Recovering Transparent Shape from Time-of-Flight Distortion

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Transparent Shape Recovery

Input and assumption

* Single viewpoint ToF depth measurement
* Two reference points for each pixel
* Refractive index is known

Output

* 3D point cloud of both side surfaces
* Normal vector for each refractive point

Transparent shape recovery problem

* Estimate two depths t and s on camera and reference rays (= find insider ray).

ToF Camera — Camera ray — Transparent object (To be estimated) — Reference ray — Two reference points — Move reference board
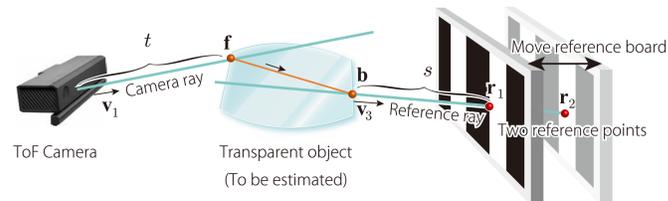
Time-of-Flight Distortion

The speed of light slows down inside transparent objects.

= ToF depth is longer than Euclidean refractive path length. (ToF Distortion)

ToF camera — speed of light = c — speed = $\frac{c}{\eta}$ — Transparent object — speed = c — Background
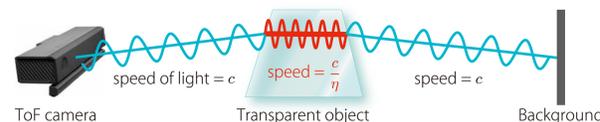
This distortion inherits transparent object information.

Method

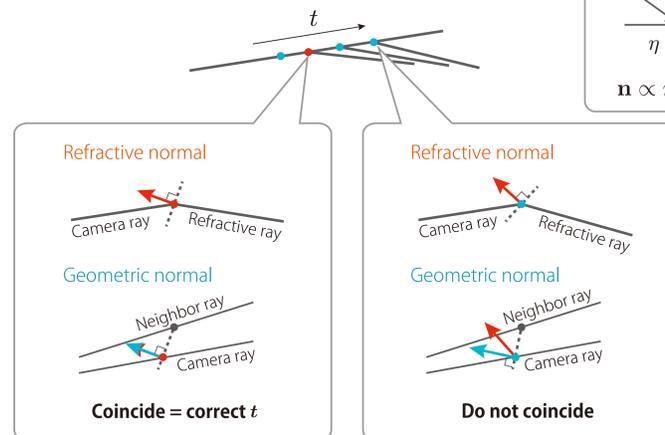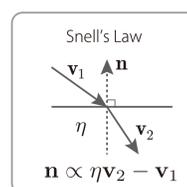**Estimating single parameter for each pixel, which determines refractive path.**

1. Using ToF distortion, back point is uniquely determined when t is hypothesized.
   → problem is converted to single parameter (t) estimation.

$$t + \eta |\!\!\!-\!\!\!| + s = l_{\text{ToF}}$$

Camera ray — Candidate front and back points pairs — Reference ray
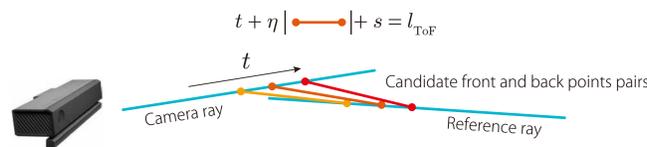
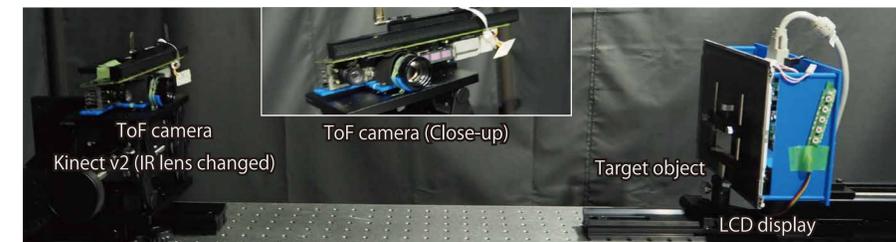2. t is estimated by "normal consistency" criteria.

   When t is hypothesized, two normals can be obtained and they should coincide.

   Refractive normal: from theory of refraction
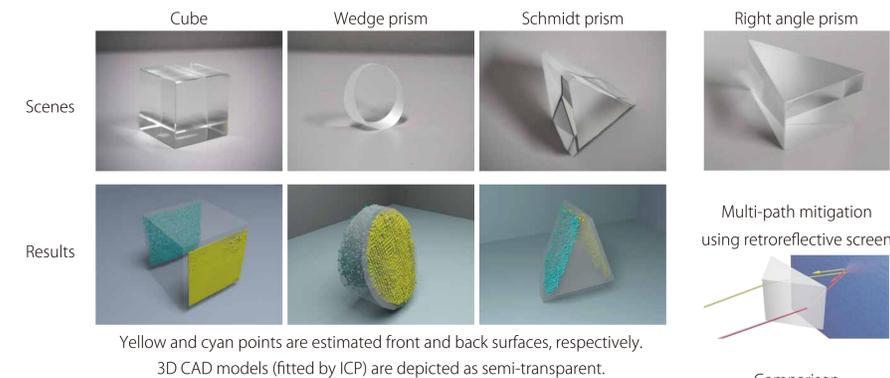   **Geometric normal**: from surface differentiation

Snell's Law

$$\mathbf{n} \propto \eta \mathbf{v}_2 - \mathbf{v}_1$$

Refractive normal — Camera ray — Refractive ray
Geometric normal — Neighbor ray — Camera ray
Coincide = correct t

Refractive normal — Camera ray — Refractive ray
Geometric normal — Neighbor ray — Camera ray
Do not coincide

Real-world Experiment

Kinect v2 and LCD display system

ToF camera — Kinect v2 (IR lens changed) — ToF camera (Close-up) — Target object — LCD display

Experimental Result

| | Cube | Wedge prism | Schmidt prism | Right angle prism |

Scenes

Results

Multi-path mitigation using retroreflective screen

Yellow and cyan points are estimated front and back surfaces, respectively.
3D CAD models (fitted by ICP) are depicted as semi-transparent.

Quantitative Evaluation

	Cube	Wedge prism	Schmidt prism
Mean Error	0.188 mm	0.226 mm	0.381 mm
Std. dev.	0.458 mm	1.137 mm	1.398 mm

Comparison
With
Without
0.745 mm → 0.448 mm
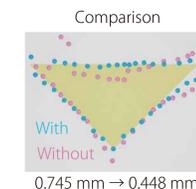
Optimization Framework

Minimizing an energy function:

$$\underset{\mathbf{t},\mathbf{l}}{\arg\min} \sum_{c \in C} \|\mathbf{n}_{\mathbf{p},c}(t_c, l_c) - \mathbf{n}_{\mathbf{d},c}(t_c)\|_2^2 + \lambda_1 \sum_{j,k \in N} \|t_j \mathbf{v}_{1,j} - t_k \mathbf{v}_{1,k}\|_2^2 + \lambda_2 \sum_{c \in C} \|l_c - l_{ToF}(c)\|_2^2 + \lambda_3 \sum_{c \in C} \left\| \frac{\partial}{\partial z} \mathbf{b}_j(t_c, l_c) \right\|_H$$
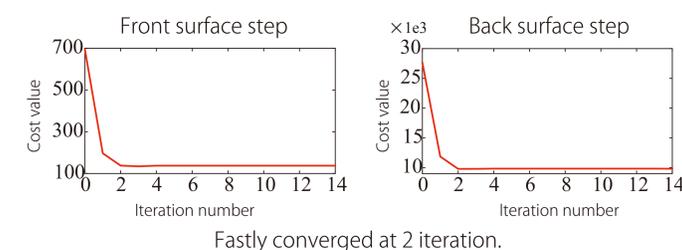
Data term: normal consistency — Front surface smoothness — Data term: ToF depth — Back surface smoothness

Alternating approach

Smooth front surface step

Estimating $\mathbf{t}$ (front surface) with keeping $\mathbf{l}$ fixed

Observation noises appear on back surfaces directly.

Camera rays — Reference rays

Repeat

Smooth back surface step

Estimating smooth back surface with fixed front shape

Fixed — Find more stable shape

Camera rays — Reference rays
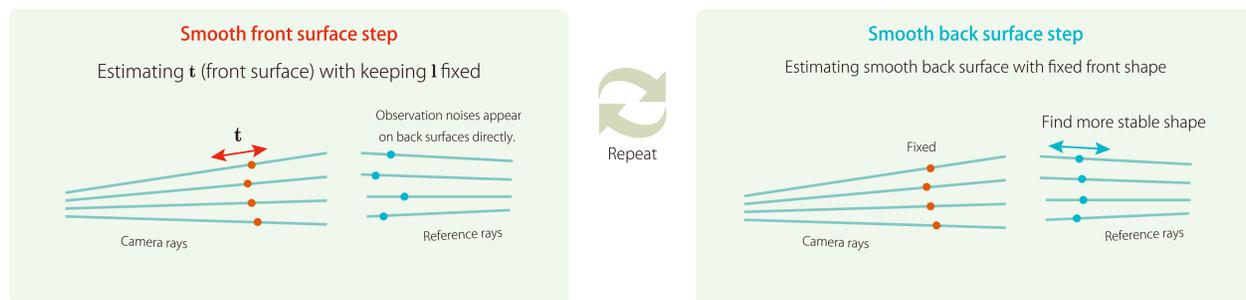
Numerical Evaluation using Synthetic Data

Synthetic data result

3-d view — Height map front back — Normal map front back

Ground truth

Estimate

0 mm   50 mm

Reconstruction error : **0.17 %**

Ground truth

Estimate

Reconstruction error : **0.26 %**

Convergence behavior

Front surface step — Back surface step

Cost value — Iteration number

Fastly converged at 2 iteration.
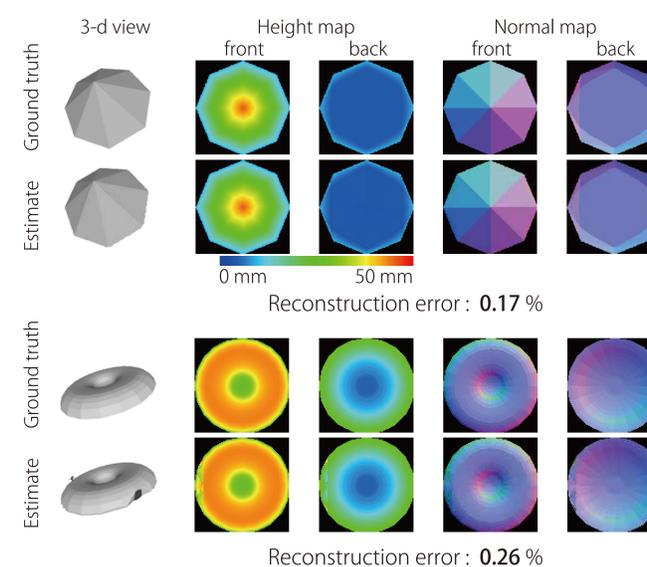
Stability against noise

Reconstruction error (%) — Noise level (%)
— Data terms only
— Alternating optimization