Evaluation of a laser based structured light system for 3D reconstruction of underwater environments

2 authors:

Miquel Massot-Campos
University of Southampton

Gabriel Oliver
University of the Balearic Islands

Evaluation of a Laser based Structured Light System for 3D Reconstruction of Underwater Environments

Miquel Massot-Campos, Gabriel Oliver-Codina
Systems, Robotics and Vision Group,
University of the Balearican Islands
Cra Valldemossa km 7.5 (07122),
Palma de Mallorca, Balearican Islands
{miquel.massot , goliver} @uib.es

Abstract — *Structure from motion or stereoscopy are used to obtain 3D from a sequence of still images. However if there is no texture or features in the images, no 3D can be obtained. Featureless environments are difficult to reconstruct in 3D using only cameras. Projected light patterns can be used to measure the shape or an object. However, scattering is the main problem in light based underwater sensors such as projectors and cameras. Collimated light such as laser minimizes this problems by focusing the light in fewer points. Ranged gated cameras can also be used with pulsed lasers to reduce even more the scattering. In this paper a new structured light laser system is evaluated to solve the scattering and featureless problems above mentioned and to perform a 3D underwater reconstruction. This system is formed by a laser projector and a camera. By means of pattern identification and triangulation, 3D can be reconstructed from a live video sequence of a featureless environment.*

Keywords — Structured Light, Laser Line Scanning, Underwater Sensors, 3D Reconstruction

I. INTRODUCTION

The performance of traditional optical imaging systems such as cameras are limited by absorption and scattering when used underwater. These two terms depend on the turbidity of the water the light is propagating in. Even when a system has been optimized to reduce backscatter it may become limited by absorption. In this situation, the propagating signal (light) is too weak to be detected by the corresponding sensor, and the system is said to be power limited. If the power is increased the scattering increases. It can increase so much that the sensor cannot differentiate the true signal from the noise. In this case the system is said to be contrast limited and can be measured with the Signal to Noise Ratio (SNR). The performance in both cases can be enhanced by choosing the light source wavelength to match the optimal underwater wavelength that minimizes both absorption and scattering, which is in the blue-green range of colors in the visual spectra. If a laser light is also chosen, polarization filters can be also used to discard the light scattered by suspended particles.

Autonomous grasping of unknown objects by a robot is a challenging task that, in the last years, is receiving increasing attention in underwater environments. These environments are highly unstructured and limit the availability and effective range of sensors. Grasping an object generally requires the detailed knowledge of a partial 3D structure where the manipulation is done, or prior knowledge of the CAD model the robot is going to manipulate. In order to obtain these data, there exist different methods. They can be generally classified according to the type of the sensing device: sonar, laser, stereoscopy, structured light. Sonar based methods are the most extended underwater. These sensors can measure distances of hundreds of meters with a resolution of a centimeter, which in some cases is not enough for manipulation. Laser rangefinders are common in wheeled robots, but they do not work correctly underwater due to energy absorption of water [1]. Laser line scanning (LLS) is being used to sweep an area while the robot is stationary and, with a camera, the 3D is recovered. This technique depends on a laser line projecting device and a camera. Furthermore, a bandpass filter can be also used to discard other light frequencies different from the pure laser source. Advanced systems reduce even more the scattering by controlling the temporal properties of light, gating both the light emitter and the receiver. This systems can either be formed by a set of moving mirrors and a PMT, or a laser projector and a camera. 3D can also be computed with two cameras, however the density of the reconstruction is directly related to the texture of the object. Finally, Structured Light (SL) projects a pattern that creates artificial texture on the required object in order to solve the stereoscopy problem.

In underwater environments different technologies have been tested and reported in the literature. In [2] Structure from Motion (SfM) is used, with an EKF and bundle adjustment, to obtain a set of poses of the 3D points with a 2% RMS error.

Stereo Vision (SV) can outperform SfM if a wide baseline is chosen. This way, the computation of 3D points is easier as the camera synchronization plays an important role. In [3] and [4] stereo cameras are used to reconstruct underwater structures.

SL systems have recently proven to be a good trade-off system, cheap and precise enough to obtain detailed 3D models. These systems are used in [5], where the problem of absorption and scattering is clear, still the images are usable to obtain 3D data with increasing error when increasing turbidity. In [6] the same behavior is tested, with an error up to 2%.

SV can be also used in combination with SL as in [7] and in [8] where stereo matching is used instead on common triangulation.

Laser overcomes absorption and helps in scattering problems. In [9] the authors detect the shape of the laser with a camera, looking for pipes, whilst in [10], LLS is used to sweep the underwater with a 0.3% error in calibration. In [11] LLS is used as input pointcloud for an autonomous grasping. Stereo cameras with a line laser has been also found in the literature [12].

LLS has been also used with Photomultiplier Tubes (PMT) as in common rangefinders or LIDARS. The advantage of those systems is that minimize both backscatter and forward scattering by minimizing the field of illumination and the field of view [13]. The laser can even be modulated to help discarding scatter from the original light signal, although this results in reducing the sensing power to increment sensing capabilities [14]. However, this systems are relatively large, complex and expensive [15, 16].

Detailed 3D point clouds are needed to perform a correct manipulation in underwater environments. The sensors that are accurate enough to perform such a task are LLS, stereo cameras and those based on SL. Stereo cameras need texture in order to compute 3D points, and in these environments the object to be manipulated and the surrounding area where it is laying can be featureless because

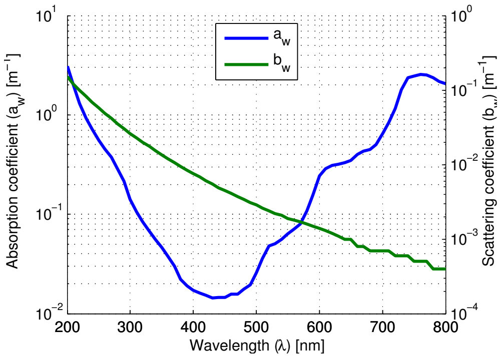


Fig. 1: Absorption and scattering coefficients in pure seawater. Reproduced from Smith and Baker (1981).

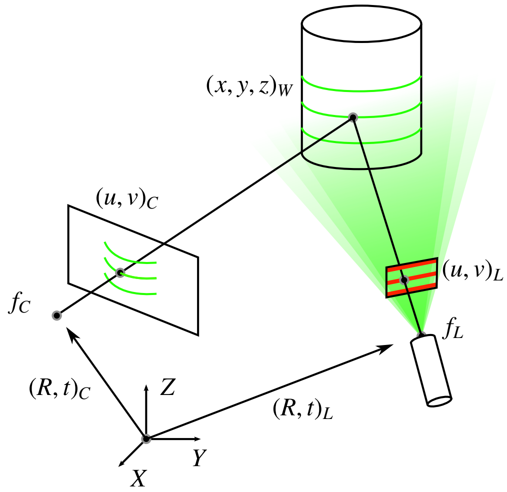


Fig. 2: Basis of triangulation. The laser pattern (shown in red) is projected on an object, which deforms the pattern. This deformed lines are recovered by the camera. Laser focal point is f_L and camera focal point is f_C. Point $(u, v)_C$ and $(u, v)_L$ are the projections of point $(x, y, z)_W$ from world coordinates to camera and laser coordinates, correspondingly. $(R, t)_C$ and $(R, t)_L$ are the transformation matrix relative to a world origin.

of mud or flora growing. LLS is slow but accurate, whilst SL is fast but in underwater environments suffers from scattering.

Other devices use also laser as an altimeter and pose estimation of the robot [17], but do not recover 3D information of the environment. Other laser solutions, similar to SL can be seen in [18] where a 33x33 dot pattern is projected onto the scanning area and detected back with a camera. That system measures up to 100 mm depth with millimeter accuracy. Also in [19] a 19x19 dot pattern is used with a 785 nm infrared laser, and in [20] 15 slits, with 660 nm red laser. However, the available literature does not report testing these devices in underwater environments, so they can be improved.

In this article, we would like to introduce a new underwater sensor based on structured light systems and laser light, which is under study.

This paper is organized as follows: firstly, section II. the design and considerations of the sensor are explained. Next, section III. the different simulation tests are presented And finally, in section IV. the conclusions and future work are outlined.

II. DESIGN

Laser color is extremely important in underwater environments due to absorption and scattering. As seen in Fig. 1, absorption and scattering coefficients vary depending on the wavelength of the light source. In order to transmit the maximum light these coefficients have to remain low. Blue-green color spectra present a good compromise between absorption and scattering. For these reasons, a 532 nm laser has been chosen as light source.

In front of the laser source a Diffractive Optical Element (DOE) has been placed to change the shape of the laser beam to a 25 lines pattern. These lines are projected on the scene and recovered by a camera.

The geometry of the system is extremely important because it is tightly related to the range and total field of view of the reconstructed 3D volume. The relative placement of the laser respect to the camera has to be carefully studied.

The camera can be modeled as a pinhole camera with a determined projection matrix. This matrix can be obtained either from camera calibration or by construction.

The laser source can be modeled as a projector with a static *virtual image* of 25 lines. A projector can then be modeled as a camera, with a particular camera matrix containing its focal distances and center distances.

This *virtual image* (in red in Fig. 2) varies depending on the focal distance and the field of view (in the case of the projector that would be the field of projection). Once the FOV is known and the image size is chosen, the focal distance can be obtained from calibration.

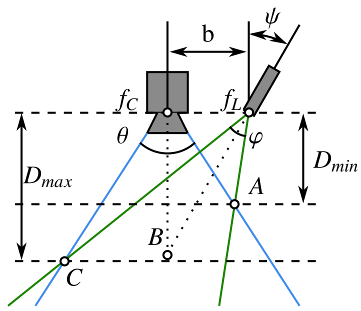


Fig. 3: Laser to camera geometry. Laser focal point is f_L and camera focal point is f_C. Point B is where the camera projection axis and the laser axis concur. The D_{min} and D_{max} distances are related to the field of view of the camera, being D_{max} the maximum distance at which all the projected pattern from the laser is seen from the camera, and D_{min} the minimum distance where that occurs.

A. Triangulation principle

The basis of a laser based structured light system is depicted in Fig. 2. The laser projects its pattern on the scene, and the deformed pattern is recovered by the camera. Both the laser and the camera have been characterized by a focal point and an image frame. In front of the laser projector the undistorted pattern is shown in red. As an example, three lines have been represented. The laser lines are detected at a sub-pixel level in the camera image and their coordinates are used to triangulate 3D points. If the transform from the laser to the camera is known, the 3D point computation can be done by projecting a 3D ray from the camera focal point through the camera image to the object, and then back to the laser virtual image and focal point. The crossing point of this two lines return the world coordinates of that point.

The geometry of the system has to be tuned depending on the desired range of the device. In Fig. 3 the most important geometry variables are indicated. Note that depending on the baseline (b), the camera and laser fields of view (θ and φ correspondingly) and the relative rotation (ψ) between the camera and the laser, the maximum measurable distance and the minimum measurable distance vary as depicted in Eq. 1 and 2.

Table 1: Simulation results of the recovered 3D mean distance, standard deviation and error to the bottom plane distance from the laser points detected at 10 Hz.

Distance (m)	μ (m)	σ (mm)	Error (%)	Points
2.5	2.505	4.64	0.2	6982
3.0	3.005	6.68	0.2	6982
3.5	3.504	10.04	0.1	6981
4.0	4.005	12.24	0.1	6979
4.5	4.505	15.37	0.1	6973

$$D_{max} = \frac{b}{\tan\left(\psi + \frac{\varphi}{2}\right) - \tan\left(\frac{\theta}{2}\right)} \tag{1}$$

$$D_{min} = \frac{b}{\tan\left(\psi - \frac{\varphi}{2}\right) + \tan\left(\frac{\theta}{2}\right)} \tag{2}$$

B. Image processing

The camera recovers the deformed lines pattern that is used to reconstruct the 3D scene in one shot. Only the illuminated points can be recovered in 3D using the triangulation principle. The points in between can be either fitted by a curve or be left unknown.

However, in order to match each laser point in the camera image to its corresponding point in the laser pattern, the line correspondence must be known *a priori*. When all projected lines are in the field of view of the camera this setup can correctly find line to line correspondences. But when one or more lines are completely or partially not in sight, the correspondence becomes a problem.

III. SIMULATION

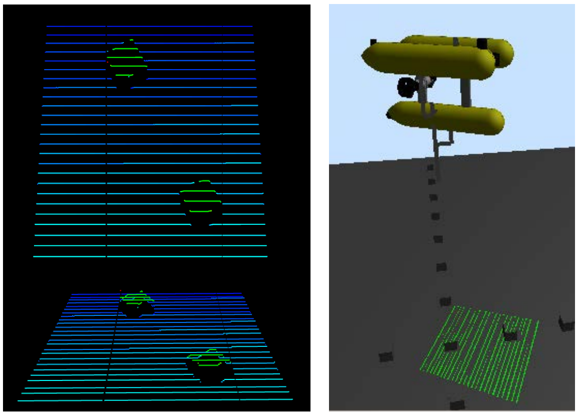
The proposed sensor has been tested in an Underwater Simulator (UWSim [21], http://www.irs.uji.es/uwsim/) and in a controlled environment. The sensor has been placed on the Girona500 AUV model and the vehicle has been placed at different fixed distances from a bottom plane. The purpose of this setup is to obtain error measurements for the sensor on development.

The camera has a resolution of 1024x768 px with an horizontal field of view (HFOV) of $\theta = 90°$, and the laser is modeled as a projector with a fixed image of 25 lines. In order to avoid the projection of light where there are no lines, the projector model has been modified not to project light other than the lines itself, thus achieving a complete laser projector model in the simulator. The projected image has a resolution of 1024x1024 and its field of view is $\varphi = 22°$. The camera is looking downward and the laser is set $b = 1,5$ m apart, rotated $\psi = 28°$ relative to the vertical.

The results of these tests can be seen in table 1. For each distance, the device has taken one shot and detected up to 6.982 different triangulations at 10 Hz. From these measures, the mean and the standard deviation has been computed. Note that for planar surfaces the error in depth is up to a 0.2% of the total range.

Other two experiments have been carried out reconstructing simple objects in a one-shot reconstruction. The first test has been done in a simulated scenario with two cubes at a depth of 3 meters. In Figs. 4(a) and 4(b) the pointcloud and the simulated environment can be seen.

In the second experiment, a more complex object has been reconstructed on the same conditions as before. An amphora model has been introduced in the simulator and the submarine has been placed on top. The resulting point cloud and the camera image can be seen in Figs. 5(a) and 5(b).



(a) Resulting pointcloud from laser triangulation. (b) UWSim scene with the AUV G500 and the laser projector.

Fig. 4: First object reconstruction test, two cubes.

IV. CONCLUSIONS AND FUTURE WORK

A new approach for laser-based structured light sensor devices aimed at underwater environments has been presented. As seen in the literature, there are not so many cases where a laser projector has been used in underwater environments. This sensor will not only be useful for AUVs or ROVs, but could be also extended to non-underwater targets or robots.

The advantages of this system include the reconfiguration of the system geometry to fit a particular application. Depending on the distance to be scanned different angles and baselines are best suited. Wider ranges can be achieved with laser light thanks to polarized and focused light. Furthermore, the 3D information can be obtained in one camera shot. With this system 3D pointcloud data can be provided at frame rate, without the need of waiting a laser sweep scan nor having the need of a textured surface.

Future work includes the prototype of this new sensor and its calibration, as well as these same tests in real underwater environments. Then 3D reconstruction surveys could be also done fitting pointcloud data with registration algorithms.

REFERENCES

[1] M. Hildebrandt, J. Kerdels, J. Albiez, and F. Kirchner, "A practical underwater 3D-Laserscanner," in *Oceans 2008*, pp. 1–5, Ieee, 2008.

[2] O. Pizarro, R. M. Eustice, and H. Singh, "Large Area 3-D Reconstructions From Underwater Optical Surveys," *IEEE Journal of Oceanic Engineering*, vol. 34, pp. 150–169, 2009.

[3] T. D. Dao, *Underwater 3D reconstruction from stereo images*. Msc erasmus mundus in vision and robotics, University of Girona (Spain), University of Burgundy (France), Heriot Watt University (UK), 2008.

[4] C. Beall, B. J. Lawrence, V. Ila, and F. Dellaert, "3D reconstruction of underwater structures," in *2010 IEEE/RSJ International Conference on Intelligent Robots and Systems*, vol. 0448111, pp. 4418–4423, IEEE, Oct. 2010.

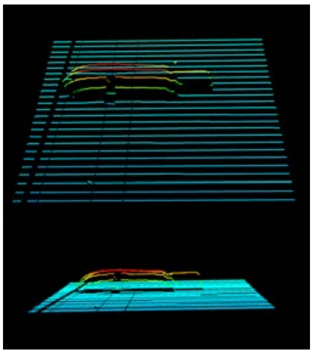
[5] S. Narasimhan and S. Nayar, "Structured Light Methods for Underwater Imaging: Light Stripe Scanning and Photometric Stereo," in *Proceedings of OCEANS 2005 MTS/IEEE*, pp. 1–8, Ieee, 2005.

[6] N. Törnblom, *Underwater 3D Surface Scanning using Structured Light*. PhD thesis, Uppsala Universitet, 2010.

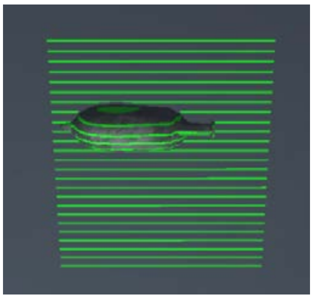
[7] F. Bruno, G. Bianco, M. Muzzupappa, S. Barone, and A. Razionale, "Experimentation of structured light and stereo vision for underwater 3D reconstruction," *ISPRS Journal of Photogrammetry and Remote Sensing*, vol. 66, pp. 508–518, July 2011.

[8] T. Pribanic, N. Obradovic, and J. Salvi, "Stereo computation combining structured light and passive stereo matching," *Optics Communications*, vol. 285, pp. 1017–1022, Mar. 2012.

[9] S. Tetlow and J. Spours, "Three-dimensional measurement of underwater work sites using structured laser light," *Measurement Science and Technology*, vol. 1162, 1999.



(a) Resulting amphora pointcloud from laser triangulation.



(b) Camera ROI image. Note that there is barely no texture in the image except for the laser.

Fig. 5: Second object reconstruction test, an amphora.

[10] K. Moore and J. S. Jaffe, “Time-evolution of high-resolution topographic measurements of the sea floor using a 3-D laser line scan mapping system,” *IEEE Journal of Oceanic Engineering*, vol. 27, pp. 525–545, July 2002.

[11] M. Prats, J. J. Fernandez, and P. J. Sanz, “An approach for semi-autonomous recovery of unknown objects in underwater environments,” in *2012 13th International Conference on Optimization of Electrical and Electronic Equipment (OPTIM)*, pp. 1452–1457, IEEE, May 2012.

[12] P. L. D. Roberts, J. V. Steinbuck, and J. S. Jaffe, “Estimation of In Situ 3-D Particle Distributions From a Stereo Laser Imaging Profiler,” *IEEE Journal of Oceanic Engineering*, vol. 36, no. 4, pp. 586–601, 2011.

[13] A. Gordon, “Use of Lases Scanning Systems on Mobile Underwater Platforms,” in *AUV Conf.*, pp. 202–205, 1992.

[14] L. J. Mullen, V. M. Contarino, A. Laux, B. M. Concannon, J. P. Davis, M. P. Strand, B. W. Coles, and M. Contarion, “Modulated laser line scanner for enhanced underwater imaging,” in *SPIE Proceedings* (G. D. Gilbert, ed.), vol. 3761, pp. 2–9, SPIE, Oct. 1999.

[15] F. R. Dalgleish, F. M. Caimi, W. B. Britton, and C. F. Andren, “Improved LLS imaging performance in scattering-dominant waters,” *Proc. SPIE*, vol. 7317, pp. 1–12, 2009.

[16] F. Dalgleish, F. Caimi, and W. Britton, “An AUV-deployable pulsed laser line scan (PLLS) imaging sensor,” *IEEE Oceans*, pp. 1–5, 2007.

[17] M. Caccia, “Laser-Triangulation Optical-Correlation Sensor for ROV Slow Motion Estimation,” *IEEE Journal of Oceanic Engineering*, vol. 31, pp. 711–727, July 2006.

[18] Y. Watanabe, T. Komuro, and M. Ishikawa, “955-fps real-time shape measurement of a moving/deforming object using high-speed vision for numerous-point analysis,” *Robotics and Automation, IEEE International Conference on*, no. April, pp. 10–14, 2007.

[19] H. Ishiyama, K. Terabayashi, and K. Umeda, “A 100Hz real-time sensing system of textured range images,” *2010 International Symposium on Optomechatronic Technologies*, pp. 1–6, Oct. 2010.

[20] T. Kuroki, K. Terabayashi, and K. Umeda, “Construction of a compact range image sensor using multi-slit laser projector and obstacle detection of a humanoid with the sensor,” *2010 IEEE/RSJ International Conference on Intelligent Robots and Systems*, vol. 2, pp. 5972–5977, Oct. 2010.

[21] M. Prats, J. Perez, J. J. Fernandez, and P. J. Sanz, “An open source tool for simulation and supervision of underwater intervention missions,” in *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 2577–2582, IEEE, Oct. 2012.