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Deep Sea Underwater Robotic Exploration in the Ice-Covered Arctic Ocean with AUVs

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Abstract—The Arctic seafloor remains one of the last unexplored areas on Earth. Exploration of this unique environment using standard remotely operated oceanographic tools has been obstructed by the dense Arctic ice cover. In the summer of 2007 the Arctic Gakkel Vents Expedition (AGAVE) was conducted with the express intention of understanding aspects of the marine biology, chemistry and geology associated with hydrothermal venting on the section of the mid-ocean ridge known as the Gakkel Ridge.

Unlike previous research expeditions to the Arctic the focus was on high resolution imaging and sampling of the deep seafloor. To accomplish our goals we designed two new Autonomous Underwater Vehicles (AUVs) named Jaguar and Puma, which performed a total of nine dives at depths of up to 4062m. These AUVs were used in combination with a towed vehicle and a conventional CTD (conductivity, temperature and depth) program to characterize the seafloor. This paper describes the design decisions and operational changes required to ensure useful service, and facilitate deployment, operation, and recovery in the unique Arctic environment.

I. INTRODUCTION

Despite the singular biological, geological and physical oceanographic characteristics of the Arctic seafloor, it remains one of the least explored sections of the planet. The Gakkel Ridge, the focus of this expedition, is the Arctic continuation of the Mid-Oceanic Ridge system. The Gakkel Ridge has an ultra slow spreading center with the potential to provide unique insights into the nature of the Earth’s mantle. Recent work has also found widespread hydrothermal venting along the Ridge. This fact, when coupled with the thirty million year geological isolation of the Arctic Ocean, holds the potential for the discovery of hydrothermal vent organisms that have been evolving independently for a long period of time.

The harsh conditions associated with year-round ice cover preclude the use of standard oceanographic technologies for mapping, sampling and otherwise exploring this region. The resources required to deploy manned submersibles under-ice in the Arctic are significantly higher than for Autonomous Underwater Vehicles, and most submersible operators consider it too risky to send people under the ice, despite the recent Russian dives near the North Pole. Towed and remotely operated vehicles are also limited in their utility by the nature of ice-breaker operations, which are highly constrained in movement by dense surface ice. AUVs hold...
the best promise for freely working on the seafloor in these limiting conditions.

Based on our experiences during AGAVE with the Puma and Jaguar AUVs, we examine the design constraints associated with under-ice AUV operations (section III), mechanical design (section V), and system software (section VI), and present the results of a typical deepwater mission (section VII) before offering some concluding remarks (section VIII).

II. Related Work

AUVs have been used for under-ice exploration in previous expeditions to both the Arctic and the Antarctic polar regions. The Theseus AUV was used to lay optical fibre under the ice in the mid nineties[1]; the Odyssey group[2][3] also conducted expeditions in the Arctic; the British AUTOSUB AUV gathered mid-water column scientific data with forays under the ice in the Antarctic[4]; and various groups have worked in lakes[5] and cenotes[6] as analogs to Arctic and Antarctic exploration. Previous groups have also examined the particularities of operating a vehicle through a hole in the ice[7]. The defining differences between these programs and ours include: a requirement for working near the seafloor in ice[7]. The defining differences between these programs and ours include: a requirement for working near the seafloor in ice[7].

III. Under-Ice Arctic Operations

During typical open-water AUV operations the control ship is positioned near the survey site, and an AUV is lowered from the deck and released on its mission. Once the mission is finished, or if a problem occurs, the AUV returns to the surface wherever it happens to be. If possible, the AUV is tracked while it is in the water (and in particular while it is on its way back to the surface). Once it reaches the surface, the vehicle is located visually, with the aid of a radio direction finder (RDF) or another radio-based localization scheme such as GPS coupled with an RF modem. The ship can then be driven to the AUV, where it is recovered.

Such a scenario is ruled out immediately for Arctic operations by the difficulty of finding and recovering an AUV through several meters of ice, and by the restrictions imposed by the ice on ship maneuverability. Underwater tracking becomes essential, rather than just convenient. Moreover it is necessary to be able to actively control the vehicle from the surface to direct it to open leads in the ice. These two requirements lead to significant changes in how the robots are built and used, and in what we as engineers did during the long periods of time that the robots were in the water.

Our basic mode of operation called for us to drive an ice-breaker to an open lead or pond within a kilometer of our area of interest. The availability of leads varied from dive to dive, as shown in Figure 2. An AUV would then be launched through the lead, from which it would follow a programmed mission, navigating primarily using acoustic beacons previously moored to the seafloor and surveyed from the ship’s helicopter. As missions could last as long as 24 hours, the open lead used to deploy the AUV would typically drift several kilometers from the dive site, making it unusable for recovery. We thus needed the ability to direct the AUV to a new recovery site, even in case of hardware or software failure, as described in section VI. Each recovery featured a unique and unpredictable set of ice conditions, including acoustic shadowing and multipath from ice floes, and salinity changes caused by surface ice melt leading to ballasting problems. These conditions near the surface precluded standard navigation and communications and posed the risk of a complete loss of a trapped vehicle. It was therefore imperative to retain as much control of the AUV as possible, despite any malfunctions.

IV. Navigation and Acoustic Communications

Electromagnetic (EM) radiation is quickly absorbed by sea water. A typical radio modem operating in the 900 MHz band stops functioning entirely as soon as the antenna goes more than a few centimeters below the surface of the ocean. Acoustic communication is the only known wireless communication method that works reliably over long distances through water. While typical surface- or air-based robots might use EM signals for both navigation (i.e. GPS) and communication (i.e. radio modems or WiFi), underwater vehicles generally rely on acoustic signalling for both navigation and communication. Puma and Jaguar both use a WHOI MicroModem [8] for long-baseline (LBL) network interrogation and for point-to-point communication between the AUVs and the ship.

A. Navigation

Since GPS does not work underwater, when georeferenced navigation is necessary a team typically deploys a set of acoustic beacons, forming an LBL network. These beacons are programmed to listen for a short sound pulse at a specific frequency (a “ping”), and respond with a pulse...
at a different frequency. An AUV interrogates the network by generating a query ping, and measuring how much time elapses before it hears the responses from the beacons. These travel times, together with the known locations of the deployed beacons, provide constraints on the possible locations of the robot. For a vehicle with an on-board depth sensor, only two LBL beacons are required to produce a fully-constrained position fix. At the second of the two AGAVE operating sites, for example, we deployed four Benthos LBL beacons from tethers suspended about 150 meters above the sea floor. Each beacon was programmed to listen for a 9 KHz ping, and reply at a unique frequency (one each at 9.5, 10, 10.5 and 11 KHz). The operating range of each beacon was about seven kilometers, so four beacons in the water gave us the flexibility to survey a fairly large area, as shown in figure 4.

An LBL network such as this is generally sufficient for open-water operation, but in the presence of ice many otherwise easy problems became difficult. The seemingly simple tasks of deploying and surveying the locations of the LBL beacons is complicated by the limited maneuverability of the ship. We were able to work around these problems by using the ship’s helicopter for the beacon survey, and in at least one case, for moving LBL beacons onto the ice for direct deployment into the water, rather than from the deck of the ship.

A more tenacious problem is caused by the fact that sound does not move at a constant speed through sea water, leading to errors in pose estimates that can grow to tens of meters on the surface. In open water this is usually not a significant issue, but in ice, errors of this magnitude can render vehicle recovery extremely difficult. In order to compensate for this, we deployed LBL beacons from tethers hanging over the side of the ship during recoveries, and computed independent AUV position estimates on the ship using travel times telemetered from the vehicle (see the next section, and also section VII-B). To add redundancy to our pose estimates, we also made use of direct ranging measurements using a backup beacon onboard the AUV, and by using the MicroModem’s built-in ranging mode. Finally, in some situations we determined AUV locations from the ship by passively listening to the robot’s LBL interrogations and the network’s replies, which provide hyperbolic constraints that can be combined to produce a fix. All of these navigation modalities are discussed in much greater detail in [9].

**B. Communication**

Encoding information in a modulated acoustic wave brings a fundamental tradeoff between range and bandwidth. The WHOI MicroModem is capable of using a variety of encodings for transmission, including frequency-shift keying, spreading codes, and block codes with varying degrees of error correction. Since the required operating range cannot be decreased without lowering the surface of the ocean (likely impractical), we chose the highest transmission rate that resulted in reasonably robust communications over the required distances. Puma and Jaguar needed to operate on the order of seven to ten kilometers from the ship, so our communications used frequency-shift keying in the regime of 8 to 12 KHz, providing a maximum bandwidth of approximately 80 bits per second in 32-byte packets or in 13-bit “mini-packets”.

In addition to the extreme bandwidth limitations, the acoustic channel is a shared (broadcast) medium, which implies that collision avoidance must be considered, particularly when the baud rate is so slow. The acoustic channel is also used for LBL navigation, as mentioned above, which further restricts the amount of communication traffic that can take place. For simplicity, we used time-division multiplexing (TDMA) to prevent collisions, and adapted our operations as necessary to cope with the relative scarcity of data available from the AUVs. On a typical deployment, we used a 90-second TDMA cycle, where each cycle contains a single 32-byte packet sent in each direction, as well as three LBL network interrogations. This resulted in an effective uplink bandwidth of less than 3 bits per second. Each uplink (robot to ship) packet contained vehicle state information, including pose estimate, mission goal information, and most-recent LBL travel times. The downlink (ship to robot) packets were only used during vehicle recovery, and contained goal positions for the robot to try to reach before surfacing.

**V. MECHANICAL DESIGN**

The two AUVs are identical in their system design, differing only in their sensor payload. They are based on the proven design of the Seabed[10] AUV. Our design constraints included a requirement for inexpensive vehicles with the ability to accommodate a suite of sensors. Puma is shown in Figure 3.

The vehicles consist of two hulls connected by a pair of aluminum spars. Each hull contains a single large pressure housing, and syntactic foam for ballast. Most of the negative buoyancy is in the lower hull; this makes the vehicle naturally stable in roll and pitch and allows for a large meta-centric height. We selected foam and pressure housings adequate for a maximum depth of 6000 meters; in practice our operating depth was about 4000 meters. The lower
pressure housing contains the batteries and the fiber optic gyro, while the upper pressure housing contains the computer which controls the vehicle. Other sensors are either contained in their own pressure housings, or are in sealed glass spheres when an opaque housing could not be used (for example in the case of the camera’s strobe). Fully assembled, the vehicles are about 2 meters long, 1.5 meters tall, and weigh about 250 kilograms in air.

The vehicles are driven using three thrusters with propellers mounted to the shafts. Two thrusters are mounted between the two hulls at the aft of the vehicles, and are used in a differential-drive configuration, providing both forward thrust and heading control. The third thruster, mounted to the top hull, provides vertical thrust. The propellers turn at a maximum of 150 RPM and consume about 100 watts of power each at that speed, providing a working forward velocity of about 35 centimeters per second, and a vertical velocity of 20 centimeters per second (12 meters per minute).

The vehicles carry 64 lithium ion batteries, providing 6 kWhr of capacity, and allowing at least 24 hours of operations depending upon the hotel load of the sensors. Without descent weights, the AUVs can spend as much as half of their power budget during the descent and ascent portions of a dive, which, while suboptimal, reduces complexity and improves safety.

The individual hull shapes were chosen to minimize drag. Subsequent to the hull design, however, we made a systems level decision to run the vehicles with a downward pitch of about fifteen degrees. This allows the main thrusters to assist the vertical thruster somewhat in maintaining depth.

The thrusters and most of the sensors are controlled via RS-232. Using RS-232 allows us to use standard through-hull connections on the pressure housings, and prevents the need for wet twisted pair wire. Jaguar carries a gigabit ethernet camera, but the through-hull connections are only reliable enough for 100 megabit speeds, and only using twisted-pair wire. For gigabit speeds we would switch to fiber, though other restrictions on camera usage prevented this from being necessary. For example, our strobe needs a few seconds to recharge after each image is taken, so our effective frame rate is only about one image every three seconds.

Under-ice operations required additional backup equipment not typically used in open ocean AUV deployments. The two vehicles carried a completely separate acoustic beacon to which we could compute ranges even in the event that the main vehicle power was lost. They also carried an isolated radio-frequency beacon that could be used to locate vehicles trapped under the ice – these beacons were expressly designed for for search and rescue of human avalanche victims, but they also work well for finding robots with depleted batteries.

A. Sensor Suite

While Puma and Jaguar are outfitted with identical thrusters and navigation sensors, they differ in their science payloads and in how they are used. Both vehicles carry standard oceanographic sensors for measuring water temperature, conductivity, pressure, salinity, and oxidation potential (“eH”), as well as navigation sensors, including a 3-axis fiber optic gyro, doppler velocity log, and depth sensor. Both vehicles also carry a WHOI MicroModem, described above. Puma (the “Plume Mapper”) carries sensors designed for water-column surveys, most notably a pair of optical backscatter sensors for measuring the amount of particulate matter suspended in the water. Jaguar carries sensors suited to seafloor surveys, including a downward-facing optical camera, an imaging sonar, and a magnetometer.

VI. VEHICLE SOFTWARE

The onboard software is divided into two distinct processes, which run on a PC/104 computer under Linux. One of these, the control process, communicates directly with the vehicle hardware, sending control commands to the thrusters, computing pose estimates from the navigation sensors, and logging data from the science sensors. The other process controls mission execution, interpreting telemetry provided by the control process and following a user-supplied script to carry out the survey. In order to maximize the robustness of the software, we implemented several failsafes to prevent loss of vehicle control. In particular, we implemented a “safe mode,” in which the robot will cancel all of its navigation goals, start to float slowly toward the surface under its own positive buoyancy, and listen for commands sent acoustically from the ship. This mode is engaged whenever:

- The on-board computer reboots (e.g. because of a power fault).
- The control process exits (e.g. because of a memory fault) – this causes a reboot triggered by an expiring watchdog timer.
- An abort is sent acoustically from the ship.
- An internal mission abort is triggered (e.g. by a maximum depth being exceeded, or by a critical sensor failing).

The safe mode ensures that the robot remains in a controllable state as much as possible. Once engineers have assessed the situation, they can send position and depth goals to the AUV to control the ascent. The only situation in which a robot floats to the surface completely passively is when the on-board batteries have been depleted.

If a mission completes normally, the robot ascends under power to a pre-determined depth (typically 200 meters), after which it holds position to listen for new goal directions sent acoustically. Because the robot passively rises as slowly as 6 meters per minute, and actively at around 12 meters per minute, there is adequate time to find a lead for recovery, move the ship, and re-establish acoustic communications with the AUV to “drive it home.”

VII. PERFORMANCE AND RESULTS

A. Overall Results

During the summer of 2007, we made two trips to the Arctic. The first trip was a 14-day engineering trial to ice just north of Svalbard, and the second was the 6-week expedition to two sites along the Gakkel Ridge, at 85 degrees north
latitude. During the course of the expedition, we deployed Puma six times, and deployed Jaguar three times. The mission track followed by the AUV in each case is shown in Figure 4. In addition to the AUVs, the science team made use of a towed sled with sampling capabilities called CAMPER, a traditional oceanographic CTD carousel, and a network of seismographs deployed directly onto the ice. The crew of the ship, the Swedish icebreaker Oden, also made use of ice drift buoys to estimate the motion of the ice pack. The details of our scientific results have been described in [11][12].

B. A Typical Dive

The second Puma dive, PUMA0001, was primarily for hydrothermal plume detection and localization, using the eH, CTD, and optical backscatter sensors. The mission called for the Puma AUV to perform 3 transects of a 1.9km by 1.9km area while ‘towyo’-ing; oscillating in depth between 3200m and 3550m through the estimated depth of a non-buoyant hydrothermal plume. Figure 5 shows the depth of the AUV against mission time.

AUV deployment was performed as shown in Figure 1. The AUV was attached to the shipboard crane, and lowered
The tracklines run by the AUV during the AGAVE PUMA0001 mission. The planned tracklines are shown in solid black. The red crosses show LBL fixes, and the green dots show locations with a bottom track fix.

At 30m depth, the AUV paused to provide an opportunity for an acoustic abort if the telemetry suggested anything was amiss early in the mission. The vehicle then continued on to 2500m, where it transited horizontally until it was directly above its first waypoint. While the Arctic provided an excellent environment for acoustic communications, transiting well above the seafloor ensured that LBL transponders were not shadowed by the mountainous bathymetry. After reaching the first trackline waypoint, the vehicle dove to 3200m and began its ‘towyo’ behavior.

The AUV was configured to use Doppler bottom track for navigation when possible, and to use LBL navigation when bottom track was unavailable. Since this dive was run primarily in the middle of the water column, LBL navigation was primarily used as shown in Figure 6. After completing the mission, the vehicle ascended to 30m while the shipboard LBL transponders and telemetry transducer were removed from the water. After the icebreaker had cleared the hole of ice, the vehicle ascended to a few meters depth and drove straight towards the ship from about 100m away. At a range of about 30m, the vehicle was spotted from the helicopter deck and brought to the surface.

During the summer of 2007, we demonstrated that autonomous underwater vehicles can be effectively used for scientific research under the permanent ice pack. We re-
Finally, a more complicated improvement would be to deploy maneuvering an AUV to an open lead quite problematic). spent reaching the sea floor (ascent weights are less advis-
descent weights to reduce the amount of time and energy
dive to end before another can begin [15].

In summary, the technology and expertise needed to explore the ice-covered oceans now exists. More development
is needed to bring the technology to maturity, and to adapt it
for exploration further afield, but the positive results of the
AGA VE expedition show that the use of robots is effective,
expensive, and much less risky than manned exploration.

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