Seafloor roughness measurement from a ROV

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Abstract - A method of seafloor roughness measurement using low-power lasers and a camcorder mounted on a ROV was demonstrated in the EVA (Experiments for Validation of Acoustics modeling techniques) sea trials, conducted near Marciana Marina, Isola d’Elba, Italy. Six red laser beams were spread by cylindrical lenses into parallel planes. The intersection of the laser planes with the ocean bottom was imaged on a digital camcorder, pitched down at a nominal angle of 45 degrees. NTSC video recordings were collected and analyzed to extract the laser profiles. After correcting for aberrations due to refraction between air and water and other imperfections, taking into account the scanning and interlacing effects of the NTSC video, and given the relative positions of the camcorder and lasers, the 3-D coordinates of the laser profiles relative to the camcorder were computed. Images of the seafloor were used in an image registration algorithm to track the trajectory of the camcorder, and stack the laser profiles to reconstruct the seafloor surface. The measurements were made in conjunction with acoustic reflection measurements to determine the effects of incoherent scattering on the mean value of the reflection coefficient over a wide range of angles.

I. INTRODUCTION

Seafloor roughness in the scale between millimeters to decimeters is of particular interest to high-frequency acoustic scattering. There are few instruments available to make the measurements. Multibeam sonars are generally designed to measure larger features. Medical ultrasound devices have the required resolution but do not have the range. A device, called IMP[1], using a conductivity probe at the end of a robot arm on a rail has been used to profile along a line over distances up to 5 m. Stereophotogrammetry has been successfully applied. Briggs [2] has obtained wavenumber roughness spectra from a variety of sediment types. There are a couple of limitations, one of which is the requirement for good visibility because the stereo processing method requires very high image resolution. Typically measurements are made over an area of about one square meter. Another limitation is that it requires a stable platform, usually a structure sitting on the seafloor, such as rail or quadrupod [3]. The laser light sheet, in which a laser beam is spread into a fan by a cylindrical lens, is another approach. By observing perturbations of the illuminated fan, it has been used in a stationary configuration to visualize sediment transport [4]. In the approach used here, which will be called laser profiling, the laser fan is projected downward to produce an illuminated stripe of the seafloor.

The basic concept consists of a number of lasers projecting parallel stripes on the seafloor and a video camera to record the images, as illustrated in Fig. 1. An early version was successfully implemented in 1999 [5, 6]. Using optical position tracking of the discrete objects on the seafloor, individual laser stripes were stacked to produce a representation of the swept surface. Using two laser stripes, the data rate was doubled and the difference between the two profiles provided fine vertical navigation information, which was not available from the optical position tracking.

Fig. 1. Laser profiling concept

II. SYSTEM DESIGN

The lasers are housed in an acrylic, transparent cylindrical enclosure. Each laser is a red, 5 mW, 635 nm wavelength emitter, from Meredith Instruments. Each laser
is paired with a cylindrical zone lens “line-generating optics” to spread its beam into a wide-angle fan. The intersection of the laser planes with the seafloor produces stripes within the field of view of the camcorder.

In this design, six lasers are used in order to increase the data rate and provide continuous coverage of the seafloor, and redundancy that can be used in a self-consistency test to estimate accuracy. The number of lasers is limited by the usable field of view of the camcorder and the maximum expected seafloor roughness consistent with maintaining separation between laser stripes. The goal was to achieve horizontal and vertical resolutions of 2 and 1 mm, respectively. The laser stripes remain separable as long as the maximum slope is less than the camera tilt angle. Since the camera is pitched forward at 45 degrees, this is also the maximum bottom slope that can be accommodated. This should be adequate for unconsolidated sand, since the angle of repose for unconsolidated sand and other granular media is usually less than 30 degrees. It also means that the maximum drop between adjacent lines must be less than the laser spacing, which is about 60 mm.

![Modified Phantom HD-2](image)

**Fig. 2.** Laser and camcorder units hosted on ROV.

The video data collection has two purposes: (1) collection of images of the laser stripes and (2) collection of seafloor images for navigation purposes. The Sony DCR-HC96 camcorder recorded digital NTSC video, with very little image compression. For 2 mm horizontal resolution and a video frame rate of 30 frames per second, to interrogate each horizontal resolution cell with all six lasers, the platform speed over the seafloor should not exceed 60 mm/s. Since NTSC video is scanned horizontally, from left to right, the camcorder was turned on its side, so that the scan direction is perpendicular to the laser stripes, for optimum resolution and consistency, and to minimize problems due to interlacing. To maintain a 2 mm cross-track resolution, with 480 scan lines, the swath width must be limited to less than 960 mm.

The laser stripes occupy approximately half of each video image, leaving the remainder to be used for image-based navigation. For robust navigation, there are three necessary components: imaging sensor, altimeter and heading sensor [7]. The camcorder is, of course, the imaging sensor. The altimeter function is provided by the laser stripes, and the heading sensor function is found in the ROV sensor suite. A magneto-inductive compass with pitch and roll sensors, in a TCMM2-50 unit from PNI Corp., provided smoothed, absolute values of heading and attitude.

The video images themselves are processed to provide fine-scale relative changes in heading. The laser profiles are processed to provide fine-scale relative changes in pitch and roll.

The hardware was hosted on a modified Phantom HD-2 ROV originally made by Deep Ocean Engineering as illustrated in Fig. 2.

### III. PROCESSING METHOD

The purpose of data processing is to produce a measurement of the fine-scale seafloor bathymetry. The process may be divided into a number of steps:

1. Extraction of 2D image pixel coordinates of the laser stripes from each video image. This worked best at zero or low light levels. The color separation in NTSC was imperfect but adequate for separating the red laser stripes from the blue-green background under natural lighting.

2. Projection of the 2D laser stripes from step 1 into 3D space referenced to the camcorder, using pitch and roll data and the known relative positions of lasers and camcorder. This is a simple geometry problem in which each pixel of the video image represents a ray emanating from the optical center of the imaging sensor. Each laser stripe is known to lie within a plane surface determined by the distance and orientation of the laser relative to the imaging sensor. The problem reduces to finding the intersection of the ray with the laser plane.

3. Computation of camcorder trajectory and fine-scale heading over the seafloor, using the altitude information from step 2 and vehicle heading sensor data, by cross-correlation of seafloor images projected onto a common seafloor plane: This is an image registration problem. To reduce it to a simple 2D correlation process, the scale and orientation of the images must be constant. This was achieved with the pitch and roll sensor data, and the height above bottom estimate from the 3D laser stripes, and the heading sensor data. In addition, there were moving debris on the bottom, particularly in the data from 20 October due to strong surge currents. The debris tended to dominate the image and the correlation process, causing
erroneous estimates of motion relative to the seafloor. The problem was alleviated by nonlinear dynamic range compression to de-emphasize the debris relative to the stationary seafloor features.

(4) Construction of the seafloor surface by stacking the 3D stripes from step 2 using the trajectory and heading data from step 3, and iteratively reducing the residual error by adjusting fine-scale pitch and roll angles to achieve a least-squares-error solution: This process requires accurate depth information which was not available. The ROV has a constant depth feed-back control that kept its depth variations within certain bounds, but it was necessary to use the data itself to compute the fine scale variations.

IV. SEA TRIAL

The sea trial took place in 10 m of water in Biodola Bay, on the north shore of Isola d’Elba, as a component of the Experiments for Validation of Acoustics modeling techniques (EVA) sea trials, a joint project between the Applied Research Laboratories, University of Texas at Austin (ARL:UT), Massachusetts Institute of Technology (MIT), Marine Physics Laboratory of the Scripps Institution of Oceanography University of California at San Diego (MPL:UCSD), Naval Research Laboratory at Stennis Space Center (NRL:SSC), and the NATO Undersea Research Centre (NURC). Since the lasers are low power (class III) units, similar to those found in laser pointers, there are no special handling requirements. The brightness of the laser stripes is limited and difficult to see in daylight. It was necessary to collect data near sunset or sunrise. Data were collected near sunset on four days: 17, 20, 23 and 25 October 2006.

Lighting conditions are very important for image formation, particularly for navigation purposes. With reference to sample images in Fig. 3, it was found that natural lighting in the period leading up to sunset tended to enhance the contrast of bottom features, particularly the casting of shadows into depressions, which suggests that the illumination is predominantly horizontal. The enhanced contrast in an otherwise feature-poor seafloor is very beneficial to the correlation processing. After sunset, since the camcorder is not capable of very low-light video, it was necessary to employ artificial lighting. The light sources were positioned high on the vehicle frame and pitched forward to minimize illumination of the area under the lasers. Unfortunately, this had the effect of reducing the contrast of the bottom features, particularly the elimination of shadowing in the troughs. All image processing, so far, has been with naturally illuminated images.

Although color separation in NTSC images is imperfect, it is adequate for detection of the laser stripes, since the background usually has very little red content. Peaks in the red signal are detected in each scan line and associated with each of the six laser profiles, based on relative position.

Projection of the 2D stripes into 3D is a straight-forward geometrical operation, based on the intersection of rays from the camcorder and the laser planes, given the position of the camcorder relative to the laser planes. Only the gray-scale image is used for navigation.

Fig. 3. Video images from 17 minutes before to 16 minutes after sunset, ROV lights turned on after sunset.

Fig. 4(a) A gray-scale image.

Fig. 4(b) Gray-scale image after projection.
from the displacement of the cross-correlation peak, referenced to a corresponding window from a previous frame. Fine scale rotation of the image is also estimated. The images may be stacked to form a mosaic. The consistency with which each bottom feature is placed on the mosaic is an indicator of the accuracy of the computed track. An example is shown in Fig. 5, which shows a mosaic from every 30th frame of the equalized image. The bottom features are stationary but the loose debris, such as blades of sea-grass moved with the bottom currents.

Finally, the 3D stripes are stacked to form the seafloor topography using the navigation results from the previous steps. Since each resolution cell is interrogated by each of the six lasers, a mean and a standard deviation of the height may be calculated. An example of the results is shown in Fig. 6. The mean values, shown in Fig. 6(a), show seafloor topography. The standard deviation in Fig. 6(b) shows the residual error, which is in the region of 2 mm RMS for the relatively flat areas.
For the sloped areas, the residual error creeps up to 6 mm RMS, simply because of the variation in height within the resolution cell. There are areas of larger residual errors due to “fuzzy” objects on the seafloor, which tend to absorb and scatter the laser illumination, as illustrated in Fig. 7. These objects are problematic because they are very porous and do not have a well-defined outer surface.

The average seafloor profile and residual error over a longer track is shown in Fig. 8 (a) and (b) covering a linear distance of 5 m. In this section, the error is generally well controlled because the ROV was moving at a steady speed. There are a few bands of higher error regions and linear gaps where the stacking process was clearly not working as well as it should because the ROV was moving too fast. In addition there are a few gaps in the profile, mostly due to fuzzy objects and moving blades of seagrass.

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Finally, the profile may be processed to give a wavenumber roughness spectrum. In this case, one dimensional spectra were computed for parallel sections in the y-direction, averaged and smoothed with a 10-point box car window. Although the spectrum covers the band from 0.2 to 250 cycles per meter, the reliable portion is between 0.4 to 40 cycles per meter. Below 0.4 there are too few cycles, while above 40 cycles per meter, there is some processing noise due to imperfections in the stacking process. The result, in Fig. 9, shows a spectrum that appears to be divisible into 2 linear sections. This spectrum is comparable to published spectra by Briggs [2]. The convention adopted by Briggs and Bell [8] is used here. That is, the integral of the one-dimensional wave number spectrum is defined as $2\pi$ times the variance.

Fig. 9. One-dimensional roughness spectrum in the y-direction.

IV. CONCLUSIONS

The measurement of small-scale seafloor roughness from a ROV, using laser profiling, was demonstrated, at horizontal and vertical resolutions of 2 and 1 mm, respectively. In the current implementation, six lasers and a NTSC video camcorder are used to collect laser stripes on the seafloor. Each laser stripe is a profile of the seafloor along a line approximately 0.5 meter long, that runs perpendicular to the ROV heading. Using optical image registration to track the position of the ROV, successive stripes were stacked to form the seafloor fine-scale bathymetry along a swath. The swath width is limited by the resolution of the video image, and currently set to 0.5 m and may be increased up to 0.96 m. The swath length is unlimited. Overlapping swaths may be combined to produce larger areas.

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