TIME-OF-FLIGHT (TOF) CAMERAS FOR UNDERWATER SITUATIONAL AWARENESS

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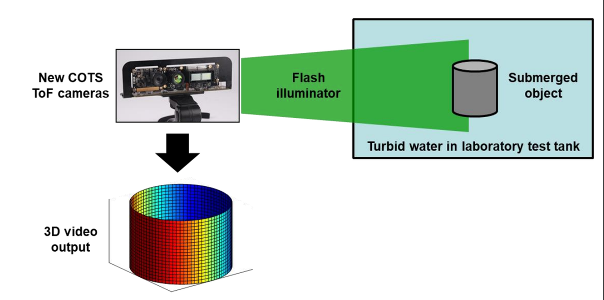
ABSTRACT

Recently developed commercial Time-of-Flight (ToF) cameras have been used to accurately and reliably measure scene depth with high resolution in applications such as automotive LiDAR. There is a desire to adapt this technology for applications in underwater environments. In this work, we establish a methodology for using modified commercial ToF cameras in turbid water. We express the need for hardware and software modifications to the camera and demonstrate initial results in the efficacy of the camera in an underwater test scenario. We include ToF camera imagery taken under a variety of water conditions to understand the performance limitations of this technology as a function of water clarity. Target detection results from preliminary laboratory test tank experiments are presented for two different classifiers, each of which achieves high accuracy for a certain range of water conditions.

INTRODUCTION

Figure 1: ToF Camera Basics

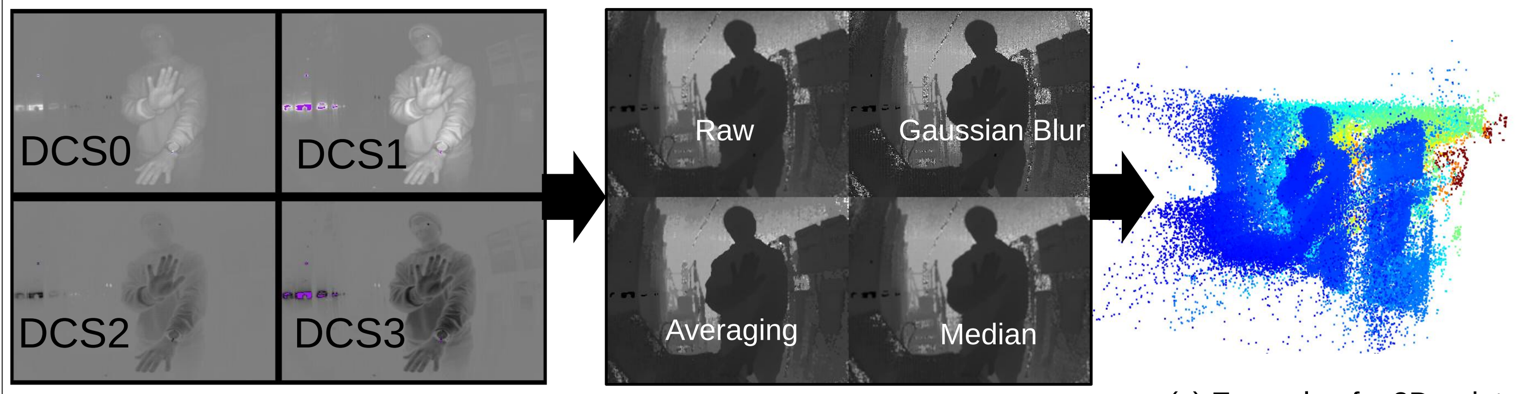


The ToF camera provides modulated flash illumination toward the target object. The reflected light is detected by the camera sensor and time-of-flight can be estimated, providing range information and the ability to produce 3D imagery

- Time-of-Flight cameras deliver video-rate 3D depth imaging using small form factor sensor
- Flash illuminator transmits modulated light which illuminates the target object
- Signal reflects off the target object and is received by specially designed sensors on the ToF camera
- Four phase measurements are made on time-of-flight data to calculate distance for each pixel:

$$D = \frac{v}{2}\frac{1}{2\pi f_{mod}}\left[\pi + atan\left(\frac{DCS_2 - DCS_0}{DCS_3 - DCS_1}\right)\right] + D_{offset} \qquad (1)$$

Figure 2: Ranging and Data Visualization



(a) Raw DCS data, which has a direct relationship with IQ data
(b) Distance images with different image filters applied
(c) Example of a 3D point cloud

TECHNICAL CHALLENGES

Technical Challenge 1:
- Underwater absorption of illuminator light
- Infrared wavelengths used by COTS ToF cameras are heavily absorbed in the underwater environment (Figure 3a)
- Wavelengths in the blue-green spectrum are least absorbed (Figure 3b, 3c)

Technical Challenge 2:
- Scattering of illuminator light becomes an issue, especially in turbid waters
- Range is limited by the presence of heavy backscatter (Figure 3d)
- Backscatter mitigation techniques are needed to address this problem

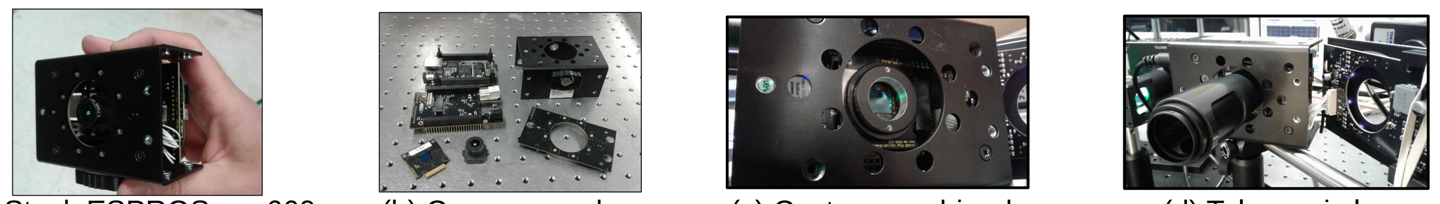
Figure 3: Technical Challenges for Adaption to Underwater Environment

(a) Absorption properties of light dependent on wavelength
(b) This photo depicts the proclivity of certain ocean waters to scatter blue light
(c) Scattering of green light
(d) Example of a LIDAR signal return in turbid water

HARDWARE MODIFICATIONS

We selected a COTS ToF camera manufactured by ESPROS as a starting point. To address the first technical challenge, several hardware modifications are needed. The camera's modular design allowed us to easily make the necessary adjustments to adapt the camera to wavelengths that are better suited for the underwater environment.

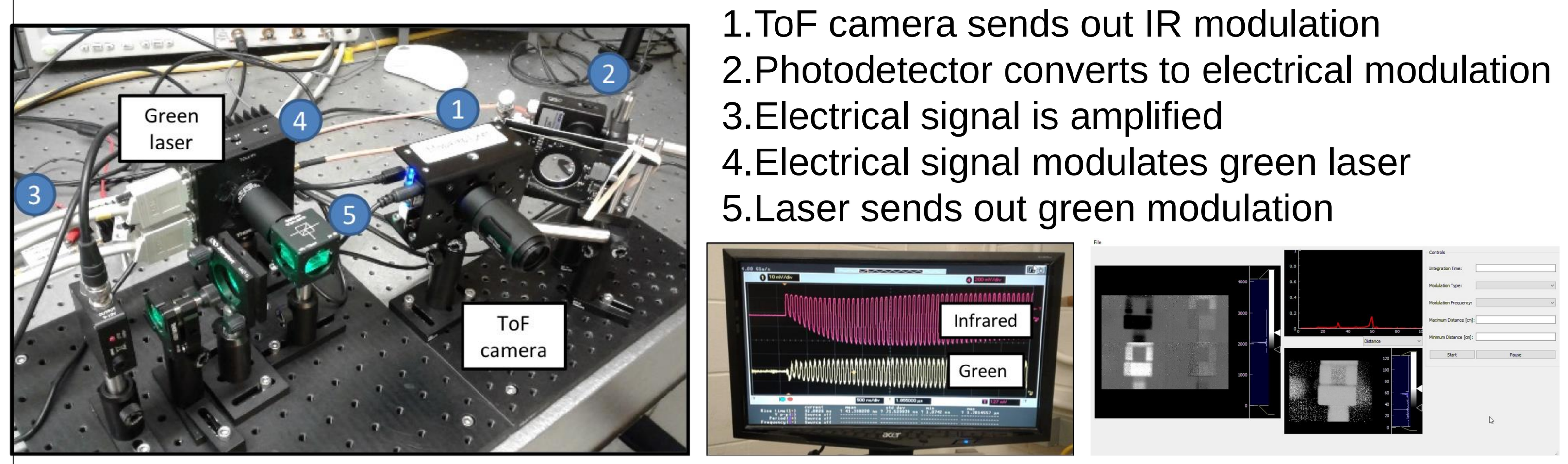
Figure 4: ESPROS ToF Camera Hardware Modifications



(a) Stock ESPROS epc660 evaluation kit ToF camera
(b) Camera can be easily disassembled
(c) Custom machined lens mount for modular optics design
(d) Telescopic lens added to mount

Figure 5: Benchtop ToF Camera Setup with 532nm Laser

1. ToF camera sends out IR modulation
2. Photodetector converts to electrical modulation
3. Electrical signal is amplified
4. Electrical signal modulates green laser
5. Laser sends out green modulation

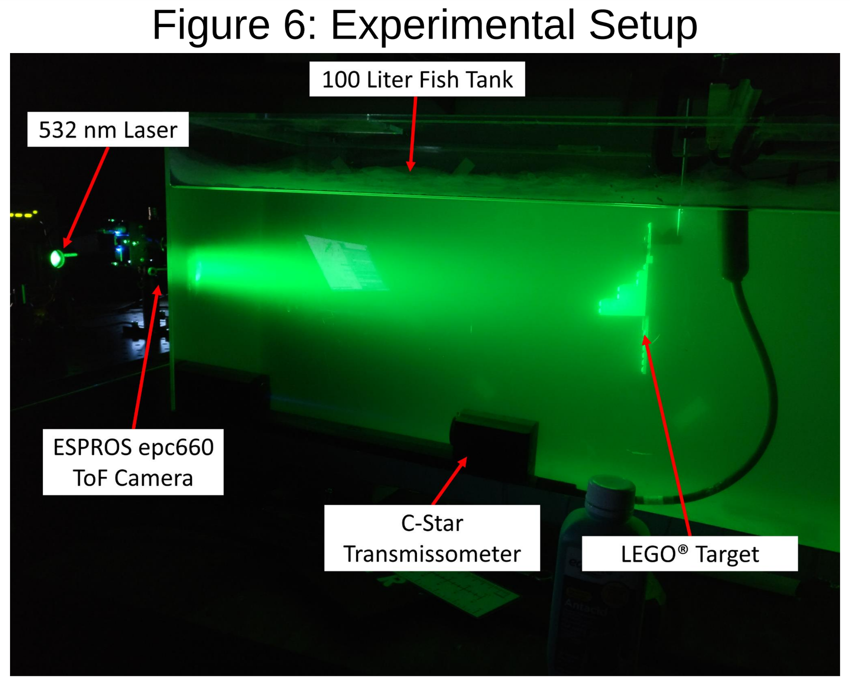


(a) Benchtop ToF camera prototype setup with green laser illuminator
(b) Modulation signal produced by ToF camera is replicated
(c) Custom GUI designed for ToF camera

EXPERIMENTAL SETUP AND PROCEDURE

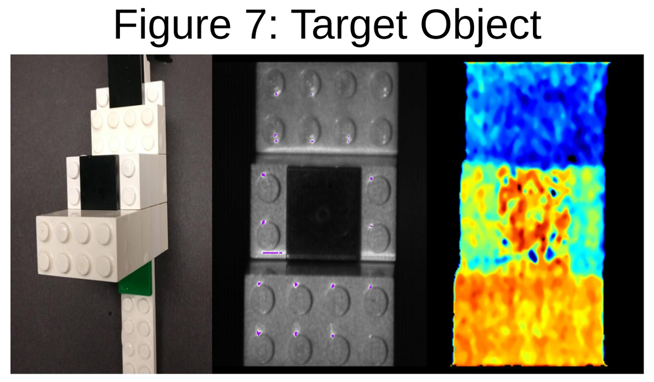
An initial experiment is performed to benchmark camera performance. The experiment is designed to test the ToF camera's ability to pick up a target signal in varying water clarities. The ToF camera is aimed at 100 liter fish tank, which contains turbid water and a submerged diffuse target object. The data collected is used for target detection classifiers.

Figure 6: Experimental Setup



A depiction of the experimental setup. The setup includes the ToF camera, the transmissometer, the laser, and the target.

Figure 7: Target Object



(a) Reference Image
(b) Grayscale Image
(c) Distance Image

- The dataset acquired in this experiment consisted of one target object, at one known distance, using one modulation frequency
- The only variability in the setup was turbidity level and presence of target (a binary variable)
- Experiment details are given in Table 1, which details the measured attenuation coefficient, c, and corresponding attenuation lengths, cz

Table 1: Experiment Control Variables

Turbidity Level	Measured c (m^{-1})	Attenuation Lengths
T0	1.233	0.740
T1	3.128	1.877
T2	4.548	2.729
T3	6.113	3.668
T4	7.658	4.595
T5	8.956	5.373
T6	11.653	6.992
T7	14.355	8.613
T8	19.521	11.712
T9	24.972	14.983

RESULTS

Results from the experiment include finding the average amplitude of the target return at each turbidity level, as well as testing target detection algorithms.

- Figure 8 depicts experimental data
- Challenge: separation of backscatter pixels from target pixels at high turbidity
- Otsu's method, given by (2), is used on amplitude data to extract the target pixels

$$\sigma_w^2(t) = w_0(t)\,\sigma_0^2(t) + w_1(t)\,\sigma_1^2(t) \qquad (2)$$

where t is the threshold, w_i is the class probability, and σ_i^2 is the class variance

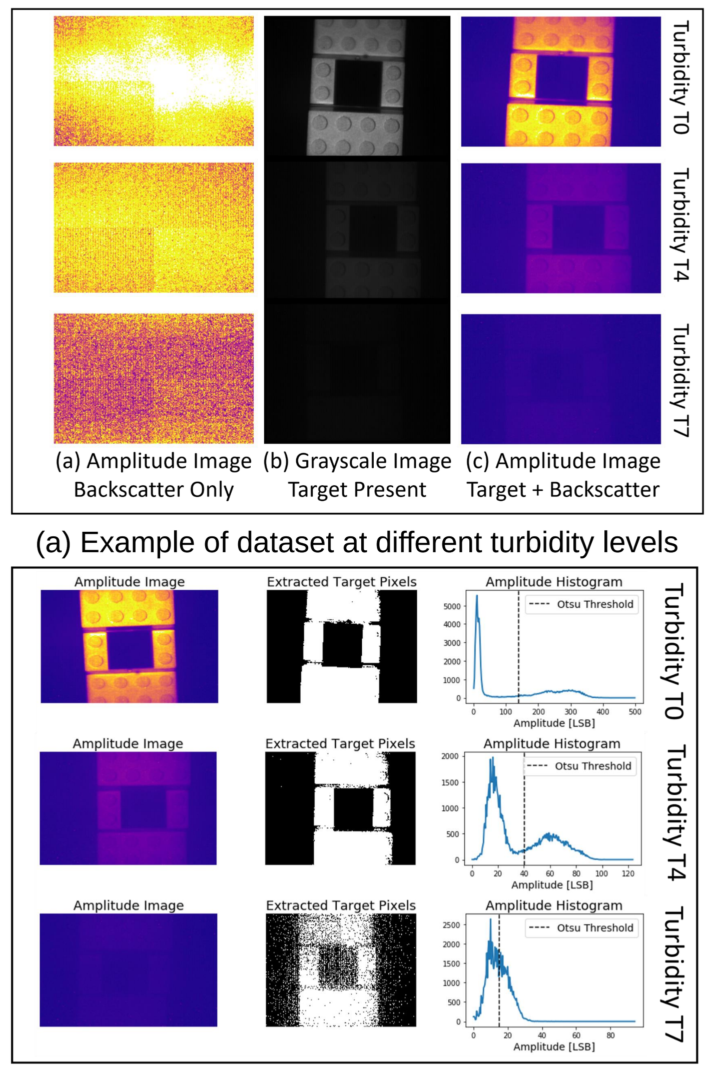
- Thresholding results are given in Figure 8
- Using target pixels extracted from each image, we can find average target return
- Average amplitude can be plotted against attenuation lengths to find the relationship
- Beer's law, given by (3), describes the relationship for EM attenuation through a scattering medium

$$P_{target} = P_0 e^{-cz} \qquad (3)$$

where P_0 is the average target return power in clear water, c is the attenuation coefficient, and z is distance downrange

- Figure 9 attenuation plot shows good agreement between theory & experiment: *validates ToF camera setup & experiment*
- Dataset was used for target detection to decide if a target was present in the scene
- Linear classifier is compared to a multi-layer perceptron (MLP) in Table 2: *accuracy decreases as scattering increases*

Figure 8: Dataset examples and pre-processing for target detection

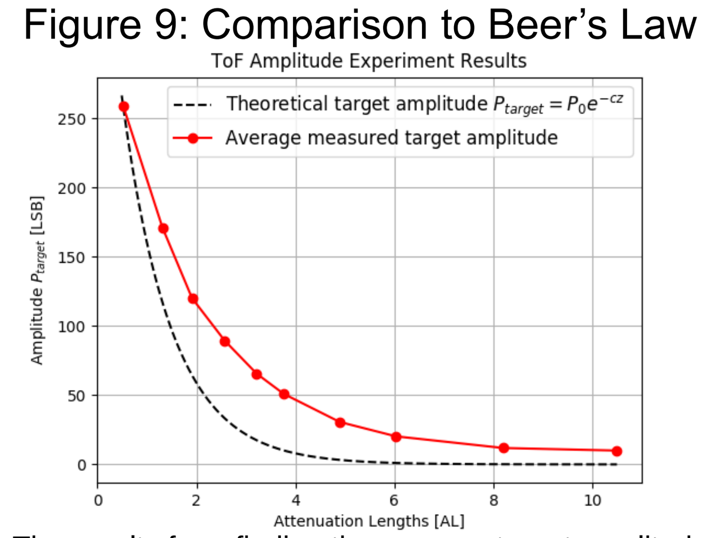


(a) Example of dataset at different turbidity levels
(b) Example of the results from Otsu's thresholding

Table 2: Target Detection Accuracy

Turbidity Level	Variance SVM	MLP Network
T0	100%	100%
T1	100%	100%
T2	100%	100%
T3	100%	100%
T4	100%	100%
T5	99%	100%
T6	98%	99%
T7	93%	98%
T8	68%	83%
T9	50%	63%

Figure 9: Comparison to Beer's Law



The results from finding the average target amplitude at each turbidity, plotted against the theoretical values

CONCLUSIONS AND FUTURE WORK

- Commercial ToF cameras are known to be cost effective, reliable, and compact instruments for ranging and 3D imaging when operating in air, with potential for underwater use
- Demonstrated proof-of-concept system that allows us to take 3D depth images through water in a laboratory environment.
- Hardware challenges related to absorption have been addressed, we are now capable of collecting ToF camera imagery
- Future work will aim to enhance the hardware of our modified ToF camera, such as increasing optical power and modulation frequency
- With greater optical power, we can test performance and target detection under conditions that are more representative of large volumes of water

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