Multidimensional laser scanning system to test new concepts in underwater imaging.

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Abstract - **A multidimensional laser scanning imaging system was developed to investigate new concepts in underwater imaging. The system is a modification of the 3D Laser Imaging & Tracking Electro-optical System (3D LITES; HBOI, patent # 5,418,608) that was developed for 3D mapping applications in biological oceanography. The new 3D-FLITES ("F" stands for added Fluorescence capability) captures both spatial and spectral data and offers extended operation capabilities. The system can capture the range to each pixel in the sensor's field of view, the relative reflectance of each pixel (similar to "conventional" images) and five channels of fluorescence emission in the scene, captured sequentially. Multidimensional data sets can be instrumental in object detection and classification. The 3D FLITES has the unique capability to operate in user-selectable line or raster scanning modes. To operate in a line-scanning mode the system needs to be mounted on a moving platform. The 3D FLITES then generates a data stream based on the forward motion of the vehicle. In raster mode two perpendicular mirrors are driven, allowing the operator to capture single frames (capturing either reflectance or fluorescence data) or a stream of images in near-video rate (20 frames per second). With this operational flexibility the operator can combine a "fly over" scanning mode with "look ahead", "look sideways" and "zoom" modes. The current system is limited in range and resolution; nevertheless it can serve as a test-bed to evaluate operational parameters, data acquisition and signal processing protocols that could lead to a smaller, more efficient system in the future.**

I. Introduction

The new system is the third generation imaging system whose predecessor is the 3D Laser Imaging & Tracking Electro-optical System (3D LITES; HBOI, patent # 5,418,608) that was developed for 3D mapping applications in biological oceanography [1]. The new 3D FLITES ("F" stands for added Fluorescence capability) captures a multidimensional dataset combining both spatial and spectral information with extended operation capabilities. The 3D LITES was developed for 3D mapping applications in close range. Unlike dual camera systems, which depend on extensive post-processing to calculate 3D coordinates, this laser-scanning system provides precise 3D data in near real time (20 fps). The original system offered sub-centimeter resolution (2.5 mm) with a field of view of 0.4 m at a range of approximately 1 m, and it used a low-power, red (670 nm) laser that is scanned in two dimensions by two mirrors (galvo-controlled mirror and 24-facets rotating polygon) in a raster fashion over the target area. A Position Sensing Diode (PSD; J2L-10 from On-Track Photonics Inc.) calculates the x, y, z coordinates for each of the 200 x 200 pixels in each frame using triangulation. The 3D LITES was developed as an unobtrusive system to observe aquatic animals in their natural habitat based on a larger, higher-powered system called 3D SUMS (Surface Underwater Mapping System [2]). The latest generation, 3D FLITES, significantly enhances the capabilities of the sensor and serves as a test platform to study new concepts in underwater imaging. In addition to 3D mapping the added capabilities include capturing 2D relative reflectance images similarly to "traditional" images, addition of up to 5 selectable channels for fluorescence images (both in 2D and 3D imaging modes), operation of the scanner as a line scanner or a raster imager while offering the user a smooth transition between all these modes of operation. The new system can simultaneously capture images while tracking particles in 3D space, offer "fly over" scanning mode with "look ahead", "look sideways" and "zoom" modes in an extended range (up to 2m, depending on water conditions). Varying the range to the target requires selection of the appropriate calibration settings to be automatically adjusted.

II. Principles of operation

Positioning

The PSD (Fig. 1) consists of n-type silicon substrate with two resistive layers separated by a p-n junction [3]. The front side has an ion implanted p-type resistive layer with two contacts at opposite ends. The backside is an ion implanted n-type resistive layer with two contacts at opposite ends placed orthogonal to the contacts on the front side. A light spot will generate a photocurrent that flows from the incident point through the resistive layers to the electrodes. The resistance of the ion-implanted layer is uniform so the photo-generated current at each electrode is inversely proportional to the distance between the incident spot of light and the electrodes. The PSD output currents track the motion of the "centroid of power density" in a resolution of one part in ten million over the 10 mm sensitive area. We utilize the PSD square detector for a 2D frame scan, but only monitor one of the photosensitive layers ($X1$ and $X2$) for positioning along a single axes. The perpendicular dimension is obtained from the position of the galvo-mirror. To calculate the centroid's position on the PSD use:

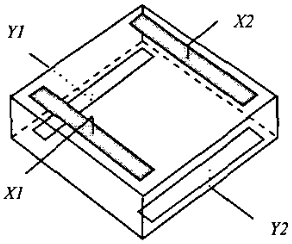


Fig. 1. Position Sensing Photodiode

$$X = L \cdot \frac{X2 - X1}{X1 + X2}; \qquad (L = 5mm), \tag{1}$$

and for light intensity at each pixel (I_P) use:

$$I_P = \sqrt{X1^2 + X2^2}. \tag{2}$$

In the 3D LITES the PSD sensor had an open aperture that was set and not synchronously scanned with the excitation beam. To reduce the cumulative electronic noise on the sensor the light source in front of the sensor was turned off at the end of each line in the frame. Therefore, the laser beam needs to be modulated. This point will be further discussed below.

Fig. 2 shows a schematic diagram that describes the operating principles of the 3D FLITES, where

θ is the angle between the laser beam and the scanner.
Z is the distance of the imaged pixel from the scanner.
f is the distance between the PSD and the receiving lens (focal length).
K is the distance between the illumination window and the receiving lens.

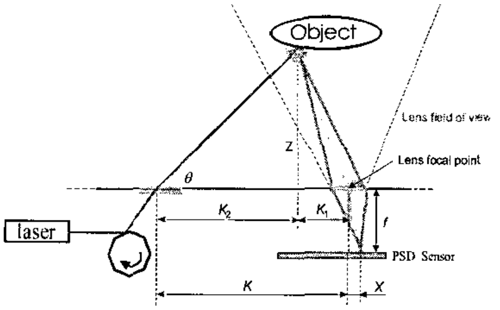


Fig. 2. Schematic diagram describing the operating principles of the 3D LITES

From similar triangles (after correcting for the water-air reflective index difference):

$$\frac{K_1}{Z} = \frac{X}{f}. \tag{3}$$

By definition,

$$\tan\theta = \frac{Z}{K_2}. \tag{4}$$

Assume that K = K1 + K2 is constant (first order approximation). Rearrange equations (3) and (4) to get

$$Z = \frac{K}{\left(X/f + 1/\tan\theta \right)} \tag{5}$$

where K and f are constant properties of the instrument and X is measured by the PSD. The angle θ is resolved for each position in the scan through calibration to a given distance. Multiple ranges (Z) require multiple calibration sets.

During a frame scan each facet of the polygonal mirror describes a line across the Y-axis (galvo) mirror. Simultaneously the galvo driven in a sweep, which covers the top of the frame to the bottom, resulting in a slightly skewed raster scan. The raw data resulting from each scan is in the form of a series of four byte voltage values for *X1* and *X2*. These are used to calculate x, y, z values in space and I_P. An example of 3D LITES data is shown in Fig. 3.

An acoustic altimeter was added to the design of the 3D FLITES for rough estimate of the distance between the sensor and the target updated "on the fly" as images are being captured.. The altimeter (Tritech PA200) has a nominal resolution of 0.025% at the range of operation (0.7 to 50m). A preliminary calibration process now includes several range settings (e.g. every 10 cm) from the target. Based on the range measured by the acoustic sensor, the appropriate calibration set can be used for accurate 3D mapping of the target. Ultimately, a data processing algorithm will automatically self adjust the system's calculations to the constantly updated range measured by the acoustic altimeter. The self ranging capability is dependent on a defined acoustic signal. This signal is not expected to be reliable from particles in the water column, therefor we don't expect that the multirange algorithm be applicable in 3D tracking of small entities.

Optics

The optimal laser source for fluorescence excitation is mainly dependent on the fluorescence pigments of interest in the observed scene. In a coral reef environment, for example, these pigments are fairly well documented [4] suggesting that a blue excitation source in the wavelength range of 430 to

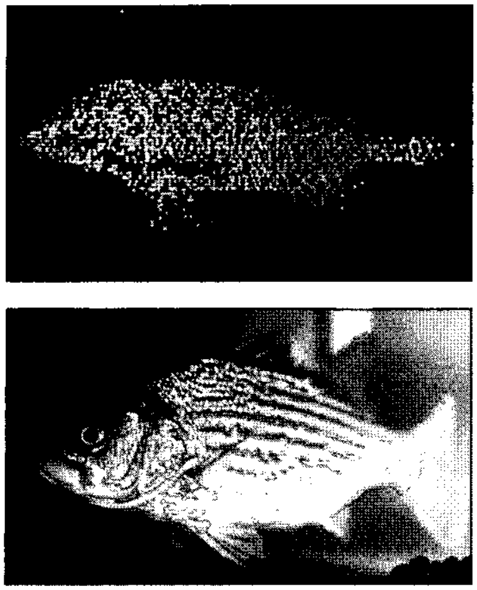


Fig. 3. A 3D-LITES image of a striped sea bass (upper image) with distance from the scanner represented by color

460 nm is optimal. In selecting an excitation source, however, one is bound by available technology. The natural selection for fluorescence excitation in the visible range is the most powerful blue laser source that is compact in size and does not require water-cooling. The Melles Griot, DPSS 58BLS series (up to 400mW at 457nm) was the laser of choice, although its beam characteristics are far from optimal (M^2<1.3, elliptical cross-section and beam divergence of 5 mrad). Melles Griot, however, offers an optical package (collimator) to improve beam quality (divergence of 0.5 mrad) at the expanse of increasing the beam waist from 0.3 mm to 1.1 mm. For our imaging application this increase in beam diameter is acceptable. Fig. 4 shows a model of the Melles Griot 58BLS blue laser head and the red laser that was previously used in the 3D LITES, demonstrating the significant difference in their physical size.

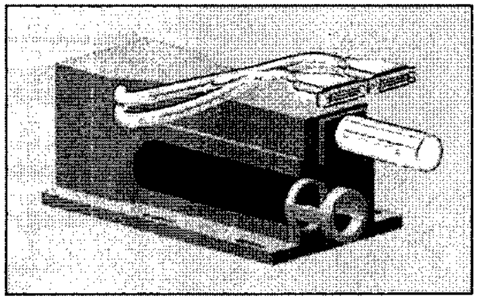


Fig. 4. Melles Griot 58BLS series laser head with its optical combiner/collimator compared with the red laser previously used in 3D LITES (black).

To improve Signal to Noise Ratio (SNR), the design requires that the laser beam is turned off at the end of each line scan, and turned back on before the next line is scanned. During the OFF time of the beam, the PSD is grounded (clamped). There are two electro-optical devices available for a fast rate and user controlled modulation of a high power CW laser beam: Electro-Optic Modulators (EOM) and Acusto-Optic Modulators (AOM). The high voltage associated with using EOMs requires a large power supply to drive the EOM, which makes them unattractive for compact applications. We therefore selected a Crystal Technology Model 3080-125 AOM for the 3D FLITES system whose driver is compact in size as can be seen in Fig. 5, where the excitation components of 3D FLITES are illustrated.

A principle ray tracing analysis verified that our design contains all the adjustability necessary for correct alignment of the laser beam. Appropriate alignment is required to ensure that the beam can be scanned across the entire available field of view of the optical sensor. Fig. 6 illustrates three of the 21 tested scenarios, addressing all relevant elements of the design. For example, we see that in Polygon Position 1 the laser beam is limited by the edge of the galvo-scanning mirror (upper-right image), while in Position 3 the housing wall is the one that blocks the laser beam (lower left image).

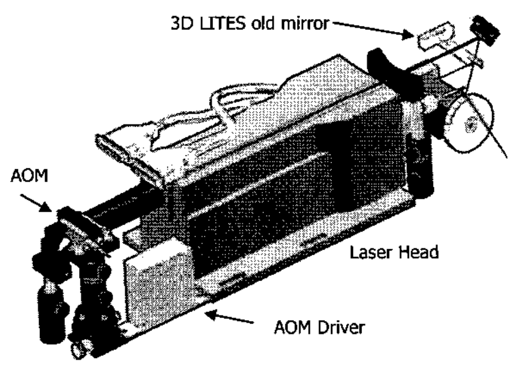
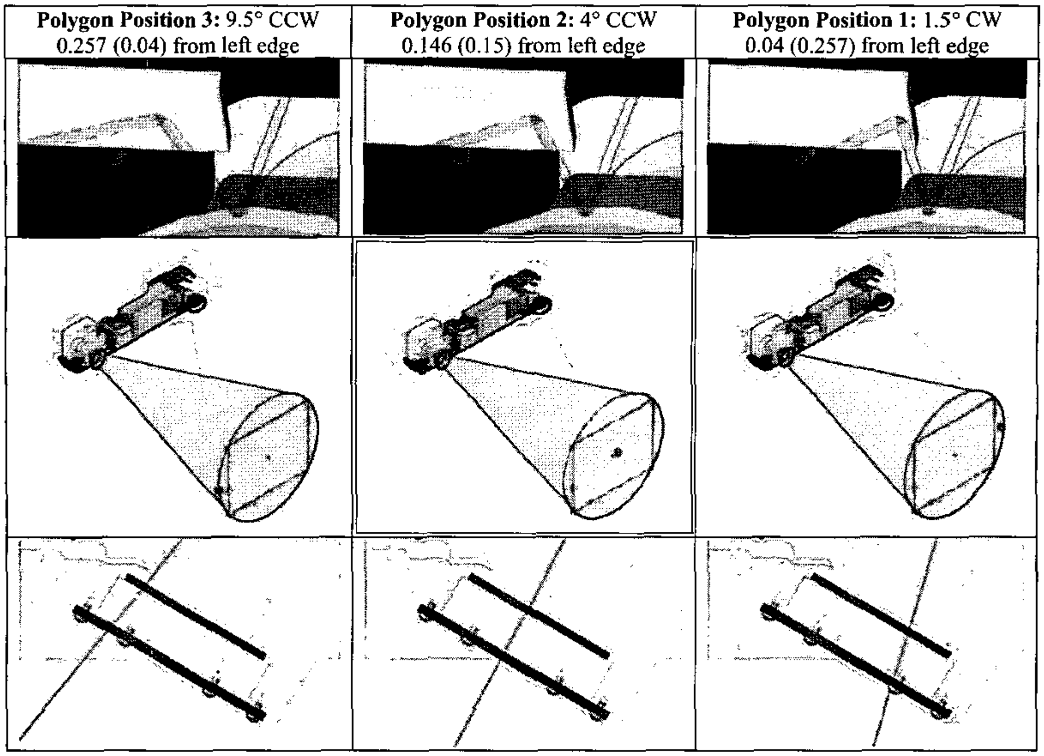


Fig. 5. Optical path of 3D FLITES. Note that an additional mirror (green) is shown to demonstrate how the new design aligns the excitation beam similarly to the previous design of 3D LITES.



Polygon Position 3: 9.5° CCW 0.257 (0.04) from left edge

Polygon Position 2: 4° CCW 0.146 (0.15) from left edge

Polygon Position 1: 1.5° CW 0.04 (0.257) from left edge

Fig. 6. Field of View Study, Principal ray tracing analysis. Galvo mirror set at 55.25° from horizontal. Polygon face is 0.296 in across. Galvo Positions at: +20°, +10°, +5°, 0°, -5°, -10°, -20° (Shown here 0°).

Data Acquisition

Four "virtual layers", as schematically shown in Fig. 7, can describe the computational architecture of the 3D FLITES that is responsible for signal flow and data handling. At the front end the signal level, X1 and X2 currents from the PSD are amplified, digitized and stored in a FIFO device ready to be delivered (Layer 1). A DSP board (Layer 2) controls the sequence of frame capture at the hardware level and delivers the data from the FIFO to a PC104 computer. This downside computer (Layer 3) handles storage of data in a Berkley database and communication via Ethernet to the GUI on the topside computer for the final layer (4) of display and user interface. This architecture separates the data-handling engine from the actual front-end sensor through the FIFO interface. The transparency of the front end to the computational engine adds to the flexibility of the system and makes future expansion possible. The MS Windows-based engine is currently capable of sustained data acquisition, storage and display at a rate of 2 Mega Samples per second, where a sample is defined as an array of 32 bits.

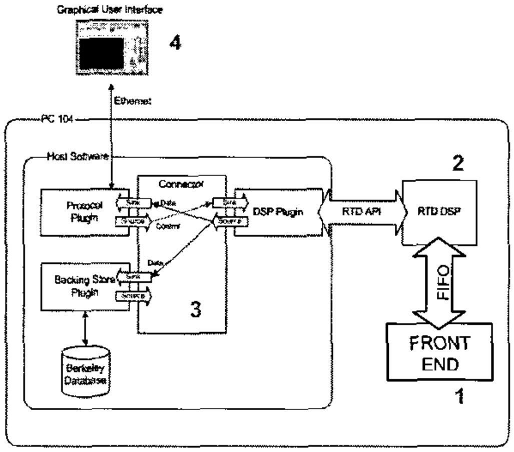


Fig. 7. Computational engine of 3D FLITES. Four virtual data handling layers: 1) Optical sensor (Front End); 2) DSP interface; 3) PC104 downside computer; 4) GUI on topside computer.

III. Preliminary results

The 3D FLITES is currently at a preliminary bench top testing phase (Fig. 8) where optical alignment, components and system integration, timing and sensitivity tuning are being carefully done before a realistic performance evaluation can be completed.

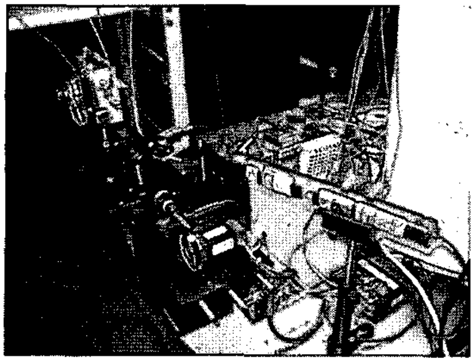


Fig. 8. Bench top testing of the 3D FLITES.

The first intensity image that was captured by 3D FLITES is presented in Fig. 9. This image was taken on the bench (setup shown in Fig. 8) at a resolution of 266x200 pixels, which can be expected to be the resolution of images at a the acquisition rate of 20 frames per second. Note that this image demonstrates a capability (relative reflectance) that did not exist in the previous generation.

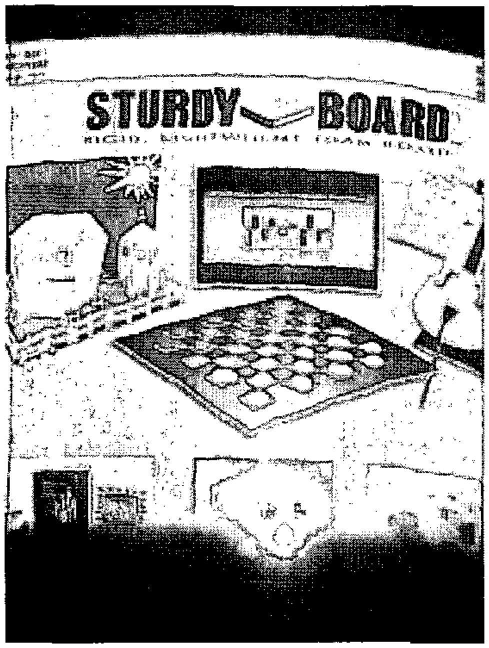


Fig. 9. Relative reflectance image captured by the 3D FLITES. Image resolution is 200x266 pixels.

IV. Discussion

The 3D FLITES is a modification of the older 3D LITES tracking and mapping system. The new generation adds capabilities that the older system did not offer: 2D images in addition to the 3D topographic mapping, multi-channel florescence as well as reflectance imaging modes, line and frame scanning options and extended and variable range to the target. We are currently evaluating the performance in all these modes of operation. Phase one of the evaluation is extended laboratory tests will be followed by a realistic field test. The system is not designed with a specific operation mode or application in mind, but rather as a test platform for new concepts in underwater imaging. Possible applications for such a system range from homeland security such as mine detection or ship husbandry to environmental studies such as tracking coral larvae for recruitment studies. A significant limitation of the system is its susceptibility to backscatter noise in turbid water due to the open and set aperture of the sensor. This noise sensitivity is a limiting factor in the sensor detection range, especially in an environment where the water clarity is poor. Unfortunately, these types of conditions are to be expected if the system is deployed in coastal or harbor locations. Techniques to improve range and image contrast may include synchronizing the detection sensor with the scanning motion of the laser beam [5]. Depending on the performance of the 3D FLITES through the current evaluation phase and availability of future funding, such implementation may be the next step in the system's evolution.

Acknowledgments

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