

Application of structured light imaging for high resolution mapping of underwater archaeological sites

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Abstract—This paper presents results from recent work using structured light laser profile imaging to create high resolution bathymetric maps of underwater archaeological sites. Documenting the texture and structure of submerged sites is a difficult task and many applicable acoustic and photographic mapping techniques have recently emerged. This effort was completed to evaluate laser profile imaging in comparison to stereo imaging and high frequency multibeam mapping. A ROV mounted camera and inclined 532 nm sheet laser were used to create profiles of the bottom that were then merged into maps using platform navigation data. These initial results show very promising resolution in comparison to multibeam and stereo reconstructions, particularly in low contrast scenes. At the test sites shown here there were no significant complications related to scattering or attenuation of the laser sheet by the water. The resulting terrain was gridded at 0.25 cm and shows overall centimeter level definition. The largest source of error was related to the calibration of the laser and camera geometry. Results from three small areas show the highest resolution 3D models of a submerged archaeological site to date and demonstrate that laser imaging will be a viable method for accurate three dimensional site mapping and documentation.

Index Terms—structured light, bathymetry, archeology, mapping

I. INTRODUCTION

Creating accurate photographic and bathymetric maps of the sea floor, and particularly archaeological sites, with robotic vehicles is a challenging task [1], [2], [3]. The accuracy requirements, set by the archaeological communities' experience with detailed land based surveys and numerous prior underwater surveys completed with SCUBA divers, demands better than centimeter level precision over spatial scales of 100's of square meters. Numerous imaging and mapping techniques such as photomosaicking [4], [5], photogrammetry [6], [7], stereo imaging [8] and high frequency acoustic bathymetric mapping [9], [10] are applicable to this problem, yet each has its own inherent limitations. This effort was completed to demonstrate the potential of laser sheet profile mapping and evaluate the trade offs in the context of other common methods.

Laser systems have been developed for both imaging and three dimensional (3D) mapping of the sea floor. Laser Line

Scan (LLS) systems [11], [12] have been used for extended range imaging and to a lesser degree range sensing. These systems minimize the common volume subject to water column backscatter between the light source and the sensor field of view [13]. Another class of three dimensional laser mapping systems use the triangulation relationship between a structured light pattern and camera sensor to solve for the scene geometry. This type of laser stripe imaging has been a common technique for many land applications in robotics and industrial measurement systems [14]. It has also been used on some underwater vehicles [15], [16] but only a few examples have been given thus far and a general approach has not been presented. Single point scanning laser triangulation systems have also been used to create very high resolution maps of sea floor micro-topography [17], [18]. These sheet and single beam mapping systems also retain desirable low backscatter performance in limited visibility environments where direct optical imaging for visual reconstructions would not otherwise be possible due to extremely low image contrast [19].

The presented sheet laser and camera system were chosen to complement an existing imaging system and avoid many of the more complicated aspects of LLS systems and specialized single beam scanning laser triangulation methods [17]. In general, laser mapping can offer narrower "beam widths" than acoustic scanning or multibeam sonars and be more robust than stereo reconstructions in areas of low textural information. Several small area surveys, $O(m^2)$, were completed to evaluate this potential as an augmentation to visual imaging typically done at submerged sites.

The remainder of this paper presents details of the overall Remotely Operated Vehicle (ROV) platform and sensors in Section II. Section III discusses the calibration and line extraction procedure used for the laser stripe measurements. Section IV presents results for the laser system in comparison to high frequency multibeam and stereo imaging. These results are summarized and directions for future work are mentioned in Section V.

II. PLATFORM DESCRIPTION

The vehicle platform used for this work was the Hercules ROV owned and operated by the Institute for Exploration based at Mystic Aquarium. This 4000 m rated ROV is closed loop controlled and can perform trackline surveys at prescribed velocities and altitudes. The navigation sensor suite includes a 1200 kHz RDI Doppler velocity log (DVL), a Paroscientific pressure depth sensor and an OCTANS fiber optic gyro system for heading and attitude information; see Table I for the sensor specifications. This data is collected using the DVLNAV software package [21].

TABLE I
NAVIGATION SENSORS

Measurement	Sensor	Precision
Heading (north seeking)	OCTANS FOG	$\pm 1^\circ$
Pitch/Roll	OCTANS	$\pm 0.01^\circ$
Depth (surface relative)	Pressure sensor	$\pm 0.01\text{m}$
Velocity (bottom relative)	Acoustic Doppler (DVL)	$\pm 0.01\text{m/s}$

A. Navigation processing

The platform navigation data were created using an iterated extended Kalman filter (IEKF) based on a constant velocity vehicle model. The pose of the vehicle was described using a six degree of freedom (DOF) parameterization with position and attitude variables measured in a local level reference frame. The complete state vector, $\mathbf{x}_v$, contains the vehicle pose, the body frame velocities and angular rates

$$\mathbf{x}_v = \underbrace{[x, y, z, \theta, \phi, \psi]}_{\text{position}} \underbrace{[u, v, w, p, q, r]}_{\text{velocity}}^\top \quad (1)$$

where, θ, ϕ, ψ are Euler angles.

The constant velocity model includes the function $\mathbf{f}(\mathbf{x}_v(t))$ which describes the kinematics and state accelerations that are perturbed by zero mean white noise $\mathbf{w}$ with diagonal covariance $\mathbf{Q}$,

$$\dot{\mathbf{x}}_v(t) = \mathbf{f}(\mathbf{x}_v(t)) + \mathbf{w}(t) \quad (2)$$

$$= \begin{bmatrix} {}^l_v\mathbf{R}(\theta, \phi, \psi) \begin{bmatrix} u \\ v \\ w \end{bmatrix} \\ J(\theta, \phi, \psi) \begin{bmatrix} p \\ q \\ r \end{bmatrix} \\ \mathbf{O}_{[6 \times 1]} \end{bmatrix} + \begin{bmatrix} 0 \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ 0 \end{bmatrix} + \begin{bmatrix} \mathbf{w}_{[6 \times 1]} \end{bmatrix}, \quad (3)$$

where $\mathbf{w}_{[6 \times 1]} = [w_u, w_v, w_w, w_p, w_q, w_r]^\top$.

This model relates the vehicle body frame velocities to local level frame velocities through the non-linear rotation ${}^l_v\mathbf{R}(\theta, \phi, \psi)$. The matrix $J(\theta, \phi, \psi)$ maps the body frame angular rates to the local level frame angular rates and the white noise $\mathbf{w}$ adds to the linear and angular accelerations. Discrete sensor measurements are incorporated asynchronously using

an independent zero mean white Gaussian noise $\mathbf{v}_k$ with covariance $\mathbf{R}_k$ where $E[\mathbf{w}\mathbf{v}^\top] = 0$.

$$\mathbf{z}[t_k] = \mathbf{h}(\mathbf{x}_v[t_k], t_k) + \mathbf{v}[t_k] \quad (4)$$

The values shown in Table II-A were used and have given results with limited phase lag that follow the sensor measurements and capture the periodicity of the small vehicle motions. For the presented results the IEKF was run to produce state estimates at the camera and sonar measurement times as a batch.

TABLE II
FILTER COVARIANCES

Process covariances, $\mathbf{Q}$	Value
$\sigma_u^2, \sigma_v^2, \sigma_w^2$	$(0.01\text{m/s})^2$
$\sigma_\theta^2, \sigma_\phi^2, \sigma_\psi^2$	$(0.05^\circ/\text{s}^2)^2$
$\sigma_{\dot{u}}^2, \sigma_{\dot{v}}^2, \sigma_{\dot{w}}^2$	$(0.1^\circ/\text{s}^2)^2$
Measurement covariances, $\mathbf{R}$	Value
$\sigma_u^2, \sigma_v^2, \sigma_w^2$	$(0.01\text{m/s})^2$
$\sigma_\theta^2, \sigma_\phi^2, \sigma_\psi^2$	$(.01\text{m})^2$
$\sigma_{\dot{u}}^2, \sigma_{\dot{v}}^2, \sigma_{\dot{w}}^2$	$(0.02^\circ)^2$

B. Mapping sensors

The cameras, laser and multibeam sonar were fixed to the stern of the ROV in a down looking configuration for a nominal survey altitude of two meters; Figure 1(a). The color and black & white (B&W) 12-bit Prosilica cameras have 1024×1360 and a nominal field of view (FOV) of $35^\circ \times 52^\circ$. The cameras were arranged in a verged stereo configuration with a nominal baseline of 45 cm. The laser was a 532 nm StockerYale 10 mW LasirisTM fit with a 45° spreading lens to produce a single thin laser sheet. The laser was fit in a simple pressure housing with a flat glass port, offset from the cameras by 500 mm and tipped to a angle of $\sim 11^\circ$ to the camera's optical axis. This arrangement translates to a nominal 0.5 cm vertical resolution per camera pixel in the B&W camera. Figure 1(b) shows a sample B&W image with the laser stripe visible on the bottom.

The multibeam sonar was a BlueView MB-2250, operating at 2250 kHz with a 45° field of view. The nominal range resolution was 0.5 cm per range sample for 280 beams formed at 0.18° spacing.

During a survey laser images were collected at approximately 3 Hz while the ROV moved at speeds between two and five cm/s along preset tracklines maintaining a constant altitude of between 1.5 and 3.0 m above the bottom. On separate surveys stereo images were collected at approximately 0.15 Hz and a vehicle speed of 15 cm/s. This produced a nominal along track image overlap of 50%. Multibeam data were collected at 5 Hz with a maximum range setting of five meters.

III. STRUCTURED LIGHT METHOD

The following sections describe the calibration for the laser system and the procedure used to extract line points from the images.

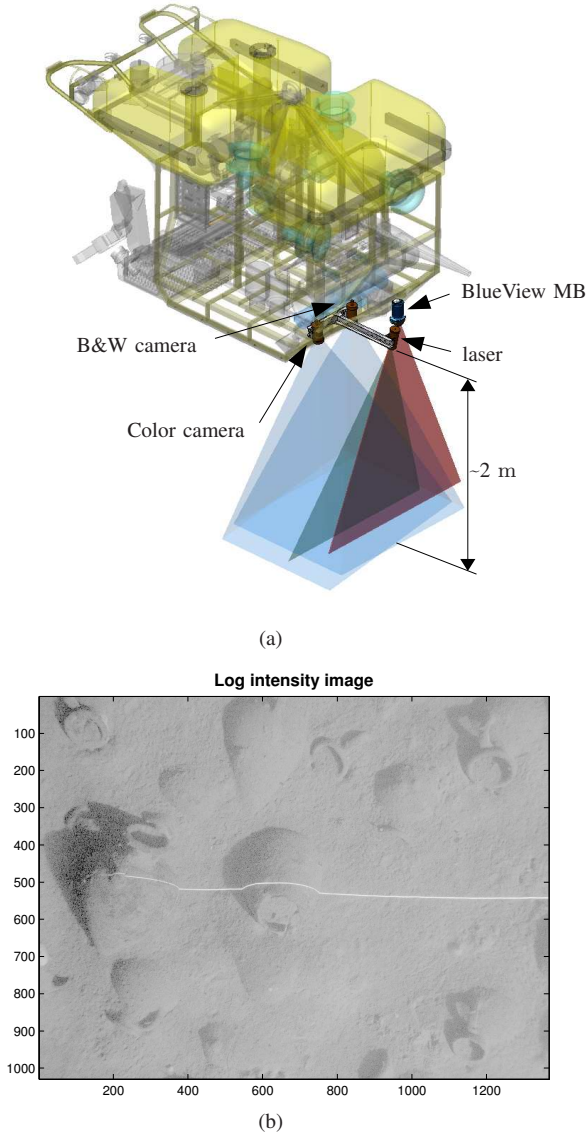


Fig. 1. (a) The Hercules ROV with stereo cameras, green sheet laser and BlueView multibeam sonar. The camera baseline is 0.45m. The laser is tipped at $\sim 11^\circ$ to the camera axis and offset 0.5m aft of the cameras. The geometry was designed for a nominal survey altitude of ~ 2 m. (b) Camera image taken under low light showing the laser strip and background over a wreck site (the log intensity is used for display here).

A. Calibration

Calibration refers to the process of determining the geometric relationship of the laser sheet to the camera as well as the projective properties of the camera. This is required to reproject the image of the laser sheet into three dimensions in a camera centered coordinate frame. By keeping the camera and laser on a single rigid bracket we were able to calibrate the lasers independent of the ROV and consider a second transform to locate the complete camera laser system in the ROV's navigation reference frame. The goal of our calibration procedure is to obtain the projectivity, $P_{4 \times 3}$, that transforms

homogeneous image points $\underline{u}$ from the image plane to the laser plane in three dimensions

$$\underline{x} = P\underline{u}. \quad (5)$$

The crux of structured light calibration is establishing known points in the camera coordinate system and their correspondences on the laser sheet as it appears in the images. Some techniques use a rig and carefully calibrated adjustable-range targets. This provides known ranges that can be used to solve for a set of model parameters related to the projectivity [14]. It is also possible to use direct measurements of the endpoints of target contours illuminated by the laser during the calibration procedure [22]. These techniques however are difficult underwater due to the difficulty of directly measuring ranges in a scene or using complex adjustable targets.

Our laser is mounted on a stereo rig which can be used to determine the camera frame coordinates of any point imaged by both cameras. This essentially splits the calibration procedure in two parts. First the stereo rig must be calibrated, and the result is then used to create scene range measurements to calibrate the laser plane. A disadvantage of this procedure is that each step produces its own errors. The advantage is that it can be done in-situ with a simple target held in the camera FOV or placed on the sea floor. The value of a field calibration procedure is also important since any changes to the rig will require a recalibration in situations where a tank is not available. Our stereo cameras were calibrated using the Matlab Camera Calibration Toolbox [23] and lens distortion was modeled and compensated for using Heikkila's distortion model [24].

Using the stereo solution, correspondences can be established between 3D coordinates and image coordinates containing the image of the laser line. These can be applied to determine the linearized projective transformation using a linear least squares method to solve for the individual elements of P . This can be written as

$$A_p = X, \quad (6)$$

where A is a measurement matrix composed of n (at least 4) image points (u, v) arranged as follows

$$A_{4n \times 12} = \begin{bmatrix} \underline{u}_1^T & 0^T & 0^T & 0^T \\ 0^T & \underline{u}_1^T & 0^T & 0^T \\ 0^T & 0^T & \underline{u}_1^T & 0^T \\ 0^T & 0^T & 0^T & \underline{u}_1^T \\ \vdots & \vdots & \vdots & \vdots \\ 0^T & 0^T & 0^T & \underline{u}_n^T \end{bmatrix}. \quad (7)$$

The right hand side X is a $4n \times 1$ vector containing the locations of the image points in homogeneous world coordinates obtained from stereo triangulation

$$X = [\underline{x}_1^T \quad \underline{x}_2^T \quad \dots \quad \underline{x}_n^T]^T. \quad (8)$$

The p vector contains the components of the linear projectivity

$$p = [P_{11} \ P_{12} \ P_{13} \ P_{21} \ \dots \ P_{43}]^T. \quad (9)$$

The least squares solution for p is determined by

$$p = (A^T A)^{-1} A^T X. \quad (10)$$

For the data presented here we completed this procedure for two cases. Prior to deployment on the ROV a small calibration data set was taken in a test tank. Using these data, that had three different depth ranges to a checkered target, we determined P and found it produced some vertical scale distortions in the reconstructed 3D points. A better projectivity estimate was obtained using simulated image coordinate data projected onto a ideal laser plane determined from the detailed CAD model of the camera and laser bracket assembly. This can easily be done by solving for the intersection of projected camera rays and the equation of the laser plane. Using these points the above steps produced a projectivity that reproduced the simulated points and showed less distortion in the resulting 3D data. The initial calibration data likely did not cover a large enough depth range to fully capture the project transform.

B. Line extraction

The laser line was extracted from the B&W camera images in batch post processing. The basic steps are illustrated in Figure 2 and described below.

- 1 The raw images were thresholded using a value determined by first calculating the mean and variance of each image. The threshold was then chosen to be 2.5 standard deviations above the mean. This worked quite well and was improved slightly by binning the image into sub regions, typically 4, when there was some small gradient of light across the image created by the utility lights on the vehicle.
- 2 The thresholded image, Figure 2(b), was processed using a sequence of morphological operators to remove spurious pixels away from the laser line and create a binary image region around the line, Figure 2(c). The sequence was a minimum connectivity test (`bwareaopen()` in Matlab), a morphological close operation using a vertical 15 pixel structuring element and a binary fill operation to close any remaining holes.
- 3 An initial line was then extracted from within the resulting binary image by selecting the v coordinate with the maximum intensity under the binary mask for each column containing a vertical region in the binary image, Figure 2(d).
- 4 Sub-pixel estimates for the line were made using a simple centroid method for a column-wise 11 pixel window centered on the maximum pixel v coordinate [25], [26]. Figure 2(e) shows the laser generally illuminating three vertical pixels in the image. This method yielded sufficient results and there was no additional smoothing or fitting done in the horizontal u direction in the image.

- 5 A median rejection filter was then run over the extracted line to remove any remaining spurious points away from line. This considered a horizontal window of 20 pixels and a rejection threshold of 50 pixels.

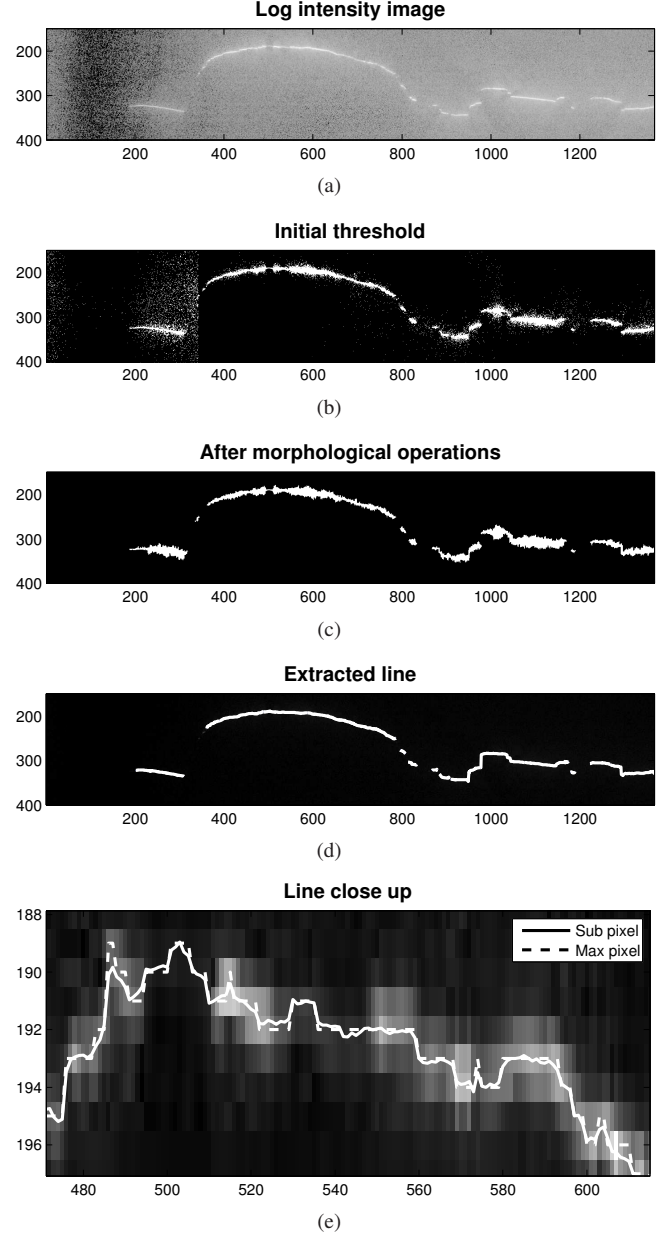


Fig. 2. Plots detailing the laser line extraction method. (a) Log intensity image showing the laser line. (b) Initial thresholding of the laser line base on the mean and standard deviation of the overall image intensity. (c) Line region after the morphological operations removed spurious pixels. (d) Extracted line determined from searching within the morphological region. (e) Close up view of the maximum pixel intensity line and resulting sub pixel line.

After these steps, for the results presented here and many other sites, there were no remaining spurious points. This is likely due to the low even lighting in the back of the ROV away from the utility lights at the front which remained on to aid piloting. The water was in general free of large scattering

particles but did have enough turbidity to prevent clear visual images at altitudes above three meters. The images shown in Figure 5 are affected by backscatter and show a low contrast haze at 2.6 m altitude. The images for the mosaic in Figure 6 were taken in much clearer water and the laser extraction worked equally well at both locations.

IV. COMPARISON RESULTS

The presented data were collected on a 2009 expedition to the Aegean Sea, which found and mapped several wrecks in water depths between 50 and 400 meters. Results are shown in Figures 3 through 6. Although additional larger imaging and multibeam surveys were completed for other purposes, the data presented here were analyzed over small areas to evaluate the baseline potential of the laser system without the compounding errors of larger scale navigation and calibration between the sensors. The results shown in Figures 3 and 5 show that the laser mapping achieved the highest definition. We are careful not to use the terms *accuracy* or *precision* here because we do know there are some small distortions remaining in our laser calibration. Without direct high frequency navigation over the site it is difficult to quantify the differences between the maps. The gridded surfaces shown in Figures 4 through 5 were made using simple local Gaussian averaging which regularizes the nonuniform point cloud data. The different wreck sites shown had different levels of water clarity but in each case the laser results were consistent. The images shown in Figure 3(d) and 6 were done at 1.8 m and 2.7 m altitude respectively, but show comparable results.

A. Multibeam sonar

The 2250 kHz multibeam data were collected and initially batch processed to return range data using the BlueView SDK. Median rejection filtering was then done within single pings and over a sliding windows of pings sequential in time to remove spurious ranges prior to assembling the maps. As shown in Figures 3(c) and 5 the multibeam at this range was able to capture a significant amount of scene detail. At these slow vehicle speeds the sounding density was the highest of the methods due to the fast ping rate of the sonar. The gridded surfaces in figures 4(b) and 5 show slightly less definition than the laser data. This is likely due to the beam pattern affect, rather than the acoustic scattering at the surface or in the upper layer of sediment. At this high frequency the volume scattering within the sediment or the ceramic amphora would be minimal.

B. Stereo imaging

The stereo point clouds were made from sparse reconstructions using feature points extracted from the local extrema of a multiscale difference of Gaussians and encoded using the Scale Invariant Feature Transform (SIFT) [28]. The feature correspondences were assigned to feature pairs with the highest similarity score calculated using the Euclidean distance between SIFT descriptors. Corresponding feature points were then triangulated into the 3D camera frame using the intrinsic and extrinsic camera model parameters established during the

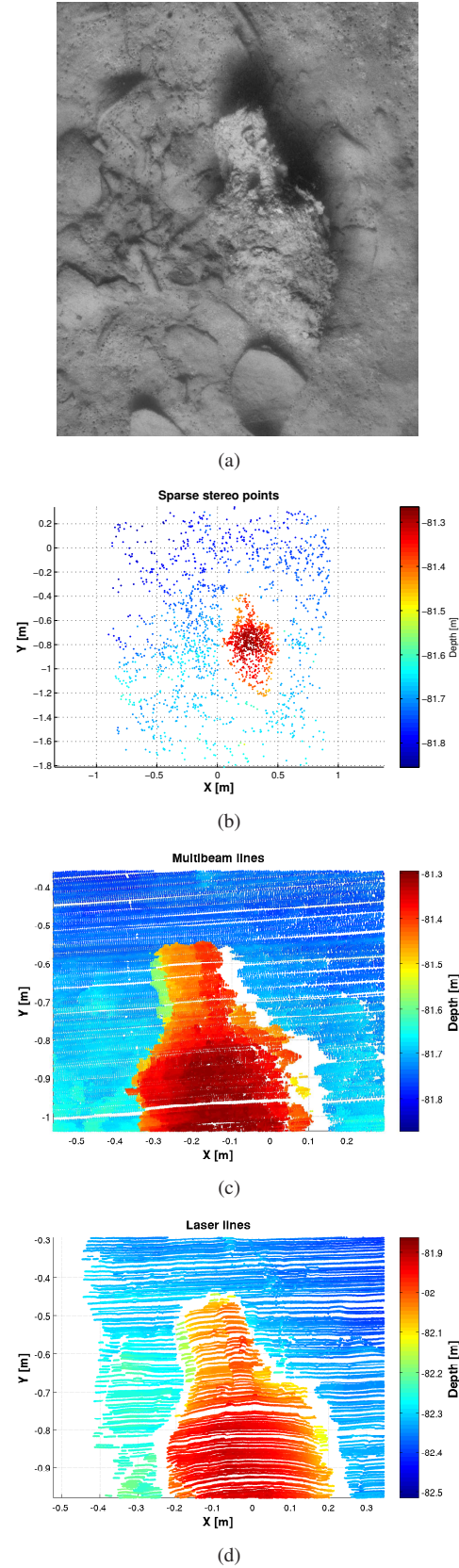


Fig. 3. Example pass over a single amphora. (a) Photo of the amphora assembled from two still images. (b) Point cloud from two stereo pairs. (c) Multibeam scan lines. (d) Laser scan lines showing the clearest edge and handle details.

camera calibration. In total the overall number of 3D points is far fewer than with the laser or multibeam sampling; Figure 3(b). The point density is also highly dependent on scene texture, as seen on the texture rich amphora where many points are found, while fewer are found on the sediment background. This is a common problem in stereo imaging and particularly challenging with the low contrast images associated with sediment covered wreck sites. More aggressive feature detection can be done, but this often just moves the problem to outlier detection to find extraneous matches. The matching points are also difficult to obtain on the edges of amphora due to direct occlusion and the difficulty of feature description on the steep curved surface. In these edge areas the laser and multibeam were able to show more definition.

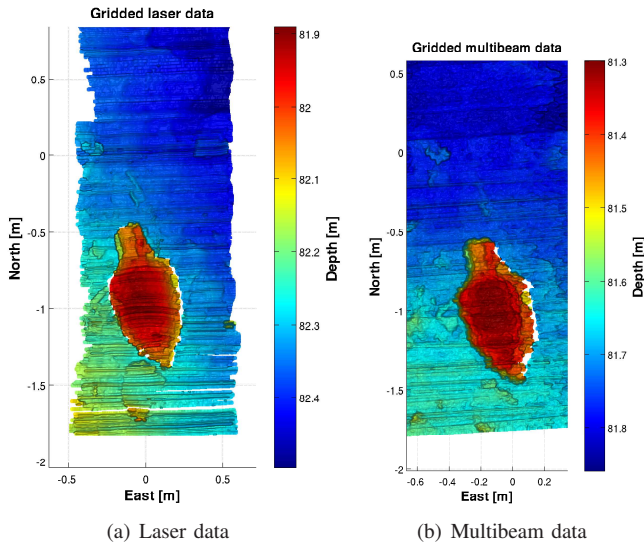


Fig. 4. Gridded surfaces using a regular 2.5 mm grid spacing and a 4.0 cm Gaussian weighted average.

V. CONCLUSIONS

In conclusion, structured light mapping offers a high resolution capability for the investigation of underwater archaeological sites. To the authors' knowledge the presented results are the highest resolution bathymetric maps that have been made of submerged archaeological sites. This archaeological work also provides a useful surrogate for numerous other scientific problems in marine geology, biology and acoustics that benefit from detailed maps of the sea floor and a characterization of its roughness. To extend the presented small area maps additional effort will focus on improving the in-situ calibration methods, which will need to be far more accurate to combine data and map larger sites. Future navigation processing will need to address both the short term vehicle motion that introduces errors across sequential laser images as well as the larger navigation requirements to consistently map an entire site. Our intent is to move toward a bathymetric SLAM approach [27], [29] to combat the time dependent error growth related to using dead reckoning navigation without ground referenced

navigation. This will also require better refinement of the vehicle to sonar transforms, which can be further refined using dedicated survey patterns which highlight specific components of the transforms.

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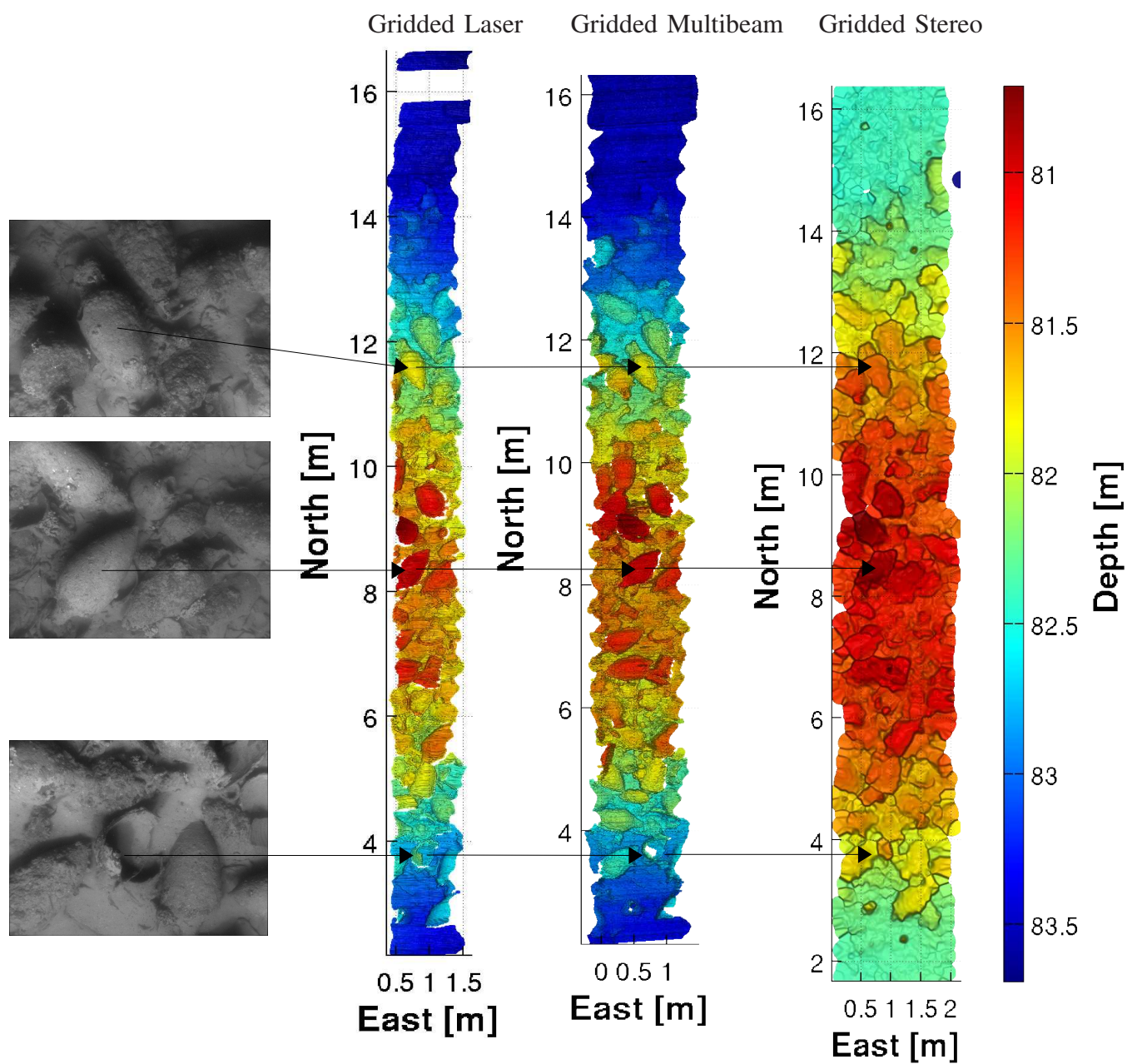


Fig. 5. Comparison passes over a wreck site for laser and multibeam data obtained at 1.8 m altitude and a forward vehicle speed of 0.025 m/s. The stereo images, including the three shown, were obtained at a 2.6 m altitude and create the wider swath width. Each data set was gridded using a 4.0 cm Gaussian weighted average. The point density for the three passes is similar to that shown in Figure 3. The laser data shows the most fidelity and is able to clearly capture sharp edges such as the broken amphora in the lower image.

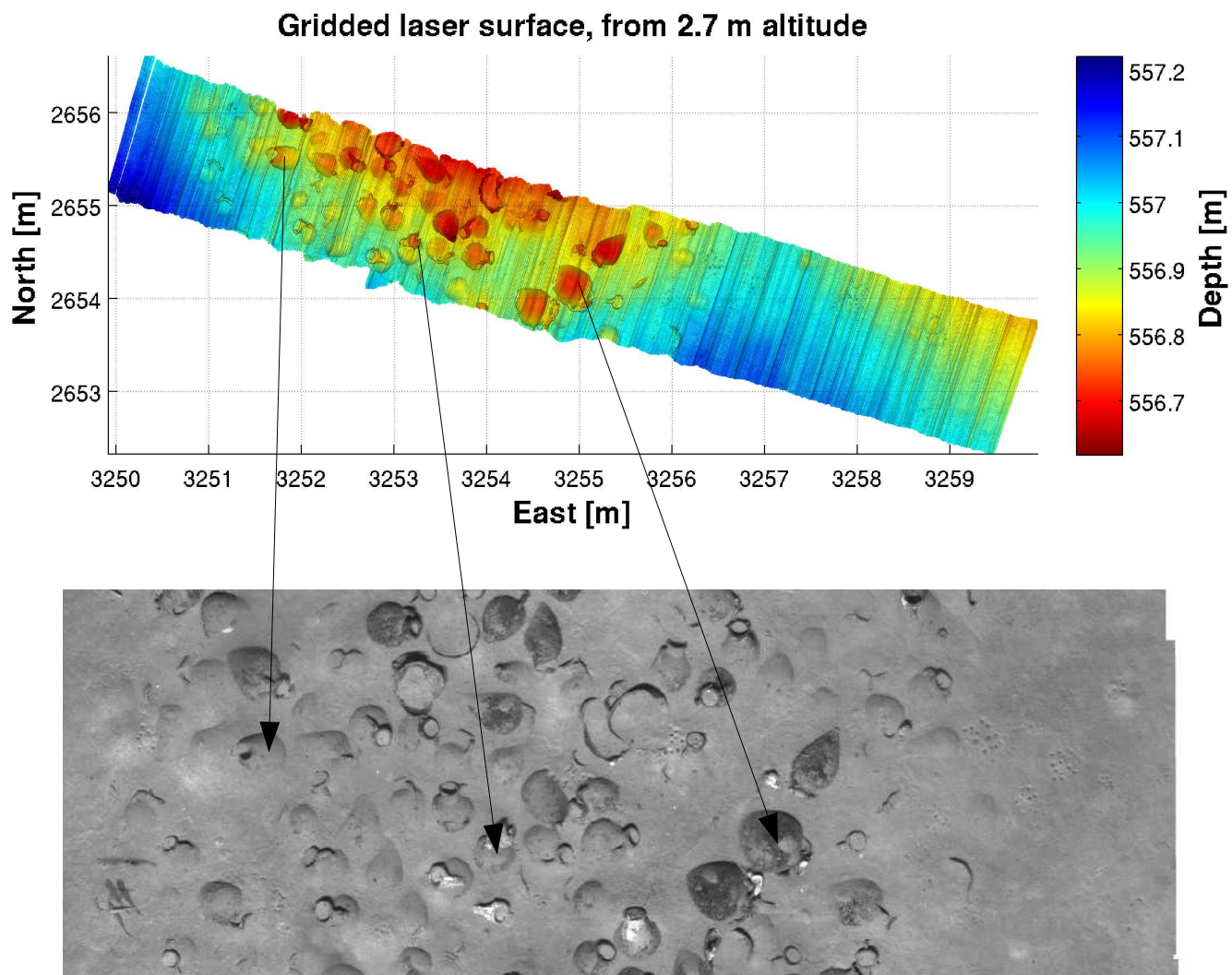


Fig. 6. Laser bathymetry and accompanying photomosaic of a low relief wreck site. The corresponding objects are indicated by the arrows. The photomosaic images were taken from 4.5 m altitude and the laser survey was done at 2.7 m altitude. Gridding was done with a 4.0 cm Gaussian weighted average.