Development of a New Underwater Bathymetric Laser Imaging System: L-Bath

KARL D. MOORE, JULES S. JAFFE, AND BENJAMIN L. OCHOA

Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California

(Manuscript received 13 August 1998, in final form 18 October 1999)

ABSTRACT

The design, construction, and performance of a new high-resolution underwater bathymetric prototype system (L-Bath) with extended imaging capability is presented. The design offers simultaneous reflectance and depth information on a pixel-by-pixel basis so that high-resolution reflectance and bathymetric maps of underwater targets can be provided with exact registration. The design supports operation in shallow coastal waters under daylight conditions where high turbidity and the influence of ambient backscatter are particularly limiting for underwater imaging systems. Its configuration is similar to existing laser line scanning systems but uses a pulsed laser for the source and a fixed field-of-view high-resolution linear charge-coupled device (CCD) as receiver. The pulsed laser allows short camera integration times, thereby reducing the influence of the ambient daylight signal, and the fixed field of view of the detector provides a precision nonmoving multielement receiver with imaging capability. As the laser sweeps across the field of view of the CCD, the position and signal strength of each laser target spot is imaged, permitting a measure of bathymetry and reflectance. Using the CCD, a high-resolution slice through the reflected target spot radiance distribution is imaged so that system resolution can exceed the target spot size. The image of the target spot radiance distribution, modified by in-water scattering and target reflectance, provides new opportunities for image manipulation compared to typical underwater laser line scanning based systems. The simultaneous acquisition of reflectance and bathymetric maps permits discrimination capability between real objects of relief from scene reflectance variations.

1. Introduction

The performance of underwater optical imaging systems is ultimately limited by the absorption and scattering properties of the water in which they operate. Depending on the application, these systems can range from the most basic and simple, such as a camera packaged in a waterproof housing, to more elaborate systems adopting structured lighting, scanning illumination mechanisms, and detector systems. In a typical application, underwater systems employ a closed-circuit television (CCTV) camera (or still, intensified, etc.) and a wide-angle panchromatic illumination source. These systems are primarily limited by backscatter particularly when the source and receiver are in close proximity (Jaffe 1990). In the case of more exotic systems, the effects of forward scatter may limit performance.

When the imaging geometry has been optimized to reduce backscatter the system may become limited by absorption. In this situation the returning signal is too weak for adequate detection and the system is said to be power limited. In the case where the amount of scattering overtakes the amount of direct signal returning to the receiver, the system is said to be contrast limited. The design benefits and implications of source–receiver separation, contrast, and power in underwater optical imaging systems have been reviewed (Funk et al. 1972) and modeled elsewhere (Jaffe 1990, 1995). A brief review of underwater imaging methods has also been documented by Caimi (1996).

Performance can also be enhanced by choosing the source wavelength to match the optimal blue-green transmission window of water. This increases operational range of the system and reduces backscatter by eliminating scattered light from photons that have a higher probability of being absorbed before reaching the target. Also, the change in the polarization state of the light field scattered by water and suspended particles can be utilized to enhance contrast (Funk et al. 1972).

More advanced and exotic systems reduce the effects of scatter by precisely controlling either the temporal or spatial properties of the illumination source and receiver. These systems mostly fall into two main categories: range gated and synchronous scanning. In range gating, the temporal aspects of the light source and receiver are controlled. This method exploits the time of flight of light in seawater and requires precise gaging of both the light source and the receiver. The method works by sending a short duration beam of light, equivalent
to the time it takes for light to travel a sufficiently short distance (typically <2 m), and gating the camera for the return pulse such that only light from the target scene is captured. For range-gated systems to effectively reduce backscatter, the pulse duration is typically much shorter than the time to travel to the target. However, range gating, as commonly used, does nothing to reduce forward scatter. Applications of pulsed-laser-based range-gated systems have been developed and tested typically yielding images ~4 attenuation lengths (A.L.) (Witherspoon and Holloway 1990; Fournier et al. 1993; Fournier et al. 1994; Swartz et al. 1993).

Synchronous scanning, on the other hand, exploits the spatial aspects of both the illumination light field and field-of-view of the detector. By structuring the illumination field to be highly collimated with minimal cross section, as in the case of a laser, small individual elements of the target scene can be illuminated, one at a time, with minimal backscatter. At the same time, a narrow field-of-view receiver tracks the target spot and reduces forward scatter from light reflected from the target. This combination of narrow field-of-view source–receiver optics minimizes the common volume between the illumination beam and the receiver so that both back- and forward scatter are reduced by spatial rejection of light from outside this region. For this reason, the laser linescan synchronous scanning system has shown superior contrast resolution over the range-gated system (Strand 1995). Different variations of the synchronous scanning configuration have been realized (Austin et al. 1991; Kulp et al. 1993; Chu and MacDonald 1995; Strand et al. 1996; Coles 1997). The concept of synchronous scanning is not new (Blanchard 1970), but the advent of high-speed sensitive detectors, precision scanners, inexpensive computing technology, and the availability of blue-green lasers, now allows such systems to be realized in practical applications.

In this paper we describe the design of a system that has the benefits of a synchronous scanning system but also provides 3D bathymetric information. Other optical methods have been pursued to obtain underwater depth information and target surface maps. Object range and plane orientation measurements have been obtained using laser patterns projected onto the target (Caimi and Tusting 1988; Davis and Tusting 1991). Interference methods using video moiré techniques have been utilized to provide higher resolution for underwater mapping and surface shape determination, although they require additional instrumentation to determine target range (Caimi et al. 1993; Blatt et al. 1992). Other interference methods have included holographic systems (Carder et al. 1982; Katz et al. 1984; Katz et al. 1999). However, interference methods are dependent on the preservation of the illumination coherency in the water, which is degraded by turbulence, thermal gradients, relative motion, and from spectral broadening by scattering processes encountered from collisions of moving particles (Swanson et al. 1993). Use of interference methods in seawater at range have been proposed and laboratory tested using quasi-coherent spatial techniques (Caimi et al. 1998). Quasi-coherent temporal interferometry has been used to produce range images (Scott 1990). A solution to the rapid loss of coherency as light propagates through the water has been pursued using a combination of lidar and radar technologies (Mullen et al. 1995).

The geometry of synchronous scanning systems, with fixed source–receiver separation, presents a means of calculating depth by triangulation. Laboratory versions in clear water and short range (0.2–0.4 m) have been developed using a low-power 10-mW laser and a proprietary position sensitive detector to achieve <1-mm resolutions (Caimi and Kocak 1997; Caimi and Smith 1995). In general, dependent on the technology, triangulation-based systems can provide higher resolutions at close range (<5 m), whereas range-gated systems may provide better resolution at range (>10 m) (Massey 1991). However, synchronous scanning systems have the advantage of eliminating forward scatter. The synchronous scanning configuration has been designed to minimize the effects of in-water scattering and produce high contrast images in turbid waters (Coles 1997), but it also provides a basis to estimate range by triangulation, since a unique pair of source–receiver angles accompanies each measurement.

Other hybrid depth imagers have been developed that utilize a combination of structured lighting and time-of-flight designs. For example, a structured fan of pulsed laser light is projected onto the seafloor as a line while a streak-tube camera is gated to time resolve and estimate the depth of the returning picture elements (McClellan and Murray 1998). The Spotmap system (Seatex) is another example and based on a laser radar approach. In this case, the pulse from a collimated laser beam interrogates each target element, in a similar manner to a synchronous scanning system, but is gated synchronously with a colinear laser to obtain depth by time of flight (Klepsvik et al. 1994; Evans et al. 1998). Also, a dual pulse/detector lidar design is used for 3D underwater imaging (Moran et al. 1993).

The L-Bath (laser bathymetry) system described in this paper has adopted the synchronous scanning configuration to provide high resolution, high contrast images, and utilizes its triangulation configuration to provide depth information by measuring the angular parameters involved in both the illumination and detection of each target element. Since the reflectance and range are derived from the measurement of each target element, reflectance images and bathymetric maps are generated at identical spatial resolution on a pixel-to-pixel basis simultaneously. In addition, the use of a solid-state charge-coupled device (CCD) array in place of a mechanical or electronic tracking receiver eliminates the need for moving components and promotes high resolution and accuracy. Since the target spot is imaged over a number of pixels, system resolution can exceed that...
defined by the target spot size. The CCD also provides the option to apply image-processing techniques by using the CCD as a variable aperture mechanism, that is, binning pixels in order to increase signal to noise or binning less to narrow the receiver field of view in order to reduce detection of forward scatter.

Here we describe a laboratory prototype version of the system, analyze its performance, and include an error analysis to extrapolate the system performance for different water turbidities and operational ranges. We also present the results of a laboratory test taken in clear water using man-made objects to demonstrate the usefulness of bathymetric and reflectance data acquired simultaneously at identical resolution, and also to validate the system design.

2. Instrument description

The L-Bath system scans in one-dimension, perpendicular to its direction of motion and builds an image line by line as it moves through the water. The light from a pulsed 532-nm Nd:YAG laser is used and deflected by a scanner across the target. A fixed distance away (~0.8 m), a linescan linear CCD array images the reflected light. From the image of the reflected light and the projected angle of the laser beam, the position and intensity of the target spot image on the array can be estimated so that bathymetric and reflectance data can be obtained.

The underwater instrument consists of three housings; scanner housing, camera housing, and a main housing that encapsulates the main computer, auxiliary electronics, and a sensor package (Fig. 1). These housings are mounted on an aluminum frame and attached to the underside of a hydrodynamical tow wing. Both the scanner and camera are mounted on a common chassis so their respective two-dimensional fields of view lie within the same plane. Both the scanner and camera are connected to the main housing by flexible high-pressure conduits. The main housing contains the drive and acquisition electronics for the scanner and camera, including a computer with acquisition and control boards, sensor package, and power supplies. The sensor package includes a compass, high-precision dual axis tilt sensor, and pressure transducer to measure depth below surface.

A 200-m electrooptical cable delivers power, laser light, and communication link between the surface and the submerged instrument. At the surface, light output from a Spectra-Physics 532-nm solid-state Nd:YAG laser is coupled into a high-power optical fiber and delivered to the scanner housing. Power is supplied by electrical wire, and the data link by two 50/125-μm communication optical fibers. A third communication fiber is used to send video images from an auxiliary
CCTV camera, positioned nadir-viewing in the main housing.

As the system moves through the water a series of laser pulses are deflected by a scanning mirror onto the seafloor in a linear fashion. By synchronization, the position of each pulse on the seafloor is captured by a linescan CCD camera and the mirror angle of the laser pulse determined from the scanner encoder voltage. Information from the sensor package is simultaneously read to correct for depth and angular attitude variations of the system during field operation.

a. Scanner housing and control

The scanner housing contains a galvanometric optical scanner (Cambridge Technology) that uses a 10-mm fused silica substrate silver-coated mirror. The laser light is first collimated into an $\sim 8$-mm-diameter beam using a 20-mm focal length, 12.5-mm diameter, and 532-nm AR laser-coated fused silica lens, producing a half-angle beam divergence of $\sim 1.25$ mrad. The beam is then reflected through a 4-in.-diameter by 3/4-in.-thick fused silica window.

The waveform used to control the mirror sweep is generated through software via a National Instruments multifunction I/O board using a 12-bit DAC output. An analog input channel on the same board is used to read the mirror position synchronously with each laser pulse and camera acquisition. A second analog output DAC channel is used to produce an enable pulse, which activates the laser and camera to acquire bathymetric information during specific periods of the mirror sweep. The waveform used here drives the mirror in a raster scan fashion; namely, a linear sweep followed by a quick reset to the start position, with the laser and camera enabled during the linear portion of the sweep and disabled during reset. Software control of these two DAC output channels creates a dynamic environment to implement various permutations of laser beam sweep and bathymetric sampling patterns.

b. Camera

A 12-bit digital camera with a 1024 pixel linear CCD array (Dalsa) is employed and operated at a maximum linescan rate of 9.1 kHz with 2-μs minimum integration time. The short integration time minimizes ambient light contributions and allows the system to operate under daylight conditions. The camera has a dynamic range of 2000:1 or slightly less than 11-bits at room temperature with a noise equivalent exposure of 66 pJ cm$^{-2}$. The camera receiving optics consists of a 35-mm format camera lens combined with a double convex lens. The combination of an f/1.4, 35-mm focal length Nikkon lens and 36-mm focal length double convex lens (used to halve the image magnification), provides the detector with a $\sim 45^\circ$ total field of view in air.

c. Computer

The system utilizes the Intel Pentium Pro based architecture running Microsoft’s Windows NT operating system. Data acquisition is accomplished using a National Instruments multifunction I/O board and a BitFlow digital camera interface. The control software was developed under National Instruments LabWindows/CVI open ANSI C development environment. The submerged host computer is remotely accessed across the fiber-optic network using a World Wide Web browser, allowing control of the system. The fiber-optic network also provides data transfer between the surface and remote computers.

The system acquires a complete linescan of 1024 pixels at 12-bit resolution equating to a maximum data rate of $\sim 18$ MB s$^{-1}$ and is accommodated by the host computer in the main housing. The host computer has a 200-MHz Pentium Pro processor with 512-kB cache, 128-MB RAM, a 2-GB-wide ultra SCSI hard drive for computer support and a 9-GB-wide ultra SCSI hard drive used to buffer data acquisition.

d. System timing

Accuracy of the bathymetric data depends on the precision with which the laser pulse, mirror angle position, and camera acquisition can be synchronized. Since the camera is set to its minimum exposure time of 2 μs, which is considerably longer than the <100 ns laser pulse duration, synchronization can be maintained provided the laser pulse appears somewhere within this exposure period. The laser is triggered by the camera and dictates the pulse repetition frequency of the laser. This timing hierarchy maintains system synchronization under different operational requirements, that is, different scan rates, camera line rates, scan waveforms, etc.

3. Theory and performance

a. Bathymetry and reflectance

In this section the triangulation geometry to estimate bathymetry is examined and applied to the L-Bath configuration with its adjustable scanner/camera housings.

1) Geometry

The geometric relationship between camera, scanner, and the illuminated target spot to determine depth is shown in Fig. 2. The depth, \( D \), of a target element measured from L-Bath system can be calculated from

\[
D = L_1 \cos \omega
\]

also,
FIG. 2. L-Bath geometry.

\[ L_1 = \frac{S \cos \phi}{\sin(\phi - \omega)}, \]

since

\[ \sin(\phi - \omega) = \frac{O}{L_1}, \]

and \( O = S \cos \phi, \)

therefore

\[ D = \frac{S}{\tan(\phi + \omega) - \tan(\omega + \omega)}, \quad (1) \]

where \( S \) is the separation between the center of the scanning mirror and the center of the primary receiving lens of the camera. Here \( \phi \) and \( \omega \) are the scanning and camera pixel viewing angles, respectively.

In the L-Bath system, \( \phi = \phi_1 + \phi_o \), where \( \phi_1 \) is the laser beam angle known from the galvanometer encoder voltage of the scanner and \( \phi_o \) is the offset-mounting angle of the scanner housing. Similarly, we have \( \omega = \omega_o + \omega_o \), where \( \omega_o \) is the offset-mounting angle of the camera housing and \( \omega_o \) is the pixel-viewing angle (with respect to the camera housing) of the \( i \)th pixel in the array that observes the target spot. That is, \( \omega_o = i\Omega_o \), where \( \Omega_o \) is the view angle subtended by each pixel. For L-Bath Eq. (1) becomes

\[ D = \frac{S}{\tan(\phi + \omega_o) - \tan(\omega_o + \omega_o)}, \quad (2) \]

2) Calculation of Bathymetry and Reflectance

During operation, the system acquires source–receiver data in terms of scanner encoder voltages and digitized radiance profiles of 1024 pixels that must be translated to angles and intensities to render bathymetric and reflectance information. This data matrix can be represented by

\[ M(u, l), \]

where \( u \) is the scanner encoder voltage recording the laser beam angle for a particular sample \( j \), where \( 1 < j < \text{total number of sample acquisitions} \). Here \( l \) is a one-dimensional matrix corresponding to a single linescan readout of 1024 pixels that has been dark current corrected. From matrix \( M \), both the depth \( D \) and reflectance \( R \) can be derived, that is,

\[ j: M \rightarrow D(u, l), R(l). \]

(i) Depth

To determine depth, the position of the target spot must be estimated from the image of its radiance distribution recorded in the linescan readout such that

\[ p_j = f_D(l), \]

where \( f_D \) is a function operating on \( l \), that determines target spot pixel position \( p_j \) in the array. For the examples used in this paper, \( f_D \) locates the position of the brightest pixel in the array, which is assumed to correspond to the center of the target spot. The function \( f_D \) can be based on other criteria involving analysis of the radiance distribution.

The angle subtended by \( p_j \) is \( \Omega_o \) and its view angle with respect to the system is given by,

\[ \omega_j = \Omega_o p_j + \omega_o \]

where \( \omega_o \) is the angular offset due to camera mounting and \( \omega_o = \Omega_o p_j \), where \( \Omega_o \) has been previously measured. Also, the scanner encoder voltage is related to the laser beam angle by,

\[ \phi_j = k u + \phi_o, \]

where \( \phi_o = k u \), since scanner mirror position responds linearly with voltage, and \( k \) is an empirically determined constant. Therefore, the depth of sample \( j \) can be expressed as

\[ D_j = \frac{S}{\tan(k u + \phi_o) - \tan(\Omega_o p_j + \omega_o)}. \quad (3) \]

(ii) Reflectance

The reflectance of sample point \( j \) is proportional to the amount of light arriving at the detector. For the purpose of intensity maps, reflectance is assumed to be proportional to the CCD detector response. The reflectance of target sample \( j \) is determined using the function \( f_R \) such that,

\[ R_j = f_R(l_j), \]

where \( f_R(l_j) = \max(l_j) \) and \( R_j \) is simply the value of the brightest pixel. It should be noted here that the sig-
nal-to-noise ratio of any reflectance map may be enhanced by binning adjacent pixels around the pixel corresponding to the center of the target spot. In this case, 
\[ f_{\text{bin}}(I) = \sum_{p=r}^{p=s} I_r, \]
where \( x = (n - 1)/2 \) and \( n \) is the number of binned pixels.

b. Bathymetric performance

The bathymetric performance of the system presented in this section has been estimated by introducing measured values of instrument error into the geometrical relationship for depth positioning by triangulation. Bathymetric performance depends on the resolution and accuracy in both positioning the laser beam and determining the pixel position of the target spot. Since the scanner-camera separation distance and mounting angles are fixed, only the laser beam positional accuracy, \( \Delta \phi_s \), and the pixel position resolution, \( \Delta \omega_c \), determine bathymetric performance. The bathymetric resolution, \( \Delta D \), can be expressed as

\[ \Delta D = \left[ \frac{S}{\tan[(\phi_s + \Delta \phi_s) + \phi_e] - \tan[(\omega_c + \Delta \omega_c) + \omega_e]} - D \right], \]

where \( \Delta \phi_s \) has been determined empirically and \( \Delta \omega_c \) expressed in terms of pixel position accuracy. While the magnitude of \( \Delta \phi_s \) is dependent solely on mechanical and electronic limitations, the uncertainty in pixel position, \( \Delta \omega_c \), is only partially described by the angular resolution of each detector pixel. The magnitude of \( \Delta \omega_c \) is also influenced by a combination of laser beam divergence, target reflectance properties, and the scattering properties of the water body itself.

The accuracy of the laser scanning mirror position, operating in a specific raster scan pattern (sweeping over a 45° angular range at 100 Hz), was determined to be \(-0.162\) mrad. This measurement was determined by repeatedly sweeping the laser beam across a photodiode placed in view of the scanner. Angular resolution of a receiver pixel was determined by measuring the total field of view subtended by the linear detector and dividing by the total number of pixels, that is, \( 0.581\) mrad (in water). The field of view subtended by each pixel is assumed to be identical, based on (i) the inherent high precision of pixel dimensions and pitch of the detector, and (ii) roll-off effects from the lens are minimal since the extreme field-of-view regions of the receiving lens combination are avoided.

Performance graphs have been generated using Eqs. (2) and (5) above. Figure 3 shows depth resolution as a function of depth for samples taken directly below the system and Fig. 4 depicts depth resolution at 10-m range as a function of scanner-camera separation distance. Figure 5 shows the depth and spatial resolution across the field of view of the camera for the system at different ranges. For simplicity, the camera and scanner housings are equally angled toward each other to provide optimal common coverage at each depth, that is, laser swath width covers full camera field of view.

Figures 3 and 4 show the expected system resolution for three different hypothetical accuracies to demonstrate its sensitivity to system parameters. "Scanner error only" considers the indeterminacy of positioning the
c. Radiometric performance and depth range

In this section we examine the radiation budget of the system to predict the range and water turbidity in which the system can operate. Radiometric performance is expressed in terms of the laser beam power and its detection by the camera. Losses in laser power resulting from the system optics, propagation through water, and reflection from a target back to the receiver are quantified for different beam characteristics, range, and optical properties of the water.

Figure 6 shows the propagation of laser radiation from the scanner to the target, and back to the camera. At the surface the laser outputs roughly 340 µJ per pulse (maximum power at 10 kHz) and roughly 200 µJ per pulse is assumed to leave the scanner housing using estimates of transmission and reflection losses due to fiber coupling, delivery down a 200-m cable, and propagation through the collimation lens, mirror, and window.

At the scanner the laser pulse is reflected off the mirror, through the housing window, and directed at angle $\phi$ through the water with an extinction coefficient $c$. (The distinction between absorption and scattering is unnecessary here, since extinction coefficient adequately represents the loss of radiant energy along the pathlength of the laser beam). The beam travels a distance $l_1$ from the scanner housing and reaches the target at depth $D$ below the system. In this simple calculation, two beam characteristics are assumed: (i) an ideal situation where the laser beam is infinitely narrow such that the laser spot size is always less than the angle subtended by a camera pixel, and (ii) beam spreading characteristics where a number of pixels are covered.

The target is assumed to be a Lambertian reflector of reflectance $R$. At a distance $l_2$ away, a pixel in the camera views the illuminated spot on the seafloor at angle $\omega$. The energy received at the camera, $E_r$, for a single laser pulse can be expressed as

$$E_r = E_s R\Omega e^{-c l_2}$$

(6)

where $E_s$ is the energy of the pulsed laser beam leaving the scanner, and $e^{-c l_1}$ and $e^{-c l_2}$ are the attenuation lengths over distances $l_1$ and $l_2$ in water with extinction coefficient $c$. The fraction of reflected light received by the camera lens distance $l_2$ away is given by the angle subtended by the receiver lens, $\Omega = \frac{\pi d_a^2}{4}$, where $d_a$ is the lens aperture diameter. (We assume no losses at the receiver lens combination.) Equation (6) becomes

$$E_r = \frac{E_s R\pi d_a^2 e^{-c (l_1+l_2)}}{4l_2^2}$$

(7)

As an example assume that $l_1 = l_2 = 10$ m, with $d_a = 0.025$ m, and $R = 0.05$. At four attenuation lengths ($c = 0.4$ m$^{-1}$ at 532 nm), we get $E_r \approx 1.65 \times 10^{-14}$ J arriving at the receiving lens. Assuming the case where the image of the laser beam is always smaller than the pixel dimensions, $E_r$ is the remaining energy intensity that arrives at the receiving lens and is focused into single pixel. The intensity of laser radiation per pixel...
is then, $I_p = E_p/a_p$, where $a_p$ is the area of a pixel (1.96 $\times$ 10^{-6} cm^2) and $I_p = 8.4$ nJ cm^{-2}.

In the second and more realistic case, the laser beam spreads according to a combination of beam divergence and in-water scattering. Its image spot size on the detector covers a number of pixels and the intensity of laser radiation per pixel becomes

$$I_p = \frac{E_p A_p}{a_p A_p},$$

where $A_p$ is the area in the object plane subtended by a detector pixel, $A_p = [D \tan(\Omega_p)]^2$. The size of target spot, $A_{ts}$, is given by $A_{ts} = \pi[D \tan(\alpha)]^3$, where $\alpha$ is the divergence half-angle of the laser beam. The target spot diameter calculated for the delivery of laser light via 50/125-μm optical fiber, and recollimated with a 1.25-mrad half-angle divergence, covers roughly 4–5 pixels on the CCD. For simplicity, laser energy is assumed to be evenly distributed over $A_{ts}$.

The camera response can be expressed in terms of digital counts (DN) by

$$DN = \frac{(I_p - NEP)}{NEP},$$

where NEP is noise equivalent exposure of the camera (i.e., amount of incident energy per pixel to produce a signal response equal to the noise level, or more simply, the minimum detectable signal per pixel). With a CCD noise equivalent exposure of 66 pJ cm^{-2} (at 25°C) and an output laser pulse energy of 340 μJ results in a ~130 DN camera response at 4 A.L. (or ~4 DN in the case of the divergent laser beam). At closer ranges, higher camera responses can be obtained at 4 A.L. For example, at 2-m range in 2.0 m^{-1} water (4 A.L.) a response of >3100 DN (or ~100 DN for divergent laser beam) could be achieved.

These calculations predict an operational limit around four attenuation lengths and do not include signal-to-noise enhancement from binning. System performance has been addressed here in terms of signal strength to estimate an operational range in turbid waters. Provided the laser signal can be detected, bathymetric and reflectance images can be obtained. Bathymetric integrity will eventually break down when the sufficiently low signal strength of the target spot profile becomes susceptible to background signal, detector noise, or target reflectance such that the center of the target spot is no longer discernable. Assuming adequate signal strength, image quality, on the other hand, depends on the reduction of scattering.

4. Results

During the development of L-Bath, bathymetric and reflectance images were obtained in a saltwater test tank. The test was carried out to verify system operation and demonstrate its capability to generate reflectance and bathymetric surface maps on a pixel-to-pixel basis. For this test, L-Bath was suspended and lowered into the tank so that both the scanner and camera housings were submerged. See Fig. 7. At the bottom of the tank approximately 1.6-m distance away, a relief target consisting of pyramid-shaped block, wrench, shackle, and cinder block resting on a plywood board background at about 1.6-m range.

Bathymetric data was calculated using Eq. (3) and reflectance data using Eq. (4). To yield bathymetric data, the angular offset parameters $\phi_o$ and $\omega_o$ were measured and applied along with measured values of $k$ and $\Omega_p$. The laser offset angle, $\phi_o$, was determined by measuring the laser beam angle when a zero voltage signal was applied to the scanner, and $\omega_o$ determined by noting the resulting pixel position of the target spot when a flat target was scanned at a similar range in water.

Analysis of reflectance and bathymetric data

In Fig. 8 a 2D bathymetric representation of the target is shown with depth depicted by gray scale, and its corresponding reflectance image is shown in Fig. 9. A black horizontal line depicts the location of a single scan of data taken for analysis used in Fig. 10. The speckled regions in Fig. 8 are the result of shadowing and from measurements taken outside the field of view of the camera. These are examples when no signal is detected.
and the algorithm to estimate depth reads detector noise. In Fig. 10 we have taken a scan running through the center of the target to analyze the bathymetric and reflectance data, and to demonstrate the performance of these two simultaneously acquired properties in understanding target characteristics. Each point represents a target element illuminated by the laser.

In Fig. 10 both the depth and reflectance profiles have been divided into sections relating to target features. The reflectance profile has been normalized to its maximum pixel response (~4096 DN). Sections a, f, and i appear to show random depth values that are unrelated to the target. Section a is a region where the camera field of view and the laser swath do not overlap and the laser spot hits the target outside the field of view of the camera. Toward the right of section a both profiles appear to show meaningful data but are the result of imaging more of the target spot as it comes into the field of view of the camera. Sections f and i are the result of shadowing where the laser spot is occluded from the camera field of view by target objects. The reflectance profile exhibits zero camera response in these regions and the scan data are left uncorrected in this figure.

Section b corresponds to the flat surface of the pyramid block, and sections g and j relate to the top surface of the sides of a cinder block cavity with a known height of ~190 mm. Sections c, e, h, and k correspond to the background comprising two plywood boards placed side by side. Sections h and k relate to the cavity regions of the cinder block. A change in the background is indicated by a change in reflectance (section e) while the bathymetry profile reveals a flat region. On the other hand, section d provides an example when there is low camera response but where there is sufficient signal to estimate its depth profile (right half of section d). On the left side of section d, the more reflecting exposed metal threads of the wrench’s adjustable mechanism, are profiled.

While the bathymetric values of the target objects are reasonable, a small slope appears when there is a transition from one object to another, particularly where the target spot illuminates a high-contrast transition region. For example, take the transition from section b to c. Here the reflectance suddenly drops to a low value and results in bathymetric error at the beginning of section c. This is the result of the reflected radiance distribution of target spot being modified by a change in target reflectance. The line profile of the target spot can be skewed toward brighter target pixels when the target spot partially covers both a bright and low reflectance region. Depending on the methods used to find the center pixel position of the target spot, a skewed line profile will complicate determination of true pixel position and also reflectance. This sloping effect is also observed at

![Fig. 8. A 2D bathymetric map of target with depth represented by gray scale.](image1)

![Fig. 9. A 2D reflectance map of target. Gray scale is the camera response in digital numbers (DN).](image2)
the beginning and end of section e, and seen when scanning the high contrast adjustment thread of the wrench (left side of section d). The bathymetry profiles at the beginning of sections g and j are affected by the transition from shadow to a high reflectance region. The rising profile in section h, in fact, also corresponds to a slight widening toward the base of the cinder block.

The reflectance profile shows some variability, particularly in sections c and e, which may suggest, in the absence of depth data, the presence of an object or topographical variation. The grain pattern of the plywood board is responsible for this variation in reflectance. This example demonstrates how the simultaneous acquisition of depth and reflectance data may be used to distinguish the presence of an object from a spatial variation in target reflectance.

5. Discussion

This in-water laboratory test was carried out to demonstrate the advantages of simultaneously acquiring bathymetric and reflectance data, and demonstrate the effect that a realistic and larger target spot size [than used in section 2(c)] has on resolution and image quality. To properly verify depth and spatial resolution over the system’s operational range, a more elaborate test is required to calibrate the system. In addition, further testing is required to examine the influence of water turbidity.

For this test, a larger 200-μm core diameter optical fiber was used resulting in an oversized target spot covering ~18 pixels half-bandwidth. The dimensions of the target objects were compared with those determined by L-Bath and were accurate to within a few millimeters of their true height. Depth and spatial resolution appear to be consistent with the prediction curves generated in section 2b. Even with a spot size much larger than that subtended by a pixel, the system produced bathymetric and spatial resolution to within a few millimeters, specifically in target data taken from regions where the reflectance and range remained reasonably constant. In this example (Fig. 10, sections b, c, e, h, and k), the laser simultaneously illuminates many pixels with similar range and reflectance properties (for the most part) such that the target does not effectively alter the reflected laser beam profile for many contiguous samples. Since the target spot profile remains relatively constant, and in the case where the brightest pixel is used to determine the center of the target spot, resolution approaches that determined by the angle subtended by a single pixel (assuming there is adequate, signal-to-noise ratio). In the case where a target spot partially illuminates both a bright and dark region within a target element, its line profile becomes skewed toward the brighter pixels. This perturbation leads to bathymetric error around the edges and borders of objects that contrast well against their background.

A large target spot is advantageous, from a mechanical design point of view, since the alignment tolerance between the plane of the camera field of view and that of the laser swath can be relaxed leading to a more robust and simpler design. It is also less susceptible to interference from large suspended particles and floculant, such as “marine snow,” that may be present in the water column. In general, however, a diverging laser beam with a large target spot is undesirable for four main reasons: 1) the rapid decrease in energy density with distance prematurely limits operational range, 2) the extra backscatter generated by illuminating a larger volume of water, 3) the additional forward scattering from excess illumination of the target, and 4) greater susceptibility to target properties.

Developing a system that uses a narrower and more collimated laser beam complicates the design by (i) requiring an optical solution to provide minimum beam divergence and target spot size over its operational range, and (ii) placing greater precision on the source–receiver optical alignment. To accommodate higher optical precision, the separate source–receiver housing configuration would be replaced by a rigid common optical chassis to maintain these higher alignment specifications. Beam divergence could be overcome by focusing the laser beam for a specific depth range. Alternatively, housing the laser source in the submerged instrument circumvents fiber-optic delivery of laser light while readily presenting a highly collimated and narrow laser beam source to the scanner.

6. Conclusions

In this article we introduce hardware and software that has been developed for an underwater optical sys-
tem that generates high-resolution depth and reflectance images. The system has demonstrated its capability to scan targets and produce reflectance and bathymetric relief maps of a topographically and contrast varied scene. Analysis of the reflectance and bathymetry profiles has indicated the importance of a narrow laser beam to produce a small target spot size. A smaller target spot has increased laser energy density allowing for greater range and reduces the probability of being influenced by target reflectance properties, while a narrow beam reduces in-water scatter.

Bathymetric performance has been predicted based on the measured accuracy of the individual scanner-camera components, and a realistic spot size has been introduced to give some indication of the system’s expected performance. These performance specifications have been generated to support the design, operation, and choice of optical and electronic components used in the system to provide high-resolution, range, and high acquisition rates in clear and turbid waters. Although subpixel resolutions have yet to be obtained, these performance curves demonstrate the sensitivity of the bathymetric measurement to the receiver angular resolution. Beam characteristics and image spot size have been calculated based on the scanner optics described in this paper, to indicate the system’s operational range, in terms of optical depth. Our estimates predict that the system should operate close to 4 A.L. at ranges approaching 10 m with 10-cm spatial and depth resolution.

The geometry involved in locating the position and measuring the response of each target element includes measurement of the pathlength and direction of laser radiation to and from the target. The measurement of pathlength can be used to improve the reflectance estimate particularly in turbid waters where it may become important to calculate the amount of light incident and reflected locally at the target. Certainly, the measurement of pathlength can provide an interesting dataset for radiation transfer studies, if not just used to correct for losses in pathlength when estimating target reflectance. The performance of the system in generating images in turbid water has yet to be investigated. This will involve analysis of the target spot radiance distribution and the effect that varying the receiver aperture, by binning different numbers of pixels about the target spot, may have on the signal-to-noise ratio and scatter reduction capabilities. Such a test will confirm the operational range of the system, and present the opportunity to assess the quality of reflectance and bathymetric maps generated from data acquired at different levels of turbidity.

The basic working concept and instrumentation has been realized in this underwater prototype. The interplay of both depth and reflectance data, acquired simultaneously, has been analyzed and investigated in interpreting target properties and has demonstrated the usefulness of providing depth and reflectance maps at complementary resolution, particularly in discriminat-

ing the presence of an object from a change in scene reflectance.

Acknowledgments. We would like to thank Fred Uhlmn for the construction of this system. We would also like to thank Neil Magtoto for his assistance and Richard Currier, who contributed to software development at the early stages of this project. This work was funded by the Office of Naval Research.

REFERENCES


