Structured light systems

Tutorial 1: 9:00 to 12:00
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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
Overview

• **Introduction**
  – shape acquisition system
• Basic problems of Structured light system
  – Calibration
  – Correspondences
• Online calibration for light sectioning method
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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
  ☹ Unstable
  ☹ 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

😊 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

Observed laser point
Camera
Stereo based active scan

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

![Stereo based active scan diagram](image1)

Stereo based active scan

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

![Stereo based active scan diagram](image2)
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
Overview

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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

![Diagram of light source and camera setup](image)
Basic approach

• Using calibration object

Calibration of laser plane

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

Laser plane
(ax+by+cz=1)

Observed laser line

Camera
Calibration of projector camera system

• Stereo method
• Estimate camera parameter

Estimation of 6 params
• Rot:3+Trans:3

Example of calibration
[projector calibration toolbox]

➔ Complicated and unstable process
Overview

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  – Correspondences
• Online calibration for light sectioning method
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Online calibration

• Calibration object in a scene
  • Frame [Chu et.al. 3DIM01]
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

\[ \Delta = 0.00017 \text{(m)} \]
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?

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

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

1. Detect laser lines from video
2. Constraint equations from intersections
3. 3D shape reconstruction by solving the simultaneous equations

Constraints from intersections (coplanar constraint)

\[
\begin{align*}
(a_1 x + b_1 y + c_1 z + 1 &= 0) \\
(a_2 x + b_2 y + c_2 z + 1 &= 0)
\end{align*}
\]

\[
\begin{pmatrix} x \\ y \\ z \end{pmatrix} = -z \begin{pmatrix} \alpha u \\ \alpha v \\ -1 \end{pmatrix}
\]
Constraints from intersections
(coplanar constraint)

\[-a_1^* u - b_1^* v + c_1 + t = 0\]
\[-a_2^* u - b_2^* v + c_2 + t = 0\]
\[-a_3^* u + a_3^* u - b_1^* v + b_2^* v + c_1 - c_2 = 0\]

3*2 Unknowns

Number of intersections: \(M\)
Number of equations: \(M\)
Number of planes: \(N\)
Number of unknown params: \(3N\)

Usually, Intersection number \(M \gg\) plane number \(N\) (unknown)

Matrix form

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

\[Lx = 0\]

\(L:\) 3\(N\)*\(M\) matrix (Intersection num \(M\), Plane num \(N\))
Reconstruction from coplanarity

\[ \mathbf{Lx} = 0 \]

Solution \( \mathbf{x} \) has **4 degrees of freedom**

*(Projective reconstruction)*

The 4 DOFs \( \rightarrow \) Found in other research areas.
- \( \rightarrow \) Polyhedra analyses in **single view reconstruction**
- \( \rightarrow \) Generalized Bas-Relief Ambiguity in photometric stereo

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Shape from coplanarity

Sort eigen values after SVD of \( \mathbf{L} \)

\[
\mathbf{U} \begin{pmatrix} \Sigma_1 & 0 \\ 0 & \Sigma_2 \\ 0 & 0 \end{pmatrix} \mathbf{V}^\perp \mathbf{x} = 0
\]

\( \Sigma_1 \quad \Sigma_2 \) Square diagonal matrix

\( \Sigma_2 \approx \mathbf{0} \) (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

Laser Plane

Laser projector with 2 line lasers

known angle (= 90 degree)

Formulation of metric constraints

Constraints from orthogonality

\[ ax + by + cz + 1 = 0 \]
\[ dx + ey + fz + 1 = 0 \]

\[ ad + be + cf = 0 \]
Upgrade to Euclidean solution-3

- Another metric constraints from laser planes

Laser Planes

Laser projector with 2 line lasers

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

Unknown object

Estimation of 6 params
• Rot: 3 + Trans: 3
Self calibration of projector camera system

Replace camera to projector

Unknown object

Projector

camera2

Estimation of 6 params
• Rot:3+Trans:3

Self calibration of pro-cams

Projecting image

Camera image

correspondence
Actual implementation

- Gray code method['86 Inokuchi]

Structured light example

- Projecting patterns → two directions

- Acquired coded images

vertical

horizontal
Correspondences from decoded images

Projector image

Camera image

Gray code image

(Xi, Yi)

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

\[ E_i(\theta, f) := |t \cdot N(p_i \times q_i(\alpha, \beta, \gamma, f))| \]

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

\[ \theta := (t, \alpha, \beta, \gamma) \]
\[ \alpha, \beta, \gamma : \text{Rotation (Euler angles)} \]

\[ \text{Extrinsic parameter} \]
\[ t : \text{Translation} \]

\[ E_i(\theta, f) \]
\[ \text{Re-projection error in real algo.} \]

Solving epipolar constraints

- Gauss-Newton method

\[ x := (\theta, f), \]
\[ y(x) := (\bar{E}_1(x), \bar{E}_2(x), \cdots, \bar{E}_k(x))^\prime \]
\[ \text{minimize} \sum_i |\bar{E}_i(\theta, f)|^2 = \|y(x)\|^2 = y(x)^\prime y(x) \]
\[ x_{k+1} = x_k + \Delta x_k, \]
\[ \Delta x_k = -\left( \left( \frac{\partial y(x_k)}{\partial x} \right)^\prime \left( \frac{\partial y(x_k)}{\partial x} \right) \right)^{-1} \left( \frac{\partial y(x_k)}{\partial x} \right)^\prime y(x_k) \]
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
Demo movie

- Pivot scan

Extended techniques

- Wide range reconstruction by pivot scanning
- Simultaneous reconstruction method
Simultaneous reconstruction
• Capture multiple scenes
• 3D reconstruction simultaneously

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?