The Memorial Explorer: Developing the role of AUVs in under-ice research

Peter King, Ron Lewis, Dan Walker*, Polly Alexander†, Neil Bose‡, and Anthony Worby§

* Marine Environmental Labratory for Intelligent Vehicles
Memorial University of Newfoundland, St. John's, NL, Canada
Email: {peter.king,ron,dwalker}@mun.ca

† Tasmanian ICT Centre, Commonwealth Scientific and Industrial Research Organisation(CSIRO), Hobart 7000 TAS, Australia
Australian Maritime College, University of Tasmania (UTAS), Launceston TAS, Australia
Email: polly.alexander@csiro.au

‡ Australian Maritime College
University of Tasmania (UTAS), Launceston, TAS, Australia
Email: nbose@amc.edu.au

§ Antarctic Climate and Ecosystems Cooperative Research Centre
Australian Antarctic Division, Kingston, TAS, Australia
Email: A.Worby@utas.edu.au

***Abstract*—Autonomous Underwater Vehicles are a leading technology for under-ice deployment and research. Memorial University and its Explorer AUV, in cooperation with the University of Tasmania and the Australian Antarctic Division, has embarked on a multi-phase development program that will lead to a scientific mission in the Australian Antarctic. Completion of Phase I saw the AUV deployed in the Canadian high Arctic and acoustic data collection performed in the Australian Antarctic. Currently in Phase II, the AUV is being fitted with a full suite of survey tools and will see developments in the fields of navigation, positioning and mission completion.**

Phase III will see further developments in AUV technology for under-ice research, with the ultimate goal being the AUV deployed in the Antarctic for a scientific mission to explore the role of sea-ice in the World's climate.

I. Introduction

Autonomous Underwater Vehicles (AUV)s are a leading technology for oceanographic operations under the ice. The capability for an unmanned and untethered vehicle to collect data from beneath the ice is invaluable for the understanding of polar regions and the ocean as a whole.

Memorial University of Newfoundland's Marine Environmental Research Laboratory for Intelligent Vehicles (MERLIN) operates a $3000m$ depth rated Explorer class AUV, manufactured by International Submarine Research (ISE) Ltd. This $4.5m$ vehicle has a large payload capacity, long endurance and is a highly stable platform suitable for under-ice survey (Fig 1). The current focus of MERLIN is to develop the Explorer as the ideal vehicle platform for under-ice missions.

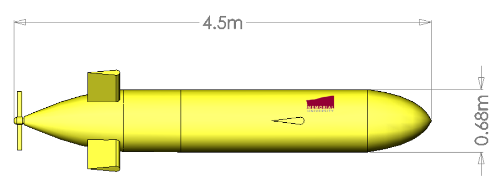

Fig. 1. The Explorer AUV.

Discussion of an ongoing three phase development endeavour will be the focus of this paper. Through partnership with the University of Tasmania and the Australian Antarctic Division, this effort will result in an under-ice research mission in the Australian Antarctic. This mission will quantify sea ice using bathymetric survey techniques to supplement existing air based survey and remote satellite sensing. The application of AUV technology to this problem will provide considerable and novel data to the area of sea-ice mass balance. Research into this specific area has potential ramifications in the larger question of the role of sea ice mass on global climate change.

A. Project Overview

This development is a multi-phase international endeavour. Key participants are Memorial University, the University of Tasmania and the Australian Antarctic Division. The develop began in earnest in 2009 and is expected to complete in 2013.

Development is divided into three phases, each focusing on a set of goals which build toward a final scientific mission in

978-1-4244-5222-4/10/$26.00 ©2010 IEEE

the Australian Antarctic. Phase I focuses on deployment issues and acoustic data collection. Phase II is a platform development phase where the AUV is to be made commercially survey capable. This phase will also see the development of advanced navigation and localization techniques for improved AUV position during long under-ice transects. Phase III will see development in the AUV for improved mission management, intelligence and under-ice communications and localization. The end of Phase III will be a mission involving the AUV to measure sea-ice ridge keels.

The following sections outline each phase, their progress and their particular goals and methodology.

II. Phase I

In 2009 MERLIN participated in two ice-based missions: first to the Canadian high Arctic and second to the Australian Antarctic. These missions provided ice deployment experience and a chance to explore issues related to AUV operations in ice covered regions.

The main goals of this initial phase were three fold:

- To understand and meet the logistical challenges involved with mobilizing a large AUV in an ice covered region
- To develop a system to allow an AUV to be docked under the ice
- To collect and analyze under-ice acoustic data that would lead to developments in both communications and positioning

A. Arctic under-ice AUV deployment

In early 2009 the MERLIN team ventured to the Canadian high Arctic as part of a developmental program to employ AUV technology to substantiate Canada's claim under the United Nations Convention Law of the Sea (UNCLOS) article 76 [1]. This mission served as a developmental exercise for logistical issues relating to vehicle mobilization, transportation, operation and demobilization on-ice. As part of this work a unique under-ice docking system known as CATCHY was developed. Many lessons were learned in this mission, from which best practices were extracted for future on-ice missions with this technology.

1) Under-Ice Mobilization: A major part of any AUV mission is the mobilization of all necessary equipment to the area. This task is non-trivial when one is deploying in a remote ice-covered region. The mobilization must provide all necessary equipment, tools and spares, as there is no opportunity for replenishment or replacement. Due to the nature of remote ice-covered regions transportation is often limited to small planes, helicopters and snowmobiles, thus all equipment and the AUV itself must be mobile utilizing only these means.

To meet transport requirement a system of modularized crating was developed to split the AUV into four sections, each with a sub-frame to support the vehicle, bracing to allow a rigid plywood covering to be attached, and Delrin skids for easy movement on any surface, from concrete to ice. Each section is easily towable by a snowmobile, handled by pallet jack, can be lifted safely by forklift and fits within the cargo hold of many aircraft. The sections can be attached together to allow re-assembly of the vehicle on the sub-frame.

2) Under-Ice docking: As part of this phase of development the Canadian AUV Through-ice Capture and Hold sYstem (CATCHY) was developed [2]. This system was tasked with providing a method to capture an AUV under the ice, retain it in variable current conditions, provide a means for charging and data upload, and to allow under-ice INU alignment. The AUV would not be recovered after docking, but rather be ready to launch for a subsequent mission.

Existing docking systems can be grouped as those employing a latching mechanism or those utilizing a cone or funnel [3]. The need for precise homing and navigation required for the cone type systems, such as the one employed by [4], does not guarantee success upon an AUV approaching for docking, as well the retention is directional and does not provide a rigid mounting point. Thus it was decided that a rigid system would be employed that did not utilize a homing algorithm for docking.

To ensure higher percentages of success, the AUV is relatively passive in the docking procedure. At the end of a long under-ice transect the AUV is only required to be within $100m$ of the docking point. At this point a small ROV is used to provide the latching of the docking system to the AUV. A cable is used to pull the AUV into the docking cradle. The complete CATCHY system and ROV operate through a hole in the ice of no more than $30cm$ x $30cm$ and is fully transportable by helicopter or by snowmobile and sled. The logistical footprint is far less than that of a full AUV recovery setup, such as would be employed at a base-camp.

Figure 2 shows the complete catchy mechanical structure. The mid-section consists of aluminium pipe in which additional sections can be added for various ice thickness, up to $5m$. Prior to deployment in the Arctic, the system was tested at Memorial University's Marine Institute $4.5m$ flume tank where the system was shown to operate in currents up to $1m/s$, with the AUV recovered and retained in orientations ranging from nose-in to full broad-side into the current. The CATCHY system also allows rotation of the AUV while docked, thereby enabling INU alignment *in-situ*.

Deployment in the Arctic allowed for several full recovery and deployment trials, as well as, two complete simulated missions. In all cases the CATCHY system with deployed ROV were successful in recovering an AUV resting under the ice and providing INU alignment.

B. Antarctic acoustic propagation experiment

In late 2009, sea ice trials were conducted in Antarctica as a collaborative effort between Memorial University, University of Tasmania, the Institut Franais de Recherche pour l'Exploitation de la Mer (IFREMER) and the Australian Antarctic Division to evaluate acoustic propagation in an under ice environment. The Australian vessel *RSV Aurora Australis* was made available for this mission. Data was collected of

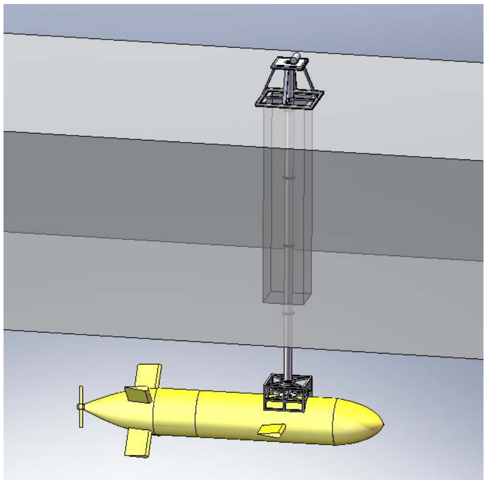

Fig. 2. CATCHY system.

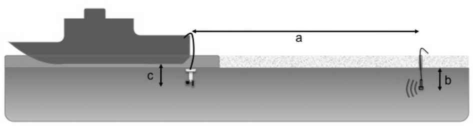

Fig. 3. Antarctic acoustic propagation setup.

the received acoustic signal and of both the ambient and ship-based noise levels. Analysis of this data will be used to develop an emergency localization system, providing a simple and robust means of locating an AUV from a moving vessel.

1) Methodology: Experiments were conducted using a pair of $10kHz$ transmit-only pingers and two receiver systems. The pingers were RJE ULB-364/10 omi-directional transmitters, set to a transmit power of $183dB$, with transmit periods of $40s$ and $600s$ respectively and a pulse width of $5ms$. Transmitters were deployed through the ice and left in free-running mode as the ship moved away.

The two receiver systems remained ship-borne with varying deployment depths. The first receiver system consisted of a broad spectrum hydrophone fed into a pre-amplifier deck unit, allowing frequency tuning and gain adjustment. This signal was subject to a super-heterodyne receiver and its output presented as an audio signal for both automated and manual ping detection. The second receiver was an ITC 8095 hydrophone connected to a pre-amplifier, DAQ card and laptop.

The first system was used for detection of transmitted pings from the transmitters, this allowed measurement of maximal ranges that signals could be detected from the deployed position. The second system allowed collection of raw acoustic data, including ambient and ship-based noise.

Figure 3 shows the deployment of the acoustic equipment.

2) Preliminary Results: Final analysis of results is currently being conducted and full Journal publication is in preparation, a brief overview of results is presented here.

Acoustic ranging utilizing the ping-detection receiver resulted in both audible and automatic detection of pings up to a range of about $2200m$. Audible only detection was possible to a range of nearly $4500m$. All data was logged and it is hoped that the automatic detector will be refined to allow full detection of all audible pings.

Noise results provided a view of the expected noise levels for ship-based acoustic detection. Experiments were conducted from the RSV *Aurora Australis*, a ship that would be typical of the kind of vessel used in a future mission. Levels were highest in the $0kHz$ to $5kHz$ band, as high as $94dB$. As frequency increased, there was a near linear reduction in noise power through the band. At the transmit signal band of $10kHz$ noise levels were observed ranging from $64dB$ to $79dB$.

III. Phase II

Starting in mid 2010 several developments will take place with the Explorer AUV. The Explorer is to be developed as a commercial survey capable AUV through the integration of a suite of instruments, including multi-beam and side-scan sonar systems. These new capabilities will be extensively field tested to ensure proper integration of the equipment and to test the AUVs capability for collecting and logging data over higher endurance missions. The navigational stability of the AUV will also be tested to ensure it is achieving its maximum potential. Lessons learned in this phase will be used for the basis of adapting the sensing hardware to upward looking, a configuration that will allow data collection in Phase III.

Developments will also take place in the areas of advanced navigation and mission accomplishment. Exploration into a Kalman filter, customized to the Explorer will be conducted. As well a new methodology for AUV path traversal will be investigated for underwater application.

A third development will see the completion of the free-running pinger localization system initiated in Phase I. Utilizing data collected in 2009, systems will be made ready for deployment under-ice. This will be the backbone of safety and loss-mitigation for future missions.

Developments are currently in progress and are described in more detail below.

A. Hardware Integrations

By the end of 2010 the Memorial Explorer is to be fitted with a Kongsberg EM2000 multi-beam survey system and an EdgeTech 2200MP side-scan sonar. The resulting payload is shown in table I. Integrations will be performed by a partnership between Memorial University's MERLIN lab and the AUV manufacturer, ISE. A series of acceptance tests will be conducted at the manufactures testing site to allow a full system-acceptance test of the vehicle as a survey capable platform.

B. Navigation and Mission Control

Through a partnership with the Institute for Ocean Technology a customized Kalman filter will be developed. This filter will be built around a dynamic model of the Explorer and will illustrate the performance gains of a customized filter over that of a commercial-off-the-shelf (COTS) system. It is the hope of this development to provide insight and gains

TABLE I
AUV PAYLOAD AT END OF 2010.

Item	Description
Navigation Unit	iXsea PHINS INU
Multi-Beam	EM 2000
Side-Scan	2200MP
CTD	FastCat
DVL	RDI Navigator
Battery Capacity	17.5kWh

into the navigational stability of the Explorer and AUVs in general. A series of benchmark trials will be conducted to gain a full understanding of the current performance of the Inertial Navigation Unit (INU) and the improvement that could be made through customization.

Research into the adaptation of Qualitative Navigation will be conducted in Phase II to determine if an alternate means of AUV path traversal would be applicable to under-ice survey. This methodology does not rely upon absolute vehicle positioning, and thus would de-couple mission performance from navigational accuracy. Sonar image data would be used to determine if the AUV is in a familiar position and which path will take it toward its ultimate goal. Again benchmark testing will be used to quantify potential gains in the alternate methodology.

C. Emergency Locator

As investigated in Phase I, a full system development will take place to produce a free-running pinger and receiver that is capable of locating an AUV from a moving ship. The pinger will be independent of all AUV systems, this is to ensure it maintains operation in the face of vehicle failure. The receiver will include hardware and signal processing capabilities to detect pings as they are received. In addition to this a novel algorithm will be developed to determine AUV position relative to the ship based on accurate time measurements of the received pings in relation to current ship's position.

Testing of this system prior to deployment will ensure its operation. This system will become a vital component to the overall risk mitigation of AUV utilization in under-ice environments.

IV. PHASE III

In cooperation with the University of Tasmania and the Australian Antarctic Division, the Explorer AUV will be used to research the role of Antarctic sea ice in climate change and the potential decline in sea ice cover caused by global warming. This phase of the project will: quantify the size and shape of pressure ridge-keels to obtain the total volume of sea ice; improve understanding that links sea ice with distribution of ice algae and krill - key components of the Southern Ocean ecosystem; and develop an ice thickness mapping capability to provide baseline measurements from the Antarctic. It will do this by creating terrain maps from the underside of the ice from which volumetric calculations can be made.These calculations will be correlated with satellite data.

A. Background

Antarctic sea ice is an integral part of the global cryosphere and strongly influences climate through the ice-albedo feedback mechanism, the insulating effect of sea ice on the ocean and the influence of deep-water formation on global ocean circulation [5] [6] [7]. One of the most serious and dramatic geophysical consequences of global warming has been the loss of Arctic sea ice, which has thinned over much of the Arctic basin by as much as 43% [8] [9] [10], and retreated to a record low in the 2007 summer [11].

In the Antarctic, the extent of sea ice has increased slightly over the last 30 years, but the changes in its total volume are unknown. Changes in the volume of Antarctic sea-ice would have major implications for global ocean circulation, climate and marine ecosystems.

The Australian Antarctic Division (AAD) is undertaking projects to map ice and snow thickness in the Antarctic and surrounding sea areas. Current techniques make use of satellite and aircraft-based measurements of sea ice and snow cover combined with techniques for estimation of the thickness of pressure keels and their subsequent volume [12]. These techniques have been partially validated using measurement of pressure keel thickness made from ice-breaker ships while they break through ridges [12]. This validation is limited to pressure keels of a size that the ship is able to break 3-5m size and with keels of potential depth up to 15m this is not sufficient. For these satellite and aircraft-based measurement techniques to be used reliably they need to be calibrated and validated by comparing results gained from aerial data and estimation techniques with accurate under-ice terrain mapping and volumetric calculation. The most accurate way of measuring pressure keel depth, shape and volume is to create a map of the under-ice 'terrain' by using a multi-beam echo sounder.

An under-ice capable AUV is the only safe and repeatable way to move this instrument, with geo-referenced coordinates, under the ice on multi-kilometre transects. AUVs have already successfully been used to take sonar images of the under-side of Arctic sea ice [13] [14] They have also been operated under glacial ice in the Antarctic [15] [16] and in the process have obtained remarkable data on under-ice fauna that has vastly improved our understanding of the ocean environment and of the biases in sampling the ocean [17] [18].

Currently, under-ice AUV missions are still high risk. There are many environmental conditions that make the under-ice environment particularly dangerous for AUVs. Most difficult of these are the inability of the AUV to surface and the highly dynamic nature of the ice, which has unpredictable movement, shape and size. The proposed site for the field trials is in the region of the Mertz Glacier at longitude 145E, almost due south of Tasmania. Key challenges for this site are strong currents, drifting pack ice, and a bottom depth of greater than 1000m. The pack ice in this area contains icebergs which have drafts of several hundred meters.

The greatest problems created by the dynamic ice conditions are: the unpredictable drift of the ship within the ice thus creating a moving target to which the AUV must return; reduction of underwater communications from multipath echoes; and the occurrence of dynamic obstacles which act as both obstacles to trajectory plans and further impair communication.

Surfacing is a technique commonly used as an input to navigation systems through GPS systems, a chance for through air communications with operators, and as an emergency response in the case of vehicle faults. The inability to surface and dynamic ice movement mean the navigation systems, fault detection and response systems and through water communication systems must be developed with several layers of failsafe and be proven to be robust in under-ice conditions before field deployment. The main ways of mitigating these risks is through the development of robust and reliable hardware and software systems that are able to interact with the environment and have undergone many hours of sea trials.

B. Goals

Phase II will bring the Explorer to a state where it has reliable under-ice communication and an advanced navigation system with minimal drift without bottom lock. The key outstanding problems are those created by the dynamic movement of the ship in the ice pack, dynamic obstacles, and the effect of the vehicle's inability to surface on fault and emergency behaviours.

A human operator in a harsh environment is equipped with a strong sense of self-preservation that motivates their decisions and actions. This sense of self preservation creates an ability to assess and make decisions based on a combination of the current and anticipated future states of the surrounding environment and their own capability, as well as the value and cost of possible escape scenarios. One of the problems with working in dynamic unknown environments is that it is very difficult for an AUV operator to foresee every possible situation the AUV may encounter and imbue the vehicle with their own value system for self preservation by explicitly programming a series of responses for every eventuality. Self-preservation in an under-ice situation is a multifaceted problem where both 'home', and what emergency behaviours will be 'safe' are dynamic concepts. It is therefore an advantage to have an intelligent planning system capable of providing a 'best fit' response to both anticipated and novel situations. For this to be the case, increased on-board intelligence and situational awareness must be developed and tested.

This intelligent system must give the AUV the ability to adapt to changes in itself or in the environment and prioritise self-preservation above the original scheduled tasks. This system can be achieved through the integration of an advanced system for fault detection and diagnosis into an architecture for real-time deliberative mission generation and re-scheduling. For the system to be effective it needs to have a comprehensive sense of situational awareness and self awareness from which it can make predictions of future states as well as assessment of current state.

C. Methods

At the moment this phase of the project is in the concept and development stage. Areas that have been identified as requiring investigation are:

- Adaptive planning architecture
- Enhanced situational awareness
- Advanced fault-detection and diagnosis

Patron et al. [19] define *Situation Awareness* as "The human capability of dealing with and understanding highly dynamic and complex environments". They further break this down into "perception of the environment, comprehension of the situation and projection of the future status."

This definition of situational awareness is a means of describing a knowledge base that takes into account a concept of past, present and future. Providing a robot with enhanced situational awareness could be seen as supercharging the Sense stage in the classic robotics Sense Plan Act (SPA) cycle. While Situational Awareness gives the tools for planning and action, it is at its core an enhanced concept of 'sensing' the environment.

Advanced fault-detection and diagnosis is another tool that feeds in to the Sense stage of the cycle. The greater knowledge that the system has of what is normal, the better and earlier its assessment of faults. Early fault detection is an important step towards increased reliability and dependability.

Adaptive planning falls into the Plan stage of the cycle and is the decision maker in system. There are many existing systems used for adaptive planning and deliberative rescheduling. Where possible this project will make use of existing software. Two adaptive planners being investigated are TREX [20], and ORCA [21].

V. Discussion

The aim of the work is to develop the AUV technology such that it can operate in an under sea ice environment as reliably as in open water. In particular it is planned to improve navigation and positioning of the vehicle as well as its fault responses in such a way that reliable missions can be conducted in a highly dynamic ice field environment.

Acknowledgements

We acknowledge the contribution and collaboration of the following: The Institut Franais de Recherche pour l'Exploitation de la Mer (IFREMER); International Submarine Engineering Ltd. (ISE); The National Research Council of Canada's Institute for Ocean Technology (IOT); and Memorial University's Marine Institute (MI).

This work is made possible through funding by: The National Science and Engineering Research Council (NSERC);The University of Tasmania; The Australian Maritime College; The Antarctic Climate and Ecosystems Cooperative Research Centre; and the Atlantic Canadian Opportunities Agency (ACOA).

REFERENCES

[1] (2009) United nations convention on the law of the sea. [Online]. Available: http://www.un.org/Depts/los/convention_agreements/texts/unclos/part6.htm

[2] P. King, R. Lewis, D. Mouland, and D. Walker, "CATCHY: An AUV Ice Dock," in *OCEANS 2009*, Oct. 2009.

[3] B. Hobson, R. McEwen, J. Erickson, T. Hoover, L. McBride, F. Shane, and J. Bellingham, "The development and ocean testing of an AUV docking station for a 21" AUV," in *OCEANS 2007*, 29 2007-Oct. 4 2007, pp. 1–6.

[4] B. Allen, T. Austin, N. Forrester, R. Goldsborough, A. Kukulya, G. Packard, M. Purcell, and R. Stokey, "Autonomous docking demonstrations with enhanced REMUS technology," in *OCEANS 2006*, Sept. 2006, pp. 1–6.

[5] JE Walsh. The role of sea ice in climate variability: Theories and evidence. *Atmosphere-Ocean*, 21:229–242, 1983.

[6] J.A. Curry, J.L. Schramm, and E.E. Ebert. Sea ice-albedo climate feedback mechanism. *Journal of Climate*, 1151(8):240247, 1995.

[7] D Rind, R Healy, C Parkinson, and D Martinson. The role of sea ice in 2 x CO2 climate model sensitivity. Part I: The total influence of sea ice thickness and extent. *Journal of Climate*, 8:449–463, 1995.

[8] DA Rothrock, Y Yu, and GA Maykut. Thinning of the Arctic sea ice cover. *Geophysical Research Letters*, 26:3469–3472, 1999.

[9] DA Rothrock, J Zhang, and Y Yu. The Arctic ice thickness anomaly of the 1990s: A consistent view from observations and models. *Journal of Geophysical Research*, 108:28–1–28–10, 2003.

[10] Peter Wadhams and N.R. Davis. Further evidence of ice thinning in the Arctic Ocean. *Geophysical Research Letters*, 27(24), 2000.

[11] M.C. Serreze, M.M. Holland, and Julienne Stroeve. Perspectives on the Arctic's shrinking sea-ice cover. *Science*, 315(5818):1533, March 2007.

[12] AP Worby, CA Geiger, MJ Paget, ML Van Woert, and SF. Thickness distribution of Antarctic sea ice. *J. Geophys. Res*, 113, 2008.

[13] P. Wadhams, J. P. Wilkinson, and S. D. McPhail. A new view of the underside of Arctic sea ice. *Geophysical Research Letters*, 33(4):L04501, 2006.

[14] P. Wadhams and MJ Doble. Digital terrain mapping of the underside of sea ice from a small AUV. *Geophysical Research Letters*, 35(1):L01501, January 2008.

[15] M. Pebody. Autosub operations under the Pine Island Glacier. In *Proceedings of IEEE AUV*, 2008.

[16] JE Strutt. Report of the inquiry into the loss of Autosub2 under the Fimbulisen, 2006.

[17] A.S. Brierley, P.G. Fernandes, M.A. Brandon, F. Armstrong, N.W. Millard, S.D. McPhail, P. Stevenson, M. Pebody, J. Perrett, M. Squires, and Others. Antarctic krill under sea ice: elevated abundance in a narrow band just south of ice edge. *Science*, 295(5561):1890, 2002.

[18] AS Brierley and DN Thomas. Ecology of Southern Ocean pack ice. *Advances in marine biology*, 43:171, 2002.

[19] P. Patrón, E. Miguelanez, Y. Petillot, and D. Lane. Fault tolerant adaptive mission planning with semantic knowledge representation for autonomous underwater vehicles. In *Intelligent Robots and Systems*, page 25932598, 2008.

[20] C. McGann, F. Py, K. Rajan, H. Thomas, R. Henthorn, and R. McEwen. T-REX: A deliberative system for AUV control. *ICAPS WS on Planning and Plan Execution for Real-World Systems, Providence, RI, USA*, 2007.

[21] R.M. Turner. Context-sensitive, adaptive reasoning for intelligent AUV control: Orca project update. In *INTERNATIONAL SYMPOSIUM ON UNMANNED UNTETHERED SUBMERSIBLE TECHNOLOGY*, page 426435. Citeseer, 1995.