ROBOTIC EXPLORATION BENEATH THE ICE: THE CHALLENGES, RISKS AND REWARDS OF DEPLOYING AN AUTONOMOUS UNDERWATER VEHICLE IN ANTARCTICA

by Peter King

(with four text-figures and one table)

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Measurements beneath Antarctic ice shelves are critical to our understanding of how the glaciers will change and melt. To access these regions, we rely on autonomous underwater vehicles (AUV), which are free-swimming robots. The Australian Maritime College in Launceston, Tasmania, is leading efforts to deploy these vehicles in some of the harshest environments on Earth. This paper provides an overview of the history and recent Australian efforts in deploying AUVs in under-ice environments and discusses recent advances in mission planning and the ongoing challenges to take measurements from beneath ice shelves.
Key Words: Antarctica, autonomous underwater vehicles, AUV, Australian Maritime College, Tasmania.

INTRODUCTION

A major consequence of climate change is the potential for sea-level rise due to the melting of Antarctic glaciers (IPCC 2019). The main contributor to this ice-mass loss is melting at the base of ice shelves, i.e., the floating extensions of glaciers, driven by ocean processes (Liu *et al.* 2015). Understanding the ocean properties beneath the floating ice shelf is key to understanding the mechanisms involved and the rate at which ice loss will occur.

Ice shelves may be tens to hundreds of metres thick and extend hundreds of kilometres from the grounding line, the point at which the floating ice shelf meets the continent. In addition, ocean depths around the ice shelves can range from hundreds to thousands of metres. What this means is that the areas beneath floating ice shelves are some of the most inaccessible regions on Earth (Dowdeswell *et al.* 2008). Figure 1 illustrates the general geometry and parts of an ice shelf.

One primary technology that allows collection of critical data in these formidable zones is an autonomous underwater vehicle (AUV). An AUV is a free-swimming robot, which does not rely on ongoing human control or any physical tether. They can carry a suite of sensors to measure critical areas of interest though self-guidance and unaided navigation, executing instructions provided by the operators.

Deployment of these AUVs under ice has immense benefits for our understanding of the interaction between the ocean and cryosphere. Deployment, however, comes with equally immense engineering challenges due to: the remoteness of the region; the lack of prior knowledge about the environment; and an invariant – that failure of any of the many sub-systems can lead to a total loss, due to the physical barrier presented by the vast ice mass. Put simply, there are no rescue plans for an AUV trapped under ice.

History

The use of AUVs beneath ice began in 1972 with the deployment of the Unmanned Arctic Submersible (UARS) beneath the Fletcher ice-island by the University of Washington's Applied Physics Laboratory (Francois & Nodland 1972). Further advancements saw the development and testing of the Autonomous Conductivity Temperature Vehicle in 1989 (Light & Morrison 1989) and the *Odyssey II* in 1993 and 1994 (Bellingham *et al.* 1993, 1994).

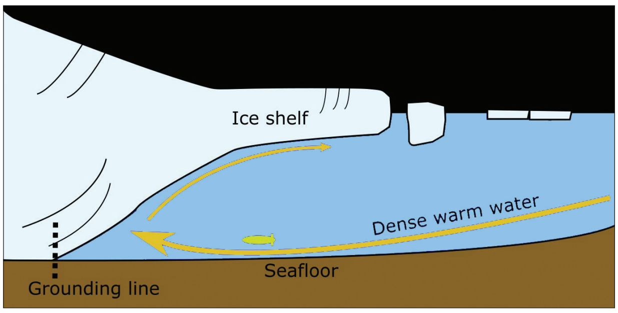

FIG. 1 — Geometry and parts of an ice shelf (not to scale). The diagram shows how the glacier flows from the continental ice sheet toward the ocean, forming a floating ice shelf. The point at which the glacier is still in contact with the seafloor is the grounding line. Icebergs are the large pieces of ice that break off the ice shelf. Sea ice is formed as seawater freezes, often in areas near ice shelves. Dense warm and high-saline water is heavy, and thus flows along the seafloor into the ice shelf cavity.

Great advancement in AUVs occurred in the late 1990s when International Submarine Engineering deployed the *Theseus* AUV for a record-breaking round-trip journey of over 300 kms beneath Arctic sea ice (Ferguson 1998). This vehicle incorporated many of the technologies still used today and made apparent that the technology could be used in these harsh environments at a meaningful magnitude of scale.

These pioneering deployments were critical, but still focused on sea ice; the bigger challenge of venturing beneath a floating ice shelf would remain unmet until 2005, when the UK's National Oceanographic Centre (NOC) would deploy their *Autosub 2* beneath the Fimbul Ice Shelf, in the Weddell Sea. The *Autosub 2* ventured 25 km into the cavity, surveying the seafloor on the incursion leg, and, for the first time, surveyed the basal surface of the ice on the excursion (Dowdeswell *et al.* 2008).

The *Autosub 2* missions also provided an unfortunate first – the loss of an AUV beneath the ice. On its last mission beneath the Fimbul Ice Shelf, the vehicle failed to return. This event manifested the worst-case estimates of loss probability for AUVs beneath ice and would shape how all future missions would be managed. The event also sparked important research into the study of risk and loss.

Tasmania's *nupiri muka* ('eye of the sea')

In 2014, the Australian Research Council Special Research Initiative, the Antarctic Gateway Partnership (AGP), began. This collaboration between the University of Tasmania (UTAS), the Commonwealth Scientific and Industrial Research Organisation (CSIRO), and the Australian Antarctic Division (AAD), had the aim of building further polar research capability in Tasmania (AGP 2020). The program was divided into four research themes: Cryosphere-ocean interaction; Open water and under-ice foodwebs; Solid earth-cryosphere interaction; and Marine technology and polar environments.

The marine technology theme's primary activity was the specification, acquisition and deployment of an AUV capable of operation in ice-covered waters and beneath ice shelves. This vehicle would serve to provide critical data to the other three research themes. In May of 2017, following a period of vendor selection, specification, factory tests and sea trials, the new AUV, built by International Submarine Engineering, arrived at the newly built Autonomous Maritime Systems Laboratory, located on the campus of the Australian Maritime College, Launceston. The vehicle was granted the palawa kani name, *nupiri muka*, meaning 'eye of the sea' by the Tasmanian Aboriginal Centre. Figure 2 illustrates the *nupiri muka* AUV in its original delivered state, showing the key internal components. Table 1 gives the key specifications as delivered and with subsequent upgrades.

CHALLENGES

There are key challenges to be met when deploying an autonomous robot in a remote and dynamic environment such as under ice.

Navigation

Electromagnetic signals do not propagate well through seawater, thus, an AUV has no access to a ubiquitous positioning source such as GPS (Al-Shamma'a *et al.* 2004). As these vehicles traverse tens to hundreds of kilometres beneath ice, attempting to return to a pre-determined recovery site and knowing its location becomes the primary challenge for an autonomous vehicle deployment. In lieu of GPS, some underwater vehicles use acoustic signals to provide positioning, but this requires deployment of beacons, which is limited by propagation ranges of tens of kilometres. In ice-covered regions, this becomes prohibitively difficult due to the physical barrier of the ice, hence beacons are often unfeasible for deployment. Long-range, under-ice deployment, as described here, is predicated on the ability of the AUV to maintain its own estimate of position and trajectory, unaided by external supports.

Modern AUVs use extremely high-quality, fibre-optic orientation and heading sensors capable of providing sufficiently accurate estimates of a true-north relative heading. When the AUV is operating in proximity to the seafloor, it can avail itself of onboard Doppler acoustic sensors to measure its velocity relative to the seafloor. The combination of heading and velocity allows for dead reckoning of the AUV's position, relative to a known start position from where it was launched.

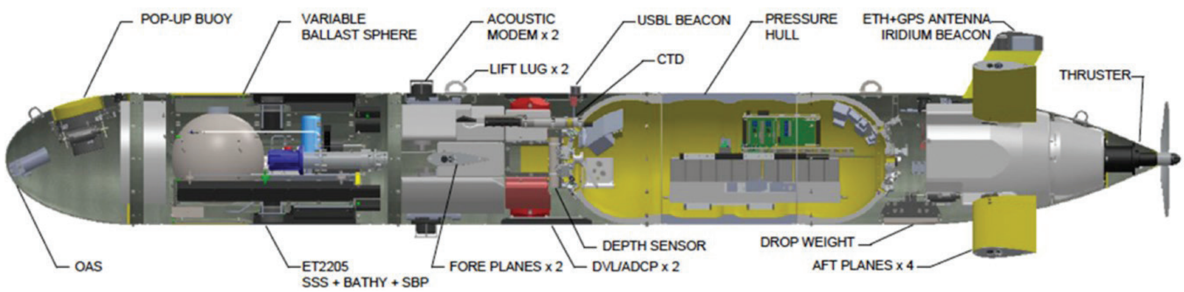

FIG. 2 — The *nupiri muka* AUV with labelled sub-components. The section labelled 'pressure hull' maintains a dry space for computers and batteries, whilst the remainder of the AUV is free flooding.

TABLE 1 — *nupiri muka* specifications

Attributes	As delivered	Upgraded
Length	6.5 m	7.6 m
Weight	1600 kg	1800 kg
Depth rating	5000 m	
Endurance	120 km	240 km
Navigation	Fibre-optic Gyroscope w/ Doppler velocity	
Variable ballast	±50 kg	
Obstacle Avoidance	Forward-looking sonar	
Sonar	- Sidescan Seafloor imagery w/Bathymetry - Sub-bottom profiler	Multibeam Bathymetry
Oceanography	- Conductivity, temperature - Water velocity	- Turbidity, Dissolved Oxygen - Trace-metal clean water sampler

Unknown and dynamic environment

An AUV must traverse an unknown area safely, avoiding the topology of the seafloor as well as the ice above. As previously stated, there is likely no prior knowledge of the locations or shape of either. Travelling towards its intended waypoint, the AUV must detect and guide itself safely through the cavity. This is accomplished by using a vertical swath of sonar beams that project forward from the AUV, which can detect the seafloor, ice and water column ahead of the vehicle. Pre-tuned algorithms determine the slope of the seafloor and range to any physical obstacles in the AUV's path. The AUV will, at first, attempt to adjust its vertical trajectory to pass unhindered, but if it is unable, the fault logic will cause the AUV to abort its trajectory and return towards the safe starting position.

In addition to the unknown topology of the seafloor and ice, there is a dynamic element where the ice may not be static. In areas with sea ice coverage and icebergs, there can be substantial movement over the temporal scale of a mission. Again, the AUV must be able to sense the world in front of it and react accordingly.

Loss under ice

The risks of operating an autonomous vehicle are greatest in ice-covered regions due to the physical barrier of ice, which prevents rescue of the AUV should it falter, and limits deployment of communication and position-aided infrastructure. In addition, the dynamic nature of floating ice can cause openings to close and move throughout the duration of a mission. This can, in turn, lead to safe launch and recovery sites not remaining a static location, thus impeding the AUV's return.

For AUV operations, in which a complex, robotic system must operate unaided and respond to the environment with no human interaction, the ice barrier can elevate even the most benign fault or failure to a catastrophic loss. Thus, planning and review of systems and instructions stages are critical. The mission and instructions provided to the AUV must be as such to provide the maximum chance of successful completion and recovery. The approach taken to address this challenge is described in the following section.

ANTARCTIC MISSIONS

The *nupiri muka* AUV has been deployed in Antarctica over two seasons. The 2018–19 season marked its maiden voyage, when it travelled to the Sørsdal Glacier in East Antarctica and in 2019–20, it went to the Thwaites Glacier in West Antarctica.

Preliminary work

Prior to its maiden voyage to Antarctica, the *nupiri muka* team convened a panel of experts in the field of polar AUV deployment to glean a set of best practices. This 'expert panel' met over three days and presented a series of findings (King *et al.* 2018), or 'best practices' for deployment of an AUV beneath ice. A methodology was then prescribed for creating risk-averse mission plans, described further by King *et al.* (2020).

A primary approach, when feasible, is to conduct a preliminary, mock mission prior to the high-risk mission. For under ice, this is a shortened version of the larger mission, in which the AUV would conduct a preliminary dive and approach to the ice along the same trajectory as the final mission but stopping and returning just prior to breaching the ice edge. The concept behind this approach is that most systematic and human errors can be caught early and corrected prior to commitment. The behaviour and response of the AUV can be analysed in situ.

Secondarily, the mission itself is constructed. Each mission is built on a strict set of sub-tasks, always undertaken in the same manner. A critical invariant is that the AUV never progresses from one sub-task to another, unless directed by the human observer or by way of a fault response. At the end of a mission, either through success or failure, the AUV will always strive to return to its initial safe location.

Initial dive – the AUV performs a vertical spiral to get to its working altitude or depth directly below the ship or support craft. This allows for minimisation of navigation error during the dive and maximises the effectiveness of acoustic communication devices.

Safe loiter – the AUV lingers beneath the surface vessel until commanded over acoustics to begin its incursion leg. If no such command is received, the AUV will eventually time-out and await further instruction or recovery.

Mission incursion – the AUV begins its mission incursion towards the ice. At any time if a fault or system value is out of tolerance, it will return to the safe-loiter location.

Mission return – if the endpoint is reached, the AUV returns to the safe-loiter location.

Sørsdal Glacier

In November 2018, the *nupiri muka* AUV was transported to Davis Station in East Antarctica aboard the RSV *Aurora Australis* for a capability demonstration of the AUV and team. The AUV was partially dismantled to fit within a standard 20-foot shipping container and was made ready on its arrival at the station. Local sea ice conditions at the station delayed AUV operations until late January 2019. Once clear, the AUV was deployed from the station via the boat ramp and transited nearly 20 km westward towards the Sørsdal Glacier Ice Shelf where it conducted several preliminary dives to gather information regarding the seafloor morphology and oceanographic conditions. This was the first such survey ever of the area; no prior measurements of ocean depth had been conducted.

In early February 2019, following several return trips to the ice shelf, the AUV was deployed beneath the ice shelf, following the seafloor on a 200-m incursion and then on a 500-m mission. Several days later, a subsequent mission sent the AUV on a 700-m incursion, transecting a large crack that had begun to open on the ice shelf. A total of three under-ice missions were conducted, collecting seafloor imagery and bathymetry, ice depth and morphology, and ocean temperature and salinity (fig. 3). As presented by Gwyther *et al.* (2020), these were the first ever such measurements in the area and included the discovery of a deep ocean trough extending into the glacial cavity, as well as a dense mass of cold water, which is likely preventing the incursion of warmer water, thus maintaining low-melt rates of the ice shelf.

Thwaites Glacier

At the end of 2019, *nupiri muka* departed New Zealand aboard the *Korean IBRV Araon* for the Thwaites Glacier region in West Antarctica. This mission was part of an international effort to determine the factors contributing to the rapid melting of the Thwaites Glacier, often referred to as the 'doomsday glacier' (Rowlatt 2020). Following a two-week journey to the region and a series of ship-based science activities, AUV deployments began in early February 2020. Locations of deployments were limited due to a massive band of sea ice extending 20–80 km out from the edge of the ice shelf.

The AUV was launched from the stern of the ship utilising a UTAS-built extendable ramp. Over five days, *nupiri muka* conducted six under-ice missions, beginning with 1-km incursions and working towards a maximum incursion of 30 km. In total the AUV conducted nearly 80 km of under-ice survey, mapping areas suspected to be pathways for warm water traversing towards the ice cavity (fig. 4). Due to the massive sea extent that season, the AUV was unable to reach the ice shelf itself.

Preliminary analysis of the data has been presented by Kim *et al.* (2020) utilising the AUV collected temperature data in conjunction with ship-based observations. A notable first on this deployment was the inclusion of a trace-metal clean-water sampler, which was able to collect over 40 samples along the entire incursion beneath the ice (analysis of this data is forthcoming).

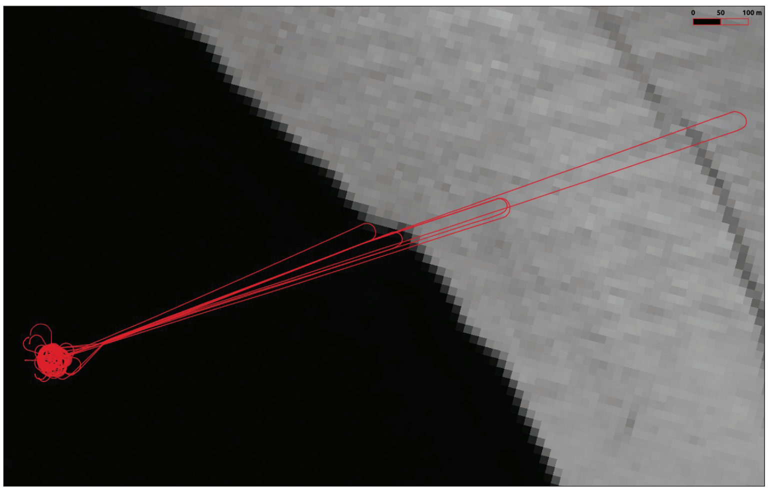

FIG. 3 — AUV track from Sørsdal Glacier ice shelf.

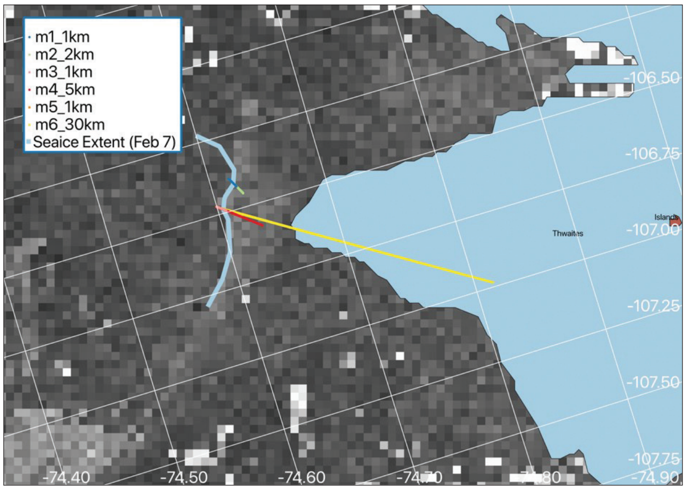

FIG. 4 — AUV missions at the Thwaites Glacier.

SUMMARY

Under-ice deployment of AUVs is a high-risk, high-reward activity. Deploying these free-swimming robots is a primary means of collecting some of the most critical data used to support our understanding of how ice shelves are changing and at what rate. Bore holes and lowered instruments can provide point sampling, but it can be argued that an AUV is the only means by which data across a geographic area from the region beneath a floating ice shelf can be collected.

The next five to ten years will see the team at the Australian Maritime College expand its international collaborations and return to Antarctica for longer and more ambitious missions. Further developments in risk mitigation, autonomy and battery technology will be key to these future deployments. In addition, more diverse vehicles and collaboration between multiple vehicles will frame the next generation of under-ice exploration.

Operating in these areas is fraught with challenges and risk, which are overcome through a combination of technology, engineering and planning. The future will see more AUVs visiting these areas, conducting more ambitious incursions each time. The risk of loss will always be present, but mitigation and the promise of reward will keep this a worthy endeavour.

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REFERENCES

AGP 2020: Antarctic Gateway Partnership, www.imas.utas.edu.au/antarctic-gateway-partnership (accessed 1 October 2020).

Al-Shamma'a, A.I., Shaw, A. & Saman, S. 2004: Propagation of electromagnetic waves at MHz frequencies through seawater. *IEEE Transactions on Antennas and Propagation* **52(11):** 2843–2849.

Bellingham, J.G., Deffenbaugh, M., Leonard, J.J., Catipovic, J. & Schmidt, H. 1993: Arctic under-ice survey operations. *8th International Symposium on Unmanned, Untethered Submersible Technology*: 50–59. https://marinerobotics.mit.edu/sites/default/files/Bellingham93uust.pdf

Bellingham, J.G., Goudey, C.A., Consi, T.R., Bales, J.W., Atwood, D.K., Leonard, J.J. & Chryssostomidis, C. 1994. A second generation survey AUV. *Proceedings of IEEE Symposium on Autonomous Underwater Vehicle Technology*: 148–155.

Dowdeswell, J.A., Evans, J., Mugford, R., Griffiths, G., Mcphail, S., Millard, N., Stevenson, P., Brandon, M., Banks, C., Heywood, K., Price, M.R., Dodd, P.A., Jenkins, A., Nicholls, K., Hayes, D., Abrahamsen, E., Tyler, P., Bett, B., Jones, D. & Ackley, **S.** 2008: Autonomous underwater vehicles (auvs) and investigations of the ice-ocean interface: deploying the autosub auv in antarctic and arctic waters. *Journal of Glaciology* **54**: 661–672.

Ferguson, J. 1998: The Theseus autonomous underwater vehicle. Two successful missions. *Proceedings of the International Symposium on Underwater Technology*: 109–114. https://ieeexplore.ieee.org/document/670072

Francois, R. & Nodland, W. 1972: Unmanned Arctic Research Submersible (UARS) system development and test report. University of Washington, Applied Physics Laboratory Technical Report 7219: 87.

Gwyther, D.E., Spain, E.A., King, P., Guihen, D., Williams, G.D., Evans, E., Cook, S., Richter, O., Galton-Fenzi, B.K., & Coleman, R. 2020: Cold ocean cavity and weak basal melting of the Sørsdal Ice Shelf revealed by surveys using autonomous platforms. *Journal of Geophysical Research* **Oceans 125:** 1–6.

IPCC 2019: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. **Pörtner, H.O., Roberts, D.C., Masson-Delmotte, V., Zhai, P. Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A., Nicolai, M., Okem, A., Petzold, J., Rama, B. & Weyer, N.M. (eds).** In press: 765 pp. (Available at: https://www.ipcc.ch/site/assets/uploads/sites/3/2019/12/SROCC_FullReport_FINAL.pdf)

Kim, H.B., Nam, S., Yoon, S.T., Lee, W.S., Yun, S., van der Merwe, P., King, P., Williams, G.D., Guihen, D. & Coleman, R. 2020: The pathways and heat transport of circumpolar deep water into the Thwaites and the Pine Island Glaciers, West Antarctica. *Proceedings American Geophysical Union Fall Meeting, December*, www.agu.org/Fall-Meeting-2020/Pages/Schedule-Program/Scientific-Program.

King, P., Williams, G., Coleman, R., Zürcher, K., Bowden-Floyd, I., Ronan, A., Kaminski, C., Laframboise, J., McPhail, S., Wilkinson, J., Bowen, A., Dutrieux, P., Bose, N., Wahlin, A., Andersson, J., Boxall, P., Sherlock, M. & Maki, T. 2018: Deploying an AUV beneath the Sørsdal ice shelf: Recommendations from an expert-panel workshop. Proceedings IEEE/OES Autonomous Underwater Vehicle Workshop: 1–6, https://ieeexplore.ieee.org/document/8729786.

King, P., Zürcher, K. & Bowden-Floyd, I. 2020: A risk-averse approach to mission planning: nupiri muka at the Thwaites Glacier. *Proceedings IEEE/OES Autonomous Underwater Vehicle Workshop*: 1–5, https://ieeexplore.ieee.org/document/9267892.

Light, R. & Morrison, J. 1989: The autonomous conductivity-temperature vehicle: First in the sea shuttle family of autonomous underwater vehicles for scientific payloads. *Proceedings IEEE OCEANS*: 793–798. https://ieeexplore.ieee.org/document/586683

Liu, Y., Moore, J.C., Cheng, X., Gladstone, R.M., Bassis, J.N., Liu, H., Wen, J. & Hui, F. 2015: Ocean-driven thinning enhances iceberg calving and retreat of Antarctic ice shelves. *Proceedings of the National Academy of Sciences* 112(11): 3263–3268.

Rowlatt, J. 2020: Antarctica melting: Climate change and the journey to the ‘doomsday glacier’, www.bbc.com/news/science-environment-51097309 (accessed 1 October 2020).

(accepted 23 March 2021)