Structured light systems

Tutorial 1: 9:00 to 12:00

Monday May 16 2011

Hiroshi Kawasaki & Ryusuke Sagawa

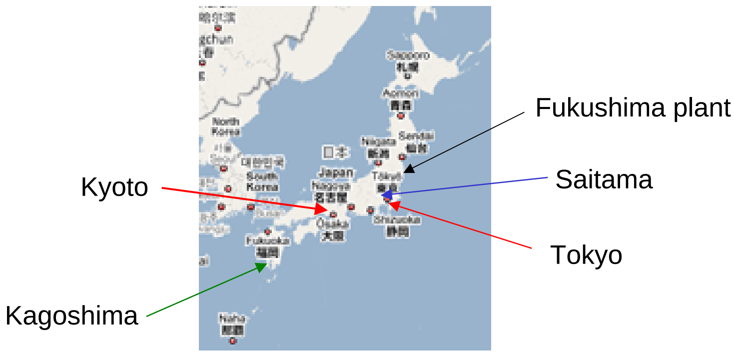
Today

Structured light systems

- Part I (Kawasaki@Kagoshima Univ.)
  - Calibration of Structured light systems
- Part II (Sagawa@AIST Japan)
  - Structured light systems for moving object

Self-introduction

- Name: Hiroshi Kawasaki
- From: Kagoshima National University, Japan
- Research interest: 3D scanning, photo-realistic CG



Overview

- Introduction
  – shape acquisition system
- Basic problems of Structured light system
  – Calibration
  – Correspondences
- Online calibration for light sectioning method
- Auto calibration for projector camera system

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Shape acquisition

- Passive method
  - ☺ Only camera
  - ☹ Unstable
  - ☹ Sparse
- Active method
  - ☺ Dense
  - ☺ Stable
  - ☹ Lighting and mechanical devices

Shape acquisition

- Passive method
  - ☺ Only camera
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  - ☹ Sparse
- Active method
  - ☺ Dense
  - ☺ Stable
  - ☹ Lighting and mechanical devices

Active scanner

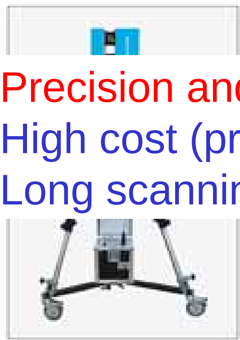
1. Time-of-flight based technique
2. Stereo based technique

Active scanner

1. Time-of-flight based technique
2. Stereo based technique


Active scanner

1. Time-of-flight based technique
2. Stereo based technique




☺ Precision and stability
☹ High cost (precision devices)
☹ Long scanning time

Active scanner

1. Time-of-flight based technique
2. Stereo based technique

Possibility of

☺ cost efficiency

☺ precision

☺ short scanning time

by computer vision techniques

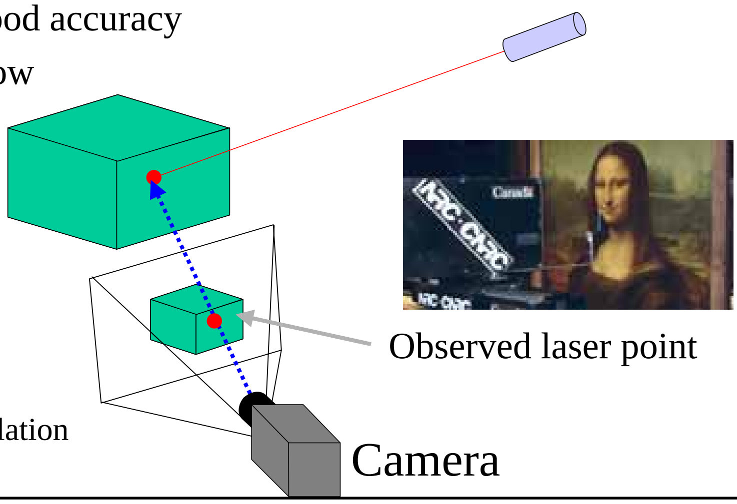
Stereo based active scan

- Camera + point laser projector

☺ Easy to make

☺ Good accuracy

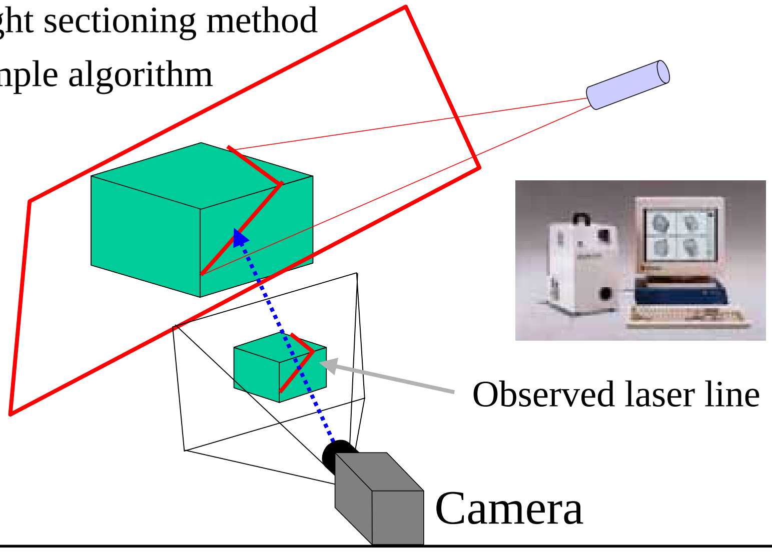
☹ Slow



•Triangulation

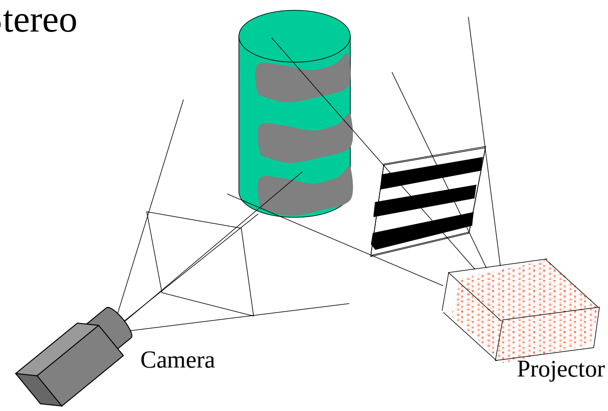
Stereo based active scan

- Camera + line laser projector
  - Light sectioning method
  - Simple algorithm



Stereo based active scan

- Camera + video projector
  - Projector camera system
  - Fast
  - Stereo



Stereo based active scan

- Camera + point laser projector
  - No structure on light
- Camera + line laser projector
  - Light sectioning method
  - Simple algorithm
- Camera + video projector
  - Projector camera system
  - Fast
  - Stereo

Stereo based active scan

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Basic problems of Structured light system

- Calibration of structured light
- Correspondences

Basic problems of Structured light system

- Calibration of structured light → Part I
- Correspondences → Part II

Calibration of structured light

- Calibration of light source (Intrinsic)
- Calibration between light source and camera (Extrinsic)

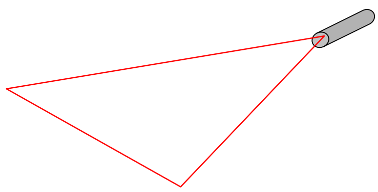
Calibration of structured light

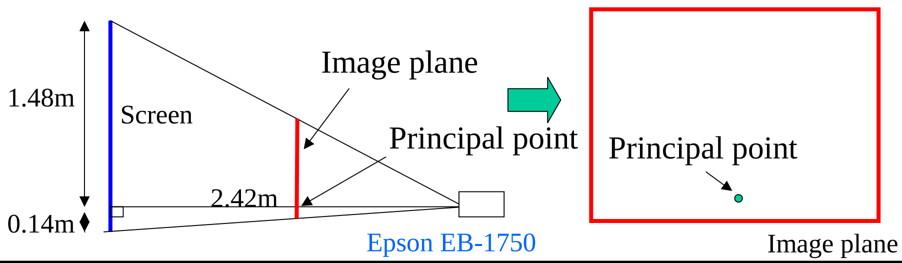
- Calibration of light source (Intrinsic)
- Calibration between light source and camera (Extrinsic)

Question
- Model of light source?
- Algorithm?
  - Projector cannot capture image
  - Calibration box or plane?

Model of light source

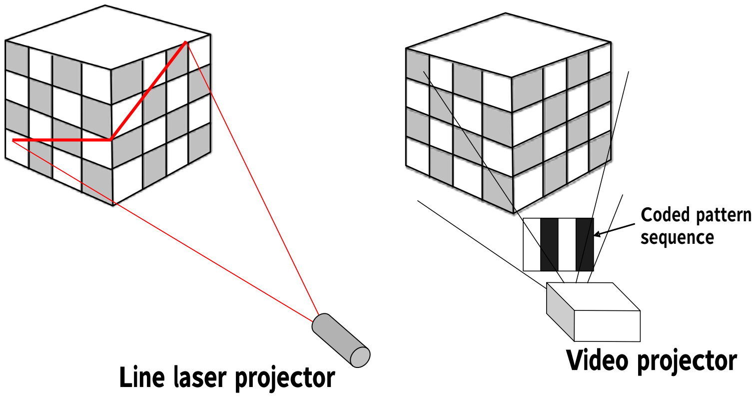
- Line laser projector
  - Plane in 3D
- Video projector
  - Pinhole camera model
  - Principal point is placed bottom





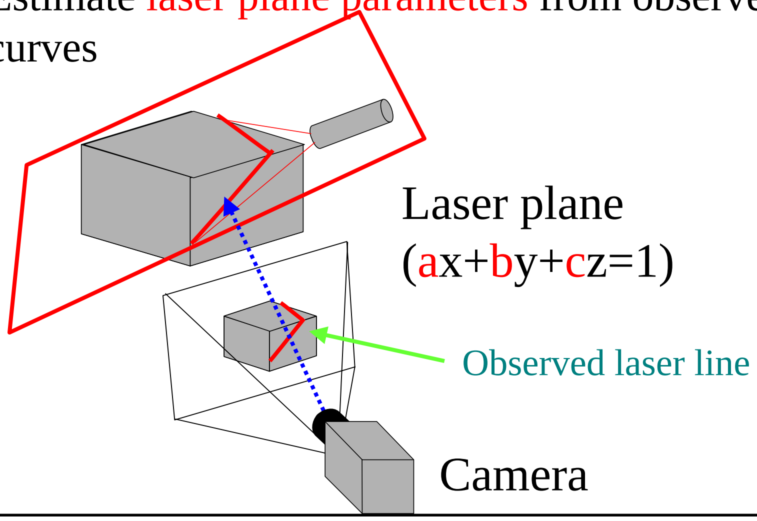
Basic approach

- Using calibration object



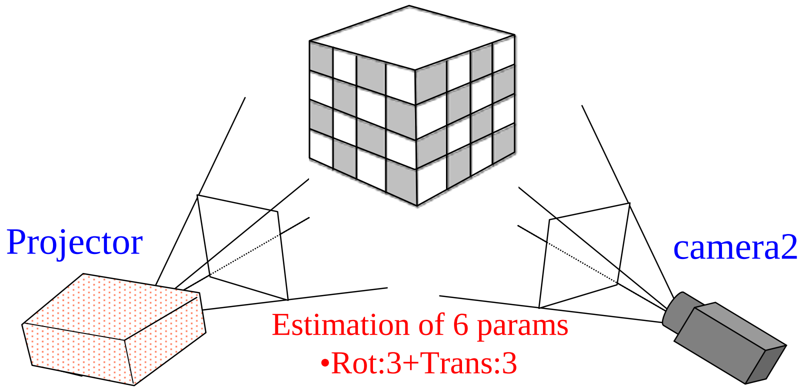
Calibration of laser plane

- Light sectioning method (triangulation)
- Estimate laser plane parameters from observed curves

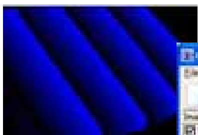


Calibration of projector camera system

- Stereo method
- Estimate camera parameter



Example of calibration [projector calibration toolbox]



→Complicated and unstable process

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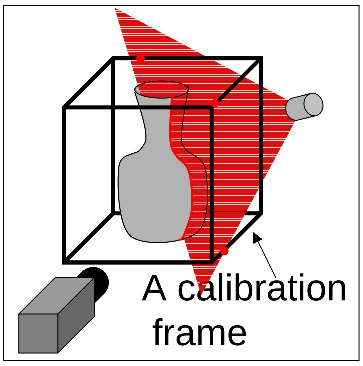
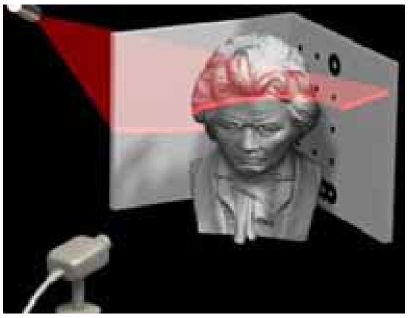
Online calibration

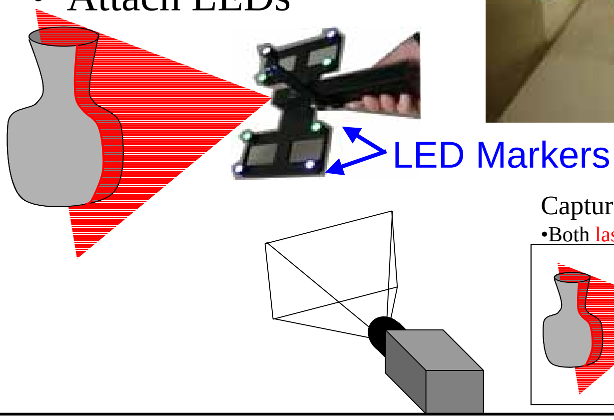
- Calibration object in a scene
  - Frame [Chu et.al. 3DIM01]
  - Planes [David 2006 http://www.rob.cs.tu-bs.de/news/david]



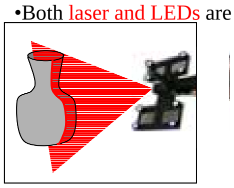


Online calibration

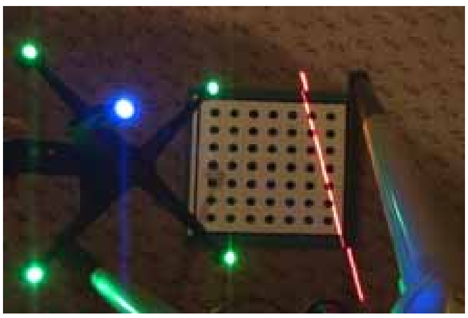
- Calibration object on the projector
  [Furukawa and Kawasaki 3DIM03]
  - Attach LEDs

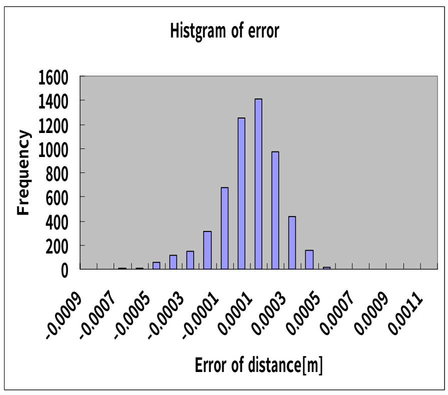


Captured image
•Both laser and LEDs are in a image



Capturing sequence and precision



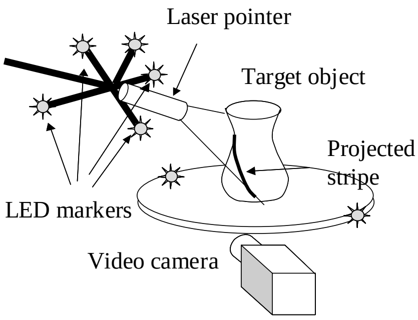


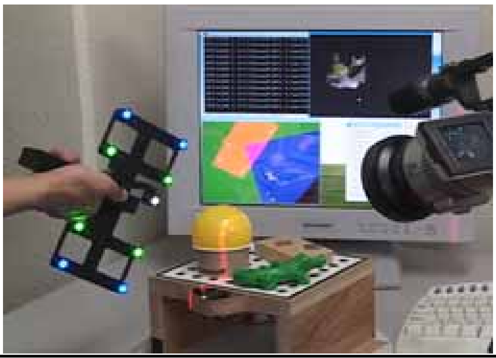
σ =0.00017(m)

Extension

Entire shape acquisition with rotation table

[Furukawa and Kawasaki 3DPVT04]

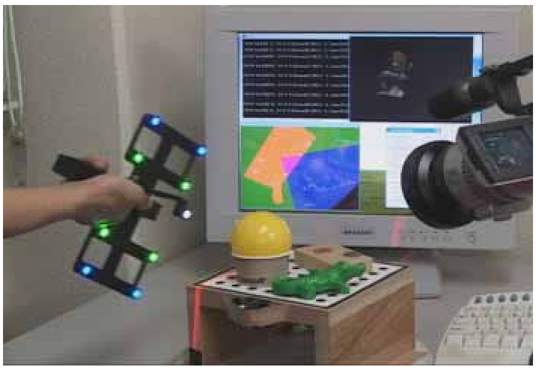




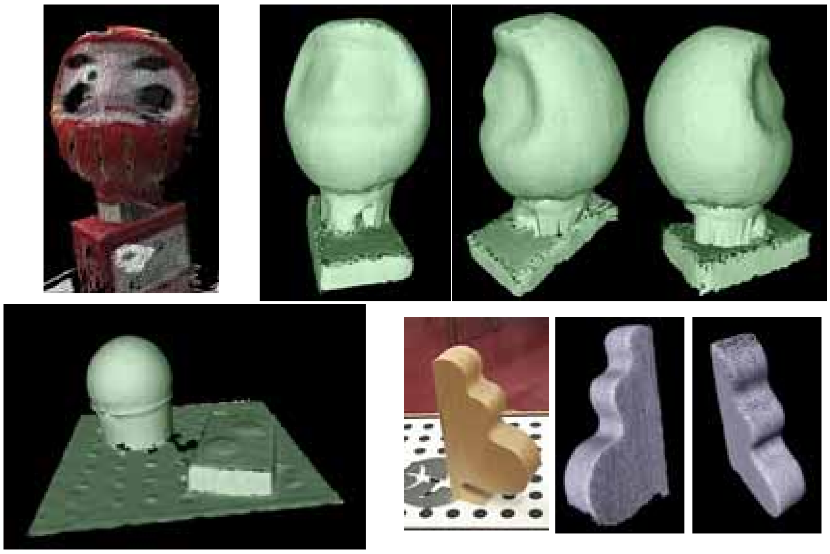
Extension

Entire shape acquisition with rotation table

[Furukawa and Kawasaki 3DPVT04]



Rotation table results

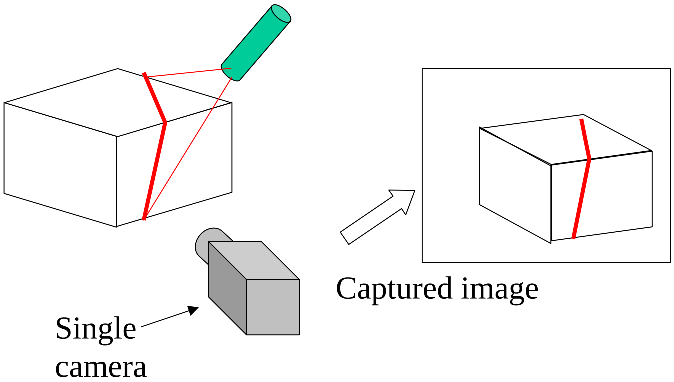


Previous method

- Pre-calibration
  - △ Hard calibration (fixed system)
  - △ Use motor and precision devices
- Online-calibration
  - △ Frames or planes are required [david'06]
  - △ LED markers required [kawasaki'03]

Can we eliminate all additional devices ?

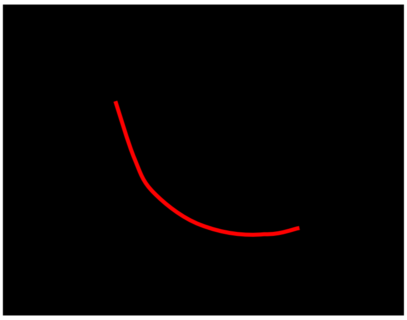
Self-calibration of laser plane without any additional devices



System configuration

Problem 1

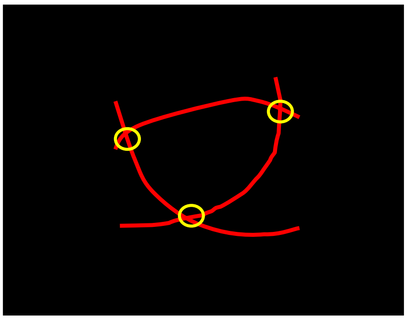
- Can we reconstruct shape from the following image?



NO!

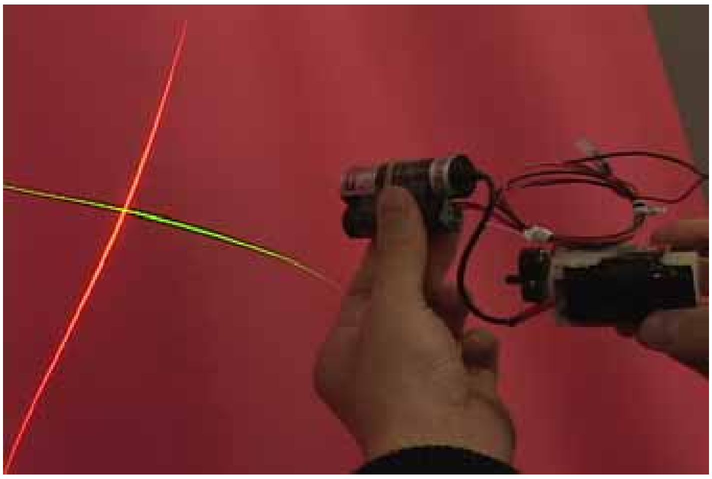
Problem 2

- How about this?

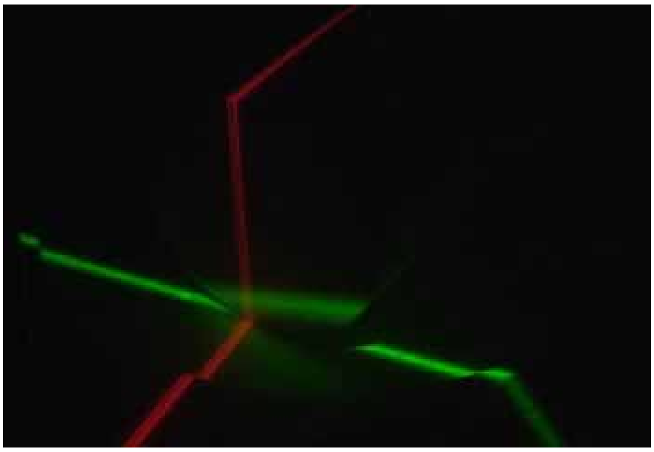


Maybe?

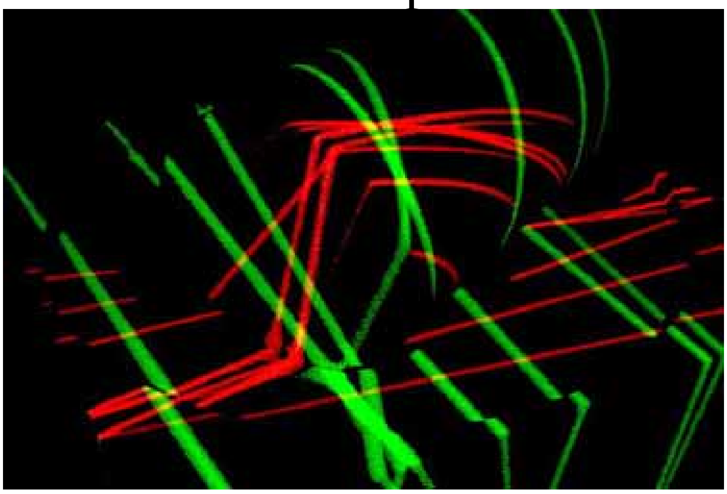
Example of line laser projector (cross pattern by two lasers)



Can you imagine the shape?

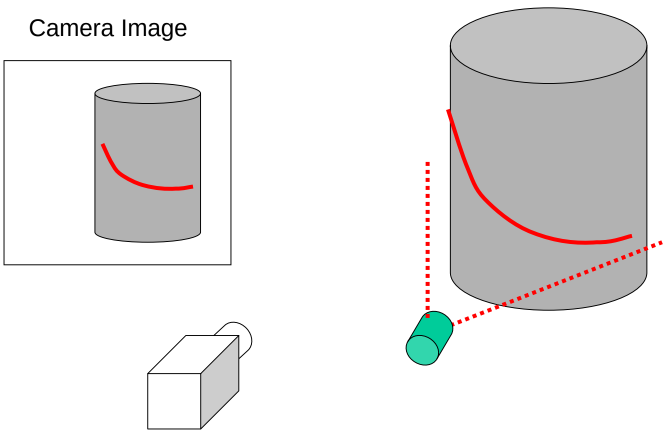


Is it possible to reconstruct the 3D shape?



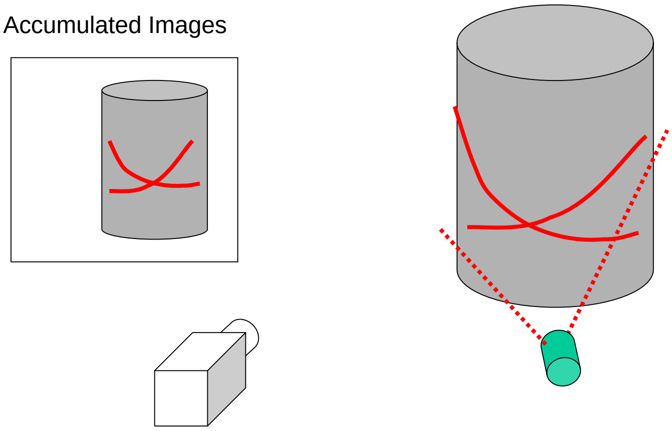
True shape

Problem definition



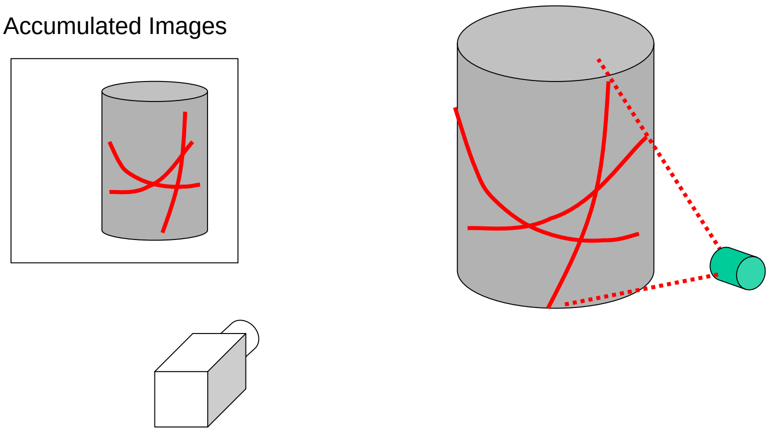
Problem definition

Accumulated Images



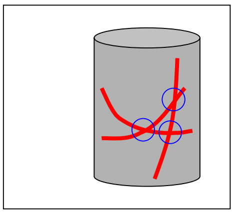
Problem definition

Accumulated Images

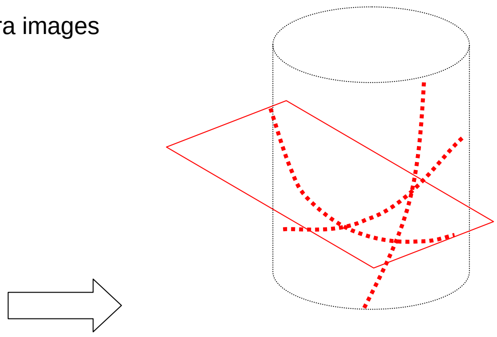


Self-calibration of planes

Temporally accumulated camera images



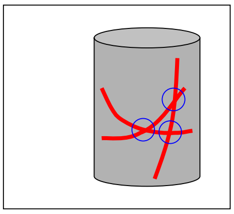
Intersections



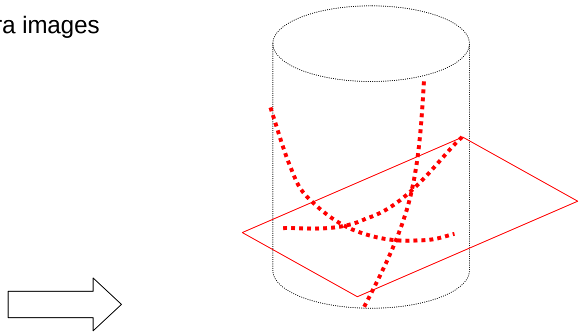
Estimation of laser planes

Self-calibration of planes

Temporally accumulated camera images



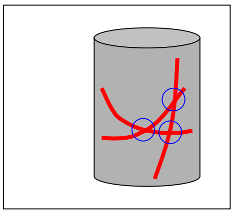
Intersections



Estimation of laser planes

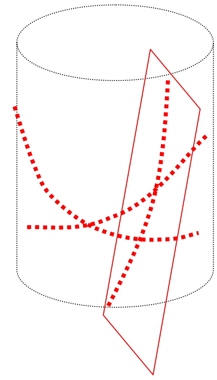
Self-calibration of planes

Temporally accumulated camera images



Intersections

Estimation of laser planes



Outline of Self-calibration and 3D reconstruction

Detect laser lines from video

↓

Constraint equations from intersections

↓

3D shape reconstruction by solving the simultaneous equations

Outline of Self-calibration and 3D reconstruction

Detect laser lines from video

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Constraint equations from intersections

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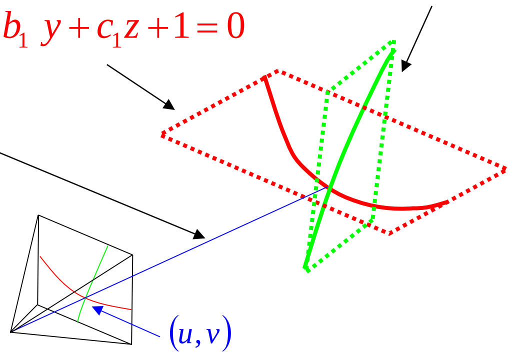
3D shape reconstruction by solving the simultaneous equations

Constraints from intersections
(coplanar constraint)

$$a_2\,x + b_2\,y + c_2 z + 1 = 0$$

$$a_1\,x + b_1\,y + c_1 z + 1 = 0$$

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = -z \begin{pmatrix} \alpha u \\ \alpha v \\ -1 \end{pmatrix}$$



Constraints from intersections

(coplanar constraint)

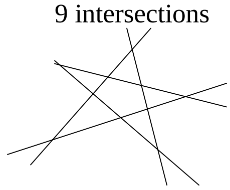
$$-a_1^* u - b_1^* v + c_1 + t = 0$$

$$- \quad -a_2^* u - b_2^* v + c_2 + t = 0$$

$$-\boxed{a_1^*}u + \boxed{a_2^*}u - \boxed{b_1^*}v + \boxed{b_2^*}v + \boxed{c_1 - c_2} = 0$$

3*2 Unknowns

5 plains
9 intersections



Number of intersections: M

Number of equations: M

Number of planes: N

Number of unknown params: $3N$

Usually, Intersection number M >> plane number N(unknown)

Matrix form

$$\begin{pmatrix} u_1 & v_1 & 1 & -u_2 & v_2 & -1 & 0 & 0 & 0 & \vdots \\ u_2 & v_2 & 1 & 0 & 0 & 0 & u_2 & v_2 & -1 & \vdots \\ \cdots & & & & & & & & & \end{pmatrix} \begin{pmatrix} a_1 \\ b_1 \\ c_1 \\ a_2 \\ b_2 \\ c_2 \\ a_3 \\ b_3 \\ c_3 \\ \vdots \end{pmatrix} = \mathbf{0}$$

$$\mathbf{Lx} = \mathbf{0}$$

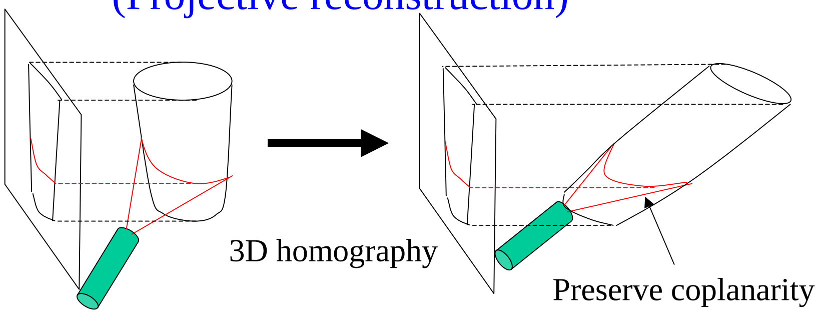
$\mathbf{L}$: $3N$*M matrix(Intersection num M, Plane num N)

Reconstruction from coplanarity

$$\mathbf{L}\mathbf{x} = \mathbf{0}$$

Solution $\mathbf{x}$ has 4 degrees of freedom

(Projective reconstruction)



The 4 DOFs → Found in other research areas.

e.g. ● Polyhedra analyses in single view reconstruction

● Generalized Bas-Relief Ambiguity in photometric stereo

Shape from coplanarity

Sort eigen values after SVD of $\mathbf{L}$

$$\mathbf{U}\begin{pmatrix} \mathbf{\Sigma}_1 & 0 \\ 0 & \mathbf{\Sigma}_2 \\ 0 & 0 \end{pmatrix}\mathbf{V}^{\perp}\,\mathbf{x} = \mathbf{0}$$

$\underbrace{}_{3n-4}$ $\underbrace{}_{\text{4 columns}}$

$\mathbf{\Sigma}_1$ $\mathbf{\Sigma}_2$ Square diagonal matrix

$\mathbf{\Sigma}_2 \approx \mathbf{0}$ (if no errors)

Outline of Self-calibration and 3D reconstruction

Detect laser lines from video

↓

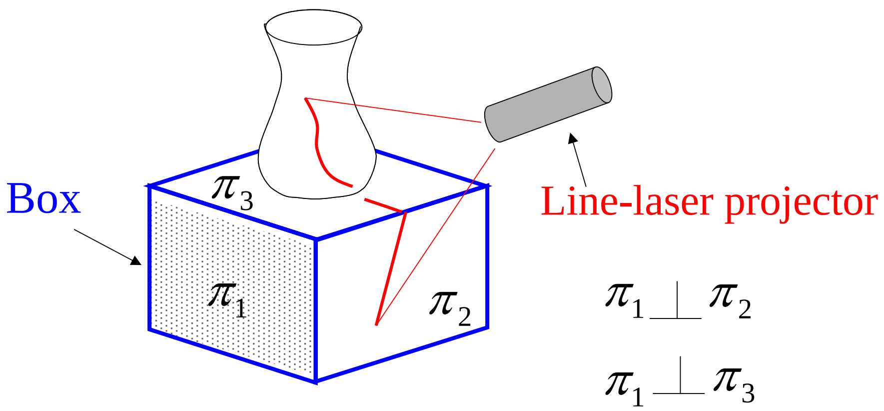
Projective reconstruction from intersections

↓ Eliminate 4dofs

Euclid upgrade using metric constraints

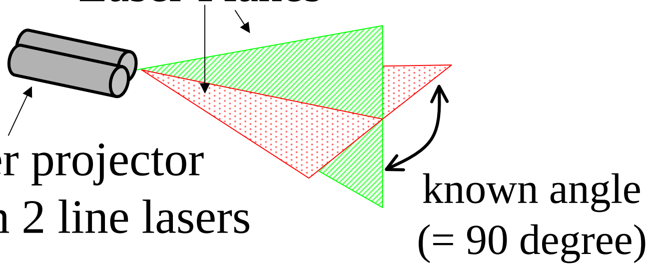
Upgrade to Euclidean solution-1

- Metric constraints from the captured scene



Upgrade to Euclidean solution-2

- Metric constraints from laser planes

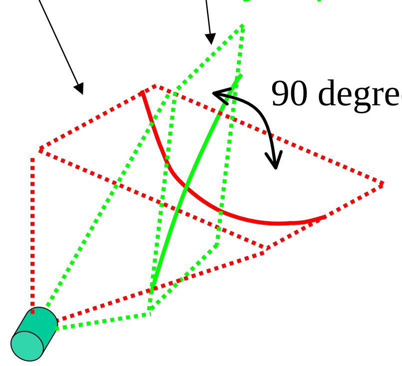


Formulation of metric constraints

Constraints from orthogonality

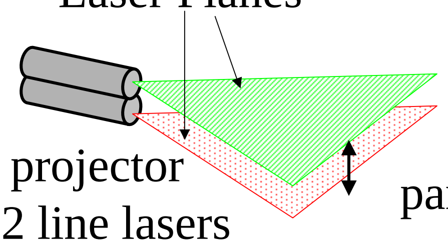
$$ax + by + cz + 1 = 0 \qquad dx + ey + fz + 1 = 0$$

$$ad + be + cf = 0$$



Upgrade to Euclidean solution-3

- Another metric constraints from laser planes



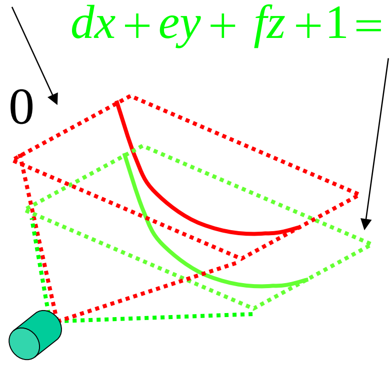
Formulation of metric constraints

Constraints of parallelism

$$ax + by + cz + 1 = 0$$

$$dx + ey + fz + 1 = 0$$

$$(a, b, c) \otimes (d, e, f) = 0$$



Outline of Self-calibration and 3D reconstruction

Detect laser lines from video

↓

Projective reconstruction from intersections

↓ Eliminate 4dofs

Euclid upgrade using metric constraints

Sparse data sets

Outline of Self-calibration and 3D reconstruction

Detect laser lines from video

↓

Projective reconstruction from intersections

↓

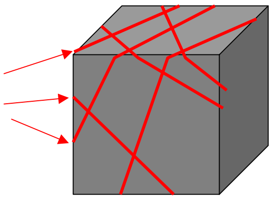
Euclid upgrade using metric constraints

↓

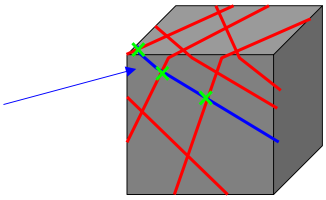
Dense shape reconstruction

Dense Reconstruction

Small number of laser planes are reconstructed.

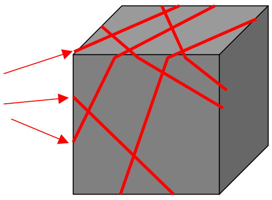


Another laser plane estimated by plane fitting.

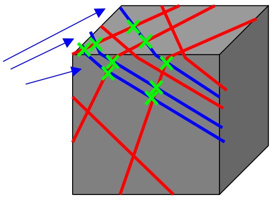


Dense Reconstruction

Small number of laser planes are reconstructed.



Iterate same process for all laser planes.



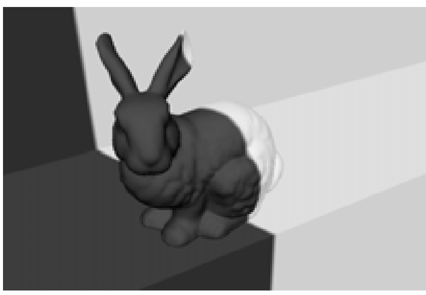
Experiments

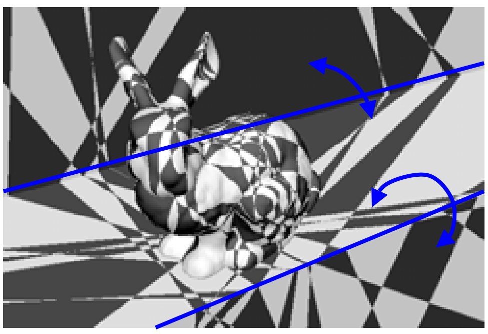
- Simulation data
- Real data

Simulation data 1

- Randomly project single line laser

20 lasers and 200 intersections

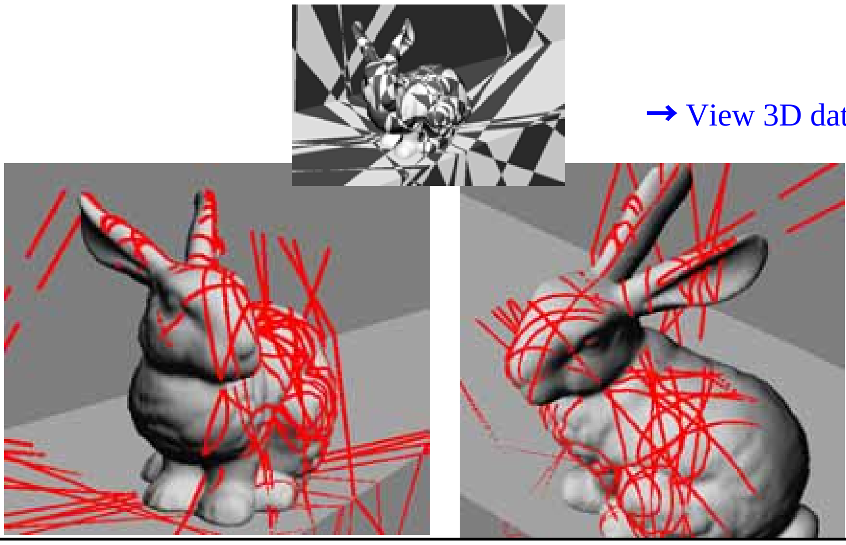




Require 3 metric constraints for Euclidean solution up to scale

Simulation data 1 – result

→ View 3D data



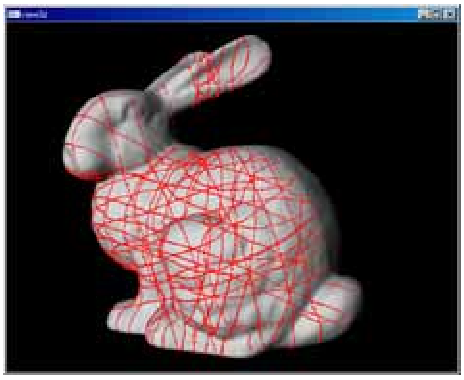
Simulation data

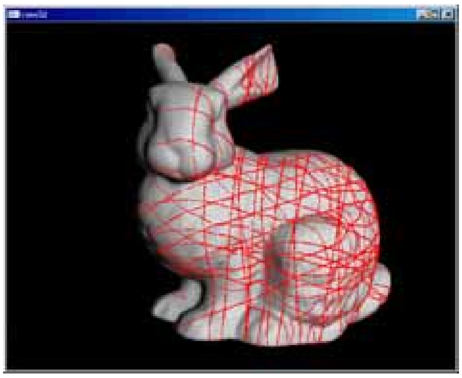
- Randomly project cross line laser

Image number:20
Plane number:40
Intersection number:613
Metric constraints:20

Simulation data – result

→ View 3D data

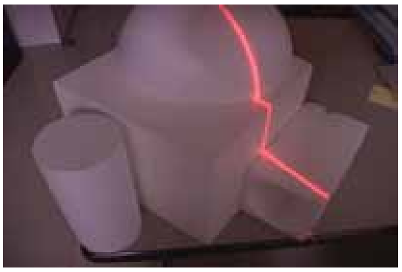


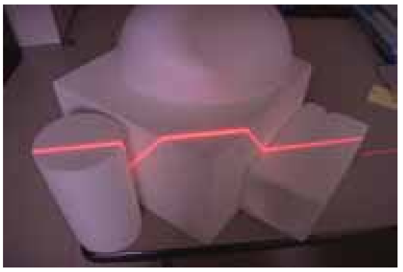


Experiment -- Real data 1

- Single line laser

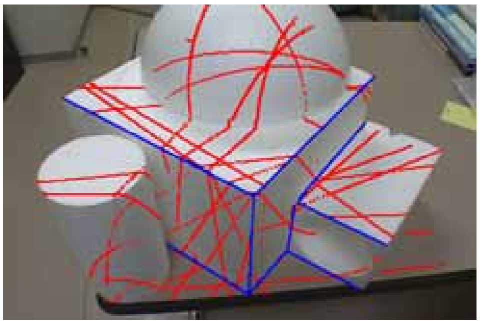
Real data 1



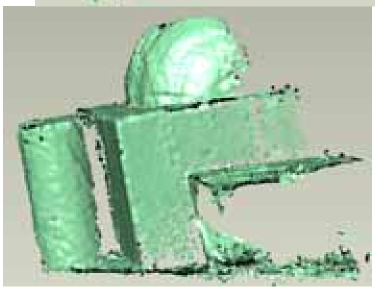


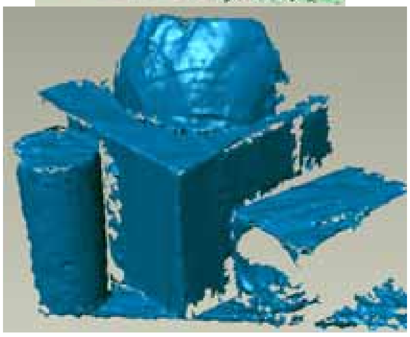
Experiment -- Real data 1

- Red --- detected laser lines
- Blue --- constraints from scene



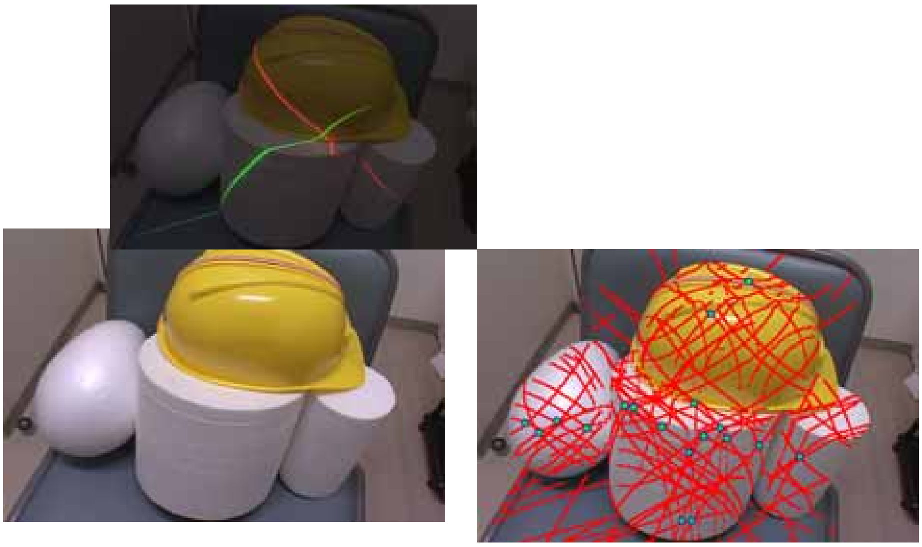
Real data 1

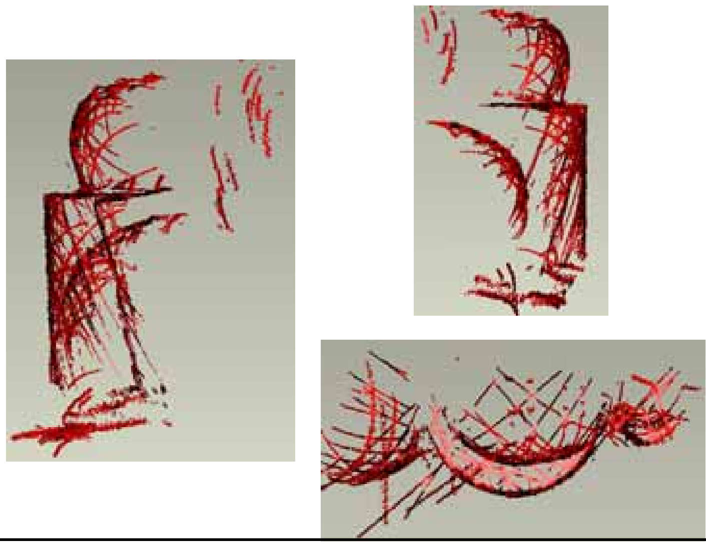


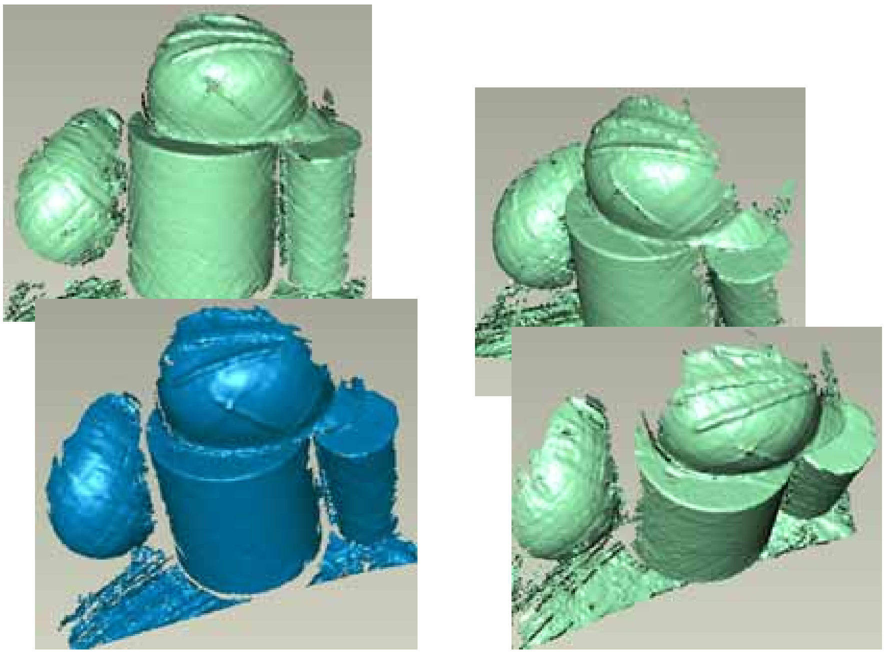


Experiment -- Real data 2

- Cross line laser





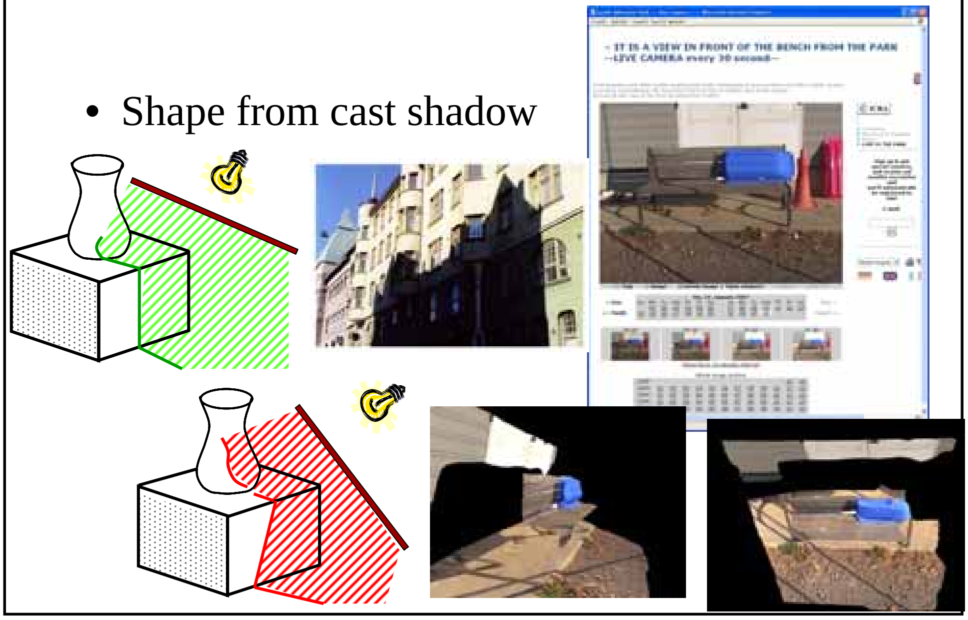


Proposed method

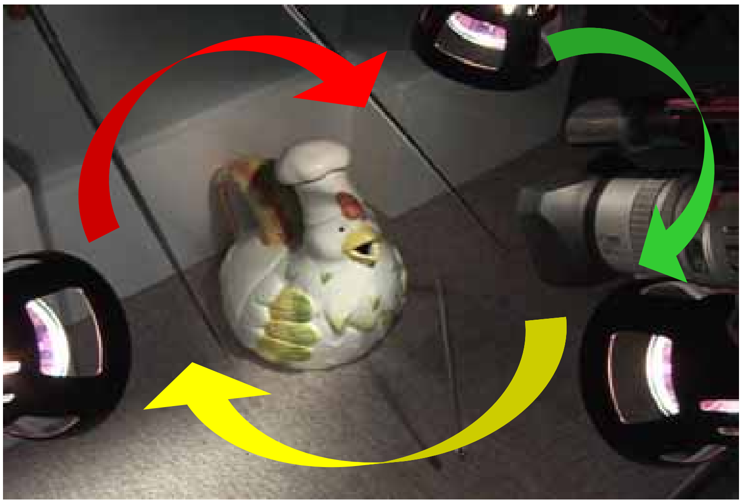
- Only require a line laser and a single camera
  - General solution for "Shape from Coplanarity"
  - Any other applications?

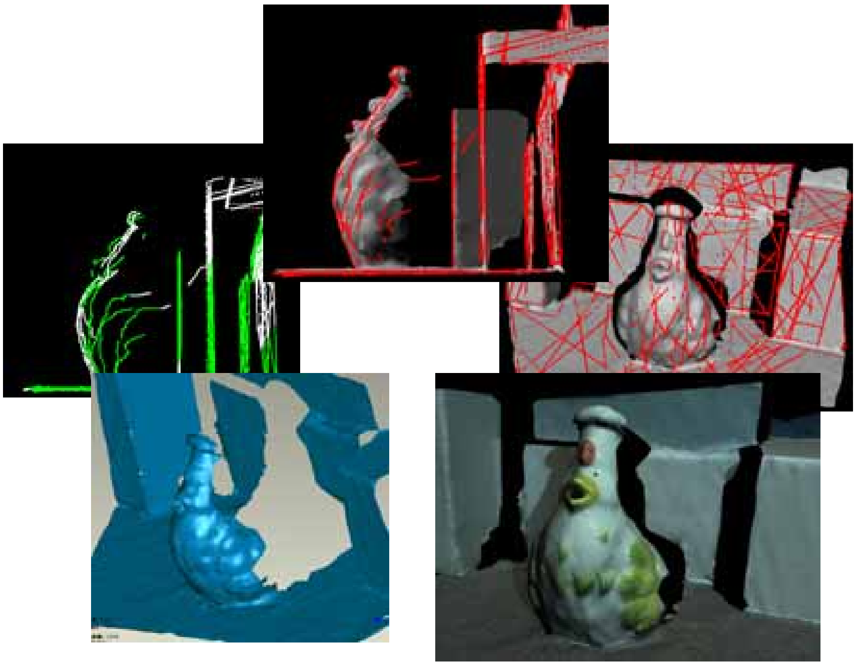
Other applications

- Shape from cast shadow



Shape from cast shadow





Other applications

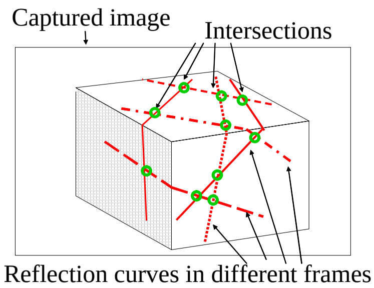
- Single view reconstruction

Other applications

- Single view reconstruction

Summary of self-calibration of light sectioning method

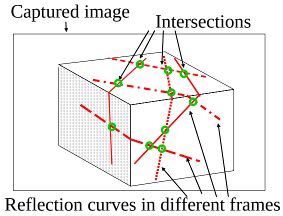
- Temporal accumulation
  - ○ Self-calibration of 3D planes from observed curves
  - △ Takes long times
  - △ Need manual steps



→ Can we make enough intersections at one time?

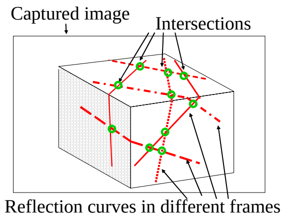
Self-calibration for 3D scanner

- Solution
  - A. Temporal accumulation

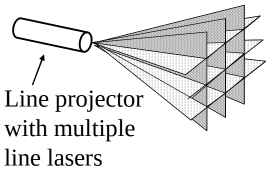


Self-calibration for 3D scanner

- Another solution
  - A. Temporal accumulation

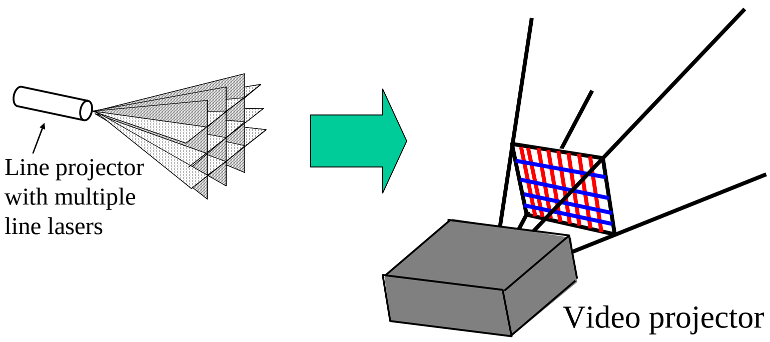


  - B. Many laser projectors



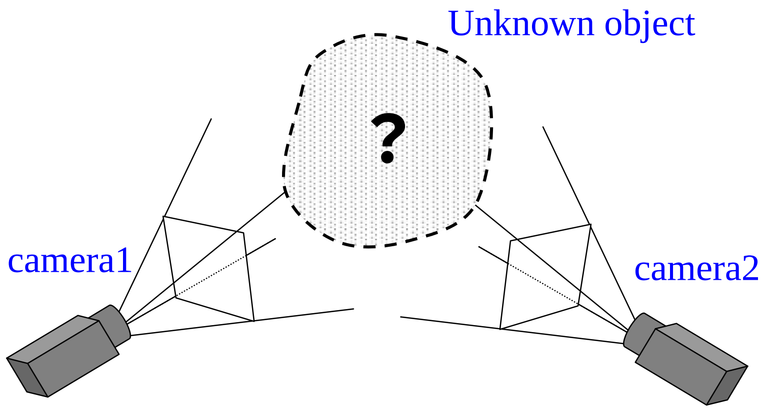
Self-calibration for Coded Structured light

- Use many laser projectors

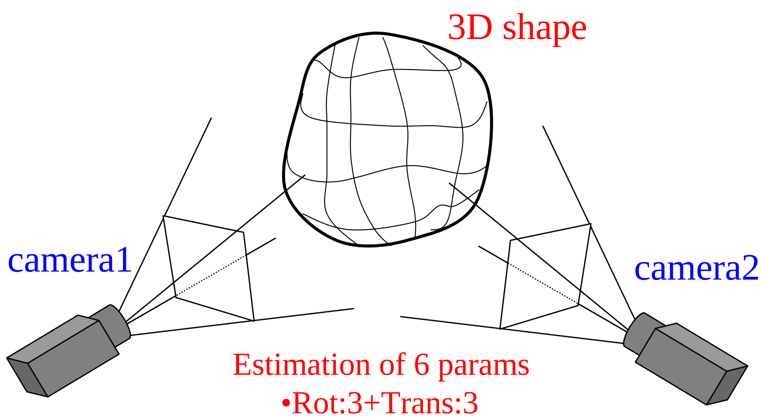


Equivalent: As many lasers as pixel resolution

Self calibration

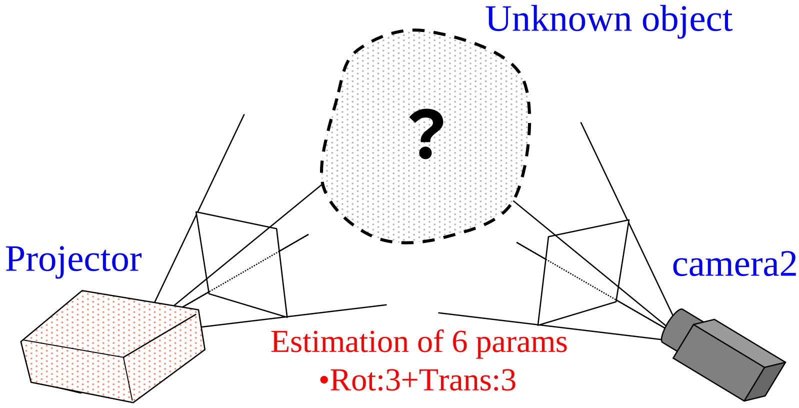


Self calibration

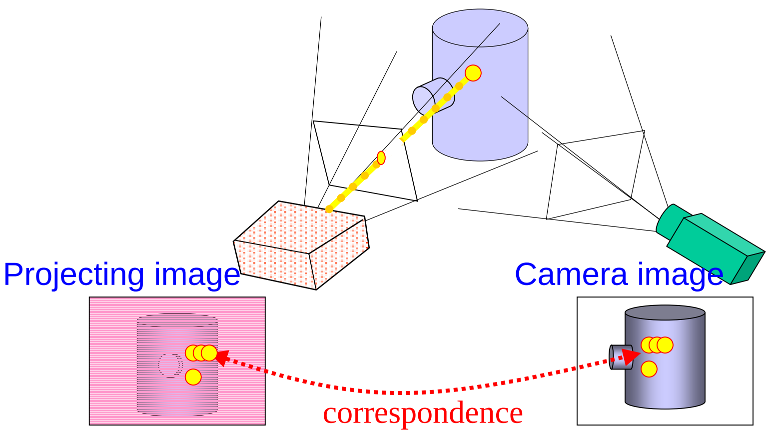


Self calibration of projector camera system

Replace camera to projector

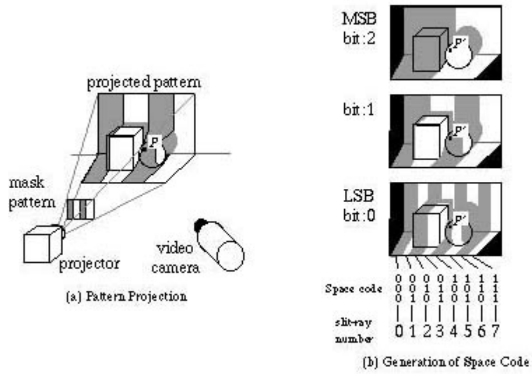


Self calibration of pro-cams



Actual implementation

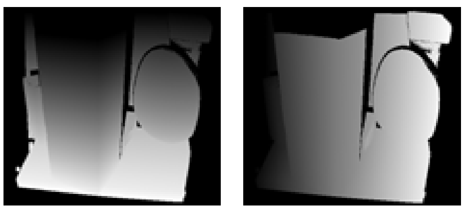
- Gray code method['86 Inokuchi]



Structured light example

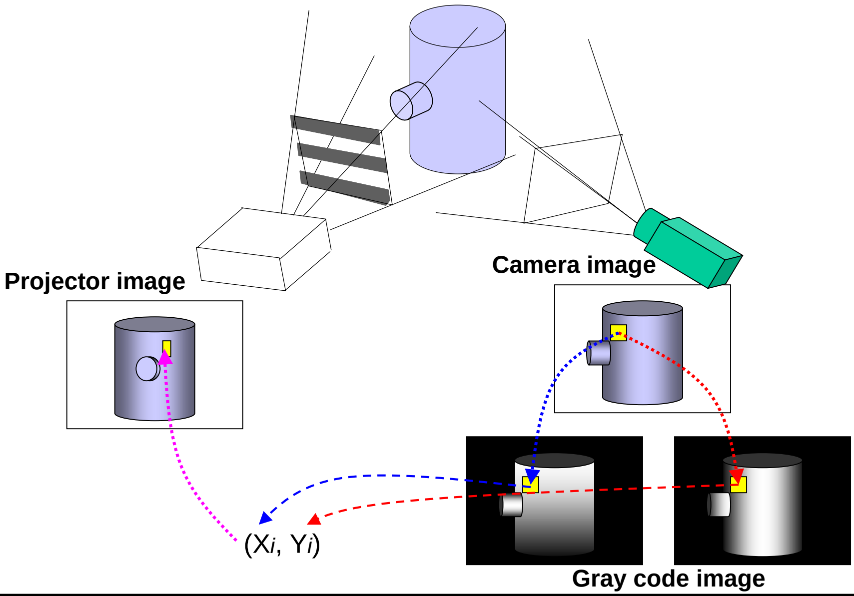
- Projecting patterns → two directions

- Acquired coded images



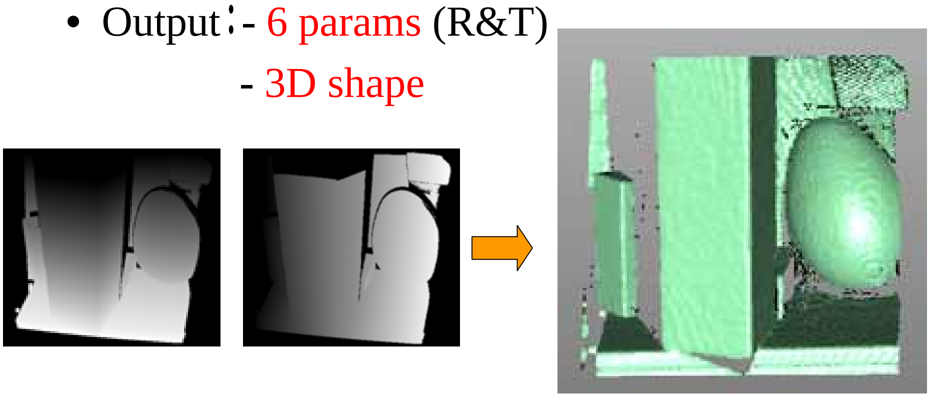
vertical horizontal

Correspondences from decoded images



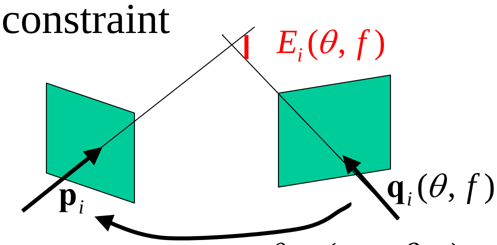
Self-calibration for Coded Structured light
- problem definition -

- Input：- camera params (focal length, etc.)
  - two index images
- Output：- 6 params (R&T)
  - 3D shape



Non-linear optimization

- Epipolar constraint



Extrinsic parameter $\theta := (\mathbf{t}, \alpha, \beta, \gamma)$

$\mathbf{t}$ **:Translation** α, β, γ **:Rotation(Euler angles)**

$$E_i(\theta, f) := \left|\mathbf{t} \cdot N(\mathbf{p}_i \times \mathbf{q}_i(\alpha, \beta, \gamma, f))\right|$$

Using $F(\theta, f) := \sum_i \{E_i(\theta, f)\}^2$ as a minimizing function.

→ Re-projection error in real algo.

Solving epipolar constraints

- Gauss-Newton method

$$\mathbf{x} := (\theta \ \ f),$$

$$\mathbf{y}(\mathbf{x}) := (\tilde{E}_1(\mathbf{x}) \ \ \tilde{E}_2(\mathbf{x}), \cdots, \ \tilde{E}_k(\mathbf{x}))^t$$

minimize $\sum_i \left\{\tilde{E}_i(\theta, f)\right\}^2 = \left\|\mathbf{y}(\mathbf{x})\right\|^2 = \mathbf{y}(\mathbf{x})^t \ \mathbf{y}(\mathbf{x})$

$$\mathbf{x}_{k+1} = \mathbf{x}_k + \Delta\mathbf{x}_k,$$

$$\Delta\mathbf{x}_k = -\left\{\left(\frac{\partial\, \mathbf{y}(\mathbf{x}_k)}{\partial \mathbf{x}}\right)^t \left(\frac{\partial\, \mathbf{y}(\mathbf{x}_k)}{\partial \mathbf{x}}\right)\right\}^{-1} \left(\frac{\partial\, \mathbf{y}(\mathbf{x}_k)}{\partial \mathbf{x}}\right)^t \mathbf{y}(\mathbf{x}_k)$$

Demo

Extended techniques

- Wide range reconstruction by pivot scanning
- Simultaneous reconstruction method

Extended techniques

- Wide range reconstruction by pivot scanning
- Simultaneous reconstruction method

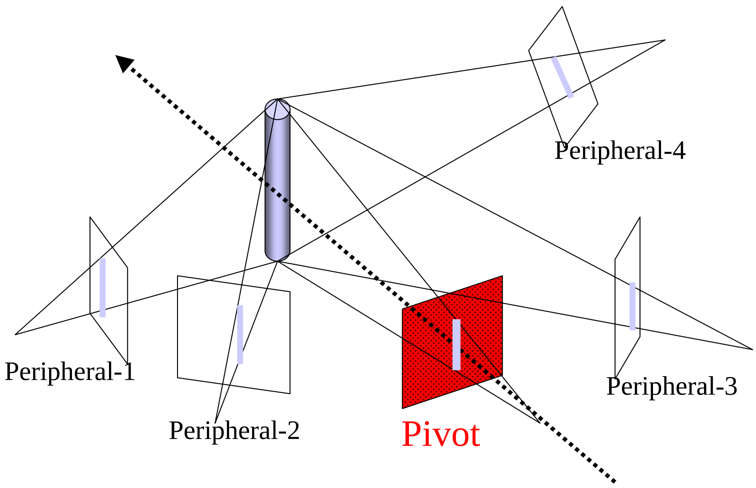
Wide view scanning

Pivot scanning (use multiple scenes)

1. Initial 3D reconstruction
2. Move camera (or projector) freely
3. Apply bundle adjustment

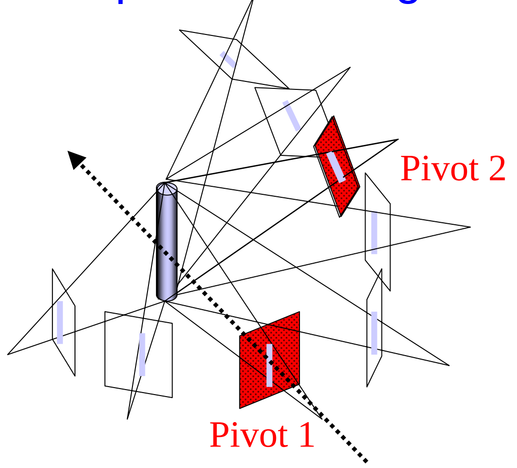
Pivot scanning

Fix pivot device and move peripheral device arbitrarily



More wide view scanning

Pivot to pivot scanning



Bundle adjustment for pivot scanning

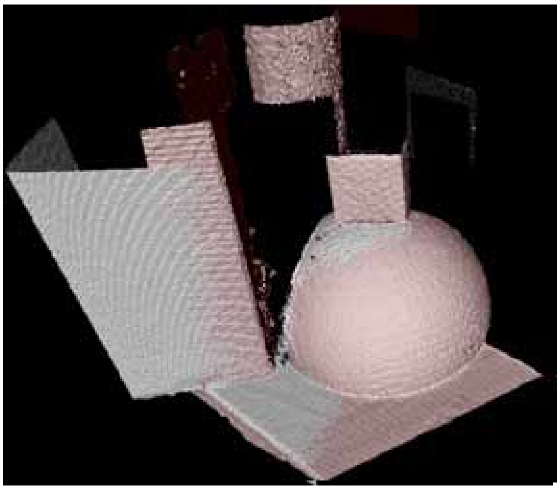
- Configuration of single camera-projector pair
  - Only epipolar constraints are available
  - Can be unstable if the projections of the camera and the projector are nearly orthogonal
- Configuration of pivot scanning
  - Constraints between multiple views can be used

Dense correspondences

Simple algorithm to enforce multi-view constraints to correct errors of self-calibration

Result – pivot to pivot

- No alignment algorithm applied



1+2 result

Demo movie

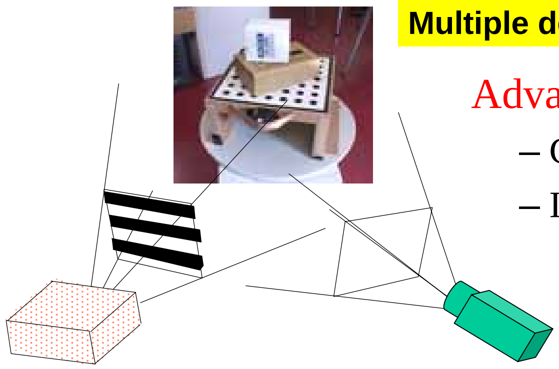
- Pivot scan

Extended techniques

- Wide range reconstruction by pivot scanning
- Simultaneous reconstruction method

Simultaneous reconstruction

- Capture multiple scenes
- 3D reconstruction simultaneously



Multiple depths for single pixel

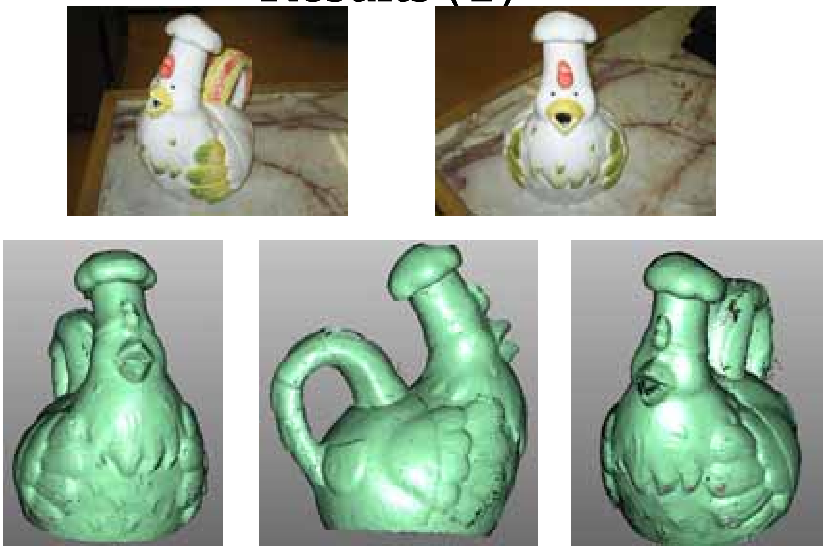
Advantage

- Consistent scaling
- Improving result
  - Redundant input

Demo movie

- Simultaneous scan

Results (1)



Results (2)

Final results

With
•Fast mesh integration [Furukawa and Kawasaki 3DIM ’05]
•seamless texture [Inose, kawasaki *et.al.* ’06 ’07]

Conclusion

- Introduction of structured light system
- Explain calibration problem
- Self calibration techniques for
  - Light sectioning method
  - Projector camera system

Discussion

- Calibration of light sectioning method and procam system is different
- Once correspondences are obtained, self-calibration is possible
  - Correspondence is an essential problem

In the next tutorial (part II)…

- Explain about correspondence problem
- Scanning techniques for moving object

Thanks

- Any question?