A comparison between co-located UUV-based optical 3D reconstruction and interferometric bathymetry

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Abstract—Seafloor bathymetry was traditionally measured with various mechanical means such as lead-lines or poles, and more recently has transitioned to acoustic methods using single beam altimeters, multibeam sonars, and interferometric sonars. New developments in structure-from-motion software have improved to a level of sophistication where sea-floor bathymetry may be reconstructed using only optical imagery captured from an on-board camera combined with vehicle state information (position, depth, altitude, etc.). In this paper, a camera and strobe system co-located with an interferometric sonar aboard an L3 OceanServer Iver3 Unmanned Underwater Vehicle (UUV) have been used to create seafloor bathymetric reconstructions from photogrammetry. This data was then compared to acoustic bathymetric data from sonar in an effort to quantify the difference between optical and acoustic products. Camera system preparation and altitude effects on both systems are discussed, and individual case studies are presented showing real-world results from both systems.

I. INTRODUCTION

Bathymetry data is of crucial importance for a wide variety of applications and users, such as recreational boaters, commercial shipping, coastal management, beach renourishment, port and harbor operations, scientific interests, and militaries around the world. Due to the never-ending cycle of sea-level rise, land subsidence, river sediment deposition, and plate tectonics, critical areas such as ports, harbors, shipping lanes, and populated coastal waters must be repetitively surveyed to ensure navigation charts are correct and up-to-date. Within the United States, the National Oceanic and Atmospheric Administration (NOAA) has the responsibility of publishing accurate navigation charts and typically uses hull-mounted multi-beam sonars to measure sea-floor depths relative to established datums.

Within the last decade, UUV manufacturers, like L3 OceanServer, have begun to integrate bathymetric sonar systems like the Edgetech 2205, Klein UUV-3500, and the GeoAcoustics GeoSwath into their vehicles. Due to a number of benefits such as precision depth control and a reduction in wave influence, the vehicle-mounted systems are gaining traction among operators. While the resulting data products from systems like these are used by commercial survey outfits, chart publishers, and hydrographers to gain a better understanding of the underwater space, bathymetric data products only provide 3D surface (point cloud) data, not an optical record of the seafloor.

Underwater photography has been conducted for over a hundred years [1], but 3D structure reconstruction from multi-view data sources is relatively new (within the past two decades). Developed primarily for land and aerial vehicles [2], [3], structure-from-motion has been applied successfully in the underwater space aboard various remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs), and on manual image acquisition from divers with hand-held cameras [4]. L3 OceanServer has recently developed a new camera system, based on over 15 years of cyclic development collaborations with customers, that can be used to collect seafloor imagery and, when paired with photogrammetric software, create optical mosaics and 3D reconstructions of the seabed. This optical 3D reconstruction provides not only the surface point cloud data similar to bathymetric sonars, but a photographic record of the seafloor.

This paper will explore the use of an L3 OceanServer Iver3 UUV (Fig. 1) with an on-board camera system and machine-vision algorithms, combined with an inertial navigation system (INS) to create image mosaics and 3D reconstruction data-products and compare the resultant products with simultaneously acquired interferometric bathymetry data. The camera and strobe system will be described, as well as highlights of optical reconstruction data products computed aboard the vehicle and interferometric products created during post-mission analysis.

Fig. 1. L3 OceanServer Iver3 vehicle deployed and awaiting mission tasking.
II. System Overview

Standard L3 OceanServer Iver3 vehicles are typically equipped with a sonar system (single or dual frequency and optional bathymetric options), navigation solutions using MEMS-based compasses or fully-developed INS solutions, and acoustic communications. Introduced recently as a new option for standard vehicles is a high-resolution GigE camera (monochrome or color versions available), stroboscopic lighting system, and a custom-built API that has been tightly integrated within the VectorMap software for a seamless front-end mission-planner for operators. A standard quad-core Celeron CPU was installed to handle both vehicle and camera system control.

A. Sonar

The sonar chosen for these trials was the standard option Edgetech 2205 dual-frequency (488.5kHz to 551.5kHz low frequency band, 1555kHz to 1665kHz high frequency band) interferometric bathymetric sonar. This system is widely used in the field [5], [6] and serves a variety of applications including survey, mapping, monitoring, and other scientific, industrial, and military uses. In addition to the bathymetric products, the unit also generates sidescan products using both frequency bands. High-frequency products (Fig. 2a) provide high-resolution images over much shorter distances, while low-frequency products (Fig. 2b) provide greater range at the expense of resolution.

![Image of Edgetech 2205 sonar](image1.png)

(a) 1.6MHz center-frequency (high-frequency) example image from the Edgetech 2205 at Hathaway’s Pond.

(b) 520kHz center-frequency (low-frequency) example image from the Edgetech 2205 at Hathaway’s Pond.

Fig. 2. This pair of sidescan sonar images shows the differences between the high-frequency (a) and low-frequency (b) products generated by the Edgetech 2205. Note that the high-frequency detail quickly is lost as the distance increases from the nadir.

B. Camera

A low-light Allied Vision camera and lens were selected for use in the down-looking camera hull (Fig. 3). Color and monochromatic versions of the camera are available and interchangeable (monochrome chosen here for imaging sensor resolution). These cameras are supported by a large API that provides interfaces to control the camera’s functionality and much of this functionality has been directly integrated into the Iver mission planning software, VectorMap. While the cameras may be powered through power-over-ethernet (POE), here power is wired directly to the circular connector to eliminate the need for an internal POE injector that occupies internal hull volume. The camera section is mounted aft of the mast section to create as much physical separation between the strobe and camera as possible. This separation reduces backscatter reflections from particles in the water column into the imaging sensor and greatly improves image quality.

![Camera system](image2.png)

The camera system is tightly integrated into Underwater Vehicle Console (UVC) and controlled through the standard mission planning tool, VectorMap, and is easily configurable depending on the application. Typical optical missions involve operating the vehicles with minimal inter-track spacing of approximately 1m-2m, vehicle speeds between 1.8kn-2.3kn, low exposure times (2ms-5ms), frame rates of 5Hz and above, and altitudes in the 1.8m-2.2m range. Timestamps are automatically inserted in the filenames and imagery can be down-sampled and processed aboard the vehicle [7], or downloaded post-mission for off-line processing. Vehicle state information can be overlaid on each image or stored as embedded EXIF data within the image file (Fig. 4).

C. Strobe

The strobe (Fig. 5), an in-house L3 OceanServer product, is designed to maximize the amount of illumination provided across the camera field-of-view, while carefully managing thermal and power constraints. Situated near the nosecone, the strobe houses six high-intensity LEDs that are electrically triggered (synchronized) through a direct connection to
the camera. Each LED can be driven with up to 2.4A (at 12VDC) and offers pre-selected color temperatures up to 7000k (nominal CCT).

The individual LEDs are situated on inclined backings that aim the center of the light cone at the center of the field-of-view of the camera. The system is designed for optimal performance at a vehicle altitude of 2m, but provides enough light for an operating range of altitudes of at least 1.8m to 2.5m depending on water clarity.

III. DATA COLLECTION AND ANALYSIS

A vehicle configured with an INS, camera and strobe system, and Edgetech 2205 interferometric bathymetry sonar, was deployed to nearby Hathaway’s Pond, in Barnstable, Massachusetts, where 41 missions (Fig. 6) were conducted over two days of testing. Hathaway’s Pond, a glacial kettle pond, boasts over 20 acres of surface area and depths up to 18.3m (60ft), and serves as a recreational SCUBA training location due to the clear water and the number of intentionally submerged objects for underwater sightseeing. Among the attractions are small boats, tractors, lawn chairs, a Halloween mask, and various submerged wooden platforms. In addition to making for interesting SCUBA dives, the objects also serve as ideal targets for testing underwater sensors and cameras.

Post-mission analysis of bathymetric and sidescan sonar data was conducted using Chesapeake’s SonarWiz and Xylem’s Hypack software. 47 targets were identified from sidescan imagery for further investigation through optical means. Optical images were processed using a number of commercially available third-party 3D and photogrammetry products. Single beam bathymetry (Fig. 7) was imported directly into the GIS solution (QGIS) and clearly shows evidence of two bridged kettles (deeper holes surrounded by shallow water near-shore). High resolution bathymetry can be created on a local scale using vehicle pose and position combined with single-point altimetry and the final 3D reconstructions, although this type of data product will be explored in future work.

The bathymetric data (Fig. 8) distinctly shows the dive platform and a statue approximately 5m from the corner. The bathymetric data is able to image large swaths of lakebed (seafloor) in a single pass. Often, a swath width of 80m (each side set to 40m) is used on a single pass. A vehicle leg of
length 1km would then capture 0.08 km\(^2\) where the camera would capture on the order of 0.002 km\(^2\), a difference of about 40 times.

In Figure 9, the dive platform is visible, along with a nearby statue. The dive platform is approximately 2.5 m by 2 m (8 ft by 6 ft) and the statue is roughly human sized. Large features like these are visible, but the many smaller objects (chairs, cinder blocks, boards, etc.) are not captured in this data.

A. Optical Target 1: Chair
An easily recognizable target found in both the sidescan and optical imagery was a folding lawn chair (Fig. 10). The chair is sitting upright in a deployed state with webbing still in-tact. A popular attraction for recreational SCUBA divers to snap a humorous photo, it also is a nice target for testing camera and sonar sensors aboard the Iver3. Figure 11 highlights the optical reconstruction showing the recovered surface and textured surfaces.

B. Optical Target 2: Cinder Block
The second target consisted of two cinder blocks surrounded by lake flora. The grasses are growing in and around the blocks, sometimes even covering portions of the blocks. The reconstruction algorithms were still able to reconstruct the scene and recover small detail on both the blocks and surrounding grasses. Similar to the chair, the reconstruction results are shown in Figure 12.

IV. CONCLUSION
A standard L3 OceanServer Iver3 vehicle equipped with interferometric bathymetric sonar and a camera/strobe system was deployed in Hathaway’s Pond, in Barnstable, Massachusetts, and conducted 41 missions gathering optical imagery and sonar data. A total of 23,277 optical images were captured during the missions, and both sidescan and interferometric bathymetric data was collected and processed into data products. Single-beam bathymetry data was captured within the standard data logging of the vehicle. Targets of interest were identified via manual sidescan review, and
Fig. 11. This 3D reconstruction was computed using 11 source images captured along-track as the Iver surveyed the lake-bed on a single pass. Initially, a 3D surface is computed (a), followed by shading (b), and finally adding a texture overlay (c).

Fig. 12. Similar processing to target #1 has been conducted on the down-looking images from a single pass near this cinder block. Note that the dimensions of the block are 8in x 8in x 16in.
further investigated using well-known photogrammetric analysis of the optical imagery.

Two representative examples (chair and blocks) of 3D reconstructions were selected and compared to sidescan and bathymetric products covering the same geographic area. A priori experience dictated that mission plans for optical image collection vary greatly from typical sidescan and bathymetric data collection mission plans. speeds of between 1.8\text{kn} to 2.3\text{kn} were found to result in the best optical imagery, with the vehicle maintaining a constant-altitude of approximately 1.8\text{m} to 2.2\text{m}. Sidescan missions are typically conducted with vehicle speeds between 2.5\text{kn} and 4\text{kn} and constant-altitudes of between 3\text{m} and 7\text{m} (sidescan ranges of 30\text{m} to 70\text{m} on each side). Bathymetric missions are planned for constant-depth, rather than the constant-altitude missions for sidescan and optical imagery. Mission settings for bathymetric collection are typically set for vehicle speeds between 2.5\text{kn} and 4\text{kn}, and a constant depth dependent on the expected water depth and bottom contours/heights.

Top-down mosaicking results were better than expected given source imagery from a single pass (viewing angle). The 3D point clouds suffered from the lack of different viewing angles, which would help fill in many of the concave surfaces observed in the imagery (i.e. under the chair, inside the concrete blocks, etc.). Features as small as 5cm (2in) were reconstructed from the single-pass image sequences, although there is theoretically no lower bound on scale given appropriate image detail. Mesh solutions exhibited convex hull characteristics with a lack of detail on undercut features (resulting from the lack of varying viewing angles). Further testing with different imaging sensor resolutions is needed and planned for the future, along with a more controlled study of lighting (both ambient and synthetic).

Future extensions of this work will use pre-planned bathymetric ranges (with known objects carefully placed and surveyed) to fully quantitatively characterize the camera and bathymetry systems. Careful patch-testing [8], [9] of the bathymetric sonar is required to optimize results and will be included in the analysis. Additional testing with repositioned cameras (providing different view angles) is hypothesized to provide much higher resolution 3D point clouds, when combined with down-looking imagery.

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