Increased Underwater Optical Imaging Performance Via Multiple Autonomous Underwater Vehicles

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Award Number: N00014-07-1-0317
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LONG-TERM GOALS

The major long-term scientific goal of this program is to explore techniques for increasing the performance of underwater optical imaging systems using Autonomous Vehicles.

OBJECTIVES

The major goal of this project is to explore the possibility of using Multiple Autonomous Underwater Vehicles for increasing the performance of underwater optical imaging systems. The main objective, in this context, is to simulate the potential benefits that multiple vehicles can have in increasing the range, imaging footprint, and potentially 3-dimensional applications that can be afforded using this new approach. This report details the Year 3 efforts that proposed a new way for obtaining extended range images without the use of scanning hardware. The proposed imaging system would be deployable on Multiple AUVs with source and receivers separated by substantial lengths.

APPROACH

Introduction: In this year's efforts we have been focusing on refined processing of the data from the last year and also testing a new idea related to the use of structured illumination. Here, a method that uses parallel one or 2-dimensional structured illumination in order to create a light pattern that consists of multiple narrow beam illuminators is described. A schematic of the system is shown in Fig. 1. The envisioned system uses a range gated, very high power laser, a DLP projection system, and a camera that has the capability to capture an exposure over a very short time (ns). The composite system permits the collection of extended range images with better resolution than possible with typical range gated systems. In the case of the illuminating system, there currently exist commercial lasers that can output ~ 100's of mJ of power with relatively short (3 – 5 ns) transmit time. The short pulse duration produces a light pulse with a linear range dimension of ~ 1 m. This pulse is ideal for range-gated systems that operate at ranges of 5 – 10 m, a desirable altitude for rapid, and safe, scanning of the sea floor.

The pulse is then reflected by a DLP projector system that can produce an illumination checkerboard-like pattern with bright illuminators separated by areas where no light was transmitted. At the next

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2009**	2. REPORT TYPE	3. DATES COVERED **00-00-2009 to 00-00-2009**
4. TITLE AND SUBTITLE **Increased Underwater Optical Imaging Performance Via Multiple Autonomous Underwater Vehicles**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of California, San Diego,Scripps Institution of Oceanography,La Jolla,CA,92093-0238**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**6**	

pulse, the bright checks become dark and the dark checks become bright. The spacing between these illuminators is dependent on the scattering characteristics of the water. The less scatter there is, the closer the point illuminators are. The system is therefore adaptive in that the illumination patterns depend on water properties. Each of these illuminating beams simulates the effect of the narrow laser beam, however, their parallel implementation permits a much larger area to be illuminated, circumventing the need for laser scanning. The acquisition of the data by a range-gated camera insures that the backscattered light is eliminated. The sequentially obtained images are then spatially filtered, in order to increase resolution and then combined so that there are no gaps in the coverage.

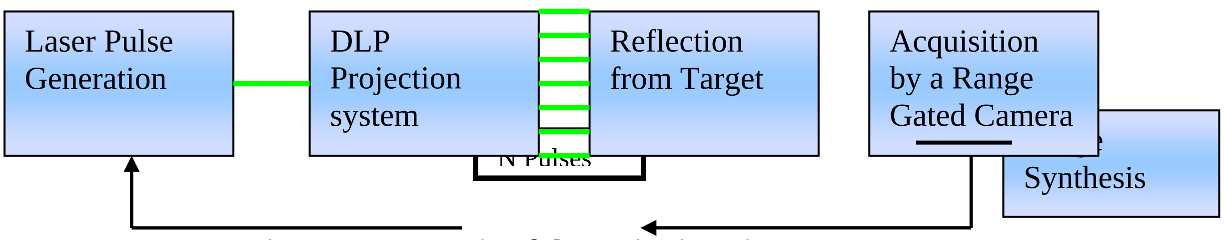

Fig 1. A squematic of the entire imaging system

Background: The basic theory for image acquisition by laser line systems was considered previously. The article illustrates, that, as in a confocal optical imaging system, laser line scan systems can improve the resolution of an underwater imaging system via a resultant point spread function that is the square of the one-way point spread function. The overall imaging process can be representeed via the equation

$$I(x',y') = w_{RP,TR}(x_1,y_1:d) \otimes T(x_1,y_1,x',y'). \quad (1)$$

where I(x',y') is the final output, "T" is the reflectance map of an image, and the operator $w_{RP,TR}$ $(x_1,y_1:d)$ is a weight function derived from the size of the input beam and the output aperture. As derived, if the input beam and the ouptut aperture, over which the function is integrated, are delta funcitons: $w_R(x_2,y_2) = \delta(x_2,y_2)$ and $w_T(x_0,y_0) = \delta(x_0,y_0)$, then

$$w_{RP}(x_1,y_1:d) = \mathrm{psf}(x_1,y_1:d) \text{ and } w_{TP}(x_1,y_1:d) = \mathrm{psf}(x_1,y_1:d) \quad (2)$$

and

$$w_{RP,TR}(x_1,y_1:d) = \mathrm{psf}(x_1,y_1:d)\,\mathrm{psf}(x_1,y_1:d) = (\mathrm{psf}(x_1,y_1:d))^2\,. \quad (3)$$

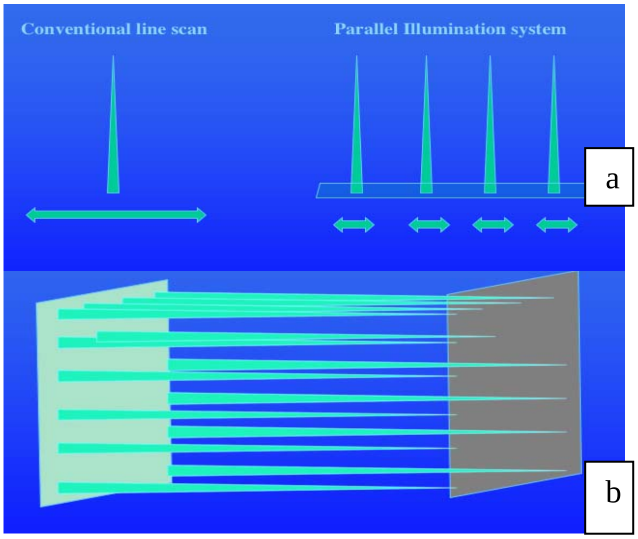

Fig 2. (a) The one-dimensional geometry. (b) The two-dimensional geometry for the parallel illumination scheme.

The equations highlight the advantages in using a narrow, collimated beam for illumination and a small, co-located aperture in that the overall point spread function of the system is the square of the medium point spread function (psf).

Unfortunately, the price paid for this superior resolution is a slow scan rate as each “pixel” of the image must be scanned sequentially, one at a time. This has motivated the development of parallel illumination schemes that can maintain the advantages of equation (3) while decreasing the time required for the acquisition of a single image.

In order to circumvent this problem in the case of underwater optical imaging, an idea was formulated that consists of illuminating the target with a grid of illumination points. The scheme can be used in either one or two dimensions as illustrated in Fig 2 (a) and (b). As can be seen, either a one or 2-dimensional array can be used. As a convenient way of performing this illumination, a DLP projection system can be used with a pulse gated laser illuminator. In this manner a range gated image can be formed. The system collects sequential images with each pulse of the laser and the images are then combined in order to create composite images for the entire field of view. One key aspect of the scheme is that the DLP array is used both for image illumination and also as a front end of a collection device. In this manner, the advantages of the “confocal aspect” can be maintained.

Computer Simulations: To test the idea a set of simulations were performed that mimicked the geometry of the system. In all cases considered here, the one-dimensional scheme of Fig. 2a was used. The simulations consisted of computing a set of point-spread function that would be due to a target located at a given range in turbid water. The point spread functions were then convolved with arrays of delta functions in order to simulate the light that would be reflected from a striped target that would be incident on a camera. These reflection images were then multiplied by the identical set of delta functions in order to compute a single instance of the propagation of the “round trip” light. The single variable used was the spacing (in angle) between the output and input delta function arrays. Note that when the spacing is a value of one this corresponds to the conventional case where a continuous sheet or wedge of light was used. In the case that the spacing is equal to the number of lateral elements in the array, the situation corresponds to that of the conventional laser line scan system. The total number of laser pulses that the system needs to project is equal to the distance in resolution elements. So, for example, in the case where the distance is one, the total number of pulses is equal to one. If the distance between the projections is equal to the total number of resolution elements, then, as in a typical line scan, the total number of pulses is equal to the number of resolution elements. The computer simulations were performed with a program that was authored by E. Zege and colleagues and follows the formulation of image formation. The parameters were adapted to mimic the conditions that would be found in bay water where the total attenuation coefficient: c is .5m (ie 2 meter water) and the single scattering albedo (b/c) is equal to .83. A single line through the two-dimensional reflectance map (Fig 3.) was used. The map consists of a series of light and dark stripes on with varying resolution. The simulations were performed at a range of 1, 3, 5, and 7 total attenuation lengths at ranges were 2, 6, 10, and 14 m. One attenuation length is easily obtained in most imaging systems, three starts to be quite challenging and necessitates some mediation of the backscatter, which dominates in many circumstances.

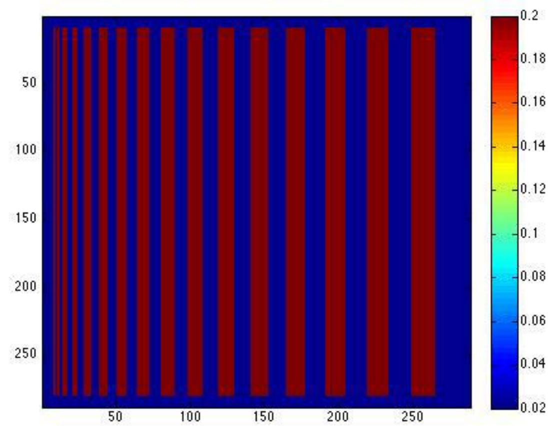

Fig 3. The two-dimensional reflectance map used for the study.

A range-gated system, as considered here, can suppress the backscatter via temporal gating out of the near field scattered signal. In this case, three attenuation lengths, with adequate dynamic range and illumination strength is quite obtainable. Five attenuation lengths starts to get quite difficult for any system as the forward angle scatter will start to degrade the images. Some remediation of forward scattered light is compulsory in this case if adequate resolution is desired. Seven attenuation lengths is the most challenging situation considered here. To the knowledge of this author, it has not been achieved in the field.

RESULTS

Fig. 4 contains the results of the computer simulation as a function of both range and also the distance between the illumination spots. Fig. 4a shows a distance of one and is identical to projecting a sheet of light onto a target while imaging the reflected light with a one dimensional array. Fig 4 b shows a distance of 5 spaces between the beams. Fig 4c shows 20 spaces and Fig 4d shows 100 spaces. In all cases, the contrast of the stripes increased as the spacing between the incident beams increased. As expected, imaging at 3 attenuation lengths was possible for all beam spacing, from the smallest to the largest with negligible increase in contrast as the beam spacing was increased. In the case of the 5 attenuation length range (green graphs), the contrast nearly doubled as the spacing was increased from 1 (case a) to 5 (case b). If 5 attenuation length ranges are acceptable, using the considered method with a set of 5 pulses is desirable. Surely, the most startling increase in contrast occurred for the 7-attenuation length case. Note that at 20 spaces, the images at 7 attenuation lengths are starting to show promise, whereas at 100 spaces, the images will be quite good. This is not surprising as the case of 100 spaces is nearly identical to the original laser line scan system that would correspond to 256 spaces.

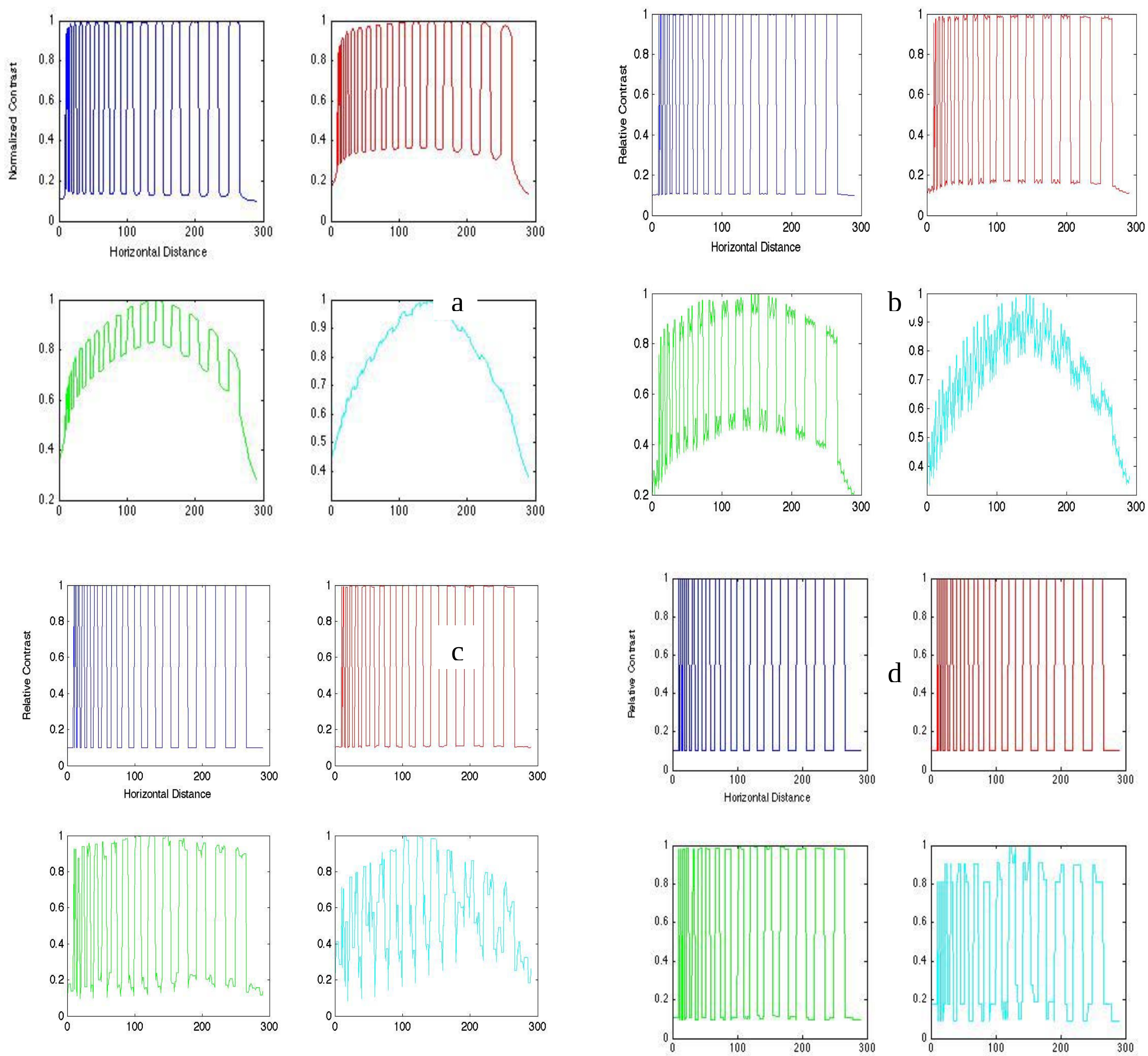

Fig 4. Results of the computer simulations for the one-dimensional case shown in Fig 2(a). Each set of four graphs shows 1, 3, 5, and 7 attenuation lengths (2m, 6m, 10m, and 14m), clockwise. (a) A single space between incident and receive beams. (b) Five spaces between incident and receive beams. (c) Twenty spaces between incident and receive beams. (d) One hundred spaces between incident and receive beams.

IMPACT

The development of extended viewing systems that do not use moving parts and have the capability for collecting two-dimensional images would be a significant advance.

RELATED PROJECTS

This project is related to, and takes advantage of some of the resources provided by our other ONR funded project: “Development of a Laser Line Scan LIDAR Imaging System for AUV Use”.