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Improving the performance of submarine launched bathymetric probes

Micro UUVs for submarine deployment

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***Abstract*—Submarines under the sea operate in a heterogeneous three-dimensional world. Knowledge of the environment is extremely important for operations as sensor efficiency is directly related to underwater sound propagation. Expendable Bathythermograph (XBT) technology, first developed in the 1960s, is the principal method used by submarines to collect data on the thermal profile of the immediate operating environment. This paper proposes that the use of micro Unmanned Underwater Vehicles (UUV) has the potential to provide both an enhanced XBT function and significant other capability for a submarine.**

Submarines; SSXBT; micro UUV; environmental sensing

I. Expendable Bathythermograph

Pivotal to effective submarine (and anti-submarine) warfare is an understanding of the bathythermic profile of the water column in the area of operations. Given the technologies available at the time, in the early 1960s the US Navy contracted Sippican Corporation of Marion, Massachusetts to develop the Expendable Bathythermograph (XBT) as a means of reliably measuring and recording bathythermic profiles. Sippican (later Lockheed Martin Sippican) became the principal global supplier, including to the RAN.

The surface-launched XBT unit is composed of a probe; a wire link; and a shipboard canister [1]. Inside the probe is a thermistor which is connected electronically to a chart recorder. The probe falls freely at 20 feet per second, with elapsed time determining its depth and providing the subsequent temperature-depth trace on the recorder. A pair of fine copper wires which pay out from both a spool retained on the ship and one dropped with the instrument, provide a data transfer line to the ship for shipboard recording. Eventually, the wire runs out and breaks, and the XBT sinks to the ocean floor. Since the deployment of an XBT does not require the ship to slow down or otherwise interfere with normal operations, XBT's used for research purposes are often deployed from vessels of opportunity, such as cargo ships or ferries, rather than a dedicated research ship where a CTD would normally be used in preference. Airborne versions (AXBT) are also used; these deploy the probe from a floating buoy and use radio frequencies to transmit the data to the aircraft during deployment. Lockheed Martin Sippican has manufactured over five million XBTs.

In the 1970s the US Navy submarine force saw the potential for launching the XBT from a submerged submarine so that it would not be necessary to change depth to determine the profile of its immediate environment. The Submarine-Launched Expendable Bathythermograph (SSXBT) was developed along with a full military specification recorder, the AN/BQH-7. This complete system was installed on every US submarine and produced an analogue paper trace of ocean temperature, a recording on cassette of the data, and a Naval Tactical Data System (NTDS) output into the fire control system.

As the use of SSXBT increased and the ASW challenge grew, modifications were made to the specific instrument for use under the ice cap. At the same time, other friendly navies started to use the submarine-launched devices. The SSBXT was demonstrated to the RAN in 1978.

The introduction of advanced combat systems for submarines resulted in the development of an electronic module to replace the AN/BQH-7 in AN/BSY-1 and BSY-2 systems. Also, the requirement for continued Arctic deployment necessitated the development of a submarine-launched conductivity and temperature sensor. This information may be used to determine the salinity of the water and the density, both key oceanographic parameters when operating in Arctic waters.

II. Technical Features

Technical features of the SSXBT system are:

- A sea water ground is used so that when an electrode within the nose of the expendable probe makes contact with the water, the circuit is complete and temperature (or sound velocity data in some versions) can be telemetered to the ship-board data processing equipment.
- Data are recorded and displayed in real time as the probe falls.
- The nose of each expendable probe is precision weighted and the unit spin-stabilised to assure a predictable rate of descent.

- From this rate of descent, probe depth is determined to an accuracy of +2%.
- The XBT contains a precision thermistor located in the nose of the probe. Changes in water temperature are recorded by changes in the resistance of the thermistor as the XBT falls through the water. The XBT is capable of temperature accuracies of +0.1°C.
- When the probe reaches its rated depth (a function of submarine speed and the quantity of wire contained within the spool) the profile is completed and the system is ready for another launch.

Temperature profiles and computed sound velocity data obtained by the XBT are used by sonar operators to identify the impact of temperature on sonar propagation and acoustic range prediction, and by submarine command and warfare officers to determine tactics.

III. XBT Biases & Errors

XBTs were originally designed for naval use, to enable rapid, inexpensive collection of a sound velocity profile and as such do not have high accuracy or precision. The research community quickly adopted the technology, and many millions of profiles have since been collected. The use of the data has changed over time and now XBT data are a valuable resource for climate studies, despite the simplicity of the probe design. The research community identified biases in XBT data [2]:

- Fall Rate Bias. Since XBTs do not measure depth (e.g. via pressure), fall-rate equations are used to derive depth profiles from what is essentially a time series. A major implication of this is that a depth-temperature profile can be integrated to estimate upper ocean heat content; the bias in these equations lead to a warm bias in the heat content estimations. XBT correction needs to include both a drop-rate correction and a temperature correction.
- Pure temperature bias correction. The pure temperature biases are not originated from the depth estimates and are temperature dependent. Studies have shown that XBT recording systems have the largest impact on the pure temperature bias.

Extensive progress has been made during the past decades regarding the understanding and assessments of XBT biases and errors. These are similar to corrections made to data obtained from other observational platforms and continuous efforts are in progress to improve the XBT dataset [3].

SSBXT are used in submarines to provide information required for the tactical decision-making processes, including propagation loss versus range curves (PROPLOSS), Mk-48 torpedo settings and search plan selection.

One analysis of 118 US Navy SSXBT traces collected during submarine exercises [4] showed that:

- 37.3% experienced system malfunctions and should not have been used as input for tactical decision-making.
- 26.3% showed partial failure but still provided useful data to a depth of at least 1,000 feet.

Unfortunately, many of the malfunctions were not recognised by the operator. When both SSXBT trace and hard copy were available from the exercise data package, it was noted that a majority of the data had not been encoded properly as input to the Sound Velocity Profile Entry and PROPLOSS routines of the US Navy Submarine Fleet Mission Program Library.

Among the recommendations from analysis were:

- *Oceanic and Transient Fronts.* When an observation differs considerably from previous data, either the submarine has entered a new water mass or the SSXBT system has malfunctioned. The boundary separating two water masses -- termed the oceanic front -- is a region of variable temperature and sound speed and is frequently accompanied by strong currents. Natural oceanic turbulence near fronts is greater than in other areas, thus SSXBT failure rate is likely to be above normal. Transient fronts may occur elsewhere owing to natural environmental occurrences such as abnormally high winds and oceanic eddies.
- *Compute Set & Drift.* Set and drift can be computed by comparison of Ships Inertial Navigation System (SINS) and electro-magnetic (EM) log observations. Currents greater than normal and a shift in current direction in the open ocean are indicative of an oceanic front.
- *Deploy after Front is Crossed.* If observations indicate that a change has occurred, an SSXBT observation is desirable. However, the SSXBT should not be deployed until the front has been crossed and acoustic conditions have stabilised. It was further recommended that an SSXBT observation be made daily even in the absence of information indicating change because of normal oceanic variability.

IV. Other Submarine Launched Technologies

Oceanographic and research institutions, offshore oil and gas facilities and naval forces and supporting agencies all over the world use more than twenty (20) variants of Lockheed Martin oceanographic probes to measure temperature, salinity, ocean currents, or sound velocity versus depth [5]. Most of these probes have an air, surface and/or submarine launch variant. To date, approximately six (6) million expendable oceanographic probes have been delivered, with 80,000 to 100,000 probes being delivered annually.

The Expendable Sound Velocity (XSV) probe measures sound velocity in water as a function of depth. Applications include antisubmarine warfare (ASW), coastal mine countermeasures and oceanographic research. It is particularly useful in regions where salinity varies with depth, making calculation of sound velocity from XBT temperature data alone impractical. Submarine-launched XSV (SSXSV) models also are available.

The Expendable Conductivity/Temperature/Depth (XCTD) probe measures water temperature and conductivity as a function of depth. From the XCTD data, the data acquisition system (DAQ) can calculate and display salinity, water density and sound velocity. Both submarine (SSXCTD) and air launched (AXCTD) versions of this probe variant are available.

In the 1980s Sippican produced the AN/BRT-1 Expendable Submarine-Launched One-Way Transmitting Device, a buoy launched from the submarine with a pre-recorded message for transmission to aircraft.

Sippican also developed for the US Navy a two-way UHF transmitter system. This employs a tether from the submarine to an antenna at the surface for communications with aircraft. This device was not put into production; however, it did result in Sippican developing the capability to wind optical fibre in 3-inch diameter packages for tethering the submarine to surface instruments. This allowed for a much wider transmission bandwidth, for example encrypted voice. A result of this innovative technology was the development and test of a Buoy Camera System whereby a submarine may remain at depth and view the surface environment by means of an optically tethered camera system.

The Sippican Submarine Mobile Acoustic Training Target (SUBMATT) can be deployed from an underway submarine to enhance fleet readiness in anti-submarine warfare.

In US submarines, the SUBMATT [6] can be deployed from the Trash Disposal Unit (TDU) or Gas Gun via the expendable TDU Launch Kit™ sabot, using Standard Operating Procedures and without modification to the submarine hull. The SUBMATT emits passive tonals to enable the crew to track course, depth and speed manoeuvers and then engage the target with active sonar and weapons to complete the scenario.

V. Technologies beyond XBT

The XBT is one element of the suite of environmental sensing capabilities of a submarine, however, the XBT is a system that provides only one function. It takes up space and weight in a submarine and can require a dedicated launcher.

Future environmental sensing technologies should address challenges that future submarine operations will face:

- *Littoral Environment.* Environmental parameters that include a greater degree and dynamism of spatial and temporal environmental variations and their effects on the performance of submarine sensors.
- *Environmental Information Models.* Ideally ships, submarines and aircraft will automatically record environmental data and upload it to shore-based data centres. Fusion algorithms will receive real-time environmental measurements from sensors in the water to merge with the model and improve the accuracy of sonar performance predictions.
- *Rapid Environmental Assessment.* Techniques and procedures to assess the sonar environment of the littoral battlespace for rapid optimisation of sensors and weapons and tactical decision support are in development. Remote offboard sensors and satellite signal processing will play key roles.
- *Environmentally Adaptive Capabilities for Sensors*. Sensors and weapons systems must also be environmentally adaptive. These sensors should be able to sense the environment, collect the observations for input to models and plans, and adjust the system accordingly, either automatically or through operator interaction.

VI. UUV Technologies

The US Navy UUV Master Plan [7] proposed four general vehicle classes ranging from Man-portable (<50 kg) to Large (approximately 20,000 kg). To this can be added a recently developed Micro UUV class represented by systems such as M3V (Hydroid Inc.), SandShark (Bluefin) Aquabotix, uUUV (RipTide) and others.

Micro UUV technology is proposed as the preferred technology for Future Submarine environmental sensing. It provides the capability for environmental sensing currently provided by the XBT, together with many other functions. Like a general-purpose computer, it can be configured to provide the capability to contribute to multiple roles identified as [7]:

- Intelligence, Surveillance, and Reconnaissance (ISR)
- Mine Countermeasures (MCM)
- Anti-Submarine Warfare (ASW)
- Inspection / Identification
- Oceanography
- Communication / Navigation Network Nodes (CN3)
- Payload Delivery
- Information Operations (IO)
- Time Critical Strike (TCS)

These functions may be applicable to submarine operations of many types.

Micro UUVs have the potential to contribute to the challenges of environmental sensing for future submarine operations in a way the “single-purpose” XBT technology cannot:

- Micro UUVs can manoeuver in both the vertical and horizontal planes allowing for multiple samples to be taken.
- They are persistent, and their endurance can be long (e.g. 7 hours) compared with an XBT cast which is instantaneous only.

- For "standard" bathymetry profiling they can be tasked to collect data primarily in the vertical plane.
- To search and characterise ocean fronts they can be tasked to collect data primarily in the horizontal plane.
- In the complex littoral environment micro UUVs can contribute to a real-time understanding of the complex spatial and temporal environment by being used in both horizontal and vertical planes as required in one or many missions.
- With long endurance they can be used by a stationary submarine to conduct multiple missions from one location to understand the time varying aspects of an operational area.
- They can be used singly or in groups (swarms) to collect data around the submarine, not just at the location of launch as is the case with an XBT.

The other applications of Micro UUV to submarine operations can be considered as:

- *ISR.* Contributing to above water surveillance while minimizing the risk of exposing the submarine. ISR tasks could include gathering visual, RF or infrared data to support submarine or special forces operations.
- *MCM.* A submarine that is located in a minefield is at a significant disadvantage and any information that can be obtained may support safe egress. A Micro UUV equipped with side scan sonar could provide useful real time data on mine location to enable safe navigation, or avoidance of the minefield in the first instance.
- *Self-Inspection / Identification.* When equipped with a camera, real-time images of the submarine hull and external surfaces can aid in battle damage or other assessment.
- *Communication / Navigation Network Nodes (CN3).* The Micro UUV can provide a discrete communication channel between the submarine and subsea assets, or by surfacing provide a radio frequency antenna. As an aid to navigation the Micro UUV can surface to provide visual or other references for operations such as amphibious landing.
- *Payload Delivery.* A Micro UUV will have limited ability for payload delivery, however, it can provide propulsive force for movement of neutrally buoyant payloads. For small payloads a range of approximately 25nm (50 km) and speed of up to 10 knots may provide timely support for special forces.
- *Information Operations (IO).* The small size and stealth inherent to a Micro UUV enables operations in coastal areas difficult or impossible for other platforms, where they could carry antennas and transmitters into locations that support electronic attack. The degree of difficulty increases as the capability moves from jamming to denial of services to injection of false data.

VII. Integration into Submarines

Section IV showed that there is a history of launch of devices from submarines available from open sources, and possibly other systems that remain classified. It can be reasoned that development of the capability to launch devices from submarines will continue to be driven by the advances in technology and the significant increase in capability that this can provide if a Micro UUV is the launch vehicle as described in Section VI.

For integration of UUV technology into submarines the form factor of the UUV is the primary consideration. Two manufacturers have chosen to develop systems that are inherently suited for submarine integration and through-hull launch:

- *Saab AUV62.* A Large UUV (21-inch diameter and 1250 kg). Prototype parts of a torpedo development project were the original start point for this UUV.
- *Hydroid M3V.* A Micro UUV that enables control authority using a vectored duct for yaw and pitch control and counter-rotating propeller for roll control. Thrust is generated by direct drive DC brushless motors.

Only the M3V will be further considered here as the AUV62 is beyond the scope of this paper. Other Micro UUV types such as those listed in Section VI are less suitable for submarine integration due to their form factor which includes fins and other devices complicating through-hull launch. The concept of operation driving the development of these UUVs is often towards swarm deployment which is also beyond the scope of this paper.

The M3V is a true A-size 91.5 x 12.4 cm (36" x 4.875") vehicle with no fins or appendages outside the A-size envelope and can be used for multi-domain deployments. It is equipped with an articulated tail control system and a positioning and navigation system as standard. REMUS M3V also has a variable centre of gravity allowing it to operate in a buoy-mode. Outfitted with a side scan sonar, the REMUS M3V vehicle has a multi-functional tail antenna that includes Iridium, WIFI and a Flasher. The REMUS M3V requires minimal logistic support and is compatible with existing survey and UUV capabilities.

For a Micro UUV such as the M3V, the capability for launch can be implemented by specifying submarine signal ejectors (SSE) to handle A-size devices (the standard size of many air-launched sonobuoys). A sleeve can be used for the launch of standard diameter submarine signals through SSEs. Submarine garbage disposal ejectors could also be adapted for the launch of micro UUVs and sea floor devices such as transponders. The requirements for the signal ejector including data and power interface across the breech door would need to be established.

VIII. Conclusion

The future submarine battlespace will be increasingly complex as it moves to the littoral, compounded by the expected adoption of small UUV swarms by potential adversaries.

Improved submarine command and warfare tactics can be aided by more accurate environmental information. Similarly, the performance of smart weapons will be enabled by rapid and accurate environmental information. Fundamental to this is the need for improved systems for sensing environmental data with increased accuracy and endurance and relaying this back to the parent platform, network and wider fleet. Failure to improve the capability for environmental sensing together with improvements in sensors and weapons will risk fielding a sub-optimal overall capability.

Micro UUV are a promising technology to not only replace existing XBT systems but to also provide enhanced capability for submarine operations in many domains.

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