

Autonomous Shallow Water Bathymetric Measurements for Environmental Assessment and Safe Navigation using USVs

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Abstract—The application of unmanned surface vehicles for autonomous shallow water bathymetric measurements, for naval mine counter-measures and hydrographic charting, and as a navigation assist for high valued ships is discussed. Defence Research & Development Canada has developed a prototype unmanned surface vehicle based on a commercially available catamaran hull-form integrated with a hydrographic quality bathymetric sonar, side-scan sonar, and an echo sounder. The unmanned surface vehicle is also equipped with a WHOI underwater acoustic modem and a 2.4 GHz RF radio to facilitate above and below water communications. The vehicle is also integrated with a mission-planner that has an advanced autonomy framework to facilitate the development and implementation of more complex robotic behaviors towards capabilities for the above-mentioned applications. This autonomous system has undergone validation and testing in the Canadian Arctic and numerous local trials in Halifax Canada. The efficacy of, and lessons learned from, using unmanned surface vehicles for these applications are discussed.

Keywords—*bathymetric survey; unmanned surface vehicle; hydrographic measurements; navigation assist; naval mine counter-measures*

I. INTRODUCTION

There is growing international interest in the Canadian Arctic due to resource development, climate change, control of the Northwest Passage and access to transportation routes. Due to the lengthening extent and duration of open (relatively ice-free) water in the summers, there is increased ship traffic transiting through the Arctic. However, only 10% of the Canadian Arctic is adequately charted to modern hydrographic standards for the purposes of safe ship navigation (Fig. 1) [1]. Additionally, climate change has altered the coastal bathymetry (underwater topography/water depth) and consequently some coastal hydrographic maps need updating due to phenomena like the slumping of shore lines. To be universally applicable, bathymetry measurements for these maps need to be of hydrographic quality. This involves the methodology which the data is gathered and processed as well as the survey accuracy adhering to a standard like IHO S-44 Special Order [2]. Arctic trials to gather the required data are costly, season-limited and logistically complex so it is extremely difficult to make Arctic bathymetric measurements and to do so frequently enough.

The requirements for bathymetric data collection for rapid environmental assessment surveys prior to a naval mine

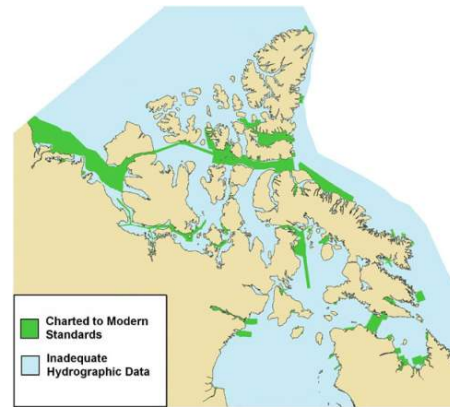


Fig. 1: Canadian Hydrographic Service estimate of Arctic charting.

counter-measures (NMCM) mission are similar to those for hydrographic mapping. The survey accuracy for hydrographic mapping tends to be more stringent than for environmental assessments. However, the relevant technologies, software tools, methodologies, and challenges for both are similar. From this point on, no distinction is made and ‘bathymetric measurements’ refers to both hydrographic mapping and NMCM environmental assessment surveys. Typically, for both applications, the surveys have been performed with ship-based sonars. The sonar is hull-mounted to the ship which travels back and forth along transects that allow the sonar to cover the survey area. The sonar can have as few as a single beam (e.g. echo sounder) or it can have hundreds of simultaneous beams (multi-beam). In these surveys, multi-beam soundings provide detailed relief of the seafloor and acoustic backscatter from the seabed to provide insight into sediment characteristics. This information is used to interpret NMCM side-looking sonar data, for example, to predict likelihood of mine burial or bottom type as it impacts mine detection.

Autonomous systems like unmanned underwater vehicles (UUV) and, to some extent, unmanned surface vehicles (USV) are lately also platforms for these sonars. While UUVs are used for NMCM environmental assessments neither UUVs nor USVs are as extensively applied to hydrographic mapping. Some of the considerations in using a robot for bathymetric measurements include how the robot is controlled to carry out its measurements, whether the data quality is comparable to that collected from surface ships, the amount of on-board

processing necessary, the endurance of the system when the sonar operates at near 100% duty cycle, etc. This is discussed in the next Section.

Another new concept is the autonomous system making bathymetric measurements in-stride with, and ahead of, the ship and transmitting the information to the ship to determine safe passage through waters that are uncharted or have dynamic obstacles (e.g. ice) [3].

This paper briefly reports on DRDC developments of a prototype system to study autonomous bathymetric measurements and ship navigation assists. The paper is organized as follows: Section II discusses advantages of autonomous systems and why a USV was chosen; Section III describes the USV-2600 prototype system for realizing the two applications. Results from in-water testing are briefly presented and discussed in Section V. Section VI concludes with a few remarks.

II. ENVIRONMENTAL ASSESSMENT AND NAVIGATION ASSISTS WITH AUTONOMOUS SYSTEMS

Autonomous system requirements to collect bathymetric measurements for environmental assessments and ship navigation assists are similar. Some of the requirements are listed in Fig. 2. If the requirements can be met, and the data quality and mission efficiency is comparable to a ship, there are additional advantages beyond using a ship for the survey though a ship is still in the picture.

The autonomous system can stay on task as long as it has sufficient energy. It can work unattended and not command the resources of a fully-crewed ship. It can better tolerate working in adverse environments and inclement weather. One ship can deploy and oversee several such systems for the survey and multiply its efforts many-fold beyond a single ship. With advanced mission-planning and decision-making capabilities on-board, the autonomous system can adapt in situ to changes in the environment, itself, or the survey tasking [4].

Candidate autonomous systems for the applications are UUVs and USVs. An analysis to determine which is the better fit compares application requirements against autonomous system class capabilities as shown in Fig. 2.

A. Quality of Measurements

The quality of the bathymetric measurements / data for the two applications crucially depends on accurate positioning and navigation for mapping and identifying navigation hazards. The USV has an advantage with its access to GPS/D-GPS whereas the UUV fuses inertial navigation systems with Doppler velocity logs and a compass to dead-reckon – a less precise navigation solution [5]. With dead-reckoning the mission efficiency also decreases due to regular UUV surfacing for GPS. The quality of the data is also affected by the motions of the system hosting the sonar. As an UUV is submerged it suffers less motions than an USV on the water surface. Here, the question posed is whether the USV motions are greater or less than the ship motions. For very deep water bathymetric measurements the UUV may make better measurements than the USV from the surface. However, this has to be traded-off against the potentially less precise

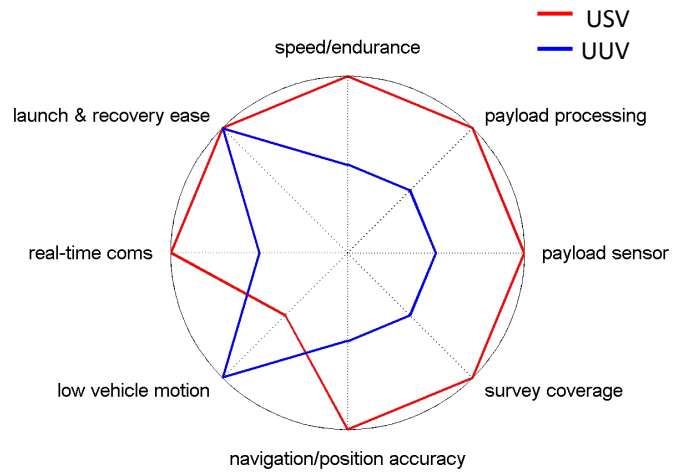


Fig. 2: Relative comparison of UUV and USV capabilities for autonomous bathymetric measurement & navigation assist requirements (based loosely on [6])

positioning of systems dead-reckoning at increased depths. Overall, the data quality in shallow water is better with an USV. Another consideration with autonomous bathymetric surveys is the mission efficiency.

B. Mission Efficiency

The efficiency of the mission depends on the density of the on-board energy. This impacts the survey coverage, speed, endurance, payload sensor, and payload processing requirements. If operating in-stride with ships as a navigation assist, a higher speed is preferred. The payload sensors are bathymetric/echo sounder sonars which are power hungry devices and especially so when run at near 100% duty cycle. On-board payload processing is for data reduction, integration of bathymetric data streams with navigational and other sensor streams, as well as advanced mission-planning and control. If computationally intense algorithms are implemented on the payload processor it can draw noticeably on the energy. High energy density sources make the mission more efficient.

UUVs and USVs can both carry higher energy density batteries on-board, like lithium-ion. Submerged UUVs are reliant on batteries alone as air independent propulsion for UUVs is an on-going research topic. USVs have additional options as they can be powered by air-breathing engines with liquid fuel which increases the energy density by a factor of at least 30 over lithium-ion batteries. USVs with air breathing engines become attractive as the autonomous system for the applications. USV access to above water communications reinforces this.

Reasonable communications in terms of range and bandwidth between the autonomous system and above-water support increase mission efficiency as the operator has better awareness of the autonomous system's condition and whether the bathymetry is correctly measured and logged. If not, the operator can implement timely corrective measures. The USV's in-air communication bandwidth and range are greater than the UUVs with underwater acoustic communications. In this way, mission efficiency is better with a USV.

Compared to a UUV in shallow water, the USV makes bathymetric measurements at higher speeds and longer ranges with lower positioning error while maintaining continuous connectivity to above-water support. Therefore, a USV was chosen for the work reported here. The question is whether the USV motions are comparable to that of a ship. Its hull-form has some influence in this.

There are a variety of possible USV hull-forms from displacement craft, semi-submersibles, and planing craft, to multi-hulls like catamarans and tri-marans. The catamaran hull-form was chosen for the DRDC prototype as it has good low speed stability for environmental assessments with the bathymetric sonars at ~ 4 kt (unlike planing hulls), reasonable sea-keeping, low drag, and good maneuverability. The catamaran hull-form is also stable when propelled at the preferred higher speeds (6+ knots) as an in-stride navigation assist with an echo sounder. The catamaran-based USV system developed described next.

III. USV PROTOTYPE DEVELOPED

Over the last 3 years, Defence R&D Canada (DRDC) has worked on developing a prototype USV for the two applications introduced earlier. To start, a 4 m length $\times$ 2 m width $\times$ 2.5 m height robotic catamaran (Fig. 3), the USV-2600 (SeaRobotics Corp.), was integrated with multi-beam sonars like the SwathPlus, a 300 kHz side scan sonar, and a Furuno echo sounder. The SWATHPlus sonar is a hydrographic quality sonar used for ship-based bathymetric mapping. Auxiliary instrumentation on-board the USV include a 360 degree pan-tilt-zoom video camera, payload computer, differential GPS, 25 kHz WHOI underwater micromodem, and a 2.4 GHz WiFi radio. The underwater micromodem is for USV duplex communications with submerged assets like underway UUVs or over-the-side deck micromodems deployed from ships or jetties. The combination of on-board WHOI micromodem and in-air radio allows the USV to be a communications relay for deeply submerged UUVs surveying the seabed (not discussed). The 2.4 GHz radio provides duplex communications between the USV (and its payload sensors) and above-water support like a ship or shore station.

The USV-2600 is powered by rechargeable lithium-ion batteries (2.7 kWh). Its top speed is about 7 knots. It can be powered by an air-breathing engine though that was not deemed necessary for the prototype here. The propulsion is two fixed electric thrusters with differential steering to give it good maneuverability.

The payload computer on-board the USV is integrated with MOOS-IvP [7] as the middleware to enable development and integration of user-developed behaviors like autonomous path-planning, adaptive acoustic transmission rates, etc. It has also been integrated with the ROS-based SeeByte Neptune for similar purposes (briefly discussed later). The results from initial in-water testing of the USV system is briefly described next

IV. RESULTS AND DISCUSSION

The USV system was incrementally developed through a



Fig. 3: Front view of the USV-2600 at the end of an Arctic survey.

series of local trials in Bedford Basin (Halifax, Canada) in 2011/2012. Then, it was taken to the Canadian Arctic to test remote autonomous bathymetric surveys and ship navigation assists in a dynamic environment with out-dated bathymetry maps, moving ice, navigation challenges from fluctuating magnetic fields, acoustic communication challenges from the inverted sound speed profile, and inclement weather. Since returning from the Arctic it has undergone more local trials.

The initial Arctic testing and evaluation of the USV system was performed during the 2012 Canadian Forces Joint Arctic Experimentation (CFJAE) program supported by the Canadian Forces Auxiliary Vessel QUEST (76 m $\times$ 12.6 m $\times$ 4.8 m). The USV system was transported from Halifax to Gascoyne Inlet, Nunavut (Fig. 4) on the northbound QUEST.

A. Ship Navigation Assist through Unfamiliar Waters

During the ship navigation assist runs, the Furuno echo sounder and multi-beam sonar's altimeter returns on the USV were transmitted to QUEST over the 2.4 GHz radio in near-real time. The USV logged and transmitted these depth readings while surveying in a zig-zag trajectory (pitch ~ 5 m) over a 15 m wide swath. This was performed through a narrow inlet (1.5 km wide) with a 600 m wide choke point with a narrower channel marginally deep enough for the ship (Fig. 5). The ship did not actually trail behind the USV as the radio range was sufficient to receive the transmitted depths from its stationary location over the ranges tested. The USV speed in the direction of zig-zag propagation (roughly, the ship heading) was just under 3 knots.

The optimizing algorithm implemented in MOOS calculates a path with the criterion that the minimum water depth based on the multi-beam altimeter and echo sounder was at least 8 m (keel depth was 5 m). Then, this optimal path was represented in the form of waypoints. The optimized path through the choke point was consistent over multiple transits in both directions. As an in-stride navigation assist to ships, the USV was able to collect timely data while underway, process it into waypoints for an optimal safe path, and transmit it to the ship for implementation. This project is

waiting to test over different ship-USV ranges and bathymetry variations.

B. Autonomous Bathymetric Surveys

The USV with its differentially driven propulsion is able to maneuver in and out of narrow inlets and fjords with a much tighter turn diameter than a ship (~ 2 m) as it turns about an axis internal to itself. This USV can also survey in much shallower waters than a ship. During CFJAE, the system surveyed in waters as shallow as 3 m and as deep as 70 m. The low speed stability of the catamaran hull-form, compared to a planing hull, made it possible for it to maneuver carefully while surveying in ice fields. When moving ice was spotted in the USV video stream, transmitted to QUEST in the near real-time, the operator maneuvered the USV to avoid it.

During the missions it is not easily possible to transmit raw bathymetry data back to the ship. However, it was possible to transmit information and summaries from limited on-board processing. Echo sounder returns were sent in near real-time to the ship.

As an autonomous platform for remote bathymetric, or side scan surveys, the USV's motions in a sea state impacts the data quality. The highest sea state tested for the USV system at CFJAE was upper sea state 2/lower sea state 3. Normally, ship-based bathymetric surveys are performed to the top end of sea state 3 (when the data from ship-mounted sonars become marginal). Consequently, the USV's motions, the sea conditions, and the sonar data were correlated and analyzed in post-processing. While the USV motions were relatively small the logged sonar data was noisy and inconclusive. The original sonar used during CFJAE12 did not have the motion compensation or fidelity to yield near-hydrographic quality data, comparable to a ship survey, even in low sea states. Therefore, the decision was made to use a hydrographic quality bathymetric sonar, the SWATHPlus and investigate the electrical noise issue.

Electrical noise interference is not uncommon when integrating systems onto small platforms where a large number of electrical devices, switches, inverters, wiring, etc.

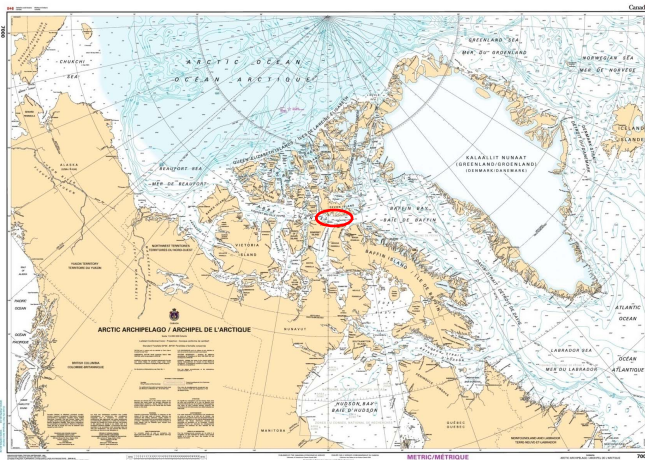


Fig. 4: CFJAE12 in Gascogne Inlet, Nunavut (CANADA) – latitude = 74.668223944; longitude = -91.30072059



Fig. 5: USV-2600 sets up to run ahead of QUEST in a zig-zag pattern to survey water depths in-stride.

all occupy a small space. Early testing of the SWATHPlus sonar on the catamaran showed that the background noise level was considerably higher when installed on the USV than it had been when installed in a more conventional hull-mounted shipboard configuration. Iterative testing and improvements to the sonar system grounding have reduced the background noise level considerably, with samples of typical sonar amplitude output shown in Fig. 6. Elevated noise level has significant impact on the width of the usable swath, i.e. as received signal level drops with range, the operating range is determined by where the return signal level reaches the noise floor. A second issue with having multiple acoustic systems installed on one small platform is acoustic interference between sensors. This can also be seen in Fig. 6, where the transmit from the catamaran echo sounder and the following seabed echo are indicated by two arrows. The interferometric phase processing is sensitive to other ping returns, such that during the receive interval for a particular ping, the bathymetric swath is corrupted at the point where the echo sounder ping occurs and beyond.

Future work includes testing in higher sea states to determine the limits of the USVs dynamic impact on sonar data quality and underwater communications.

C. Other USV Developments

As mentioned earlier, the USV payload computer has also been integrated with the SeeByte Neptune (Naval EOD Planning Tool for Unmanned systems NEtworks) planning tool for NMCM minehunting surveys. These surveys collect primarily side-looking sonar data with UUVs to detect mine-like objects. Currently, on the USV, Neptune provides an environment where the operator can plan USV missions without having to be familiar with the detailed USV workings (Fig. 7). It integrates the underwater acoustic modem with the in-air radio so the USV can serve as a relay between the UUV and the operator. The underway UUV can transmit Neptune mission status and its positional information to the operator and the operator can send commands to the underway UUV.

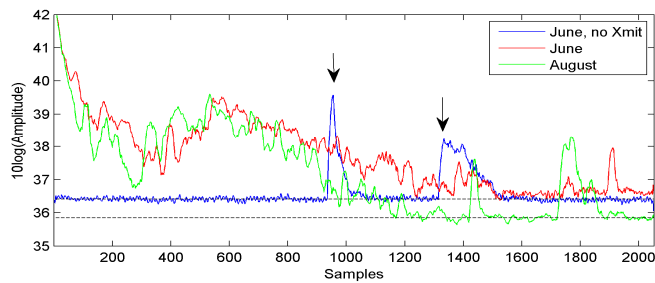


Fig. 6: Samples of the SWATHPlus sonar amplitude data recorded prior to (June 2015, blue and red) and post (August 2015, green) improved electrical grounding. The black arrows indicate cross-talk from the echo sounder, both transmit and later seabed return. The horizontal dashed lines show the background noise level before (higher) and after (lower) grounding improvements.

Neptune also provides a framework for autonomous adaptive transmission rates for the underwater acoustic behaviors. Neptune has demonstrated multi-UUV missions and DRDC plans to develop this capability further. As well, there are several capabilities that are in advanced stages of in-water testing and slated for on-board integration with Neptune. They include adaptive transmission rates for the underwater acoustic modem [8] and a behavior that optimizes the USV path relative to the submerged UUVs' for more optimal underwater acoustic communications and assists with UUV navigation [9]. Future bathymetric measurement behaviors that use all these capabilities are under consideration.

V. CONCLUDING REMARKS

This paper looks at the use of USVs for autonomous bathymetry measurements for environmental assessments prior to naval mine counter-measures missions and hydrographic mapping as well as navigation assists for ships travelling through dynamic and unfamiliar waters. The

strengths that USVs bring to these applications, relative to UUVs, include their ability to use high energy density sources, continuous access to GPS for accurate localization and navigation, high bandwidth and long range in-air RF communications for data transfers and coordination. The Arctic example highlights the efficacy for considering unmanned surface vehicles for autonomous shallow water bathymetric surveys.

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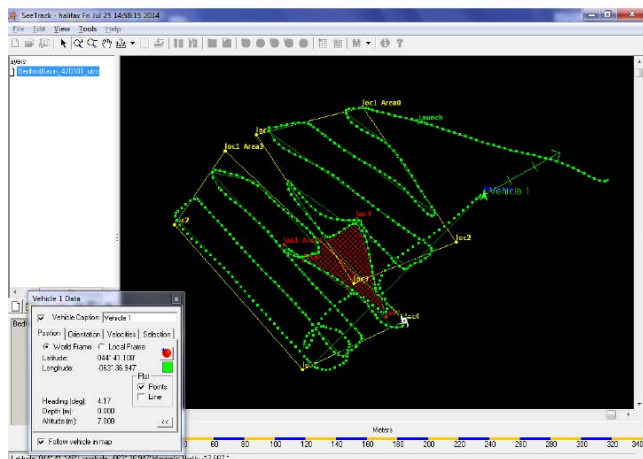


Fig. 7: Screen shot of USV NEPTUNE mission with exclusion zone (red) in higher winds.