Polarimetric Underwater Stereo

Ryo Kawahara[1] Meng-Yu Jennifer Kuo[2] Takahiro Okabe[1]

[1]Kyushu Institute of Technology [2]University of Minnesota

Underwater Shape from Specular Reflection

Past works which extend in-air methods are still insufficient to recover per-pixel surface normals and depth of general surfaces simultaneously.

We show that surface normals and depth at each pixel of underwater objects can be separately recovered by a single image captured using polarization camera + LCD.

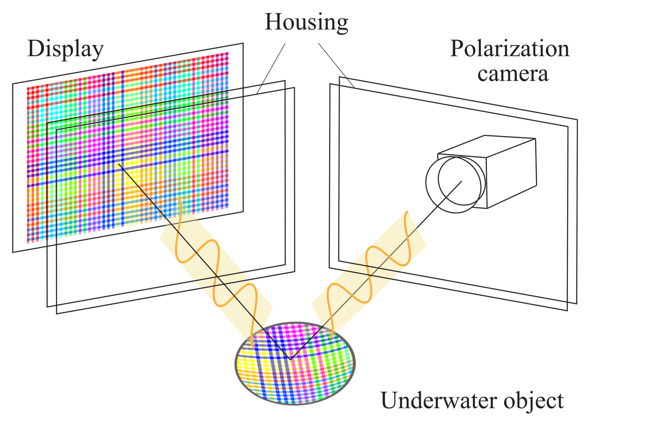
Polarized, color encoded light source (LCD)

- LCD allows a simple light source color separation for textured objects.
- A coded stripe pattern allows pixel-wise correspondence search in a single shot.

Vector-point correspondence is not enough to determine the surface normal.

Key idea: is to leverage **polarized rays (9D vectors)** along different underwater light paths.

- A polarimetric constraint allows surface normal estimation and triangulation.



Assumptions:

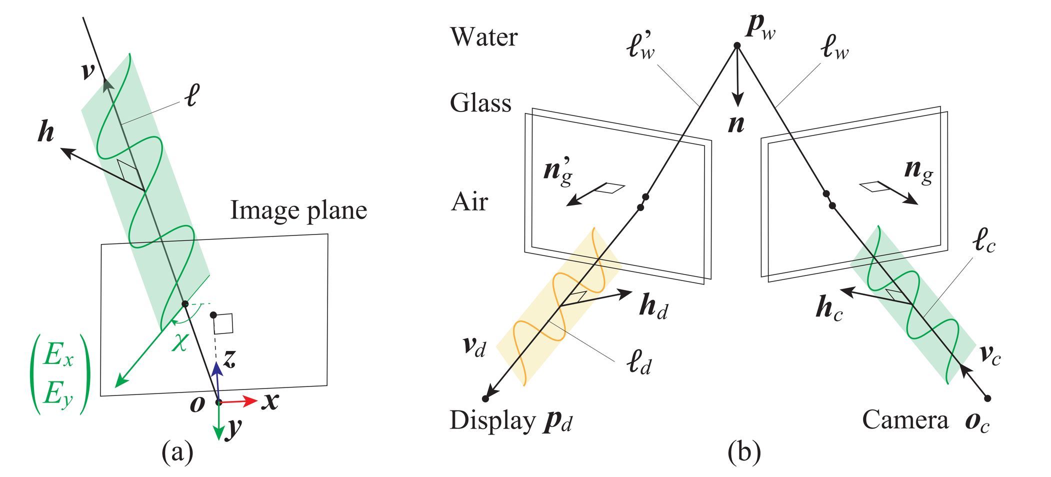
- Refractive index of the target is known
- Diffuse polarization component is small enough
- Scattering and absorption effects are negligible
- Mutual reflection components can be ignored

Underwater Polarimetric Light Field

Polarized Ray

Plane of Polarization (PoP) is spanned by the viewing direction $\boldsymbol{v}$ and the Jones vector on the image plane:

$$\boldsymbol{h} = \frac{\boldsymbol{v} \times \left(E_x \; E_y \; 0\right)^\top}{\left\| \boldsymbol{v} \times \left(E_x \; E_y \; 0\right)^\top \right\|}. \quad (1)$$



Introducing this for an extension of the Plücker coordinate system, the polarimetric ray $\boldsymbol{\ell} \in \mathbb{R}^9$ can be defined as follows,

$$\boldsymbol{\ell} = \begin{pmatrix} \boldsymbol{v} \\ \boldsymbol{o} \times \boldsymbol{v} \\ \boldsymbol{h} \end{pmatrix}, \quad (2)$$

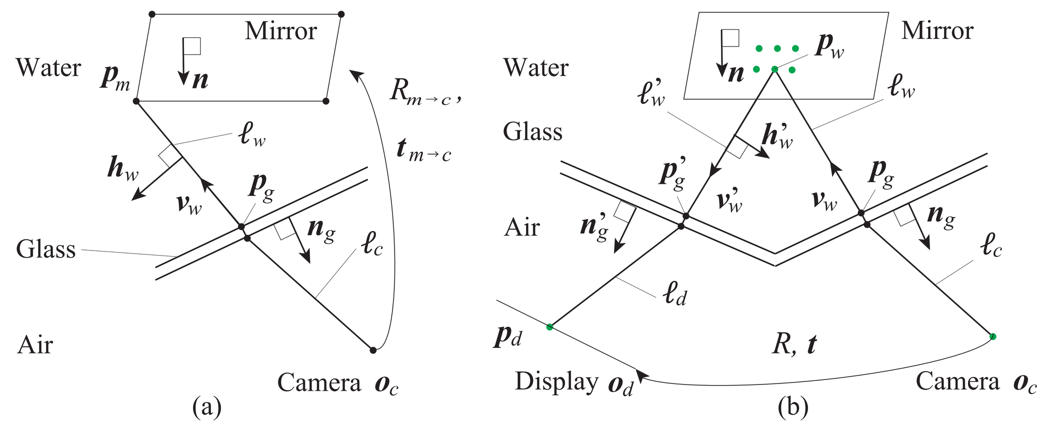
$\boldsymbol{o}$: the origin of the ray.

We describe complex transformation between the ray of display $\boldsymbol{\ell}_d$ and the ray of camera $\boldsymbol{\ell}_c$ by the following ray-dependent matrix production,

$$\boldsymbol{\ell}_c = M^{(T)}_{w \to a} M^{(R)} M^{(T)}_{a \to w} \Theta \boldsymbol{\ell}_d, \quad (3)$$

Θ : coordinate transformation, $M^{(T)}$: refraction, $M^{(R)}$: reflection

Polarization-guided Calibration of Underwater Display



Calibration of Water-Proof Camera

Using a captured image of a checkerboard as a reference object, we can calibrate the parameters [Agrawal *et al.*, 2012].

Calibration of Water-Proof Display

Mirror Pose Recovery : estimate the orientation $R_{m \to c}$ and the position $\boldsymbol{t}_{m \to c}$

- input : correspondences between 2D reference points on the mirror $\boldsymbol{p}_m$ and its observed directions $\boldsymbol{v}_w$

Display Pose Recovery : estimate the parameters $\{R, \boldsymbol{t}, \boldsymbol{n}'_g, d'_a, d'_g\}$

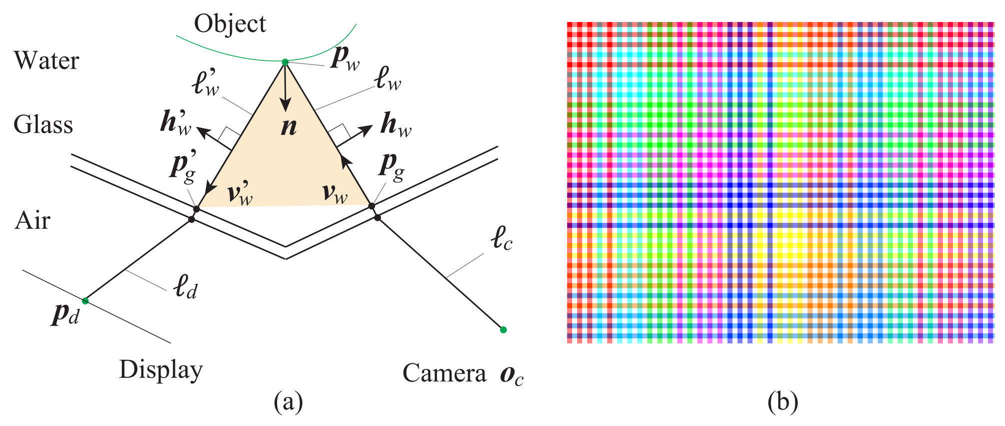
- input : correspondences between 2D points on the display $\boldsymbol{p}_d$ and its observed directions $\boldsymbol{v}'_w$

Single-shot Polarimetric Underwater Stereo

Initial normal estimation

Ignoring the thickness of the display housing d'_g, we obtain following co-planarity constraint:

$$\boldsymbol{v}_w^\top \left(\boldsymbol{n} \times (\boldsymbol{p}'_g - \boldsymbol{p}_g)\right) = 0. \quad (4)$$



Furthermore, ignoring the distortion of the polarization angle due to the rays direction of the display and Fresnel reflectance, we obtain

$$\boldsymbol{h}_w^\top \left(\boldsymbol{n} \times \hat{\boldsymbol{h}}'_w\right) = 0. \quad (5)$$

Combining (4) and (5), we obtain a linear form for the unknown surface normal $\boldsymbol{n}$.

Underwater Triangulation

Once the normal $\boldsymbol{n}$ is given, we can calculate the reflected ray direction. Therefore, an underwater triangulation can be formed by the corresponding rays $\boldsymbol{\ell}_w$ and $\boldsymbol{\ell}'_w$.

We further optimize the initial surface normal and depth by minimizing the square error of (3).

Experiment

Setup

As an equivalent environment to an underwater system, we built a system with

- LCD (EIZO FDX1203- GY)
- A water tank with 5mm housing thick
- Color polarization camera (FLIR BFS-U3-51S5PC-C)

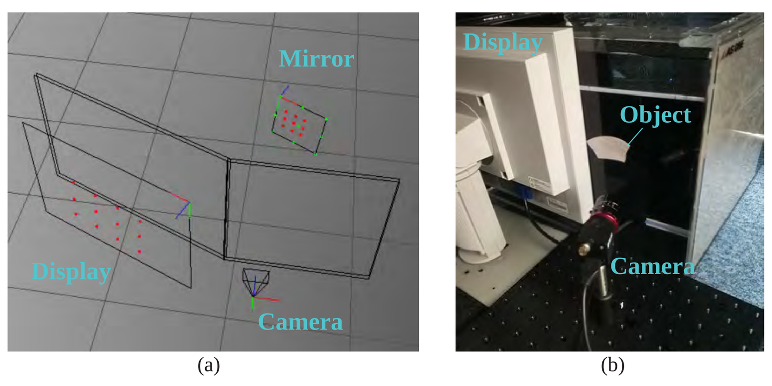


Figure: (a) Simulated calibration result. (b) Imaging setup.

Calibration errors with synthetic noise

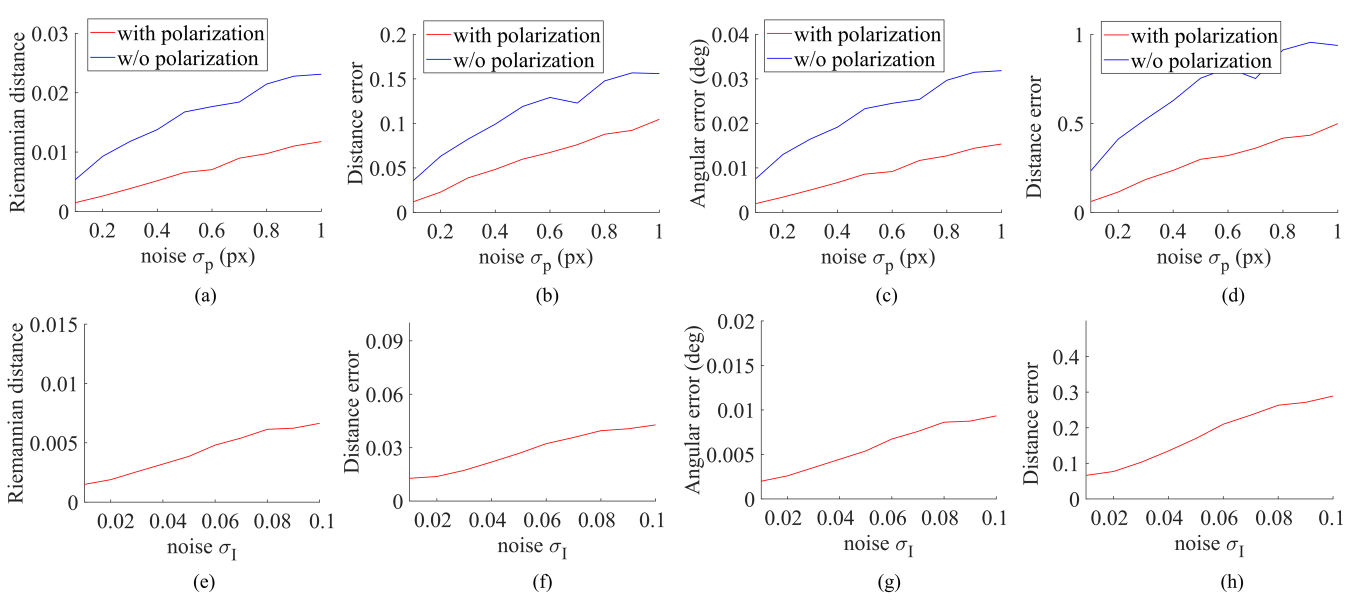


Figure: Upper: different noise for pixel position, lower: different noise for intensity. (a) the rotation error (Riemannian distance) of the display plane, (b) the translation error of the display normalized by the ground truth, (c) the angular error of the housing normal for the display (degree), and (d) housing distance errors for the display normalized by the ground truth.

Real Object Reconstruction

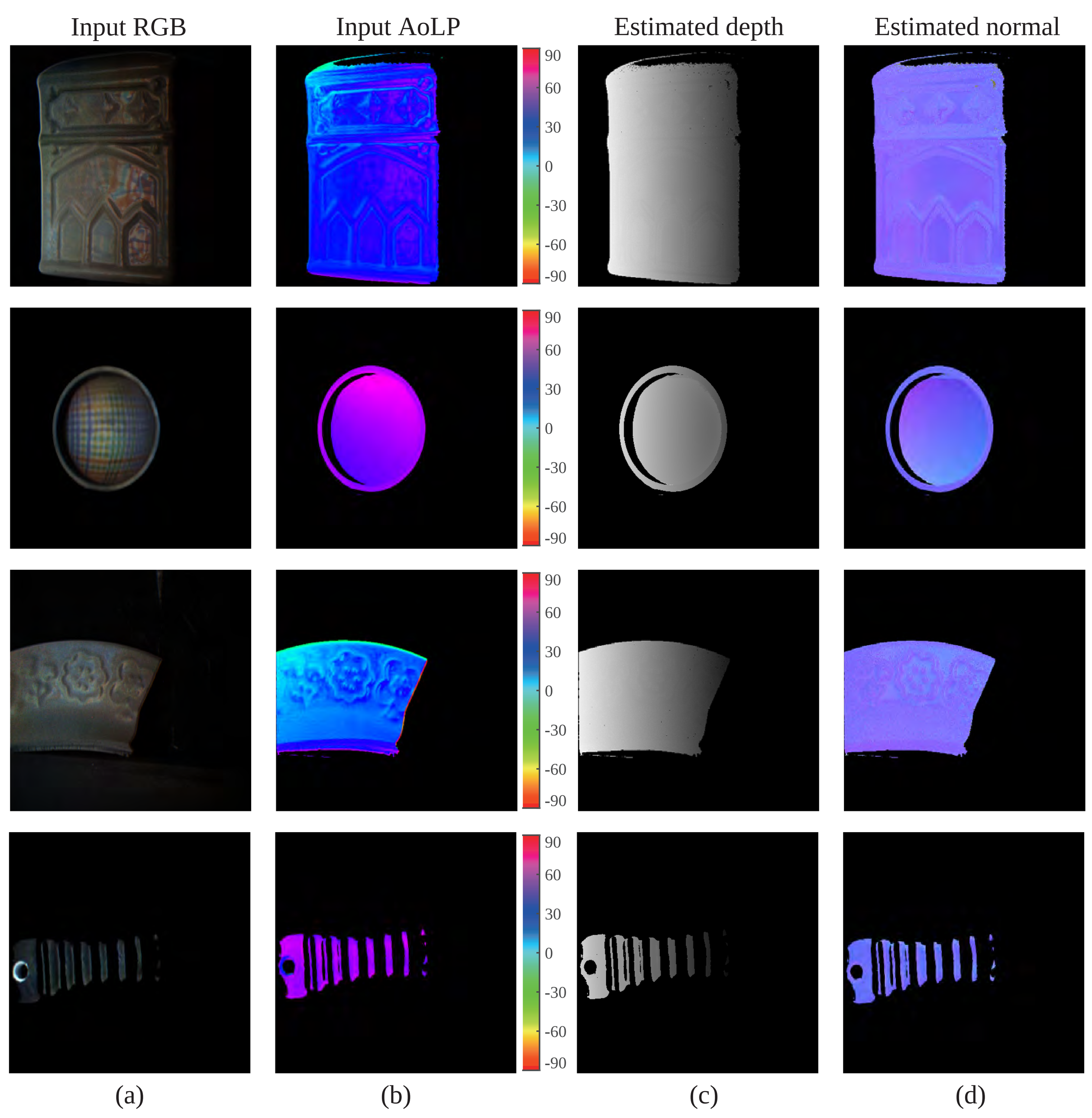


Figure: Recovery results. From left to right, we show (a) input RGB and (b) AoLP images, (c) estimated depth, and (d) estimated surface normals. For depth, the darker color indicates the closer distance to the camera.