Applications of Today's 3D Forward Looking Sonar for Real-time Navigation and Bathymetric Survey

Matthew J. Zimmerman
Vice President of Engineering
FarSounder, Inc.
Warwick, RI, USA
Email: matthew.zimmerman@farsounder.com

Heath Henley
Software Engineer
FarSounder, Inc.
Warwick, RI, USA
Email: heath.henley@farsounder.com

***Abstract*—Currently, the main application of commercially available three-dimensional forward looking sonar (3D FLS) technology is for real-time vessel navigation. Using 3D FLS technology, the vessel operator can detect not only the range and bearing to a navigational hazard, but also the depth of the hazard in the water column. However, 3D FLS is itself a nascent technology for which many exciting applications are yet to be realized. In this work, the current applications of 3D FLS are surveyed, and some useful metrics for the evaluation of a 3D FLS are defined. New possible applications of 3D FLS are introduced. Performance for all known commercially available 3D FLS products according the FLS metrics previously defined is summarized. Finally, some of the differences in applicability for current and emerging applications of the most robust 3D FLS systems are discussed.**

I. Introduction

Navigation upon the world's oceans has improved significantly over past centuries. Since the beginning of GPS development, nearly 40 years ago, the pace of navigation improvements has accelerated continuously. Today, mariners are able to locate themselves with previously unheard of accuracy. However, despite accurate position information, the question of what is underwater ahead of one's vessel still arises. Though some areas of the world have excellent chart coverage, many locations which are highly valuable in terms of natural resource extraction, commercial shipping, tourism, climate study, and enforcement of national sovereignty have little or no reliable chart data. Commercially available, 3-dimensional forward-looking sonar (3D FLS) products offer the vessel operator improved situational awareness and can provide real-time information as to the depths ahead of a vessel and the locations of potential hazards to navigation. The use of 3D FLS is not currently included in the International Maritime Organization (IMO) Safety Of Life At Sea (SOLAS) convention nor required by the Polar Code. Consequently, many vessel operators underestimate the value of adding additional, non-required navigational equipment to their ships. However, such systems can add significant value when used effectively. This paper highlights a number of surface ship applications which can be addressed using 3D FLS products currently available. Additionally, this paper also introduces a number of applications which could be addressed with 3D FLS in the near future. Due to the nature of these applications, this paper focuses particularly on the needs of, and uses by, ships large enough to require a licensed captain and generally greater than 25 meters in length.

II. Realtime Applications

The primary use of 3D FLS technology is for real-time applications. Similar to a marine radar which is used to provide real-time sensing above the water, 3D FLS provides real-time sensing below the water. Vessel operators use such products to provide added situational awareness beyond what is possible with electronic charts (i.e. vessel positioning and historical chart data) and visual observations. As such, vessel operators demand an easy to use, easy to understand display of the sensor data. Depending upon a vessel's current operational environment, the user may interact with the sensor data in different ways. Like with modern radar systems, 3D FLS data is most effective when it can be visualized with geo-referencing as a layer on top of an electronic chart in addition to a stand alone, single sensor display.

A. System Performance Metrics

Before exploring the capabilities of a 3D FLS and its various real-time applications, it is important to first understand the metrics associated with such as sensor. The most important metric in evaluating a forward looking navigation sonar is "coverage zone". If the sonar can't detect navigation hazards, it can't be used to protect a ship. Coverage zone is a pretty broad term and actually covers a number of characteristics:

1) Detection Range
2) Water Depth Performance
3) Field-of-View
4) Vertical View

Each of the above characteristics are discussed briefly in the following sub-sections.

1) Detection Range: One metric which seems obvious is range. But even range metrics can be deceiving as it should be evaluated both for maximum detection range to an obstacle and maximum range at which the sonar can map the bottom (also known as a 3D FLS's water depth limit) [1]. A high performance 3D FLS will be able to operate beyond its water depth limit, detecting navigation obstacles out to the full range of the product. This should be true even in shallow water.

In this case, the maximum detection range is a function of how good the obstacle reflects sound (e.g. small buoys will be detected at shorter ranges than large rocks and reefs).

2) Water Depth Performance: A good 3D FLS should be more than just a forward looking depth sounder. They should be able to produce a complete 3-dimensional image of the sea floor ahead of the ship. The maximum distance of this 3D map ahead of the ship is a function of the depth of water below the sonar. This type of range is often called "water depth limit". Such products are specified as "X water depth sonars". This can be understood to mean that one can generally produce a 3D map out to a distance of at least X times the depth below the transducer.

3) Field-of-View: Sometimes referred to as sector size, a sonar's field-of-view defines the horizontal angle displayed to the user. Obviously, a larger field-of-view enables the ship operator to have greater operational awareness and see what would be ahead of them if they were to change course. Some forward looking sonars only provide a single vertical slice ahead of the boat. With these sonars it would be necessary to change heading into the unknown to see what is in that direction.

4) Vertical View: In addition to the horizontal field-of-view, all forward looking sonars have some sort of vertical view. The way a sonar is installed has a significant effect on how this vertical coverage can be utilized and varies greatly from product to product. Some sonars are designed to be installed on the bottom of the hull similar to an echosounder. Because these installations are below the hull, the sonar is pointed downwards. Therefore, due to limitations in their installation design, such sonars will never detect any object that the vessel can hit. They can only detect objects that are below the hull. A high performance 3D FLS will have a forward facing installation and allow the sensor to look up as well as down from the bow, enabling the sonar to detect targets from below the vessel all the way up to the sea surface.

5) Update Rate: Another important metric is the "update rate". To provide the situational awareness needed to avoid hazards, an effective navigation sonar needs a fast update rate. This allows the user to better understand the underwater scene ahead of them as the vessel moves and conditions change. It also enables the potential for the processing software to compare the signals from ping to ping and track in-water targets. Such algorithms result in an image that is significantly more stable than one generated from a single ping. Unlike radar systems, the acoustic energy from 3D FLS does not travel at the speed of light. Rather, the acoustic energy travels at the speed of sound in water (approximately 1,500 meters per second). This means that a simple, single channel scanning sonars can't provide a good update rate at navigationally significant ranges. Therefore, a 3D FLS utilizing a transmitter which is capable of ensonifying the entire volume of interest with a single ping is the ideal solution for a fast update rate.

B. Transiting "Known" Waters

Vessels often travel along routes that are generally considered well known. That is to say, there is general belief (either correctly or incorrectly) that the area is well surveyed and the charts are up to date. While there are efforts to improve identification and display of survey quality on charts to mitigate incorrectly believing that a chart is reliable, this does nothing to mitigate obstacles that have been missed during surveys, are transient (such as lost shipping containers or whales), or are newly introduced since the chart's production (such as debris moved by seasonal ice or debris generated post natural disaster). In such locations, vessels often travel at higher speeds while the bridge crew rely on charts, radar, AIS, and visual observations to make navigation decisions. 3D FLS can still be valuable addition to the aforementioned traditional navigation tools. In this scenario, the 3D FLS can be used to gauge the chart's bathymetric measurement accuracy and to detect objects not indicated on the chart. To gauge the accuracy of a chart's bathymetric accuracy, the operator can compare the bathymetry measured by the 3D FLS within the sonar's water depth limit to the chart. When the 3D FLS measured bathymetry matches the chart's values well, then the operator can have greater confidence in the bathymetric information displayed on the chart. When the measured bathymetry does not match the chart well, the operator may decide to downgrade his or her confidence in the chart data and reduce the vessel's speed. To use the sonar for the detection of objects not marked on the chart, the operator should use a chart display with a sonar data overlay. A high performance 3D FLS will be able to detect obstacles beyond the sonar's water depth limit. For such long range targets, the sonar will not be able to determine the object's exact depth. However, it will be able to determine the object's location, range, and reflectivity level. Generally, if such an object is detected and is large enough to be considered a navigation hazard, its reflectivity will be larger than the reflectivity of the general sea floor in that area. By plotting the target's location on top of the chart, the operator can quickly determine if it corresponds to something marked on the chart. If not, and the reflectivity is large, the operator may consider the detected target to be a possible obstacle. If the target is detected at long range, then the operator has the opportunity to avoid the potential obstacle with a minor course change (if any is needed at all, assuming the detected target is directly ahead). The operator can easily gauge the target's reflectivity level as compared to the seafloor by displaying the sonar data with color mapped to signal level. The use of an automated alarm can bring such targets to the attention of the vessel operator without constant sonar monitoring. Obvious requirements for 3D FLS to be effective in these applications are a navigationally significant detection range, a fast update rate, and full coverage from the sea surface down to the seafloor.

C. Exploration

Many classes of vessels participate in applications which the authors term exploration. In these scenarios, the vessel operator is purposefully sailing in waters where underwater obstacles are not well known. The waters of many coastal locations around the world are relatively unknown outside of the marked shipping/transit lanes. Such applications include: performing coastal hydrographic surveys, operating in polar regions, participating in post-disaster recovery efforts, and navigating through unfrequented lagoons and reefs. In such location and scenarios, vessel operators must set their vessel speeds appropriately and often operate at reduced speeds. 3D FLS can be used to determine specifically where the water is deep enough to transit, where navigation hazards extend up, off the seafloor, and to where icebergs extend under the sea surface. When measuring the specific depth of the water ahead of the vessel, the operator should concentrate his or her attention to within the sonar's water depth limit. In very shallow water, the sonar's water depth limit is generally less than the full detection range of the sonar. However, in such locations, the vessel should already be operating at reduced speeds. When looking for the exact location of reefs that are only generally marked on a chart, the operator can use the sonar out the full detection range. This mode, too, is suitable for determining the underwater extent of icebergs. Obvious requirements for 3D FLS to be effective in these applications are a navigationally significant detection range, a fast update rate, and full coverage from the sea surface down to the seafloor, and a large water depth limit capability.

D. Anchorages

Another application for the real-time use of 3D FLS is determining the suitability of an unknown anchorage. In some locations, commercial anchorages and seafloor composition are marked on the chart. However, in many austere locations, charts lack seafloor composition information. One characteristic of a good anchorage location is a seafloor devoid of coral heads or boulders large enough to foul the anchor chain. A 3D FLS with its seafloor detections colored to signal level can be used to estimate bottom composition. By using a 3D FLS in this manner in areas where the bottom composition is known, the operator can gain an understanding of how the bottom will appear on the sonar for a given bottom composition. In areas with a homogenous bottom composition, the seafloor image will generally have a signal level that is relatively smooth and homogenous. In areas with various coral heads or boulders large enough to foul the anchor chain, the seafloor image will generally have various bright spots indicating an object on the seafloor that has a larger reflectivity than the rest of the seafloor.

III. Historical Data Applications

The use of 3D FLS for real-time applications has become more commonplace over the last 15 years with sophisticated commercial systems available since 2004 [2]–[4]. Though these early products did not include the ability for users to record data for future review, initial analysis suggest that data from 3D FLS could be suitable [5]. Current products now include capabilities to store bathymetric measurements as a function of location similar to a traditional, down-looking 2D multibeam surveys [6]. There are numerous bathymetric survey applications which are relevant to a vessel's navigation team. Unfortunately, down-looking 2D multibeam sonar equipment is not generally installed on vessels which are not dedicated hydrographic survey platforms. Therefore, vessels which already have 3D FLS installed for real-time applications could also use the same hardware to fulfill some of theses currently unaddressed survey needs. Due to the system configurations currently used in commercial products, bathymetric survey outputs from 3D FLS will never meet the depth and resolution accuracies of highest resolution 2D survey solutions performed by professional hydrographers. However, existing 3D FLS products currently approach International Hydrographic Organization (IHO) S-44 Order 1a/1b performance [7]. This means, that current 3D FLS products are not yet suitable for performing official hydrographic surveys. Further, Henley and Zimmerman [8] present a comparison of bathymetric data collected using one of FarSounder's 3D FLS products in FLMB mode. The survey results are compared to NOAA reference data in two survey areas in the Narragansett Bay. The FarSounder data collected in realtime without postprocessing (but including a tide height correction) is in agreement with the NOAA reference data with a mean absolute percent error (MAPE) of 6.6% and 2.2% over the two survey areas considered [8]. Though some of the data did not meet IHO order 1a/b uncertainty requirements, much of the data fell within the requirements. This promising finding suggests that once the processing method for bathymetric data collected using a 3D FLS system is improved, IHO uncertainty requirements could be met. There are, however, also numerous applications where bathymetric survey performance well beyond IHO S-44 Order 1a/1b specification is not required. In these cases, vessels which already have a need for real-time 3D FLS use can now perform bathymetric surveys without the need to install a separate, and often very expensive, set of 2D multibeam sonar hardware.

A. Returning Along a Previous Route

One clear application where the historical bathymetry data can be useful is sailing a vessel along a previous route. By referencing bathymetric surveys made during a previous passage, a vessel operator can easily see the exact locations of previously detected shallows and obstacles. In locations where official chart data is lacking, the previous survey can provide an increased margin of safety in the vessel's current route planning. Certainly, a similar operational approach can be used by recording the vessel's position and echosounder data. However, since the swath width of a 3D FLS survey is, in most cases, much wider than a standard echosounder footprint, the vessel has a significantly wider track in which they can operate while still staying within previously surveyed waters [9]. While staying within the coverage of the previous survey, on the return trip, the vessel could even purposefully travel near the edge of the previously surveyed track swath such that new data from the current passages expands the coverage of the previously surveyed waters. In this example, the previous route may refer to a previous passage along the same path (e.g. a cargo ship repeating a leg of a loop some days, weeks or months in the future) or the vessel exiting an area along the same path on which they previously entered the area (e.g. a yacht returning to established transit lanes after carefully passing through a barrier reef to a secluded lagoon). With appropriate data management processes, the historical survey data could be stored and recalled years later upon future visits to the surveyed area.

B. Local Surveys

Another clear application for bathymetric survey using 3D FLS is to perform a small scale, local survey which relates directly to the mission of the vessel. One such example is surveying an anchorage location before anchoring. When operating outside of well charted areas, specific details about the anchoring location may not be well known. In these cases, if the vessel is already outfitted with a 3D FLS for real-time applications, the operator could perform a small survey, covering the expected extents of the area over which the vessel is expected to swing. Displaying the survey as an overlay on top of an electronic nautical chart, makes it easy for the bridge crew to visualize the vessel's current position and orientation relative to any features or obstructions found with the survey; even when the obstruction is not within the current field-of-view of the sonar's real-time display. A second such example is surveying a potential dive site for mission planning purposes before deploying recreational explorers (i.e. technical scuba/rebreather divers or manned submersibles). Recreational explorers are often interested in visiting previously unvisited or rarely visited dive sites from depths of 30 meters to 100 meters or more [10], [11]. Though a nautical chart may indicate a slight feature on the seafloor, the bathymetric detail found on a nautical chart can be quite limited once the depth is greater than of concern to surface ships. On the other hand, the diver or submersible operator would like to have a more detailed representation of the dive site. The maximum swimming speed of a human swimmer is reported as $\approx$ four knots (2 meters per second) [12] while common manned submersibles are generally limited to no more than three knots ($\approx$ 1.5 meters per second) [10]. This means that if the diver or submersible is not deployed directly on the feature of interest, the recreational explorer may not be able to visit the intended feature on a given dive. Certainly, these types of surveys can be achieved with traditional 2D multibeam or towed side scan sonar. However, such traditional solutions require additional equipment not normally installed for ship navigation purposes. In cases where the vessel already has a 3D FLS for real-time operations, these types of surveys can be realized with the same sonar equipment.

C. Crowd Sourced Data Applications

Once the survey capabilities of 3D FLS are understood, one can quickly imagine scenarios where buzzwords like cloud computing, social, and big data could be applied to even larger applications. With the appropriate network infrastructure, all bathymetric data collected by a real-time navigation sonar could be uploaded via Global System for Mobile communication (GSM) and/or satellite for further processing and distribution [13]. A simple extrapolation of one historical data application is to consider bathymetric survey data from other vessels shared among a fleet when transiting through unknown waters. In this manner, a vessel could use the data collected from a previous passage aboard another vessel as a reference when returning along a previous route. However, in this case, the vessel currently following the route may have never previously acquired the data themselves. A number of governmental agencies, international organizations and commercial entities have begun working on early efforts to collect crowdsourced bathymetry data (CBD). Such efforts include a collaboration between NOAA and the IHO to extend the IHO Data Centre for Digital Bathymetry to include BSD [14] and a collaboration between Rose Point Navigation Systems and NOAA which allows users of their Coaster Explorer product to submit bathymetry measurements to a database managed by the NOAA Centers for Environmental Information [15]. Unfortunately, the term crowdsourced data often is associated with low quality data. The IHO has formed the the Crowd-Sourced Bathymetry Working Group which is tasked to develop a guidance document for the collection and submission of CSB data [16]. To date, the vast majority of CSB originates from single-beam echosounders and often from recreational boaters. The provenance of such data is often poor since the details of echosounder transducer and gps antenna installations are often not well known. CSB data sourced from 3D FLS has the potential to offer higher value data to CSB databases since the installation details for 3D FLS systems and the vessel's corresponding gps antennas are often known at a high level of accuracy. The Crowd-Sourced Bathymetry Working Group recently recognized that 3D FLS may be a potential source of CSB data in the future [17]. Once the leap is made from processing and storing data from a single vessel, to processing and storing data from multiple vessels, the possibility of mining the data for off-ship applications is also possible. One such application is sedimentation and scour monitoring. By comparing the bathymetry from multiple vessels and/or over multiple transits, particular features on the seafloor can be monitored for changes. Over time, the level of sedimentation in a previously dredged channel or the depth of scour around a bridge piling can be determined. Off-ship data mining of these types of features can be used by regulatory agencies to provide insight into the current state of various marine infrastructure. By comparing the collected 3D FLS bathymetric survey data to current charts, hydrographic offices could identify locations which may require chart updates. This information can play a valuable role in the planning schedules of these agencies, helping to determine where and when a professional hydrographic team should be deployed to perform an official bathymetric survey.

Another potential off-ship use of the collected bathymetry data is using it as an additional input into automated route

TABLE I
COMPARISON OF CURRENT COMMERCIALLY AVAILABLE 3D FLS SYSTEMS

	FarSounder-500 & FarSounder-1000 [18]	Sonardyne NOAS [19]	Simrad (B&G) Forward Scan [20]	Garmin Panoptix [21]	EchoPilot FLS FLS [22]
Navigationally Significant Ranges (i.e. >300 meters)	yes	yes	no	no	no
3D Image Generation	yes	yes	no	yes	Some models
Update Entire 3D Image with a Single Ping	yes	no	n/a	no	unknown
Update Rate at Full Range	1.6 seconds	unknown	unknown	unknown	1.6 seconds
3D Information Displayed with Color Mapped to Depth	yes	yes	n/a	yes	yes
3D Information Displayed with Color Mapped to Reflectivity	yes	unknown	n/a	unknown	no
Detection of In-Water Targets Beyond the Water Depth Limit	yes	unknown	no	no	no
Forward Looking Multibeam Mode Included	yes	yes	n/a	no	no
Historical Data History Length	One hour [1]	Unknown [2]	n/a	n/a	n/a
Tide Correction for Historical Data	yes	unknown	n/a	n/a	n/a

planning algorithms. A number of companies offer sophisticated route planning services [23] which take into account a variety of external factors. Updated bathymetry data could be a valuable input to the models employed in these products. Furthermore, as unmanned commercial shipping vessels become a reality [24], these automated route planning algorithms may play an important role in the unmanned vessel's navigation planning (not to mention that a 3D FLS would be a valuable real-time sensor for the unmanned platform).

IV. CURRENT CAPABILITIES

At the time of this writing, there are only a small handful of which call themselves a Forward Looking Sonar. These products and a comparison of basic features are shown in Table 1. All details in the table were gathered from publicly available product literature. The following discussion of current capabilities includes only the FarSounder and Sonardyne products since they are the only ones which operate at navigationally significant ranges.

A. Addressing Real-Time Applications Today

Both the FarSounder and Sonardyne products were developed originally to address the real-time applications. According to publicly available literature known to the authors, both systems are capable of addressing some or all of the real-time applications previously discussed in this paper. The FarSounder products meet all of the needs for those applications with numerous videos, screenshots, and tech blog postings demonstrating specific scenarios. The Sonardyne product appears to meet many of the needs for those applications. However, the publicly available information on their products is limited.

Limitations of the Sonardyne NOAS to fully meeting these needs may include:

- An update rate which may be slower than ideal since the NOAS requires multiple pings to build a complete 3-dimensional image.
- Reduced information about bottom composition since it is unknown if the reflectivity level of the sea floor can be displayed in the NOAS 3-dimensional image.

B. Addressing Historical Data Applications Today

Both the FarSounder and Sonardyne products include some capability for operating in a Forward Looking Multibeam mode. To address the historical data applications previously discussed in this paper, it is necessary that the 3D FLS system is able to build a bathymetric survey that is able to persist over an extended period of time and/or be stored and recalled for future use. Additionally, in order to be effective reference at a later time, the historical survey data must be able to be corrected for and referenced to the current tide height. In the case of Returning Along a Previous Route, the system must be able to either persist the data indefinitely over a wide geographic area, or allow the user to store and recall a smaller amount of survey data over a smaller geographic area. In the case of performing a Local Survey, the system must be only able to persist the data indefinitely over only

[1] Increased history length expected in upcoming software updates.
[2] Brochure states Sonar imagery is temporarily retained on the display.

a smaller geographic area. From the public literature, it is unclear how large a survey and how long a duration of history the Sonardyne NOAS is able record and display. No details on or analysis of the performance of the NOAS historical data is publicly available. FarSounder released their Local History Mapping (LHM) capabilities in April 2017. The initial LHM release persists only one hour of the vessel's bathymetric history. However, additional software updates are planned which will extend the system's LHM capabilities. A detailed analysis of FarSounder's LHM performance in two example surveys is presented in Henley and Zimmerman [8].

V. Future Capabilities

It is clear that there are a number of valuable applications to which real-time 3D FLS is a great match and that today's products can meet those needs. It is also clear that using 3D FLS in a forward looking multibeam mode can unlock even greater value to the mariner without the need to install additional 2D multibeam equipment. FarSounder foresees the continual evolution of real-time system performance via software upgrades to its existing products. However, more excitingly, FarSounder foresees large advancements in the use of historical bathymetric data generated by 3D FLS. Specifically, FarSounder's software development plans include improvements to their Local History Mapping capabilities which include: storing a longer duration of historic data, enabling the saving and recalling of surveyed routes similar to the saving and recalling of waypoints associated with ECDIS route planning, and the sharing of surveyed routes among a fleet. As data from 3D FLS becomes more commonplace, FarSounder also envisions additional advances in how the 3D FLS data will be used. For example, FarSounder sonars already integrate directly with a select number of ECDIS systems where FarSounder 3D FLS data is displayed inside 3rd party ECDIS software. Additional integration partners are anticipated in the future. Another example is using real-time and/or historic 3D FLS data to generate a set of virtual Electronic Aids to Navigation (eAtoNs) as presented by Wright and Baldauf [25]. Such visualization could allow for a standardization of survey data display inside ECDIS systems.

VI. Conclusion

There are a variety of real-time and historical data applications that could be addressed with 3D FLS. Currently available 3D FLS products are able to address all the real-time applications discussed in this paper. These same 3D FLS products show promise in being able to soon address the discussed historical data applications with anticipated software developments. These historical data applications could be addressed with existing down-looking 2D multibeam products. However, such systems are rarely installed on vessels which are not hydrographic survey specific. Therefore, such applications are not currently being addressed. Since 3D FLS is currently being installed on a variety of vessel classes purely for their real-time capabilities, the addition of bathymetric survey capabilities to 3D FLS products would enable vessels to address the aforementioned historical data applications without the installation of additional sonar hardware.

References

[1] M. Zimmerman, "Explaining the Water Depth Limit and Other Unexpected Reflections," 2016. [Online]. Available: http://www.farsounder.com/technology/blog/water_depth_limit

[2] FarSounder, "FarSounder, Inc. to Provide Advanced 3D Sonar Systems to High End Cruise Ship Industry Leader: New World Ship Management." [Online]. Available: http://www.farsounder.com/press-release/farsounder-inc-provide-advanced-3d-sonar-systems-high-end-cruise-ship-industry-leader

[3] ——, "FarSounder Chosen for Project Lana Superyacht Under Construction at the Devonport Royal Shipyard." [Online]. Available: http://www.farsounder.com/press-release/farsounder-chosen-project-lana-superyacht-under-construction-devonport-royal-shipyard

[4] ——, "M/Y Falcon Selects FarSounder Sonar for Ship Navigation System." [Online]. Available: http://www.farsounder.com/press-release/my-falcon-selects-farsounder-sonar-ship-navigation-system

[5] R. G. Wright and C. M. Zimmerman, "Vector Data Extraction from Forward-Looking Sonar Imagery for Hydrographic Survey and Hazard to Navigation Detection," in *OCEANS*. Washington, DC: IEEE, 2015.

[6] M. Zimmerman, "Local History Mapping with Forward Looking Sonar," 2016. [Online]. Available: http://www.farsounder.com/technology/blog/local-history-mapping-forward-looking-sonar

[7] IHO, "IHO Publication S-44: Standards for Hydrographic Surveys," International Hydrographic Organization, Tech. Rep., 2008. [Online]. Available: http://iho.int/iho_pubs/standard/S-44_5E.pdf

[8] H. Henley and M. Zimmerman, "Performance of 3D Forward Looking Sonar for Bathymetric Survey," in *OCEANS*, 2017.

[9] I. Russel and R. G. Wright, "NAVIGATION SONAR: MORE THAN UNDERWATER RADAR Realizing the full potential of navigation and obstacle avoidance sonar," *International Hydrographic Review*, no. May, pp. 41–60, 2017.

[10] NOAA, "Submersibles." [Online]. Available: http://oceanexplorer.noaa.gov/technology/subs/subs.html

[11] U-Boat Works, "U-Boat Worx Website." [Online]. Available: https://www.uboatworx.com

[12] M. Truijens and H. Toussaint, "Biomechanical aspects of peak performance in human swimming," *Animal Biology*, vol. 55, no. 1, pp. 17–40, 2005.

[13] e3 Systems, "e3 Systems Web Site." [Online]. Available: http://e3s.com/services/hybrid

[14] E. Robertson, "Crowd-sourced Bathymetry Data via Electronic Charting Systems," in *ESRI Ocean GIS Forum*, 2016. [Online]. Available: http://proceedings.esri.com/library/userconf/oceans16/papers/oceans_12.pdf

[15] A. L. Reed, "Beta test of crowdsourced bathymetry holds promise for improving U.S. nautical charts," 2016. [Online]. Available: https://noaacoastsurvey.wordpress.com/2016/06/14/beta-test-csb/

[16] IHO, "IHO Crowd-Sourced Bathymetry Working Group," 2017. [Online]. Available: https://www.iho.int

[17] ——, "Guidance on Crowdsourced Bathymetry," Tech. Rep., 2017. [Online]. Available: https://www.iho.int/mtg_docs/com_wg/CSBWG/CSBWG_Misc/CSB-Guidance_Document-v3.11.pdf

[18] FarSounder, "FarSounder Product Web Page." [Online]. Available: http://www.farsounder.com/products/navigation_sonars

[19] Sonardyne, "NOAS Product Web Page." [Online]. Available: https://www.sonardyne.com/product/navigation-obstacle-avoidance-sonar-system/

[20] Simrad, "ForwardScan Product Web Page." [Online]. Available: http://www.simrad-yachting.com/en-GB/Products/Echosounders/Transducers/ForwardScan-Transducer-en-gb.aspx

[21] Garmin, "Panoptix Product Web Page." [Online]. Available: https://explore.garmin.com/en-US/panoptix/

[22] EchoPilot, "EchoPilot 3D Product Web Page." [Online]. Available: http://www.echopilot.com/products/echopilot-3d/

[23] Klaveness, "Klaveness Web Site." [Online]. Available: http://www.klaveness.com/

[24] O. Levander, "Forget Autonomous Cars - autonomous Ships Are Almost Here," 2017. [Online]. Available: http://spectrum.ieee.org/transportation/marine/forget-autonomous-cars-autonomous-ships-are-almost-here
[25] R. G. Wright and M. Baldauf, "Virtual Electronic Aids to Navigation for Remote and Ecologically Sensitive Regions," *Journal of Navigation*, vol. 70, no. 02, pp. 225–241, 2017.