A Linear Extrinsic Calibration of Kaleidoscopic Imaging System from Single 3D Point

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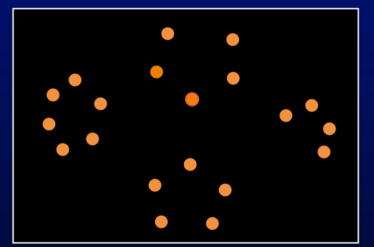
Code Available http://vision.kuee.kyoto-u.ac.jp/~nob/proj/kaleidoscope/

Summary

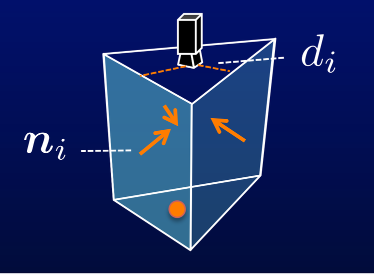
This paper proposes a new linear extrinsic calibration method of kaleidoscopic imaging system from a single 3D point of unknown geometry.

INPUT
Projections of single 3D point and its reflections



Proposed Method

OUTPUT
Mirror normals n_i and distances d_i.



Background

Aqua Vision

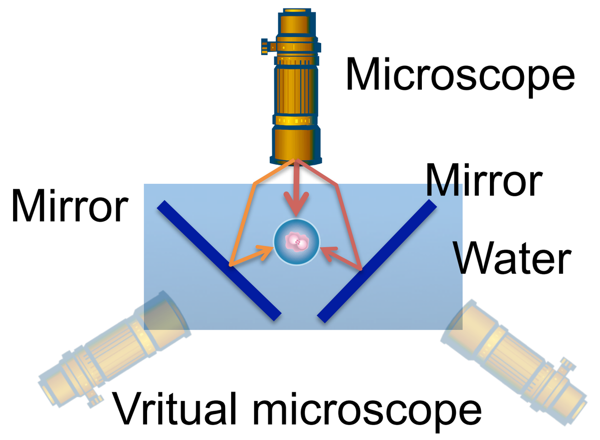
3D reconstruction and motion analysis of micro-scale objects in water.

Many applications

- Bioinformatics
- The marine products industry

Final goal : 3D Reconstruction of micro-scale objects

Our goal is 3D reconstruction of
- Object : micro-scale object (An embryo, a water flea, etc)
- Scale : mm, nm, μm
- Device : microscope + camera.



It is difficult to capture multi-view images with multiple microscopes due to physical constraints

In this work, we utilize a **virtual multi-view system with planar mirrors** (**KIS** : **K**aleidoscopic **I**maging **S**ystem)

Outline of this work

Purpose

This paper is aimed at proposing a new method of extrinsic calibration of KIS, i.e. estimation of mirror normals n_i and distances d_i.

Conventional method

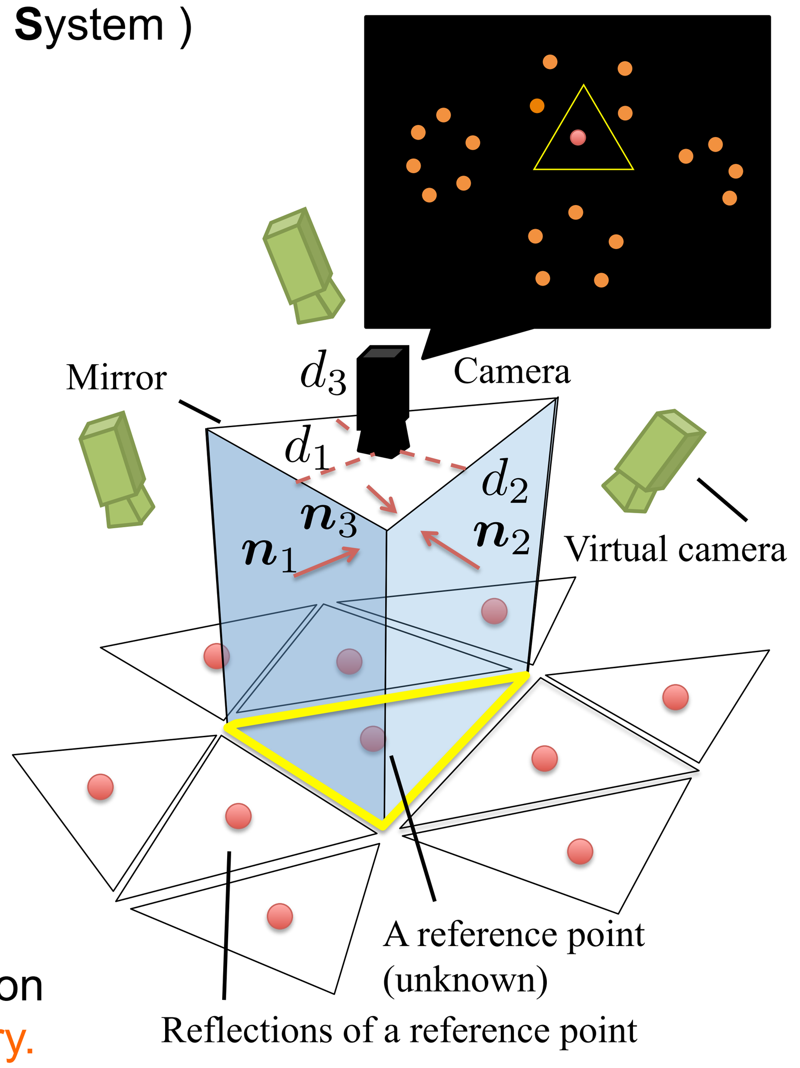
Zhang utilizes a reference object of known geometry such as a chessboard.

Problem

It is difficult to prepare such reference object of known geometry in micro-scale.

Contribution

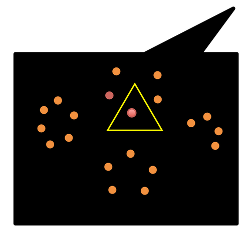
This paper proposes a new linear extrinsic calibration method from a single 3D point of unknown geometry.



KIS : Kaleidoscopic Imaging System

Proposed method

INPUT
Projections of single 3D point and its reflections

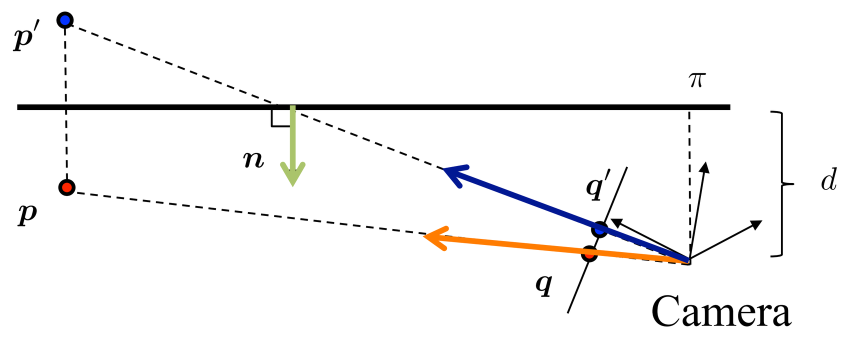


Estimation of mirror normals

Epipolar geometry with a planar mirror

A is intrinsic parameters

$$(n \times p)^\top p' = 0 \qquad A^{-1} q = (x, y, 1)^\top$$
$$\Leftrightarrow \quad q^\top A^\top [n]_\times^\top A^{-1} q' = 0$$
$$\Leftrightarrow \quad (y - y' \quad x' - x \quad xy' - x'y) n = 0$$



n has 2 DOF

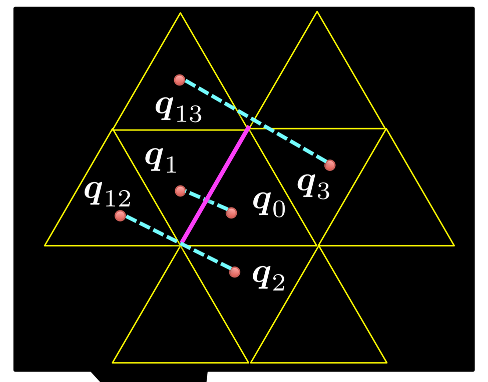
▶ n can be estimated by using more than or equal two reference points.

Key Idea: Utilizing 2D projections of multiple reflections to form a linear system on mirror parameters

p_0 → Reflection on π_1 → p_1 → Reflection on π_{12} → p_{12}

First reflection ▶ Linear

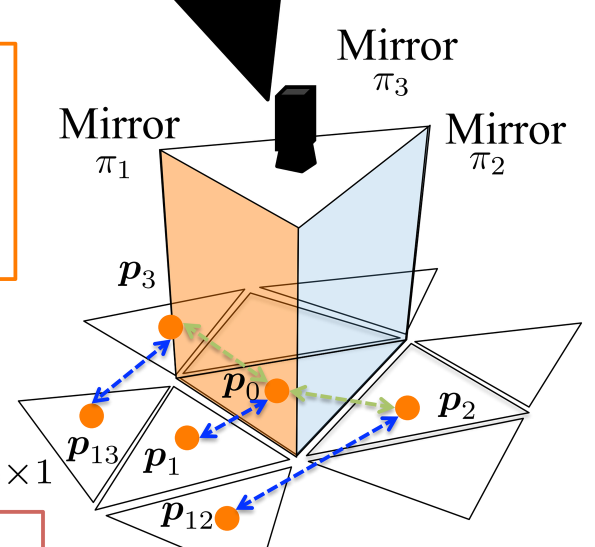
Second reflection ▶ Non-linear



$$p_{12} = S_{12} p_1$$
$$= S_{12} S_1 p_0 \quad = S_1 S_2 p_0 \quad = S_1 p_2$$

p_{12} is expressed as the first reflection of p_2 on π_1.
▶ A linear constraint on π_1 is hold as follow,

$$(y_2 - y_{12} \quad x_{12} - x_2 \quad x_2 y_{12} - x_{12} y_2) n_1 = 0$$



p_3, p_{13} provide similar constraints as well.

Implicitly requests to be consistent with the other mirrors.

$$\begin{bmatrix} y_0 - y_1 & x_1 - x_0 & x_0 y_1 - x_1 y_0 \\ y_2 - y_{12} & x_{12} - x_2 & x_2 y_{12} - x_{12} y_2 \\ y_3 - y_{13} & x_{13} - x_3 & x_3 y_{13} - x_{13} y_3 \end{bmatrix} n_1 = 0_{3\times1}$$

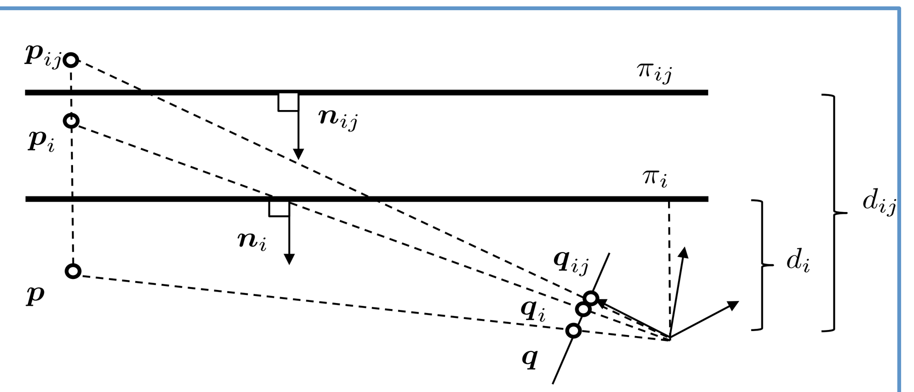
Linear

▶ n can be computed from single 3D point and its reflections.

Estimation of mirror distances

Colinearity constraint

[First reflection]
$$(A^{-1} q_i) \times p_i = x_i \times p_i = 0_{3\times1}$$
[Second reflections]
$$(A^{-1} q_{ij}) \times p_{ij} = x_{ij} \times p_{ij} = 0_{3\times1}$$



$$K [p_0 \quad d_1 \quad d_2 \quad d_3]^\top = 0_{30\times1}$$

Linear

Bundle Adjustment

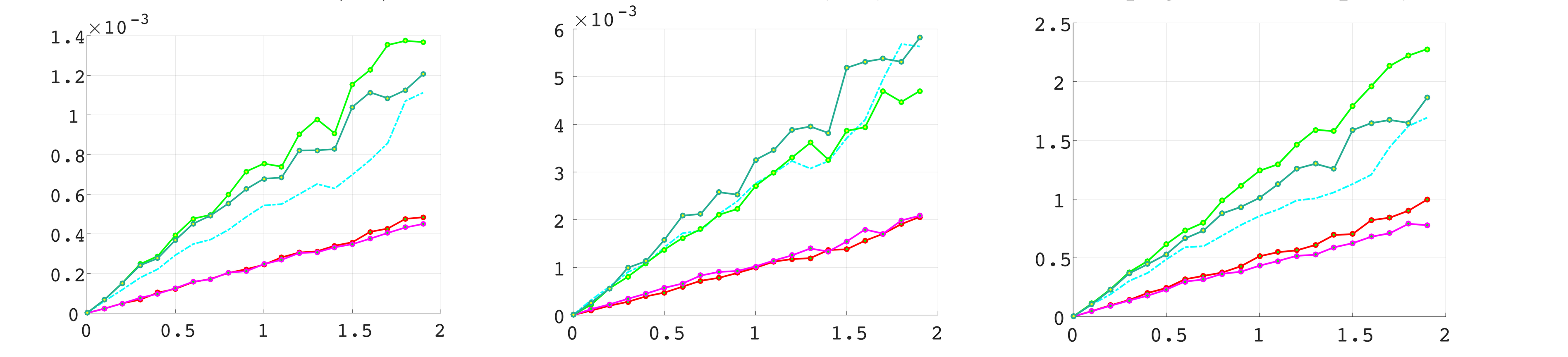
Minimizing $||E(\cdot)||^2$ nonlinearly over $n_1, n_2, n_3, d_1, d_2, d_3$.

$$E(n_1, n_2, n_3, d_1, d_2, d_3) = [q_0 - \hat{q}_0, e_1, e_2, e_3, e'_{1,2}, e'_{2,3}, e'_{3,2}, e'_{3,1}, e'_{1,3}]$$

OUTPUT
Mirror parameters
$n_i \quad d_i$

Experiments: Simulation

Evaluation of our proposed method under the observation noise.
[Baseline] Zhang's method with a chessboard.

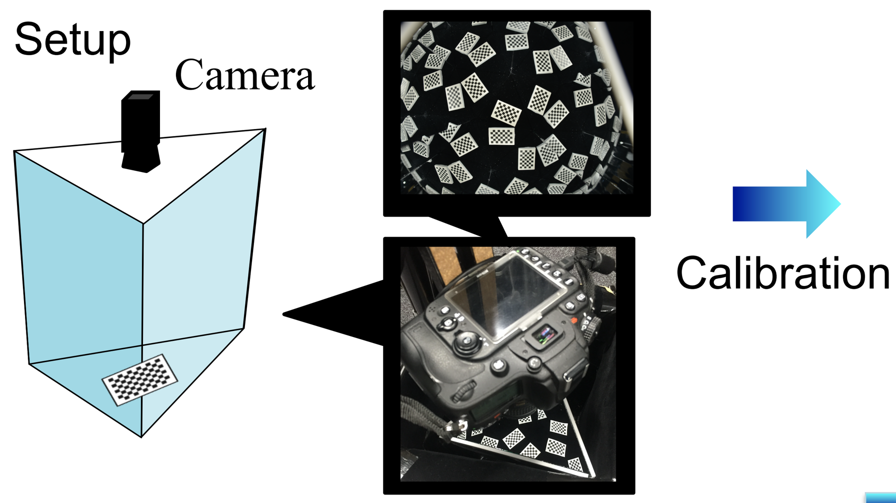


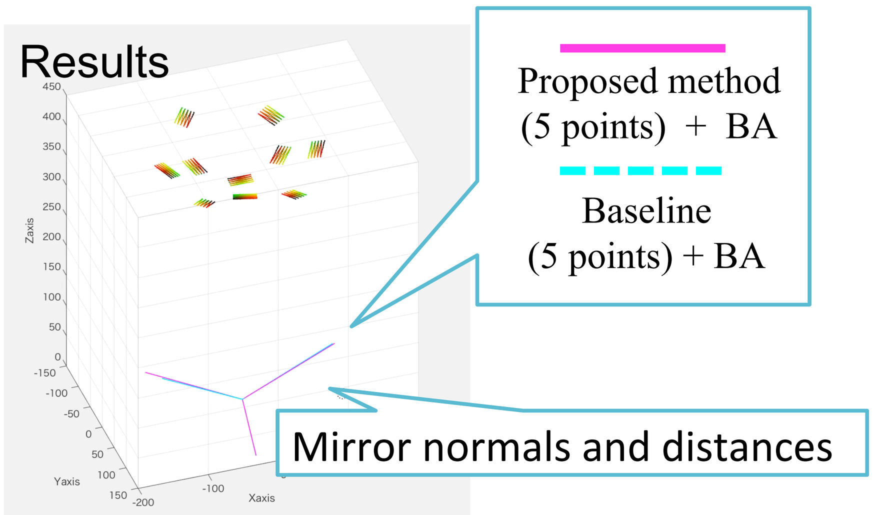
Vertical axis : Estimation error of each parameter. Horizontal axis : The standard deviation of Gaussian noise (pixel).

We can conclude that the proposed method
(1) outperforms baseline method even without final BA.
(2) can achieve comparable estimation linearly even with a single point.

Experiments: Real data

Evaluation of our proposed method with real data.
[Baseline] Zhang's method with a chessboard.





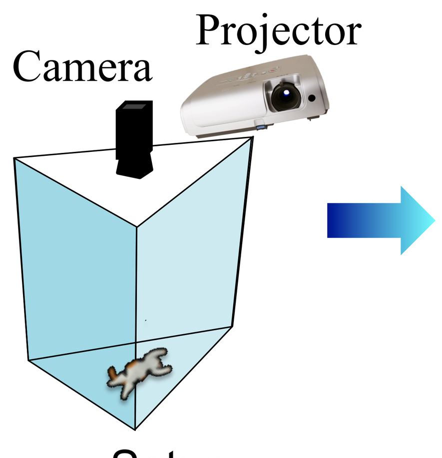
While the estimated mirror parameters look close to each other, the reprojection error of the proposed method is smaller than that of the baseline method.

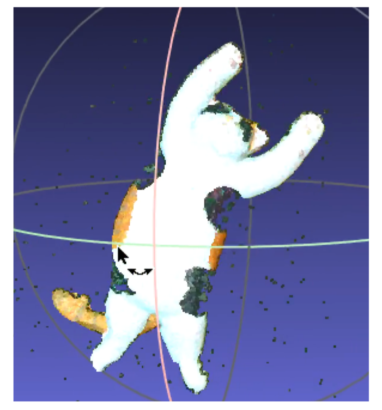
Method	Reprojection Error (pixel)
Proposed + BA	3.37
Baseline	4.75

(Image size: 6000x4000 pixel)

Application: 3D reconstruction

Right figure shows a 3D rendering of the estimated 3D shape using the mirror parameters estimated by the proposed method. These results show the proposed method provides a sufficiently accurate calibration for 3D shape reconstruction.





Result