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Applying an Uncrewed Surface Vessel to Measure Under-Pier Bathymetry

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***Abstract*—Determining accurate latitude and longitude positions in GPS-denied environments is a long-standing issue in the fields of navigation and positioning. Much of the ongoing research in these fields centers on costly, evermore sophisticated sensor and algorithm development. Yet, several applications exist, which do not require high levels of precision or investment. This article describes a simple and cost-effective solution developed to map generalized, georeferenced bathymetry underneath piers using an uncrewed surface vessel (USV) with the minimum number of instruments. Under-pier areas are challenging environments constrained by tides, ship movements, varying pier architectures, and sporadic or nonexistent GPS signals. Working within these constraints, we used a small, remotely operated USV with an integrated single-beam sonar system (for depth, *z* measurements) and geographic positioning system (GPS; for some latitude/longitude, *x,y* positions) and also used an ultrashort baseline (USBL) acoustic positioning system to determine *x,y* positions when GPS was denied under the pier. We developed data processing steps to correct the positional and bathymetric estimates and assessed the accuracy of these values. We found that our quality-controlled USBL positions were reasonably precise compared with GPS positions (1.2 and 0.6 m average standard deviation, respectively), although there was also an apparent horizontal offset between USBL and GPS positions that averaged about 3.25 m. However, comparing the sediment volume under piers estimated using this low-cost USV method with that calculated from sidescan sonar-generated bathymetric maps, we found that these volume estimates agreed closely, within $\sim$ 0.6%. This manuscript presents the methods developed, including the approach used to integrate these different data streams, to allow other researchers to collect and process similar data sets in constrained environments.**

***Index Terms*—Acoustic positioning system, bathymetry, uncrewed surface vessel (USV).**

I. Introduction

Oceanographic data collection in challenging environments, such as very shallow, confined, or wave-dominated locations has spurred many recent innovations. Small uncrewed surface vessels (USVs) represent a major pathway for oceanographic innovation (reviewed in [1]). Many small USVs are now available that collect water depth measurements along with *x,y* positions to map bathymetry and other environmental variables (see, for example [2], [3], [4], [5], [6], and [7]). These small USVs can be operated at lower cost and/or in locations too shallow (e.g., [8]) or otherwise constrained than traditional hydrographic survey vessels. However, some physically constrained locations where USVs can uniquely operate and collect data have intermittent or zero GPS signal, affecting the utility of the resulting data sets.

Determining accurate *x,y* positions when GPS is not available is complicated due to many factors. Signals from satellites cannot penetrate through overhead structures, into buildings, or underwater and can be intermittently lost in locations with limited open sky view, such as in deep canyons or amongst tall buildings or ships. For some surveys that intermittently lose GPS signal, but where the USV is traveling in a straight line between good GPS fixes, such as when a USV passes under a bridge, the *x,y* positions data can be simply interpolated between positions for the portion of the track where there was no GPS. However, obtaining GPS fixes on either side of a straight transect is not always possible; for example, obstructions may prevent the USV from exiting an overhead structure, or GPS signals may be highly intermittent in locations such as a deep canyon or a busy harbor with larger vessels or buildings. Therefore, an alternative method is needed to provide *x,y* position data that can be correlated with continuous depth soundings when GPS is unreliable.

Potential solutions to estimate locations above-water when GPS is denied have been developed largely for aerial drones and include using inertial measurement units (IMUs) to measure relative position from a known starting point combined with a system to determine absolute position at intermediate steps, such as cell phone towers (e.g., [9]), an independent array of transmitters and receivers (e.g., [10] and [11]), or vision sensors (e.g., [12]). Collectively, an IMU combined with an additional positioning system, such as GPS, is referred to as an inertial navigation system (INS). INSs have also been applied to autonomous underwater vehicles (AUVs), but accuracy drift means that the vehicle either has to resurface to regain a GPS position or the IMU needs to be coupled with another system, often acoustic transponders and receivers, to determine positions underwater (e.g., [13] and [14]). Other approaches developed for the problem of position and navigation for AUVs include using terrain and bathymetry features to feedback and improve localization and mapping (e.g., [15], [16], [17], and [18]). These approaches are promising, but several applications exist which do not require this level of sophistication or do not have the budget necessary to operate and maintain AUVs.

For example, the overall goal of this project was to use a low-cost approach to determine the volume of sediments underneath Navy piers for the purpose of estimating the potential for these sediments to slump into recently dredged areas adjacent to the piers. We used a commercial USV to collect bathymetry data and an ultrashort baseline (USBL) acoustic positioning system, originally developed to track divers underwater, to supplement *x,y* positioning when the USV's GPS was denied under piers within a confined, busy harbor (see Fig. 1). To create bathymetric maps of under-pier sediments, we integrated the positions recorded by the USV GPS and the USBL system

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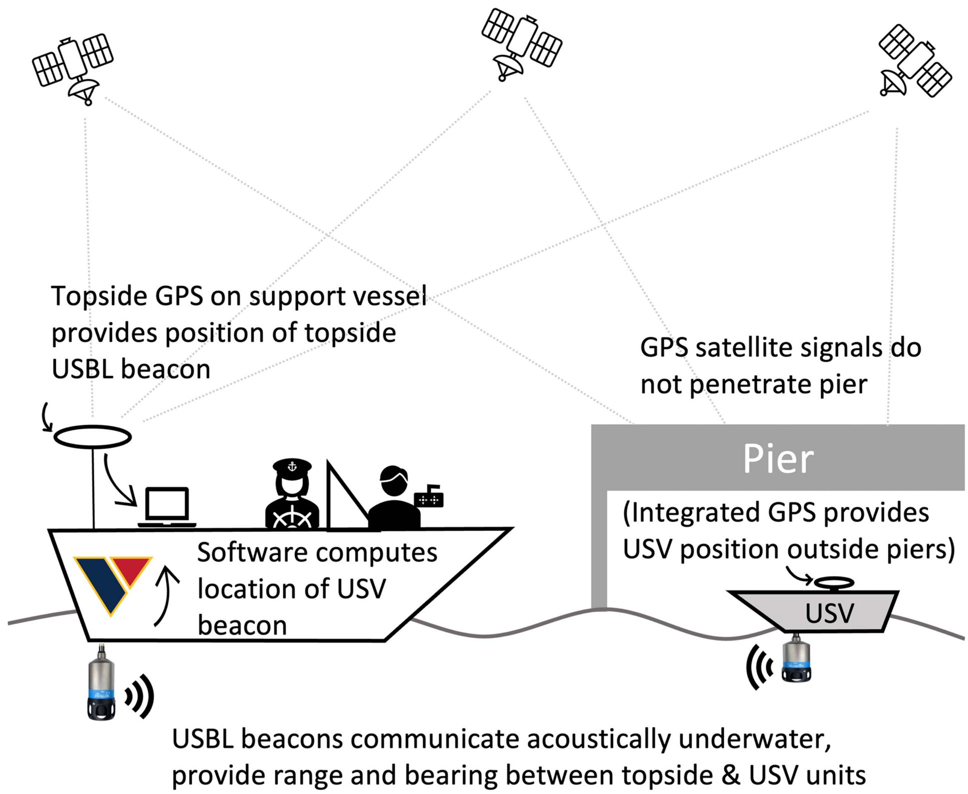

Fig. 1. Schematic showing the overall concept, using a USBL system to provide *x,y* positions for a USV when GPS is denied under piers.

so that every depth measurement was associated with a corresponding *x,y* position. Other existing solutions for estimating position under the piers (described above) were explored and determined to be either cost-prohibitive, ineffective, unavailable due to supply-chain impacts, or too logistically complex for our application.

In order to address the lack of detailed, reproducible, cost-effective methodologies in the current literature on USV navigation in GPS-denied environments, we present our approach for further consideration and adoption within the applied ocean observing community here. We outline the data collection and post processing steps in detail in Section II, provide accuracy estimates from validation tests in Section III, discuss the utility and limitations of this technique in Section IV, and provide concluding remarks in Section V.

By integrating two relatively low-cost off-the-shelf systems and developing postprocessing software that integrates the various data sets, we developed and tested a novel solution for using USVs, a burgeoning platform for oceanographic data collection, in constrained locations, such as under overhead obstructions like piers or bridges, in deep canyons, or other locations where GPS is denied or unreliable.

II. Methods

A. Study Design

By mapping the bathymetry under piers, we were able to estimate the volume of sediments accumulated under the piers. The surveyed piers were generally supported by rows of pilings spaced closely together in the cross-pier direction, with somewhat wider spaces in the along-pier direction between rows of pilings. Each pier had varying architecture and different orientations of obstructions, such as oil booms and ships at berth; therefore, the USV was visually piloted for all surveys. These obstructions usually prevented direct access for the USV to enter or exit the under-pier environment and instead a small number of access points along the piers were typically used for the start and end of the surveys. Generally, the USV was driven in a relatively straight line from one side of the pier to the other between two rows of pier pilings, then was turned at the far side and returned again down the same row, before moving along the side of the pier to the next row (either outside of the pier when possible, or, more often, under the pier near the edge) and repeating the pattern between the next set of pilings. Because the USV was visually piloted, pier sections were surveyed only when there was an open berth on at least one side of the pier, to allow direct access to that section of the pier.

B. Remotely Operated Hydrographic Surface Vessel

The remotely operated USV, measuring approximately 1.8 m $\times$ 1 m $\times$ 1 m (inclusive of antennas), was developed by Oceanscience Group Ltd. (now Teledyne Oceanscience) to conduct hydrographic surveys in hard-to-access environments such as very shallow waters [19]. This type of small USV is now commercially available from multiple different vendors in various configurations, and has become a relatively standard tool for shallow-water bathymetric survey projects in locations without overhead obstructions.

The USV used here [Z-boat; Fig. 3(a)] incorporates a small electric outboard motor that drives the boat and is controlled with a remote control, a GPS system (Hemisphere Crescent A100 [20]) that records the *x,y* positions of the Z-boat, a single-beam echosounder located directly below the GPS antenna (Ceepulse 100 from CEE Hydrosystems [21]) that measures the depth below the boat, and a compass that records the heading of the vessel. The position, heading, and depth data are saved on an onboard computer in National Marine Electronics Association (NMEA) format ordered in sequence based on when the position, heading, or depth information were queried by

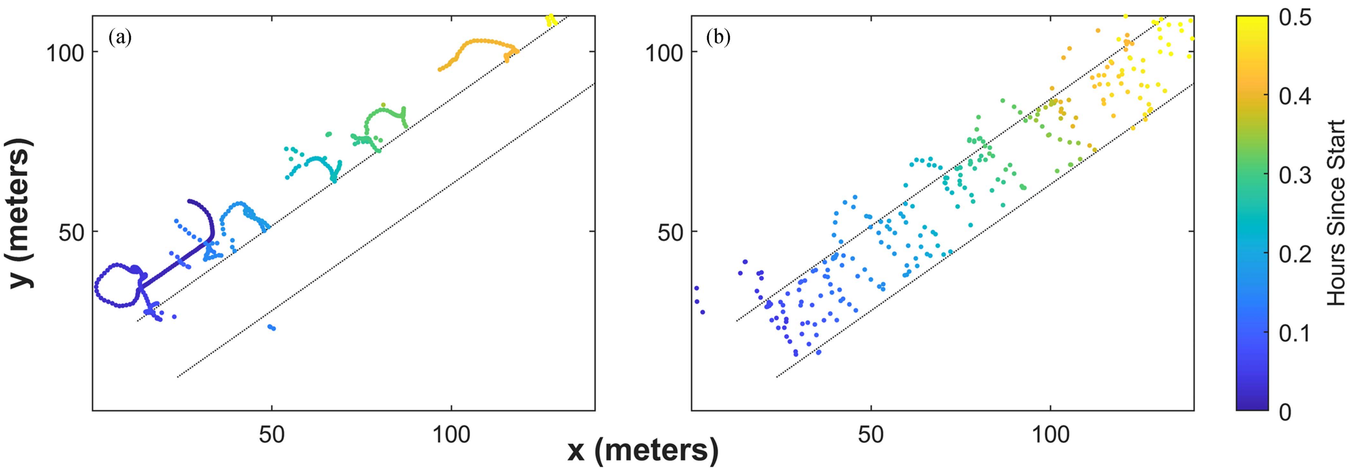

Fig. 2. Comparison of the location data of the USV collected by the (a) GPS and (b) USBL systems for a section of an example pier survey (pier outlined with black dotted lines). Colors indicate the elapsed time since the start of the survey. The positions shown are raw NMEA data and have not been filtered or quality controlled.

the incorporated instruments and communicated to the computer. These data can then be downloaded from the boat computer after a survey is complete for processing (Fig. 2).

C. USBL Acoustic Positioning System

To provide independent *x,y* positions of the Z-boat when the integrated GPS system had poor or zero GPS satellite connectivity, we used an USBL acoustic positioning system (SeaTrac from Blueprint SubSea [22]), typically used for tracking underwater assets such as divers and AUVs. A USBL system has two beacons that communicate between one another underwater using sound (see Fig. 1). One beacon (topside beacon) is rigidly mounted underwater over the side of a support vessel, or from a shoreside platform such as a pier, and the second beacon (USV beacon) is rigidly mounted underneath the asset to be tracked, in this case, the USV. The topside beacon is connected to a field computer, which is also connected to a separate (directional) GPS antenna (Hemisphere Vector V103 [23]). The topside beacon generates acoustic pings, which are received by the USV beacon, which then responds. The topside beacon contains three receivers that register the reply ping and use the difference in timing that the reply is registered to triangulate the distance and bearing between the topside and USV beacons. Proprietary software from the USBL manufacturer then calculates the real-world position of the USV beacon based on the coordinates of the topside GPS antenna and fixed *x,y* offsets describing the relative position of the topside beacon compared with the topside GPS. The calculated position of the USV beacon can be monitored in real-time using the USBL software, as well as recorded and later saved in NMEA format (Fig. 2).

For this project, the USV beacon was located approximately 0.5 m forward of the echosounder on the USV [see Fig. 3(b)]. This position was selected to minimize interference from bubbles and sound produced by the outboard motor with the USBL, and to avoid the USBL interfering with the function of the onboard echosounder. The topside USBL beacon was rigidly mounted over the side of the support vessel (Boston Whaler) using a custom mounting system, then cabled to a field computer on the support vessel [see Fig. 3(c)]. A directional GPS was placed on the bow of the support vessel, and was also cabled to the field computer.

D. Data Processing

To align *x,y* positions from the USBL to the bathymetric data (and intermittent GPS positions) collected by the USV, the two data sets were processed using custom software written in MATLAB, described here.

1) Timestamps: The USV and USBL data sets were aligned using timestamp matching. Latitude and longitude (*x,y*) positions from both the onboard USV GPS and the USBL included associated times in their NMEA sentences. For this project, the USV received good GPS positions and associated timestamps for some portions of each survey, for example when the USV was launched and retrieved by the support vessel adjacent to a given pier. Additional timestamp-only NMEA sentences in the USV data set incremented properly even when GPS positions were denied and the USV reported stale last-known positions in the data set. Depth measurements were not individually associated with timestamps in the USV NMEA data, so we assigned a timestamp to each depth by linearly interpolating between recorded timestamp values [see Fig. 4(a)]. Importantly, during this work it was discovered that the NMEA files created by the USBL software applied timestamps to the USBL data set based on the computer clock time instead of the GPS time, which resulted in offset timestamps between the two systems for several surveys, due to clock drift on the computer. As a result, we had to manually adjust the times recorded in the USBL NMEA files to properly align the USBL positions to the USV positions and depths [see Fig. 4(b)]. This extra effort and resulting uncertainty could have been avoided if the USBL data recording system used GPS-based timestamps and/or if the computer clock was updated to match GPS time immediately before each survey.

2) Position Filtering: We applied several criteria to filter the *x,y* positions from the integrated GPS and the USBL to create the most reliable survey track possible for timestamp matching to the depth data [see Fig. 4(c)]. For the USV GPS positions, we only retained reported positions that used differential GPS (DGPS) and that had a horizontal dilution of precision (HDOP) of less than 2 (considered "excellent"). HDOP is impacted by the spatial spread of GPS satellites across the sky. More dispersed satellites will result in a more accurate position than if all the satellites are clustered together. Especially in a constrained environment, such as under piers, it is important to take the quality of the positions into consideration because the limited view of the sky may result in low-precision positions. Given the higher accuracy of good-quality USV GPS positions compared to USBL positions, when

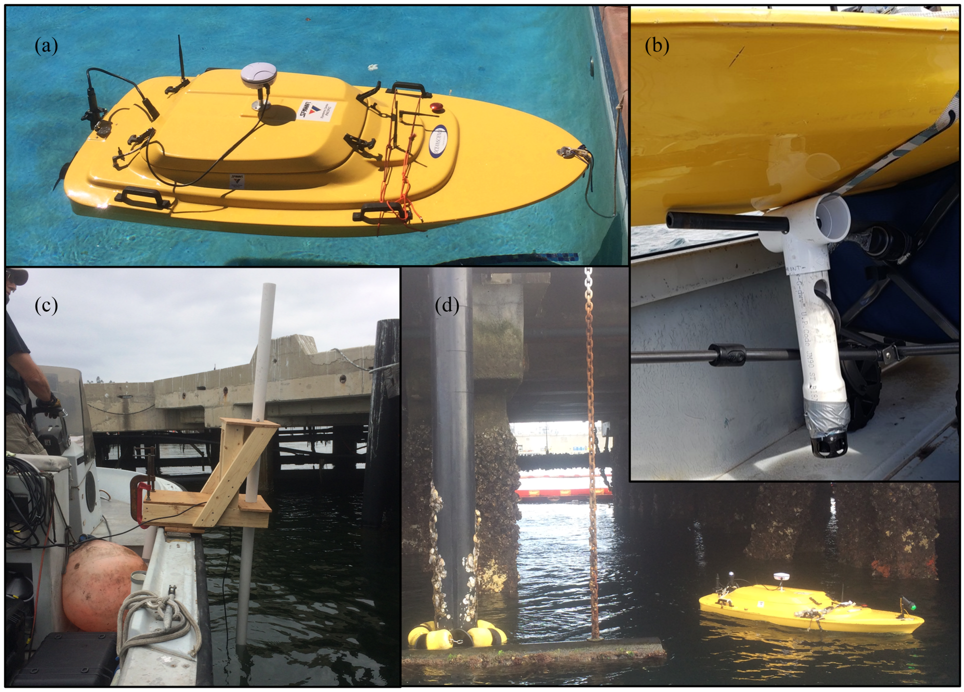

Fig. 3. Photographs of (a) USV used for this project, (b) custom mount holding the USBL beacon underneath the USV, (c) custom mount holding the topside beacon rigidly over the side of the support vessel, and (d) USV exiting a section of the pier next to a floating camel. On the far side of the pier, an orange oil boom is visible and prevented the USV from exiting that side of the pier during the survey.

good GPS positions were available, these were preferentially used to provide the USV *x,y* locations; we used USBL positions if there were no good GPS positions reported within a 3-s window.

We also applied an acceleration filter to both the USV GPS and USBL positions separately, and then again after the two data sets were combined. Although different under-pier obstacles and USV operators resulted in a variety of USV speeds for various portions of the different surveys completed, the USV used is not capable of changing speeds abruptly. Therefore, if the difference in speed required for the USV to have traveled between subsequent reported positions was greater than 2 m/s, we removed the second point of the position pair that caused the apparent high speed-difference. We did this iteratively until there were no more positions which would have required the boat to achieve abnormally high acceleration to move between those locations.

3) Depth Filtering: The depth data were also filtered to remove spurious measurements [see Figs. 4(d) and 5]. First, recorded water depths (*z*-measurements) were adjusted for tides using a local National Oceanic and Atmospheric Administration tide gauge time-series (obtained in relation to mean lower low water [MLLW] [24], Fig. 5(b)). This station was very near our survey site, and negligible phase differences were assumed between the station and survey data. We used observed water levels; however, predicted water levels may be used in regions where the tidal constituents are well documented. Even in nontidal basins, it is critical to ensure that *x,y,z* data are collected in, or processed into, equivalent coordinate systems (described in [25]). Next, measured depth versus time was plotted and visually inspected to select appropriate thresholds (shallow and/or deep) for each set of survey data that would remove obvious outliers (spurious points that did not follow the depth trends) while retaining the accurate data [see Fig. 5(c)]. Finally, we further reduced depth measurement errors (i.e., from heave, pitch, and roll) by calculating the running average of depth measurements $\pm$ 0.5 s from every measurement time [see Fig. 5(d)]. Some data processing software intended for bathymetric surveys (e.g., Hypack) have built-in algorithms to compensate for heave, pitch, and roll, but the unique data stream for this project (i.e., using *x,y* positions from the USBL when the USV GPS was denied) precluded their use.

4) Matching Positions to Depths: Once the survey track was finalized by combining the USV and USBL data sets and filtering to remove spurious positions, and the depths were adjusted relative to MLLW and to reduce measurement errors, the reported *x,y* positions were linearly interpolated to match to the times of the depth measurements. The depth measurements were reported at a higher rate (9–10 per second) compared with the positions (at most, 1 per second and frequently less often). Typically, it took about 1 min for the USV to transit from one side of the pier to the other, a few seconds to turn, and another minute to transit back to the initial side of the pier. Therefore, for most of the time the boat was completing a given survey, it was tracking in a relatively straight line, and linearly interpolating positions to match to the depth measurements was considered acceptable. However, we removed depth values that did not have a reported position within a 3-s cutoff, to avoid over-interpolating the positions.

III. Method Validation

A. Horizontal Data Accuracy

The reported accuracy of the DGPS positions is <0.6 m for the GPS antenna on the USV (Hemisphere Crescent A100) and on the support vessel which informed the USBL positions (Hemisphere Vector V103), and the reported accuracy for the USBL system is 50 mm. We found the actual accuracy of horizontal positions to be significantly lower than these reported values in the complex environment around the studied piers.

Many factors can affect both the position and depths recorded by a USV, and a complete hydrographic-survey grade assessment (see EM 1110–2–1003) [28] is beyond the scope of this project. We nevertheless

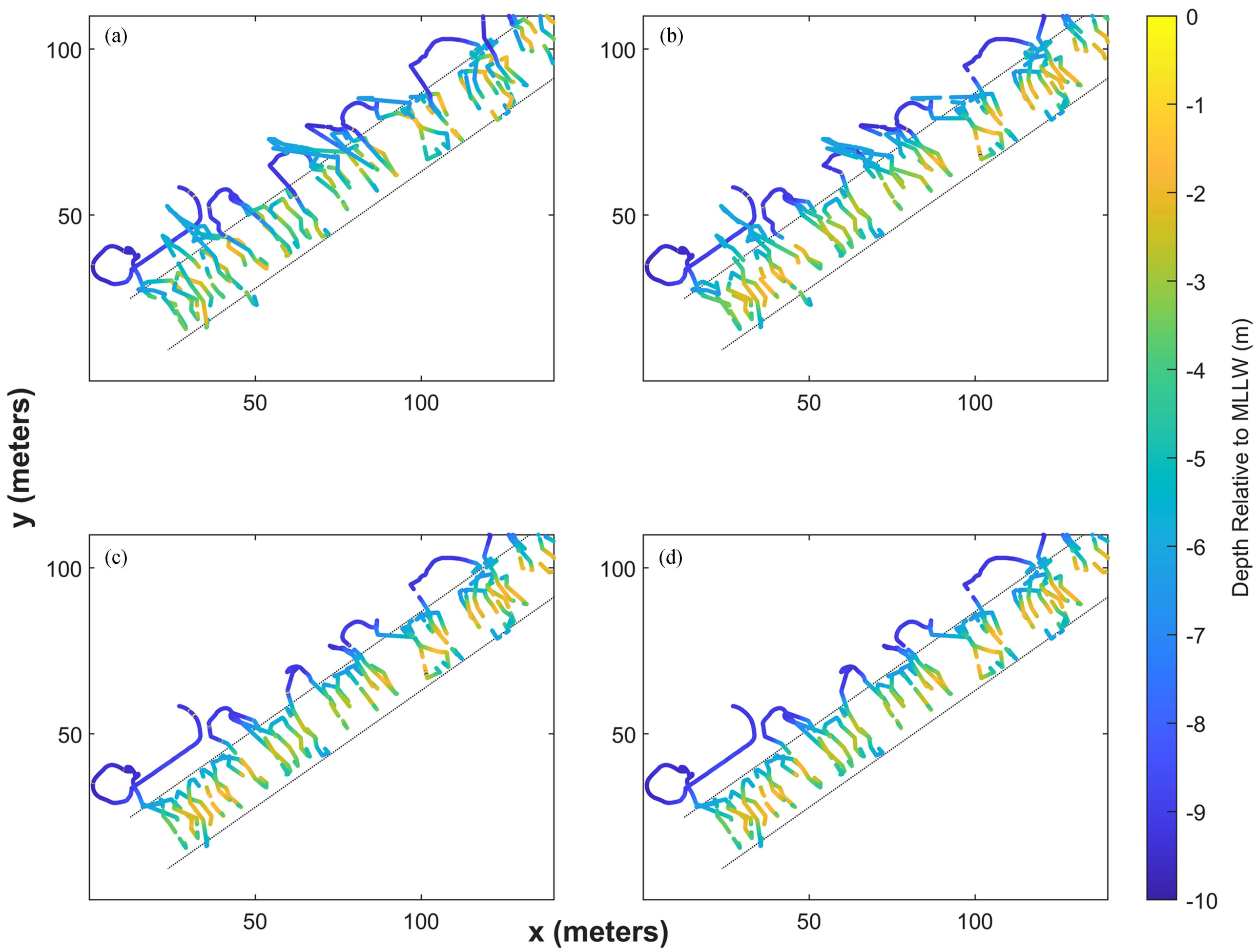

Fig. 4. Successive data processing and correction steps used to combine data collected by the USV and USBL systems and refine the *x,y,z* positions. The survey shown here is the same as that shown in Fig. 2. (a) Depth and associated position data from both the GPS and USBL systems, corrected for tidal fluctuations, relative to MLLW. USBL positions were only used if there was no GPS position within 3 s and depths were only included if there was a position within 3 s. (b) Includes the time shift to correct the recorded times from the USBL positions. (c) Includes the position filtering steps: only using high-quality GPS positions, and incorporating an acceleration filter. (d) Includes the depth filtering steps: removing outliers and using a running average of depths shown in detail in Fig. 5. In each panel, the pier is outlined with black dotted lines and colors indicate the depth in m relative to MLLW.

estimated position accuracy in several different ways. For the first approach, we investigated the positions recorded during a time period when the USV was stuck in one place at the far edge of a pier. For this analysis, we assessed three aspects of the horizontal positions: the horizontal standard deviation in both *x* and *y* positions from the USV GPS positions and the USBL positions, and the difference between the reported GPS and USBL positions. Although the USV was stuck for an hour, the middle 30 min of data, when the vessel was not being moved except by minor wave action, was used for this analysis (see Fig. 6).

For this GPS position accuracy assessment, as with our data processing steps, we only used DGPS positions with an HDOP <2. The standard deviation of the GPS positions that met these quality criteria was 0.3 m in the *x* direction and 0.8 m in the *y* direction, for an average horizontal standard deviation of 0.6 m. Unlike the GPS positions, the USBL positions, unfortunately, do not include an indicator of the quality of the position in the NMEA data output, so all reported positions were used during this 30-min window. The standard deviation of the USBL positions was 1.1 m in the *x* direction and 1.3 m in the *y* direction, for an average horizontal standard deviation of 1.2 m.

The positions reported by the USBL and GPS were also offset from each other (see Fig. 6); the difference between the mean positions was 3.7 m. Part of this can be explained by the known offset between the GPS antenna and USV beacon on the USV since the USV was oriented at a heading of 14°–19°during this period. Correcting for this offset still results in an approximate difference between the reported USBL and GPS-based positions of 3.2 m. Note that this offset between the GPS and USBL sensors on the USV was generally not taken into account for other aspects of this project, as it represented a relatively minor error compared with other factors.

For the second approach, we compared the integrated USV GPS-based positions with the USBL-based positions for times when the USV was not under a pier and could, therefore, receive both GPS and USBL fixes. For one survey, a long track segment spanning most of the pier length was recorded by both devices in addition to other shorter segments (see Fig. 7). The mean difference between the USV GPS positions that met the above quality criteria and the reported USBL positions for times when both were available was 1.6 m in the *x* direction and 2.6 m in the *y* direction, with an average overall offset of 3.3 m (see Fig. 8). The positional offset of

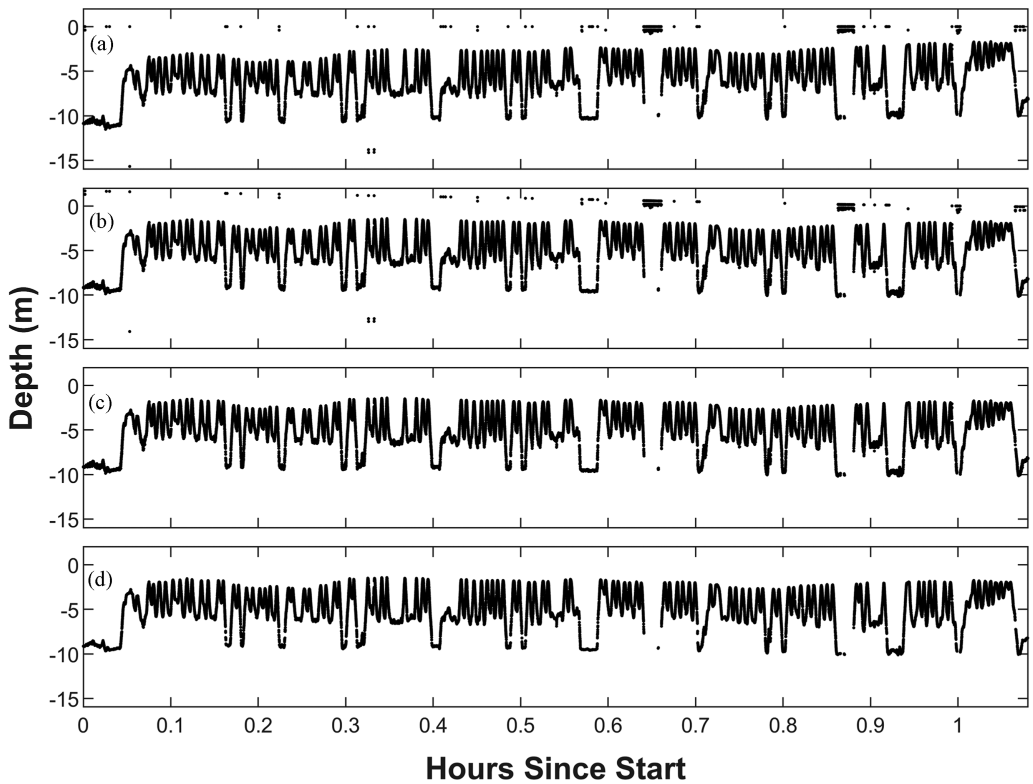

Fig. 5. Successive depth correction steps, showing depths as a function of hours since the start of the survey shown in Fig. 4. (a) Shows the raw depths measured by the USV. (b) Shows those depths corrected for tide fluctuations, relative to mean lower low water (MLLW). (c) Depths with outliers removed based on manually-set minimum and maximum thresholds. (d) Running average of depth measurements.

the GPS and USBL is remarkably similar between these two approaches, adding confidence to these estimates of true horizontal data accuracy.

B. Sediment Volume Accuracy

Data Sets, such as those from a USV-mounted echosounder, are often interpolated across a grid to create a raster data set of seafloor bathymetry. For this project, seamless bathymetric maps were created by generating a grid covering the survey area, populating the grid with depths from an *x,y,z* file, and then filling in the rest of the grid using an inverse distance weighted interpolation. Maps were compared using *x,y,z* data from the same pier using the methods described here and using *x,y,z* data derived from a sidescan sonar survey completed from outside the pier. The resulting two maps from both the sidescan survey and the USV- and USBL-based methods described here showed generally similar patterns, with shallower depths along the middle spine of the pier, which shifted toward one side of the pier with increasing distance from the quaywall (see Fig. 9). The total volume of sediment under the pier was also calculated for each map by numerically integrating over the domain volume. The vertical integral lower bound was set to the depth of the dredge design, i.e., 30 feet (9.1 m) below MLLW, and the lateral bounds were set by the horizontal extent of the pier. These volume estimates agreed within ~0.6% (26 837 versus 26 775 m^3). Thus, the low-cost solution described here compared well with survey-grade side scan sonar results, and may be a suitable option for many applications.

IV. Discussion

This work developed a relatively low-cost, logistically simple method to acquire georeferenced bathymetric data in locations with overhead obstructions that interfered with accurate GPS positioning by incorporating a USBL system into a USV observing platform. One limitation of USBL positioning is that it can suffer from interference in environments with acoustic obstructions. Indeed, the underwater under-pier environment is complicated with pier pilings, camels, mooring dolphins, and more acoustically reflective objects that can temporarily obstruct communication between the USBL beacons, or can cause echoes which can result in false apparent positions of the USV [see for example "jumps" outside the north side of the pier in Fig. 4(a) and (b)]. The accuracy of USBL systems generally decreases with increasing distance between the topside and subsurface beacons (e.g., [26]) and can be degraded if the beacons are not installed properly [27]. However, these limitations can be reduced by careful placement and/or piloting of the support vessel with the topside beacon to maximize line-of-sight and minimize distance between the USBL beacons, and by including data postprocessing to filter out degraded positions (see stepwise improvements visualized in Figs. 4 and 5).

Hydrographic surveying is a complex and highly technical field of engineering (see the Army Corps of Engineers Hydrographic Surveying Manual, EM 1110-2-1003 for further details [28]). While the Ceepulse 100 single-beam echosounder used for this project is a survey-grade device (i.e., is capable of high precision measurements), the actual accuracy of the depth measurements and their associated *x,y* positions obtained with these methods should not be considered survey-grade or used for requirements that require very high accuracy. We took steps

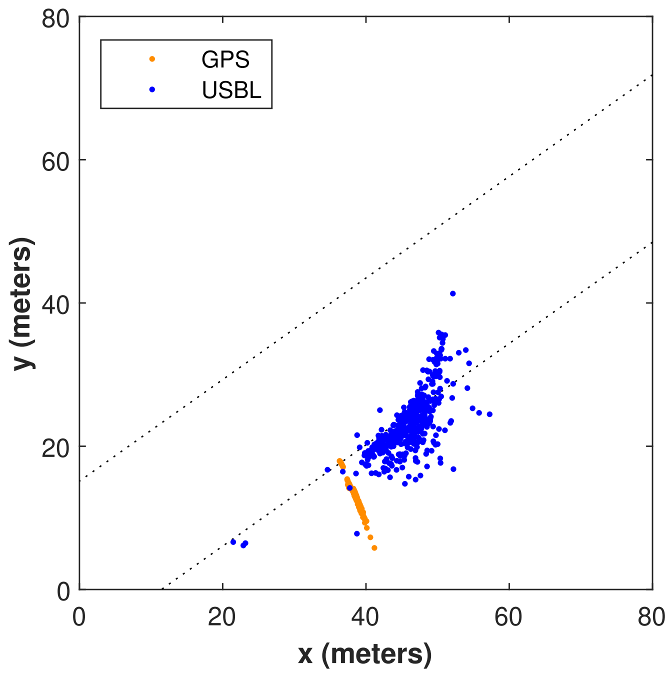

Fig. 6. Position estimates of the USV from GPS (orange) and USBL (blue) when the USV was stuck at the southern edge of the pier over a 30-min time period. The outline of the pier is shown with black dotted lines.

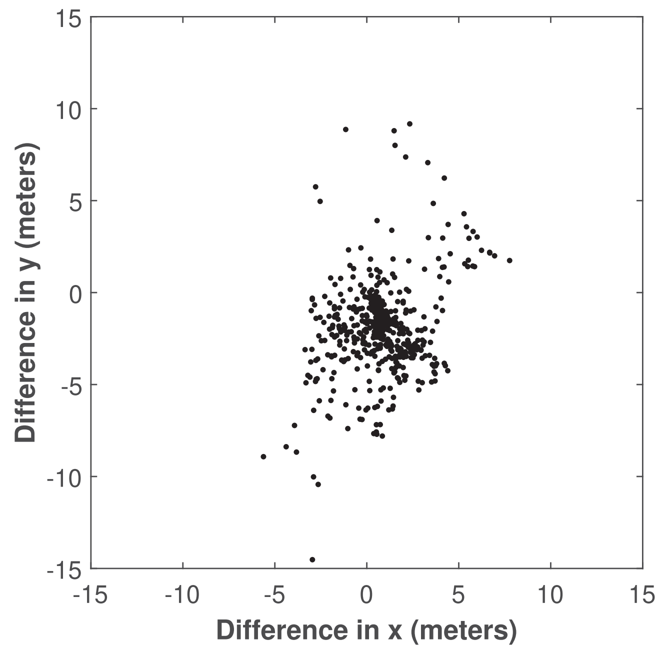

Fig. 8. Position differences for the USV from GPS and USBL locations reported when the USV was transiting along the south side of one of the piers, shown in Fig. 7. A positive value indicates that the USBL position was east (x) or north (y) of the GPS position.

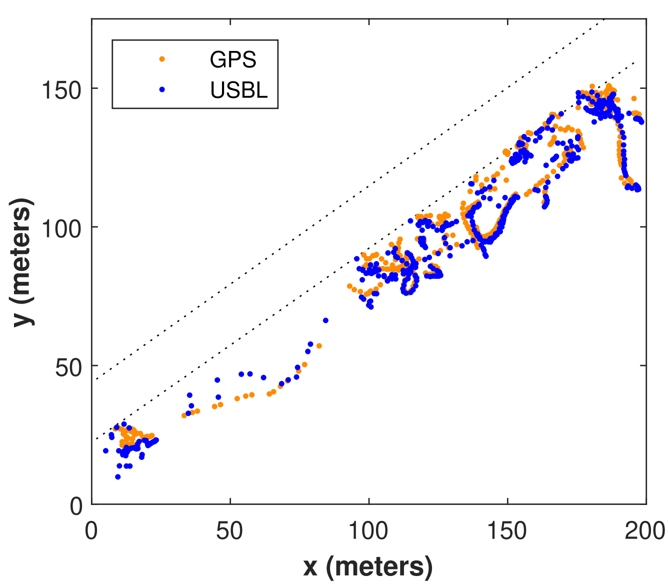

Fig. 7. Position estimates of the USV from GPS (orange) and USBL (blue) when the USV was transiting along the south side of one of the piers (shown with dotted outline), not underneath the pier. Only positions that were simultaneously collected by both the USBL and USV GPS are plotted.

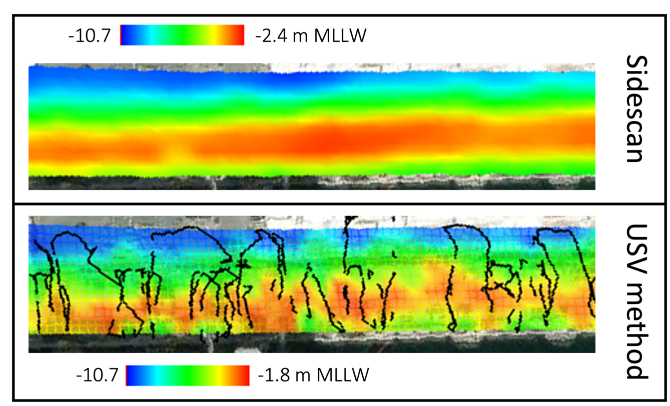

Fig. 9. Seamless bathymetric maps created by populating a grid of the pier area with *x,y,z* data derived from (top) a sidescan sonar survey and (bottom) the USV+USBL method presented here for the same pier. Colors show elevation of the bottom in meters in relation to MLLW. The USV survey track is shown in black for data collected using this method.

to filter the resulting data to eliminate as many inaccurate position and depth measurements as possible, and described here how this was done so that others can apply this novel approach to other applications. While the methods described here can be applied in many situations, if detection of relatively small-scale features or highly accurate bathymetric assessment is required, such as to plan for dredging, sediment amendment placement, or construction, a sidescan survey should be completed by licensed hydrographic professionals. The methods presented here can provide a reasonable estimate of bathymetry, but should not be relied upon for such precise applications.

This study also identified several potential improvements that could be made in off-the-shelf USBL systems that would improve their utility for scientific applications: 1) USBL positions should include accuracy indicators in NMEA output, as with GPS positions and 2) the USBL positions should include timestamps from the GPS times in NMEA output, not computer clock time. We had to come up with an apparent-speed-based filtering approach to remove spurious USBL positions because the NMEA output did not include accuracy indicators. We also had to manually align the timestamps from the USBL with those of the GPS because the USBL output data did not store GPS times and were affected by computer clock drift. The USBL system used here was beneficial due to its low cost in comparison with other acoustic positioning systems; however, its utility would be greatly improved if GPS times and position accuracy indicators were stored in the final data output.

V. Conclusion

This project was designed to demonstrate a low-cost solution for mapping georeferenced bathymetry underneath Navy piers and estimate the volume of accumulated sediments. While other methods exist for bathymetric mapping, which may result in more accurate measurements on finer scales, many of these methods rely on expensive equipment and/or consistent GPS signals. To generate bathymetric maps in a complex, under-pier environment, we leveraged and combined recent innovations in both uncrewed hydrography and underwater positioning by integrating two relatively low-cost, off-the-shelf systems: a small USV with a built-in single-beam echosounder and GPS, and a USBL system. While the results shown here provide horizontal accuracy estimates and demonstrate that this method compares well to sidescan sonar estimates, future work could investigate the robustness of this approach under a range of different conditions. The use of small USVs is becoming more common for oceanographic and hydrologic data collection. The detailed, reproducible methodology for acquiring position estimates in a GPS-denied, shallow-water environment described here may be useful for other projects collecting data in locations where high-quality GPS signals are intermittent, such as underneath piers, bridges, in canyons, or in busy harbors.

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