozen surface. Here a relatively thin ice cover provides comparably easy access for the deployment of underwater vehicles, and the vehicle position is constrained by the lake volume, which – while still extensive – can be a big plus in the case of a lost vehicle. A more complex situation particularly given the logistics of access is the operation on the landfast sea ice in fjords or around coasts. What really steps up the game, however, is a deployment underneath the freely drifting ice covers in the Arctic or Antarctic Ocean. Here the movement of sea ice with wind and current starts to complicate all positioning efforts. While positioning in the world fixed reference of exploration underneath the big glacial ice sheets of the Antarctic is technically slightly easier, the absolutely impenetrable top layer of the ice shelf dramatically increases mission risk: Any vehicle malfunction will very likely result in loss of the vehicle as surfacing underneath a hundreds of metre thick ice shelf does not provide a safe haven. Knowing vehicle position and being able to navigate accordingly becomes a key element of mission success in these scenarios.

If robotic operations under ice are so challenging, why even wander under ice and risk expensive robotics assets? The driving forces of under-ice robotic exploration were shared between the curiosity of polar researchers and the interest of defence organisations in gaining superiority in a hard to access region. Only in the last decade, under-ice robotics has become of interest to the energy sector as well, where oil and gas installations are moving to even more extreme areas of our planet. Over the last 50 years, many programmes have proven that operations under ice are feasible: The first dives under Arctic sea ice were conducted by the Unmanned Arctic Research Submersible developed by the University of Washington in 1972, later followed by the International Submarine Engineering (ISE) vehicle *Theseus* laying hundreds of kilometres of fibre optic cable underneath sea ice in 1995. A big milestone was also the Autosub programme of the National Oceanography Centre with its first explorations of ice shelf cavities in West Antarctica. Many more successful missions have proven that under-ice operations are feasible. However, many examples also point out the vast challenges of under-ice robotics and multiple million-dollar vehicles have been lost in action. While many have proven that it can be done successfully, nobody yet has developed under-ice operations into a routine robot deployment – a crucial milestone for sustained robotic exploration of the polar seas.

In the following I want to give an overview about the challenges of position determination in under-ice scenarios:

Impermeable ice cover

As mentioned before, the ice cover itself is a major hindrance. Not only to vehicle deployment, but particularly to vehicle recovery. Cutting deployment holes through the ice is a challenge in its own, so that the hole a vehicle has to return to is typically just a bit larger than itself. This highlights the importance of positioning, as minor errors in position estimation can cause the loss of a vehicle if it does not hit the hole in the ice.

Most subsea vehicles simply jettison their ballast weights in case of a suspected emergency situation. However, surfacing is not a viable emergency strategy underneath ice covers. While locating a dead vehicle underneath the ice and cutting a hole to retrieve it might still be feasible underneath sea ice covers, it is certainly not a possibility under glacial ice cover.

This complication also affects possibilities to deploy acoustic ranging beacons. While drilling through the ice and deploying them from the ice might be feasible in some locations, seafloor transponders for ranging will not be easily recoverable after a mission deployment.

Unreliable heading information:

Positioning by trilateration of acoustic ranges or the determination of vehicle position by range and bearing is not strictly dependent on accurate heading information. However, most survey sensors and particularly any sort of position estimation by dead reckoning are heavily dependent on reliable heading information. This is tricky to achieve in the polar regions due to their vicinity to both, the geomagnetic and the geographic poles.

Depending on the quality of compass sensors, magnetic heading can still be reliable in many polar regions. However, once one gets within 500 nautical miles of the geomagnetic pole, compass heading can start to first drift slowly, then accelerate to drifts beyond 180° within ten minutes, and at last become completely jumpy and erratic. This can have drastic influence on any automatic vehicle stabilisation or auto-piloting, as well as seriously affect dead reckoning calculations.

Gyro-compasses can provide some relief in these situations, but their precision is also determined by the distance to the geographic pole as the earth rotation axis. Hence they typically only help to stabilise erratic magnetic heading readings, but their inherent strong drift in these regions makes them unreliable as absolute heading source as well. First manufacturers have developed heading sensors which fuse inertial and magnetic readings to achieve better compass stability in these complex scenarios, but there will be a limit to their applicability.

Coordinate transforms: everything is moving

Polar applications are the extreme test scenarios for most positioning software packages. Working in standard UTM zones or geographic coordinates is usually unpractical for the visualisation of positioning at high latitudes. Often, special polar coordinate grids (like the UTM polar cells) are not supported in positioning software and the application of inappropriate coordinate conversions from relative local coordinates can lead to significant distortions or even major software glitches.

This issue is further complicated by the fact, that particularly free drifting ice cover is on the move. Ice floes move with typically 0.1 to 0.5 kn and rotate relative to the world geographic reference system. This has tremendous repercussions on positioning operations: The area of interest can quickly drift out of, e.g., a field with deployed seafloor transponders or even worse, the location of a recovery hole changes continuously. This also affects acoustic positioning beacons deployed through a drifting ice cover. This ice motion can be sensed by arrays of deployed GPS drifters, but a subsea vehicle performing dead reckoning by Doppler velocity log (DVL) against a moving ice floe will likely not correctly predict its geographic position. Particularly, such bottom tracking against moving sea ice can not measure rotational movement of the floe above. This lacking rotational information and the mismatch between inertial sensors (accelerometers and gyroscopes) and DVL tracking against the ice and potentially a seafloor can lead to confusion during the sensor fusion process in dead reckoning estimates of inertial navigation systems (INS). Any such glitch can easily lead to vehicle loss when the vehicle loses good positioning and decreases ist chance to get back to its recovery point.

Complicated under-ice acoustics

In a traditional set-up, these shortcomings could easily be overcome by frequent acoustic tracking using LBL (long base line) or USBL (ultra-short base line) acoustic methods. However, the acoustic situation under ice can be extremely complex as well.

As a start, ice-covered regions can exhibit a large amount of natural underwater acoustic noise. Be it from crumbling and turning icebergs, movement cracks in glaciers or simply the crunching noises of an ever-moving sea ice cover driven by currents, winds and tides.

This is further complicated by the complexities of sound transmission in the water overall. While polar waters are often extremely clear providing sometimes too few targets for water tracking by DVLs, particularly melting ice can lead to a strongly stratified water column, where large variations in salinity modify sound speed. This can lead to narrow acoustic channels blocking acoustic devices deployed in different depths from communicating with each other. While this might seem beneficial by concentrating acoustic energy to allow longer ranges, it can actually increase acoustic absorption due to frequent interactions with the rough ice cover. Especially for operations close to the sea ice, this surface roughness of the ice underside makes for an extremely difficult situation, as large pressure ridges which easily protrude to depths bigger than 15 m can lead to significant shadowing of acoustic communication lines. Hence, keeping an uninterrupted acoustic tracking by USBL or regular interrogation of a sufficient number of LBL beacons can pose a huge challenge to under-ice positioning.

In a further complication, robotic operations under ice often involve the tracking of vehicles in very shallow tracking angles close to the surface and at large horizontal standoff distances. Often the target of investigation is directly at the underside of the ice, which always results in shallow tracking angles contrary to typical seafloor operations, where positioning systems are optimised for tracking close to the nadir direction. Even for seafloor investigations, however, complications like the horizontal drifting of sea ice or the impossibility of access to areas underneath ice shelves leads to large horizontal standoff distances between robots and mothership. While many of the acoustic tracking systems claim to operate well with omnidirectional or even toroidal sensitivity, the resulting accuracies at shallow tracking angles can be a severely limiting factor to under-ice operations.

Deep water

While no ice-covered waters exhibit extreme depths beyond 5500 m, they are certainly too deep to allow vehicle navigation to rely on DVL bottom tracking during entire dives. Simultaneous DVL bottom tracking during under-ice surveying is only available in shallow coastal waters. In deeper waters, robotic vehicles will, however, accumulate a larger position uncertainty during descent if there is no additional support by acoustic tracking.

In summary we see, that the under-ice environment exhibits many challenges that can easily confuse state of the art inertial navigation and positioning systems (see Fig. 1). How these systems handle such mismatches in incoming sensor data becomes crucial for under-ice robotic systems to keep a workable positioning solution. A big challenge remains to build reliable systems that ensure sufficient real-time positioning accuracy that can reliably guide an under-ice robot back to its deployment location and avoid mission failure and vehicle loss. While increasing navigational performance during post-processing is certainly beneficial for survey data processing, it is not sufficient for real-time operations and the challenge of getting a vehicle back in the first place.

Addressing these challenges and mitigating some of the associated risks is crucial for under-ice operations and many different tactics have

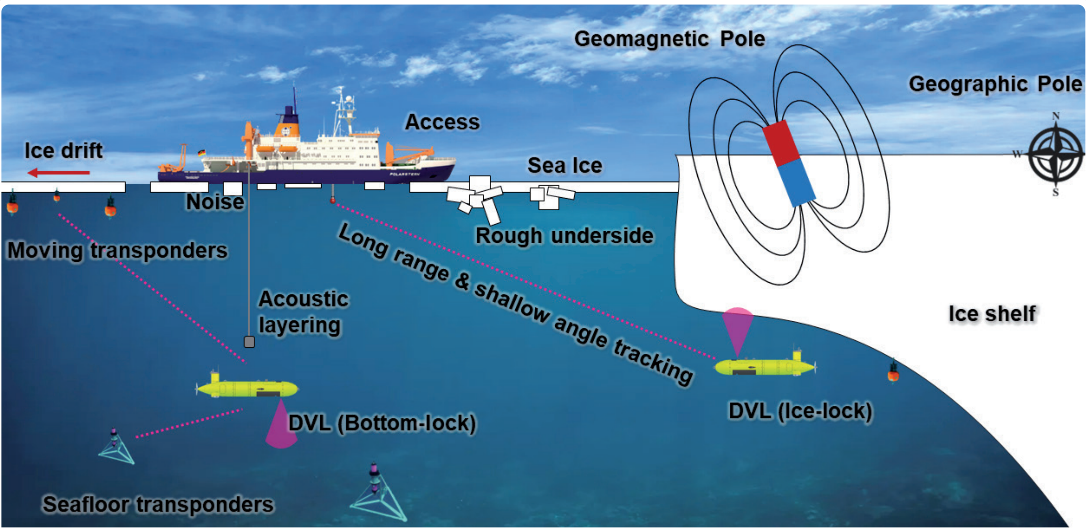

Fig. 1: An overview of some of the main challenges complicating under-ice positioning

been employed to solve these challenges. Unfortunately, most solutions come with high cost and increased system complexity and no single system can address all of them. Luckily, in most situations not all of the previously presented difficulties apply all at once, so that individual solutions suiting most mission profiles can be found. In the following some of the most useful adaptation strategies are discussed:

Keep things tethered

The most obvious solution to avoid vehicle loss is to keep it physically tethered, so that the vehicle will always be at maximum one tether length away. While coming with its own challenges, like the entanglement of tethers and thruster propellers, this solution is a quick fairly low-cost fix for many small-scale surveying applications. It needs to be noted that adding a tether alone does not provide sufficient protection against vehicle loss, but vehicle buoyancy needs to be considered as well. For a positively buoyant vehicle that has floated up into a heavily deformed sea ice ridge cavity, pulling on the tether might damage the tether and not be helpful for vehicle recovery. In situations like these a slightly negative vehicle trim can help to recover a vehicle by pulling on a tether string. To be fair, we need to acknowledge that probably half of the literature on smaller scale under-ice AUV surveys has been conducted with the safety of a tether – either some kind of rope or high strength multifilament fishing line.

Fibre optic gyro compasses and high grade INS systems

As mentioned before, heading information is crucial to both the processing of survey data as well as dead reckoning calculations. Some of the limitations of magnetic and gyro compasses can be overcome by fibre optic ring laser gyroscopes, when used in high grade marine inertial navigation systems. These systems have shown to work excellently even at 90° north, but also come with a big associated cost. They typically cost well above 100,000 € and due to their large size they can typically only be incorporated into larger vehicles. In combination with upward looking ice-tracking DVL sensors or traditional DVLs for seafloor missions, these INS can, however, provide the best stand-alone positioning accuracy available for under-ice systems.

Sparse LBL

Another approach to deal with the complexities of the under-ice acoustic environment with limited acoustic performance, intermittent shadowing of transponders and few attainable positioning pings is sparse LBL, also known as single transponder navigation. In this method, a vehicle merges information from the INS with acoustic fixes or ranges to generate an optimal position estimate. The main task of acoustic ranging to known locations in this approach is to constrain INS drift and reduce the size of the error ellipse around an underwater vehicle. When this method combines a high-grade fibre optic gyro INS with high-quality acoustic ranging it results in the highest attainable position accuracy achievable at the moment. However, the associated cost is very high and the complex positioning algorithms need to be robust against potential mismatches of inertial, DVL and ranging information already in-mission and not only during post-processing. This method could be further refined for under-ice applications, by using drifting transponders deployed on the moving ice, which communicate their GPS positions over an acoustic link, so that they can be used for range aiding by the sparse algorithms. Such systems have been demonstrated by scientists at MIT and concepts have been developed by commercial companies, but no supplier is yet offering this capability in his commercial off-the-shelf portfolio.

Acoustic homing

Acoustic homing has been successfully used by several missions to redirect an AUV to a deployment hole or a docking station. This method is typically based on two or more hydrophones, but sophisticated versions include an inverted USBL transceiver array located in the nose of the vehicle to determine range and bearing to an acoustic transponder. This configuration can achieve longer acoustic ranges but is not commercially available as typical input for INS position estimations. Relying on homing at the end of the mission also has the drawback, that the accumulated position uncertainty during the mission time needs to be smaller than the acoustic range of the homing system. To maximise this distance, these acoustic beacons are often working in the lower frequency range below 15 kHz. While a homing system solves the issue of coming back to the deployment hole with a dedicated piece of hardware, this also comes with added costs and takes up space in the nose of a vehicle, which often is a highly contested area for the location of sensors and recovery mechanisms.

Adapted diving behaviours

As discussed above, unintended surfacing to the underside of ice has to be avoided for a successful mission. This implies two necessary adaptations for under-ice systems: Firstly they should be equipped with (upward looking) obstacle avoidance. While most AUV can keep a safe distance from the seafloor out of the box, under-ice systems should come with the same function to avoid ice above. The fact that upwards is not necessarily a safe direction for obstacle avoidance manoeuvres also has to penetrate into all other autonomous vehicle behaviours in such a way that a vehicle either decides if it needs to deviate upwards or downwards, or even rather should turn around on its current track to avoid any collisions. Some vehicles even possess the awareness of being stuck, when inertial measurements do not correspond to the actions of thrusters and control surfaces and can then respond with specialised »get un-stuck« behaviours.

The complexity of the under-ice world should also be reflected in appropriate handling of emergency situations. Dropping a weight and rising to the surface is often a wrong choice under ice, so vehicles should decide to dive back on their previous track out of a danger zone, or wait for operator contact at a predefined emergency loiter location. While dropping of ballast will often result in a vehicle stuck underneath the ice cover, jettisoning buoyancy might be a preferable solution in some scenarios, where a dead vehicle could be more easily recovered from the seabed than from underneath a drifting ice pack.

Emergency recovery preparedness

A big factor for de-risking under-ice deployments is the preparedness for emergency recovery situations. Here again positioning plays a crucial role, to determine where a lost vehicle is. This involves having the right acoustic ranging equipment at hand: handheld ranging or USBL transponders, that can be easily transported by sledge, small boat or helicopter are very helpful to locate the hopefully existing independent backup transponders of a vehicle stuck at the ice underside. Once located, it is necessary to have the right drilling and cutting equipment for extracting the vehicle from underneath the ice, or employ a backup ROV system to attach a line and weights to the vehicle. In many cases missions have only been successful because a vehicle considered lost, could be relocated within a short time frame due to a thorough preparation of emergency response actions.

To not frustrate the reader too much about the complexities and problems of under-ice positioning and operations, I want to end this article with a description of three recent successful under-ice deployments and go over the applied methods for under-ice positioning and the most notable special preparations.

ROV BEAST on the MOSAiC Drift

During the MOSAiC Drift expedition from October 2019 to 2020, the Alfred Wegener Institute deployed its large observation-class under-ice ROV nicknamed *Beast* (Ocean Modules M500, see Fig. 2). It carried an extensive sensor suite including upward looking multibeam sonar and was deployed on average twice per week through a hole in the ice floe of the drifting camp. During winter, this hole was covered by a heated tent. Year-round ROV observations were relying on a Linkquest Pinpoint 1000 LBL positioning system with 3 to 6 deployed transponders. Transponders were deployed on 5 m long chains through the drifting ice cover and positions calibrated to a local floe-fixed x/y-coordinate system using measurements from a terrestrial laser scanner. The vicinity of the magnetic pole made vehicle heading information useless most of the time, so that heading information was derived from the filtered acoustic tracking in post processing by ignoring vehicle crabbing angles. Due to the high latitude and glitches in the survey software's coordinate conversions, we had to virtually move the surveys and use ›fake‹ geographic positions centred around 1°N/1°E. As emergency backup, two spare ROVs and plenty of ice drilling equipment were available.

Hugin AUV in the North-West Passage

In October 2021 together with University Laval (Quebec City) we conducted two successful


Fig. 2: The observation class ROV *Beast* deployed in its ice hole during the polar night of the MOSAiC expedition


Fig. 3: The AUV of Université Laval (Quebec City) during its deployment in the Canadian Arctic off *CCGS Amundsen*

under-ice dives with a recent model of a Kongsberg Hugin 1000 AUV (see Fig 3). The dives covering several kilometres under a loose and drifting ice pack, were conducted in shallow waters of less than 200 m depth to allow for DVL bottom tracking. Vehicle positioning was further supported by sparse LBL navigation with a single seafloor CNODE transponder and simultaneous tracking with a HiPAP502 USBL mounted on a deployment machine in the hull of research icebreaker *CCGC Amundsen*. The vehicle used its native features of surface avoidance and successfully dodged several thick pieces of ice throughout the dive. A small mini ROV was kept at hand for emergency preparedness, as well as ice drilling equipment.

Fig. 4: A SAAB-Sabretooth hybrid vehicle during recovery after a dive under the sea ice during the Endurance22 expedition to the Weddell Sea

The search for the wreck of *Endurance* in the Weddell Sea

In March 2022 a privately funded expedition hired offshore contractor Ocean Infinity, as well as many different support companies including ice information provider Drift & Noise Polar Services and scientists from the Alfred Wegener Institute. The successful search for the wreck was conducted with two SAAB Sabretooth hybrid vehicles (see Fig. 4). These are autonomous vehicles with up to 13 km of fiber-optic cable tether, that allowed live operator control and intervention during the dives. Survey-grade under-ice positioning at the seafloor in 3000 m depth was achieved by DVL bottom track aided inertial navigation additionally supported by long-range USBL tracking using a Sonardyne Ranger 2 low-frequency GyroUSBL deployed through the ship's moon pool. Vehicle deployments were aided by a team of experts on board, providing real-time ice drift forecasting and analysis of high-resolution radar satellite images. Emergency preparedness included a second vehicle equipped with a manipulator arm, as well as handheld dunking transceivers.

These three examples show, how successful ice operations can be conducted, if the right strategies are applied to the particular limitations of the mission at hand. Plenty of examples, however, demonstrate that ignorance of the complexity of under-ice operations and the lack of special precautions can lead to failed missions and expensive vehicle losses.

For the future, under-ice robotic exploration can hopefully be made a regular activity, as every mission contributes to the advancement in technology robustness. The market of consumer quadrocopters has shown in an impressive way how changing the scale of the vehicle fleet has led to quantum leaps in vehicle capabilities. As currently most strategies to improve under-ice operations involve high equipment costs, a critical prerequisite to regular under-ice missions is to lower the cost of systems and improve the development of low-cost solutions. A second priority comes to improved acoustic positioning capabilities, particularly at shallow tracking angles and large standoff distances in the complicated under-ice environment. //