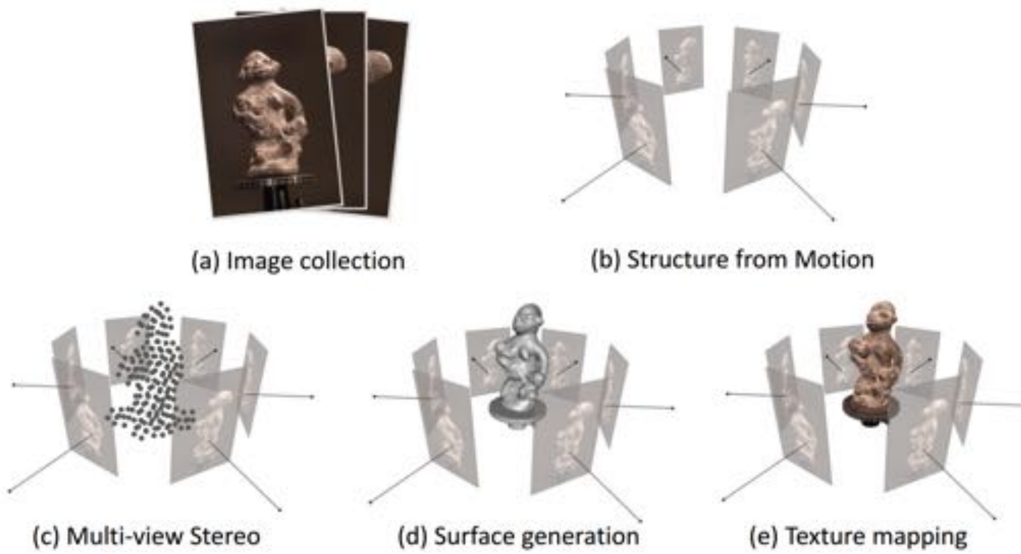
Part II

Long Quan

High-quality Textured Surface Reconstruction from Registered Images:

State-of-the-art methods



The pipeline of image-based 3D reconstruction

(a) Image collection (b) Structure-from-Motion

(c) Multi-view Stereo (d) Surface generation (e) Texture mapping

THE DEPARTMENT OF
COMPUTER SCIENCE & ENGINEERING
計算機科學及工程學系

The pipeline of image-based 3D reconstruction

(a) Image collection

(b) Structure-from-Motion

(c) Multi-view Stereo

(d) Surface generation

(e) Texture mapping

The pipeline of image-based 3D reconstruction

(a) Image collection (b) Structure-from-Motion

(c) Multi-view Stereo (d) Surface generation (e) Texture mapping

The pipeline of image-based 3D reconstruction

(a) Image collection

(b) Structure-from-Motion

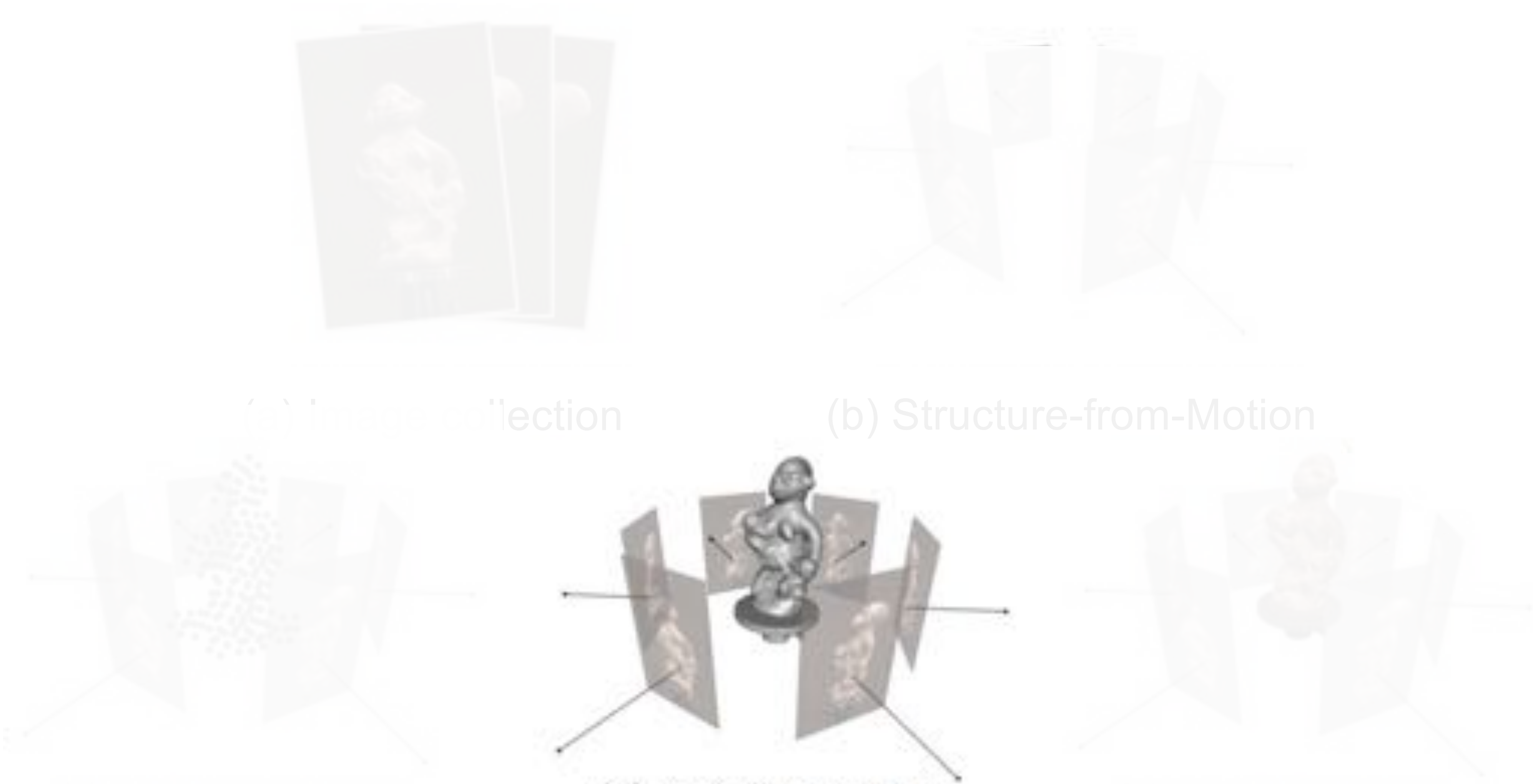
(c) Multi-view Stereo

(d) Surface generation

(e) Texture mapping

THE DEPARTMENT OF
COMPUTER SCIENCE & ENGINEERING
計算機科學及工程學系

The pipeline of image-based 3D reconstruction

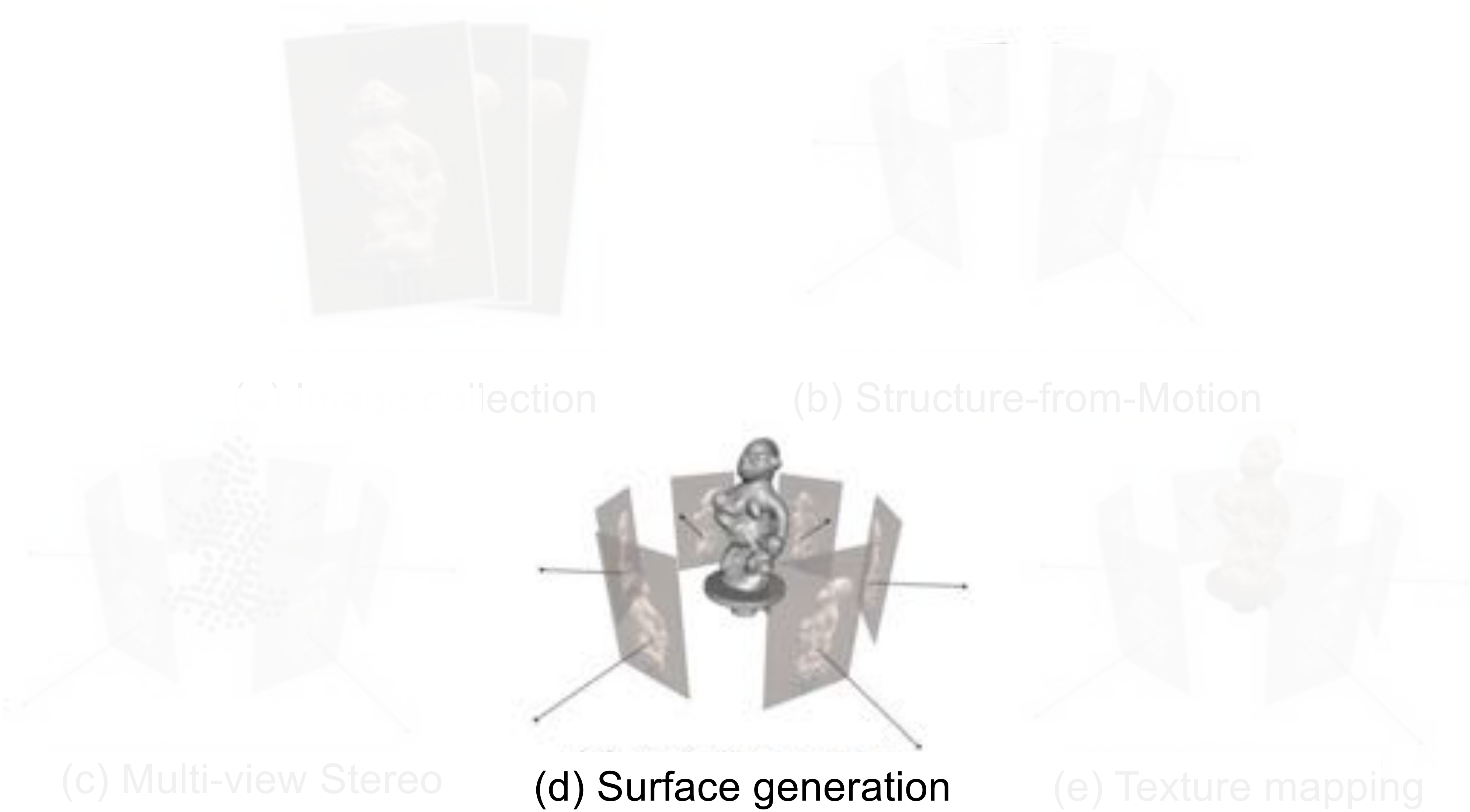


(a) Image collection (b) Structure-from-Motion

(c) Multi-view Stereo (d) Surface generation (e) Texture mapping

THE DEPARTMENT OF COMPUTER SCIENCE & ENGINEERING 計算機科學及工程學系

The pipeline of image-based 3D reconstruction



THE DEPARTMENT OF COMPUTER SCIENCE & ENGINEERING 計算機科學及工程學系

The pipeline of image-based 3D reconstruction

(a) Image collection

(b) Structure-from-Motion

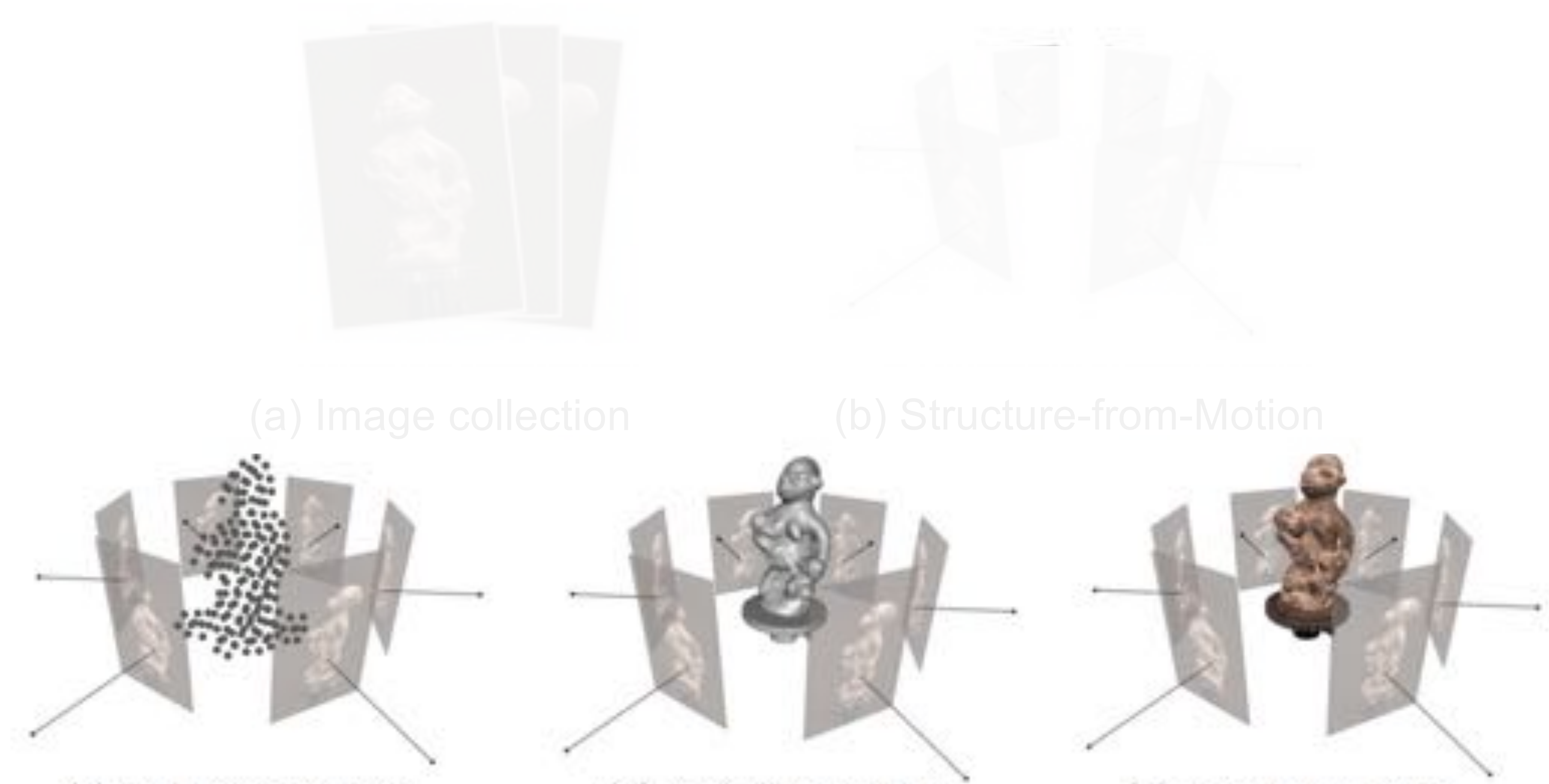
(c) Multi-view Stereo

(d) Surface generation

(e) Texture mapping

THE DEPARTMENT OF COMPUTER SCIENCE & ENGINEERING 計算機科學及工程學系

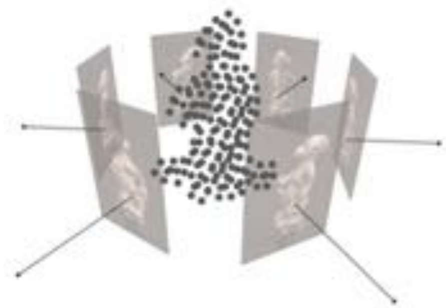
The pipeline of image-based 3D reconstruction



(c) Multi-view Stereo (d) Surface generation (e) Texture mapping

Content

- Multi-view Stereo
  - Pairwise Stereo
  - Propagation Stereo

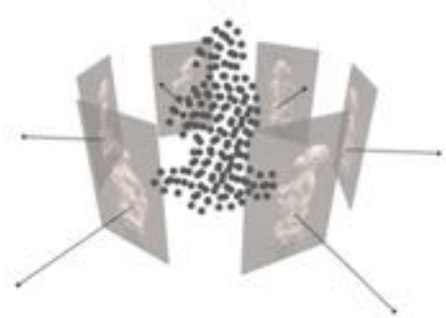


- Surface generation
  - Surface extraction
  - Surface refinement

- Texture mapping
  - View selection
  - Color adjustment and blending

Content

- Multi-view Stereo
  - Pairwise Stereo
  - Propagation Stereo



- Surface generation
  - Surface extraction
  - Surface refinement

- Texture mapping
  - View selection
  - Color adjustment and blending

Multi-view Stereo

- Problem definition: given several **registered images** of the same object or scene, compute a **dense representation** of its 3D shape

- "Registered images of same object or scene"
  - Known camera parameter
  - Arbitrary number of images (from two to thousands)

- "**Dense representation** of 3D shape"
  - Depth maps
  - Point clouds
  - Patch clouds
  - Meshes
  - Voxels

THE DEPARTMENT OF
COMPUTER SCIENCE & ENGINEERING
計算機科學及工程學系

Multi-view Stereo

- Problem definition: given several **registered images** of the same object or scene, compute a **dense representation** of its 3D shape

- "Registered images of same object or scene"
  - Known camera parameter
  - Arbitrary number of images (from two to thousands)

- "**Dense representation** of 3D shape"
  - Depth maps
  - Point clouds
  - Patch clouds
  - Meshes
  - Voxels

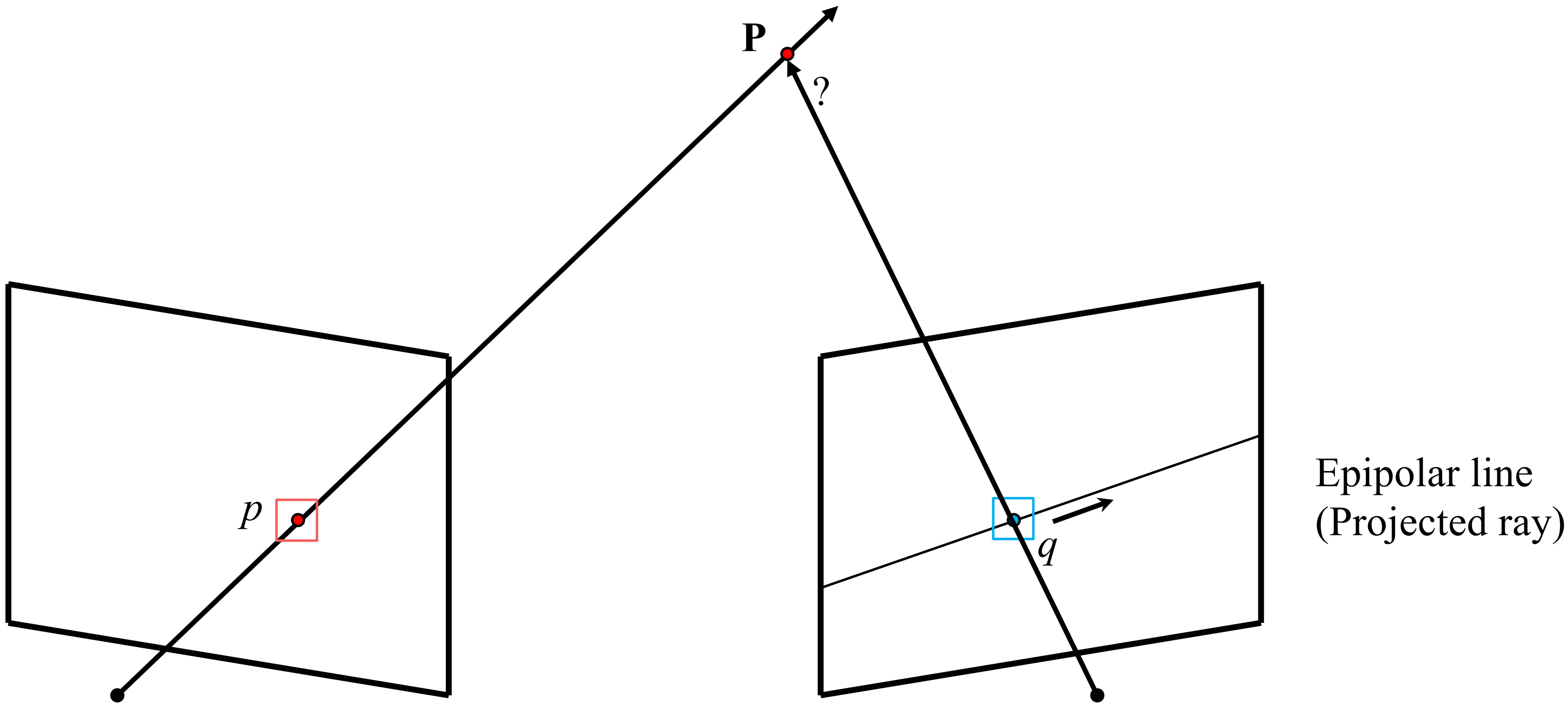
Multi-view Stereo

- Problem definition: given several **registered images** of the same object or scene, compute a **dense representation** of its 3D shape

- “Registered images of same object or scene”
  - Known camera parameter
  - Arbitrary number of images (from two to thousands)

- “**Dense representation** of 3D shape”
  - Depth maps
  - Point clouds
  - Patch clouds
  - Meshes
  - Voxels

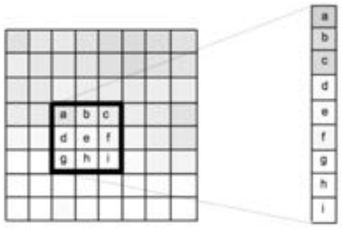
Multi-view Stereo: 1D matching problem



Compare the similarity between p and q, find the best q

Multi-view Stereo: Similarity measure

- Convert the patches p and q in to vectors f and g



SSD (Sum of Squared Differences)

$$\rho_{SSD}(f,g) = ||f - g||^2$$

- Pros: efficient, derivable
- Cons: sensitive to bias/gain

NCC (Normalized Cross Correlation)

$$\rho_{NCC}(f,g) = \left\langle \frac{f}{||f||}, \frac{g}{||g||} \right\rangle = \frac{f \cdot g}{||f|| \cdot ||g||}$$

- Pros: robust to gain, derivable
- Cons: sensitive to bias

SAD (Sum of Absolute Differences)

$$\rho_{SAD}(f,g) = ||f - g||_1$$

- Pros: efficient, robust to salt/pepper noise
- Cons: non-derivable, sensitive to bias/gain

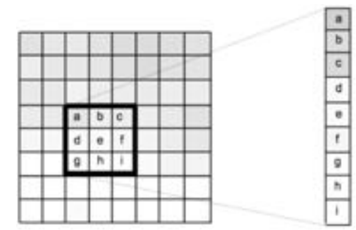
ZNCC (Zero-mean Normalized Cross Correlation)

$$\rho_{ZNCC}(f,g) = \left\langle \frac{f-\hat{f}}{||f-\hat{f}||}, \frac{g-\hat{g}}{||g-\hat{g}||} \right\rangle = \frac{(f-\hat{f}) \cdot (g-\hat{g})}{\sigma_f \sigma_g}$$

- Pros: robust to bias/gain, derivable
- Cons: less efficient

Multi-view Stereo: Similarity measure

- Convert the patches p and q in to vectors f and g



SSD (Sum of Squared Differences)

$$\rho_{SSD}(f,g) = ||f-g||^2$$

- Pros: efficient, derivable
- Cons: sensitive to bias/gain

NCC (Normalized Cross Correlation)

$$\rho_{NCC}(f,g) = \left\langle \frac{f}{||f||}, \frac{g}{||g||} \right\rangle = \frac{f \cdot g}{||f|| \cdot ||g||}$$

- Pros: robust to gain, derivable
- Cons: sensitive to bias

SAD (Sum of Absolute Differences)

$$\rho_{SAD}(f,g) = ||f-g||_1$$

- Pros: efficient, robust to salt/pepper noise
- Cons: non-derivable, sensitive to bias/gain

ZNCC (Zero-mean Normalized Cross Correlation)

$$\rho_{ZNCC}(f,g) = \left\langle \frac{f-\hat{f}}{||f-\hat{f}||}, \frac{g-\hat{g}}{||g-\hat{g}||} \right\rangle = \frac{(f-\hat{f}) \cdot (g-\hat{g})}{\sigma_f \sigma_g}$$

- Pros: robust to bias/gain, derivable
- Cons: less efficient

THE DEPARTMENT OF COMPUTER SCIENCE & ENGINEERING 計算機科學及工程學系

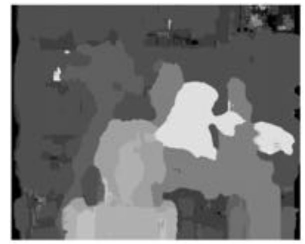
Multi-view Stereo: two branches of methods

- Pairwise depth map reconstruction
  - Input two images
  - Output per-image depth map
  - Need fusion afterwards

- Global point cloud propagation
  - Input N images
  - Output global 3D points
  - Difficult parallelism

Multi-view Stereo: matching strategy

Local matching



Naive winner-take-all

Image segmentation
Gerrits et.al., CRV2006

Global regularization

Graph cuts
Kolmogorov et.al. ICCV2001

Semi-global matching
Hirschmüller, CVPR2006

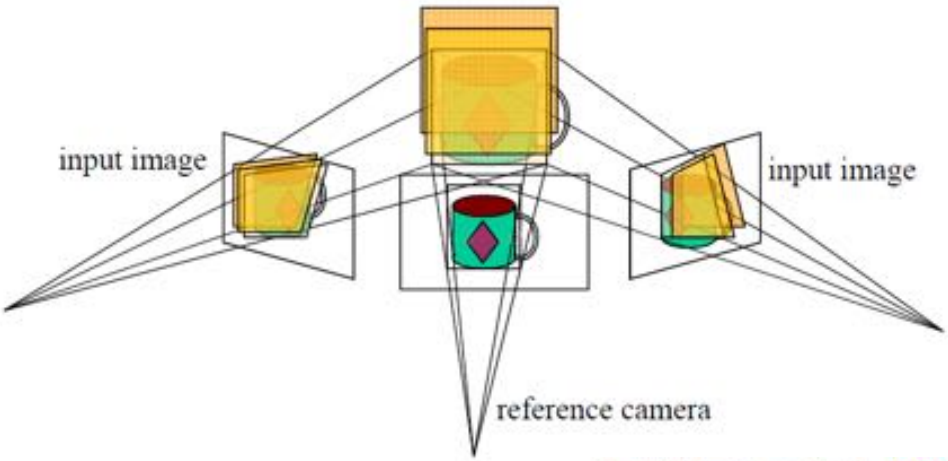
Belief Propagation
Klaus et.at. ICPR2006

Deep learning

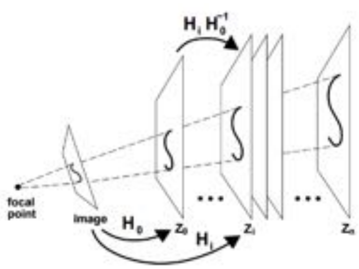
CNN
Žbontar and LeCun. CVPR2015

next……?

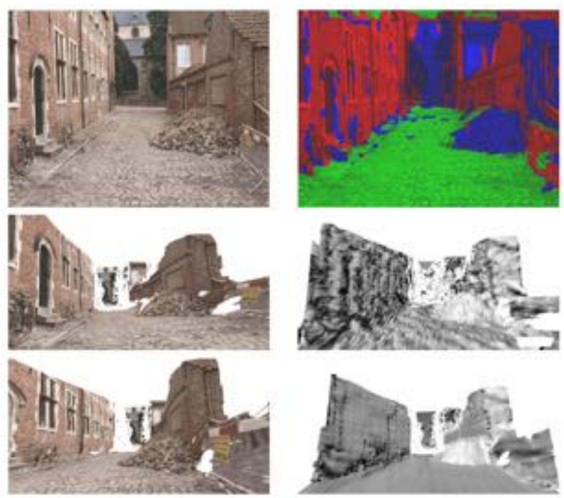
Multi-view Stereo: plane sweep stereo



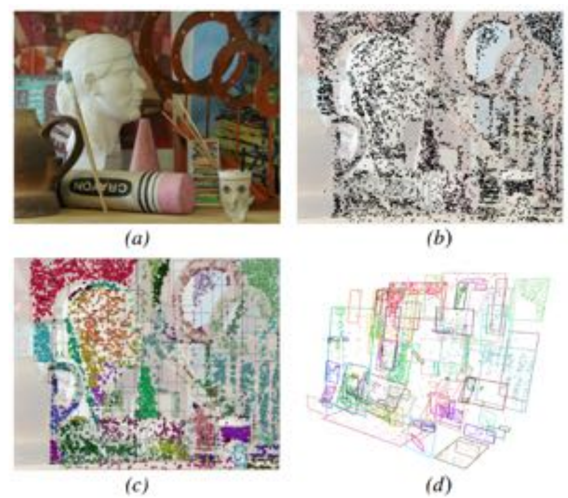
- Winner-take-all
- GPU projective texture mapping
- Highly efficient and parallelable
- Noisy output, need filter afterwards



Space-sweep
(Pioneer)
Collins, 1996



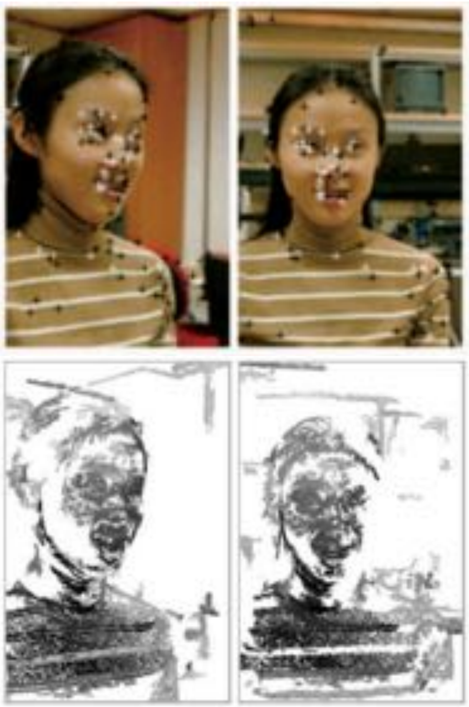
Multi-direction Planesweep
Gallup et.al. CVPR2007



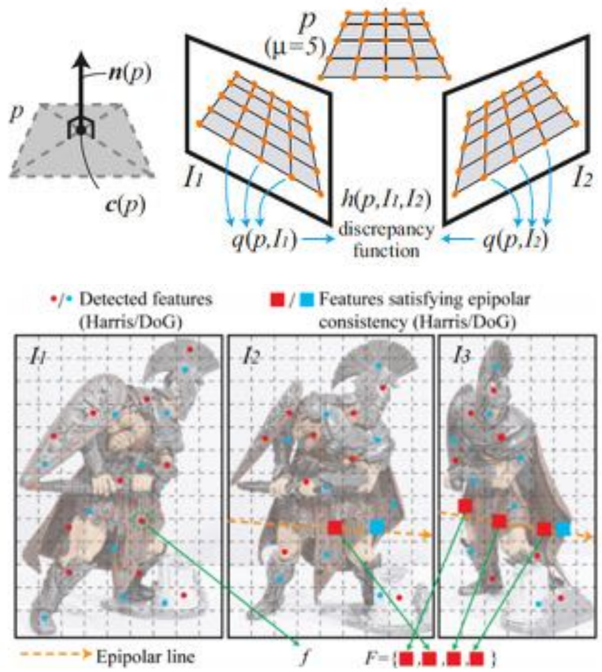
Local Planesweep
Sinha et.al. CVPR2014

THE DEPARTMENT OF COMPUTER SCIENCE & ENGINEERING
計算機科學及工程學系

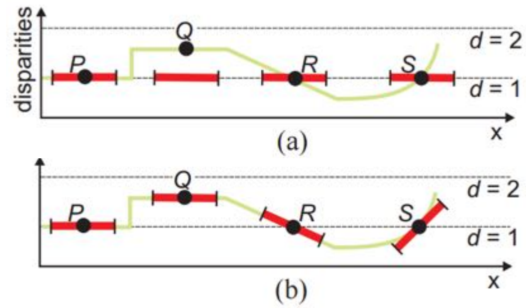
Multi-view Stereo: point cloud propagation



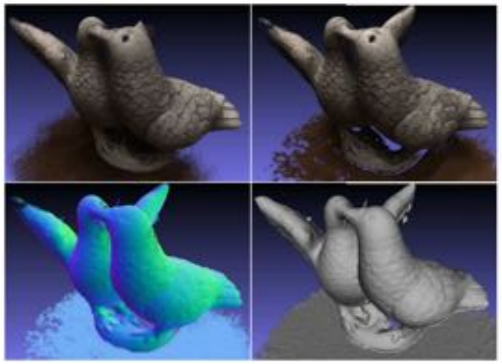
Pioneer: Quasi-dense approach
Lhuillier and Quan. PAMI2005



Patch-based MVS (PMVS)
Furukawa and Ponce. PAMI2010



PatchMatch Stereo
Bleyer et.al. BMVC2011

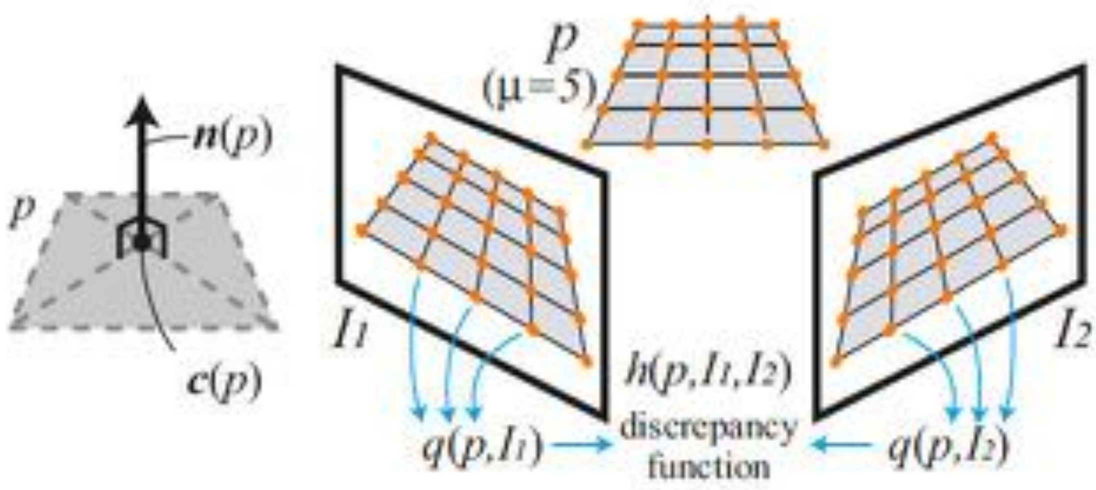


GPU PatchMatch
Galliani et.al. ICCV2015

THE DEPARTMENT OF
COMPUTER SCIENCE & ENGINEERING
計算機科學及工程學系

Multi-view Stereo: PMVS

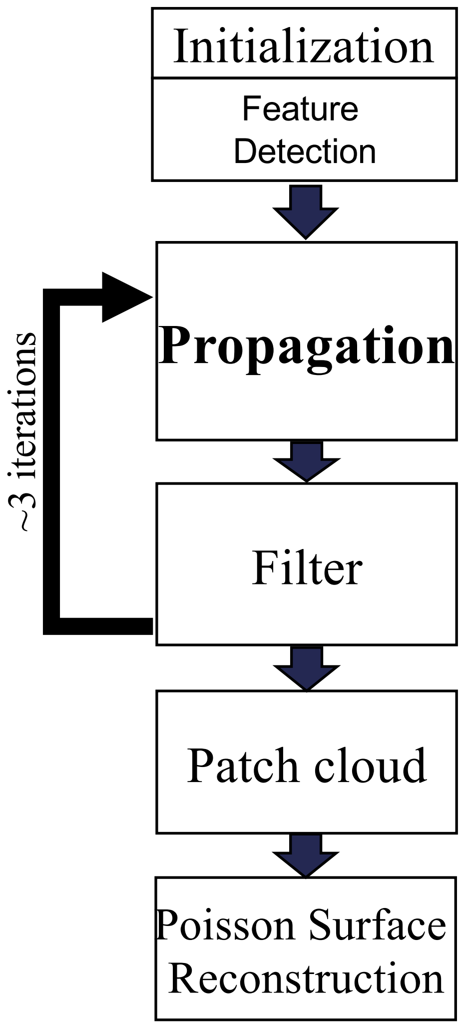
- Patch model



- A 3D patch has
  - Position
  - Normal
  - Scale
  - Visibility

Patch-based MVS (PMVS)
Furukawa and Ponce. PAMI2010

Multi-view Stereo: PMVS



- Harris and DoG
- Sparse seed patches

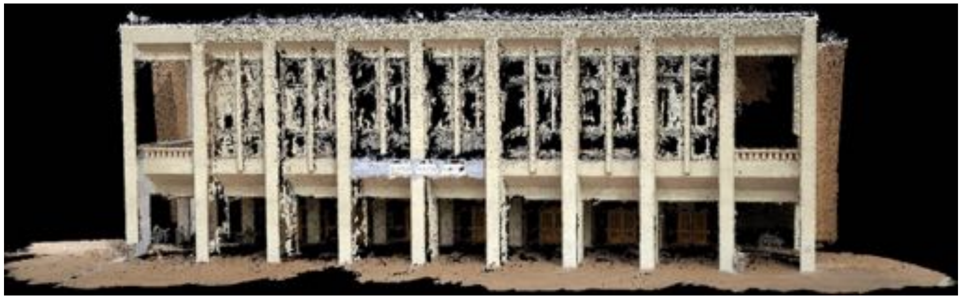
- Propagation, then optimize
- Optimize via Levenberg–Marquardt
  - Position
  - Normal

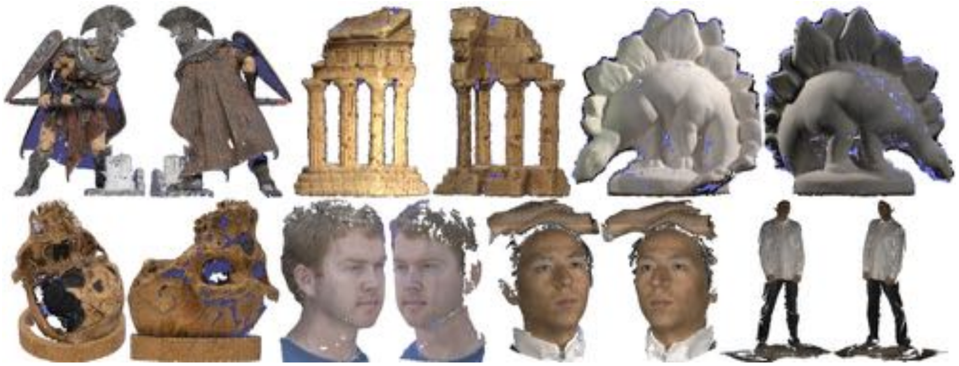
- Confidence filter
- Visibility filter
- Small group filter

- Point cloud with **orientations**

THE DEPARTMENT OF COMPUTER SCIENCE & ENGINEERING 計算機科學及工程學系

Multi-view Stereo: PMVS





THE DEPARTMENT OF COMPUTER SCIENCE & ENGINEERING 計算機科學及工程學系

Content

- Multi-view Stereo
  - Pairwise Stereo
  - Propagation Stereo

- Surface generation
  - Surface extraction
  - Surface refinement

- Texture mapping
  - View selection
  - Color adjustment and blending

THE DEPARTMENT OF COMPUTER SCIENCE & ENGINEERING 計算機科學及工程學系

Surface representation

	Meshes	Volumetric
Space Discretization	Adaptive	Yes
Topology Handling	Difficult (Self intersections,...)	Naturally handled
Memory	Compact, Limited	Large
Parallelization	Sometimes	Very good
Scalability	Very good	Difficult
Adaptive Resolution	Very good	Difficult (Octree, Narrow band)
Surface extraction	Natural	Precision Loss (Marching cubes)

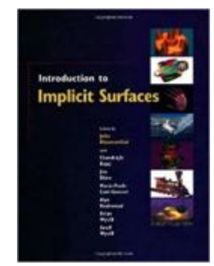
Mesh rocks! triangular mesh is more suitable for mesh processing

THE DEPARTMENT OF COMPUTER SCIENCE & ENGINEERING
計算機科學及工程學系

Surface extraction from point cloud

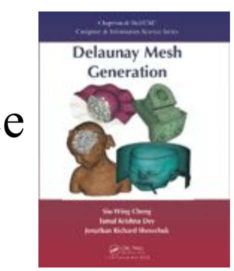
Definition: Given a set of points $\mathbf{P} = \{P_i\}_{i\in[1,N]} \in \mathbf{R}^3$ sampled from a surface S, find a best approximate surface S' to the original S.

- Implicit surface (Computer Graphics)
  - Model the surface implicitly with a function $f(x,y,z) = 0$



Bloomenthal, 1997

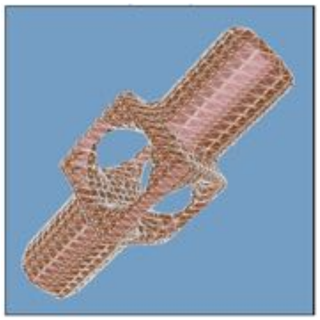
- Delaunay approach (Computational geometry)
  - Based on Delaunay triangulation/tetrahedra, find the best mesh surface



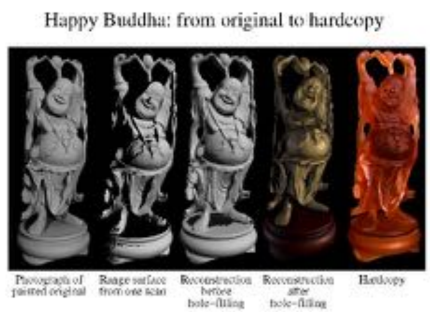
Cheng et.al. 2012

Implicit Surface

Distance functions



Local tangent plane + MST
Hoppe et.al. SIGGRAPH1992



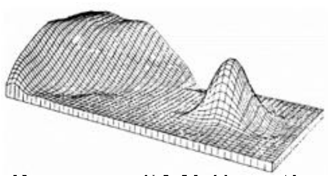
Line of sight distance weighted
Curless & Levoy. SIGGRAPH1996

Radial basis functions (RBF)

RBF approximation
Carr et.al. SIGGRAPH2001

Multi-level partition of unity
Ohtake et.al. SIGGRAPH2003

Moving Least-squares (MLS)

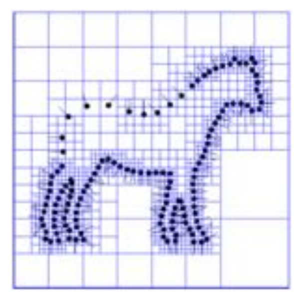


Pioneer of MLS method
Lancaster and Salkauskas. 1981

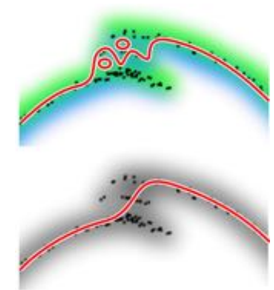
Least-MEDIAN-of-squares
Fleishman et.al. SIGGRAPH2005

Interactive, constrained
Shen et.al. SIGGRAPH2004

Indicator functions



Poisson Surface
Kazhdan et.al. SGP2006



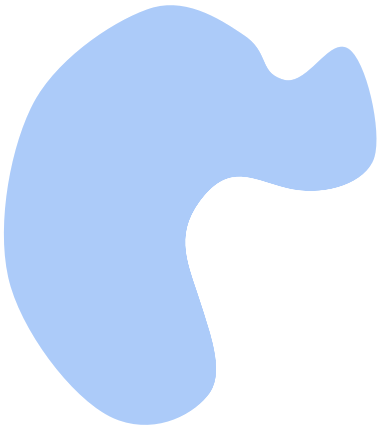
Signed distance function
Hornung & Kobbelt. SGP2006

THE DEPARTMENT OF
COMPUTER SCIENCE & ENGINEERING
計算機科學及工程學系

Implicit Surface: Poisson method

- Reconstruct the surface of the model by solving for the <u>indicator function</u> of the shape.

$$\chi_M(p) = \begin{cases} 1 & \text{if } p \in M \\ 0 & \text{if } p \notin M \end{cases}$$



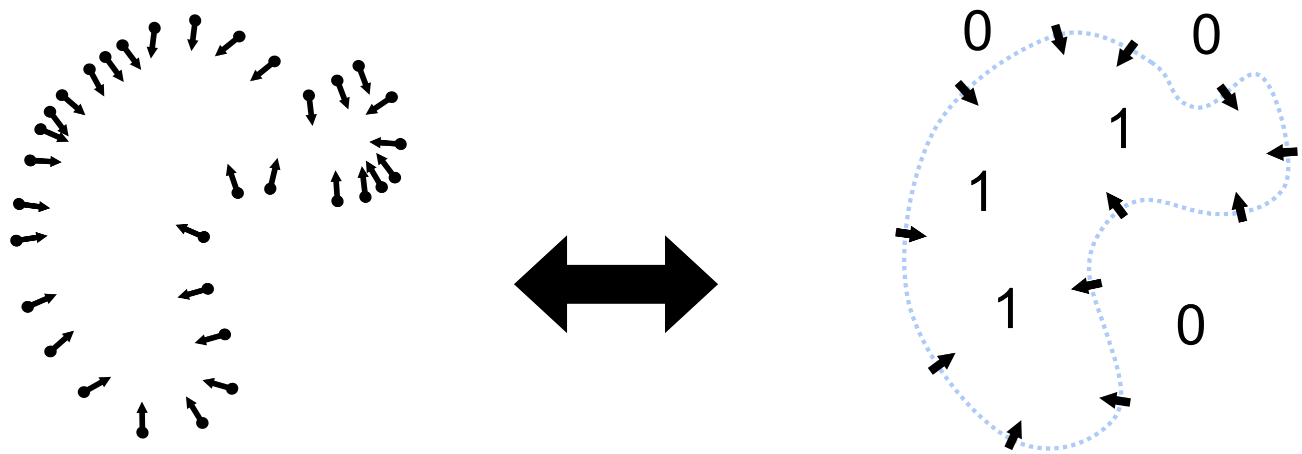
Indicator function

χ_M

THE DEPARTMENT OF COMPUTER SCIENCE & ENGINEERING 計算機科學及工程學系

Implicit Surface: Poisson method

- There is a relationship between the normal field and gradient of indicator function



points + oriented normals

Indicator gradient
$\nabla \chi_M$

THE DEPARTMENT OF
COMPUTER SCIENCE & ENGINEERING
計算機科學及工程學系

Implicit Surface: Poisson method

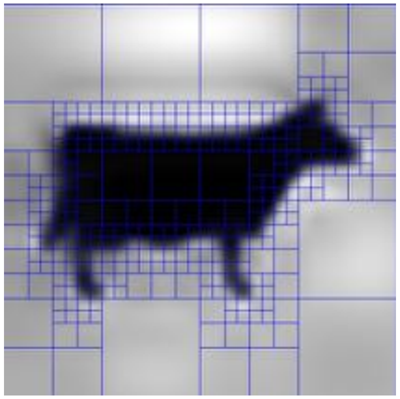
- Represent the points by a vector field $\vec{V}$
- Find the function χ whose gradient best approximates $\vec{V}$:

$$\min_{\chi} \left\| \nabla \chi - \vec{V} \right\|$$

- Applying the divergence operator, we can transform this into a **Poisson** problem:

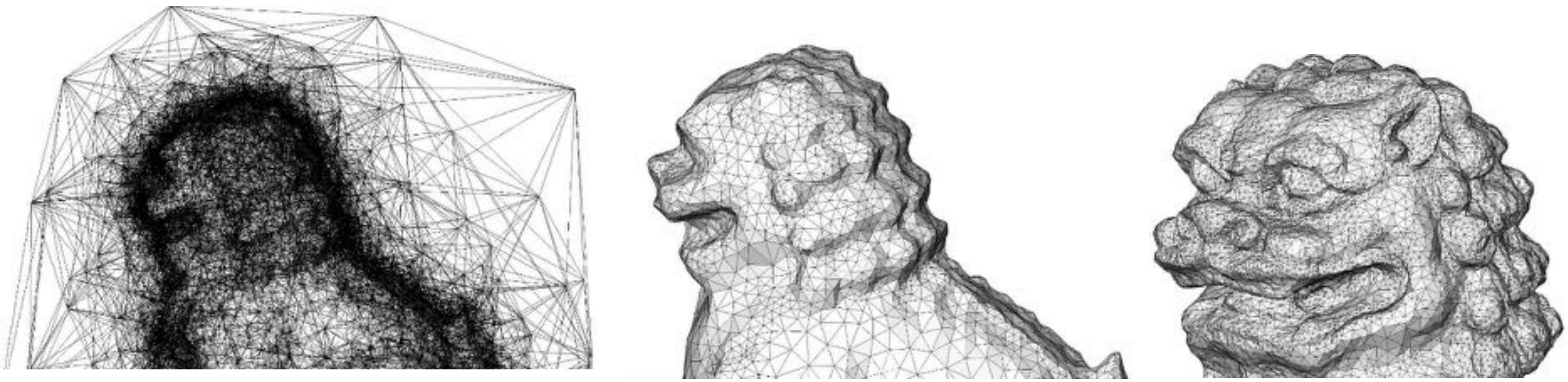
$$\nabla \cdot (\nabla \chi) = \nabla \cdot \vec{V} \quad \Leftrightarrow \quad \Delta \chi = \nabla \cdot \vec{V}$$

- Discretize from coarse-to-fine over an octree.

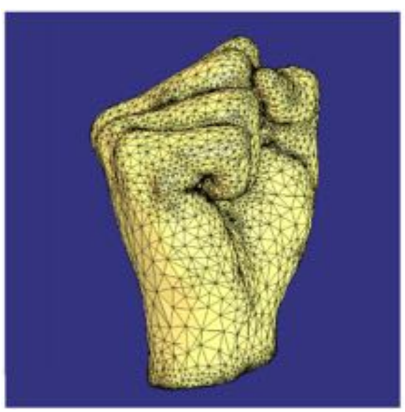


THE DEPARTMENT OF COMPUTER SCIENCE & ENGINEERING 計算機科學及工程學系

Delaunay method



Points -> Delaunay tetrahedron -> Mesh surface



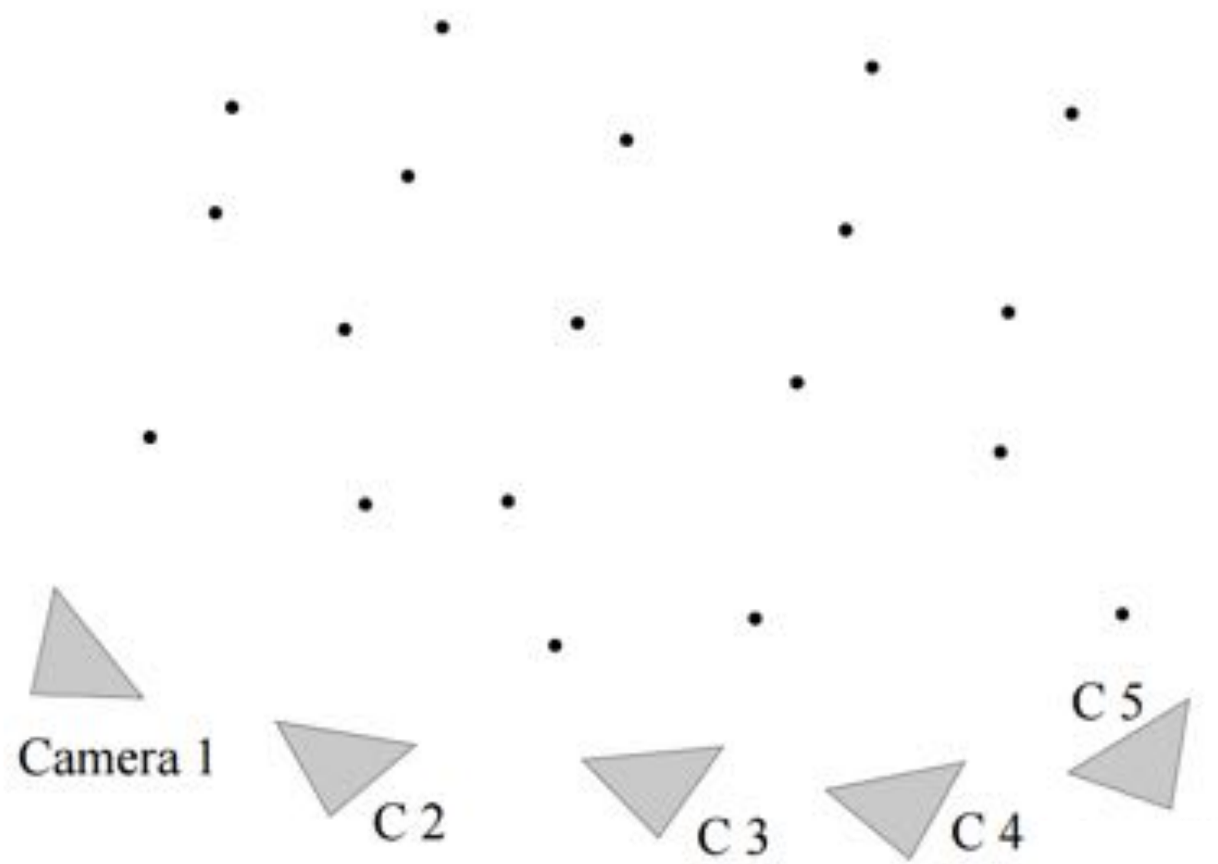
Power Crust
Ameta et.al. SIGGRAPH1998

Robust Cocone
Dey & Goswami. SoSMA2003

Visibility-consistent
Vu et.al. PAMI2012

Delaunay method: visibility-consistent

Point cloud reconstructed by multi-view images

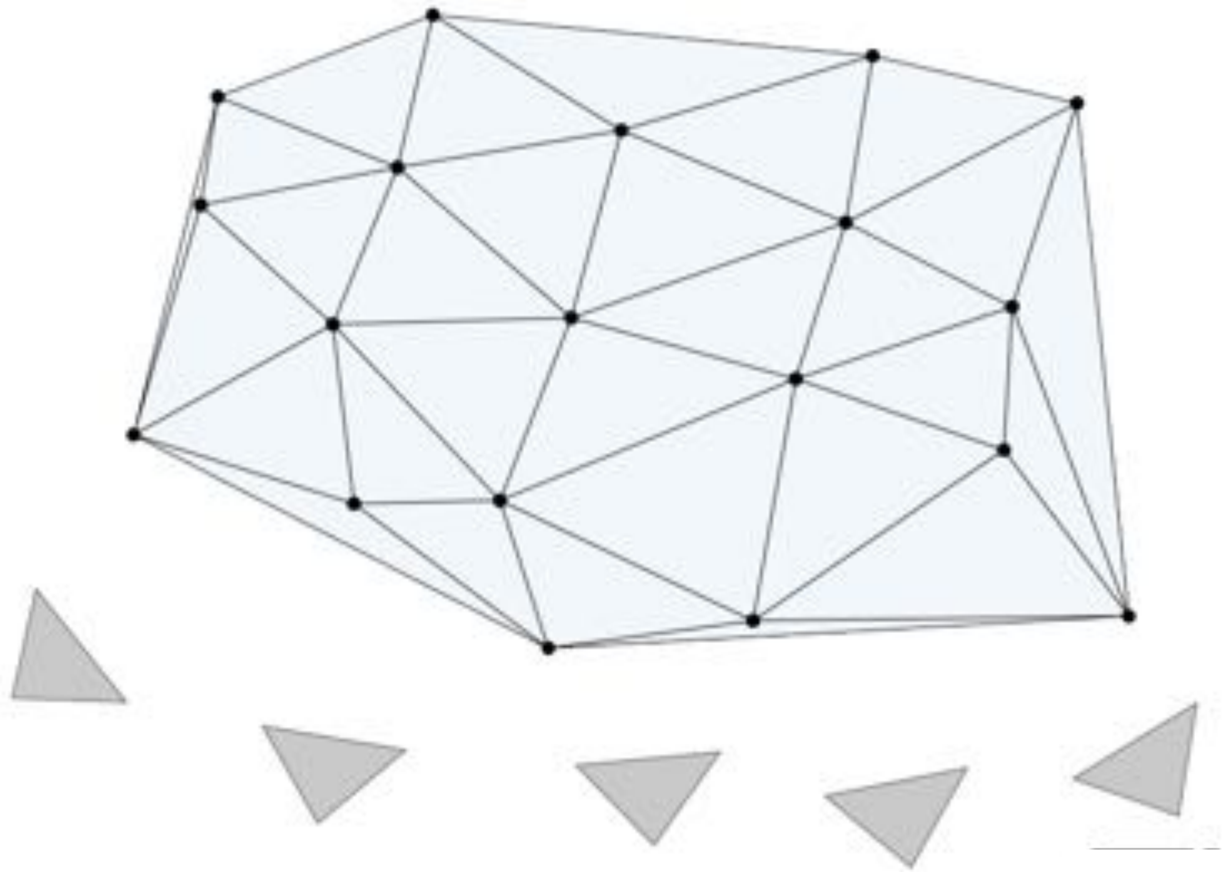


(credit to the course material of *ETH Computer Vision*)

THE DEPARTMENT OF COMPUTER SCIENCE & ENGINEERING 計算機科學及工程學系

Delaunay method: visibility-consistent

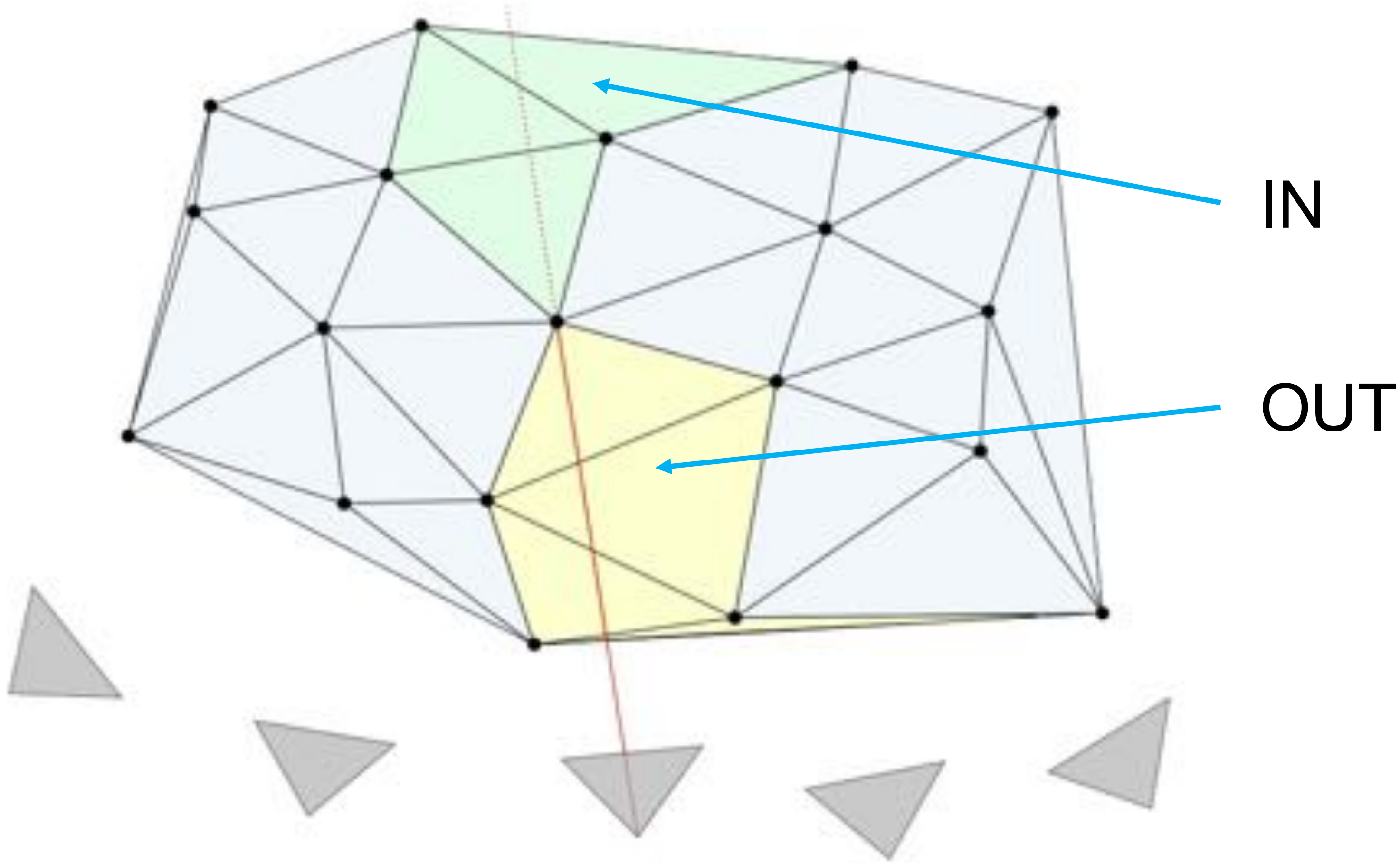
Delaunay Triangulation of Point cloud



(credit to the course material of *ETH Computer Vision*)

Delaunay method: visibility-consistent

Visibility of a vertex, labeling the tetrahedra

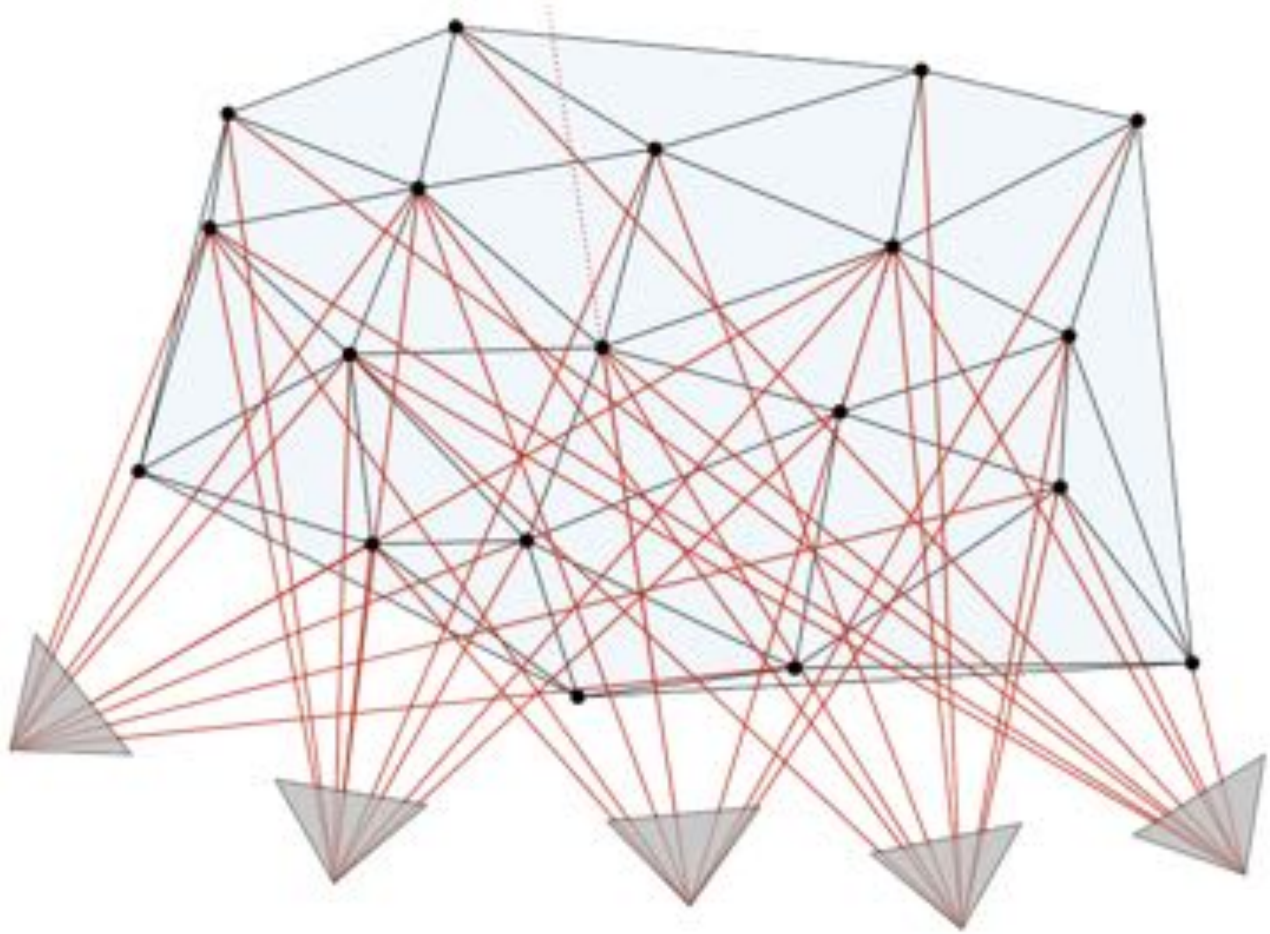


THE DEPARTMENT OF COMPUTER SCIENCE & ENGINEERING 計算機科學及工程學系

(credit to the course material of *ETH Computer Vision*)

Delaunay method: visibility-consistent

Visibility conflicts

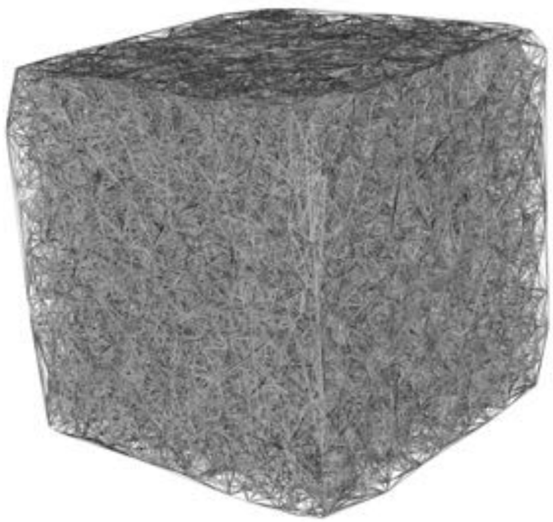


(credit to the course material of *ETH Computer Vision*)

Delaunay method: visibility-consistent

Extract a mesh surface from tetrahedron

- A tetrahedron is a graph
  - Every tetrahedral (cell) is a node
  - Linking the source and sink by visibility
  - Smoothness by neighboring relations
  - Additional terms
    - Surface area
    - Photo-consistency



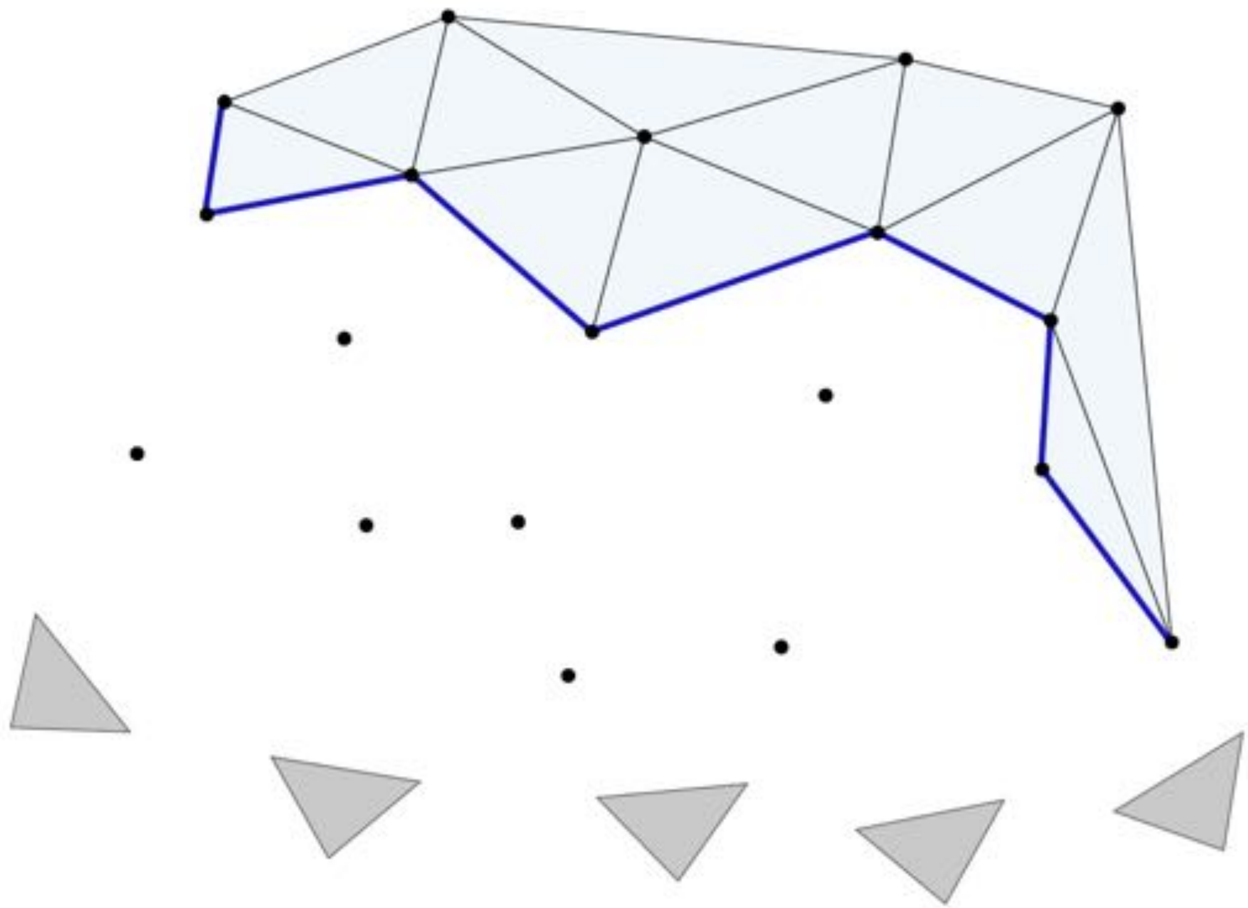
- Energy minimization via Graph Cuts

(credit to the course material of *ETH Computer Vision*)

THE DEPARTMENT OF COMPUTER SCIENCE & ENGINEERING 計算機科學及工程學系

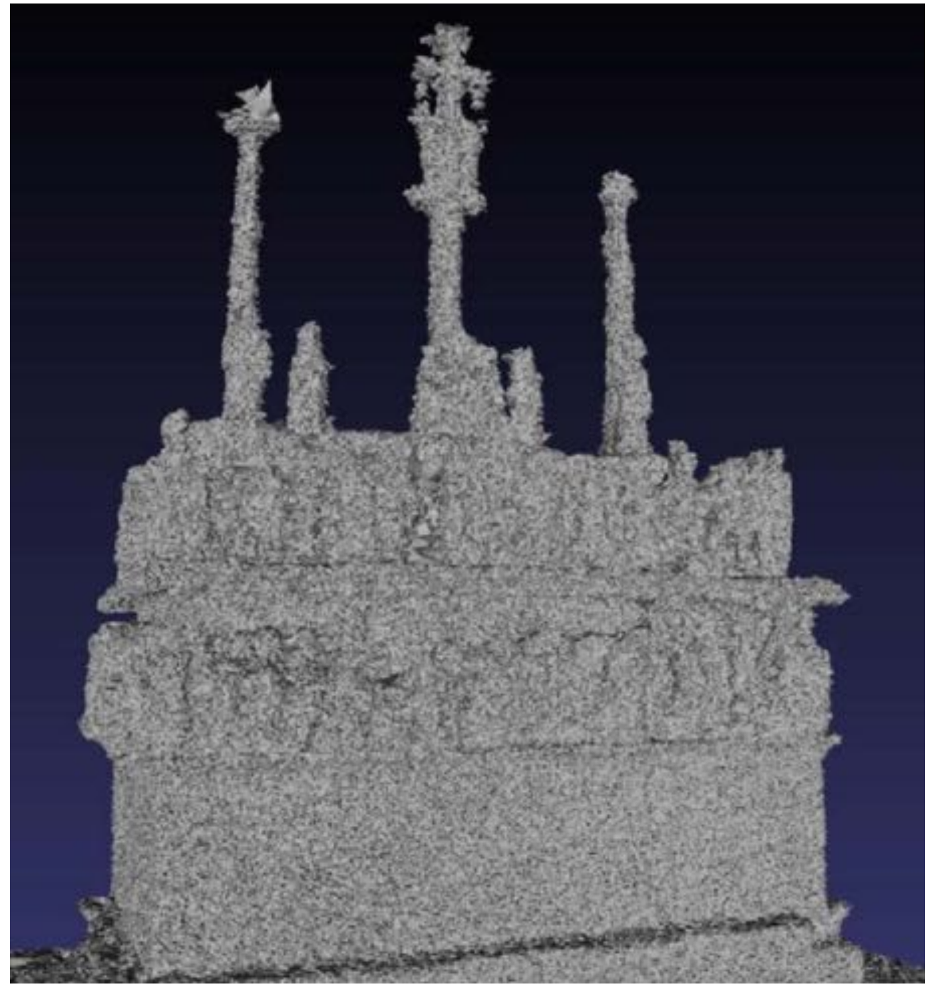
Delaunay method: visibility-consistent

Mesh surface as the boundary between IN and OUT



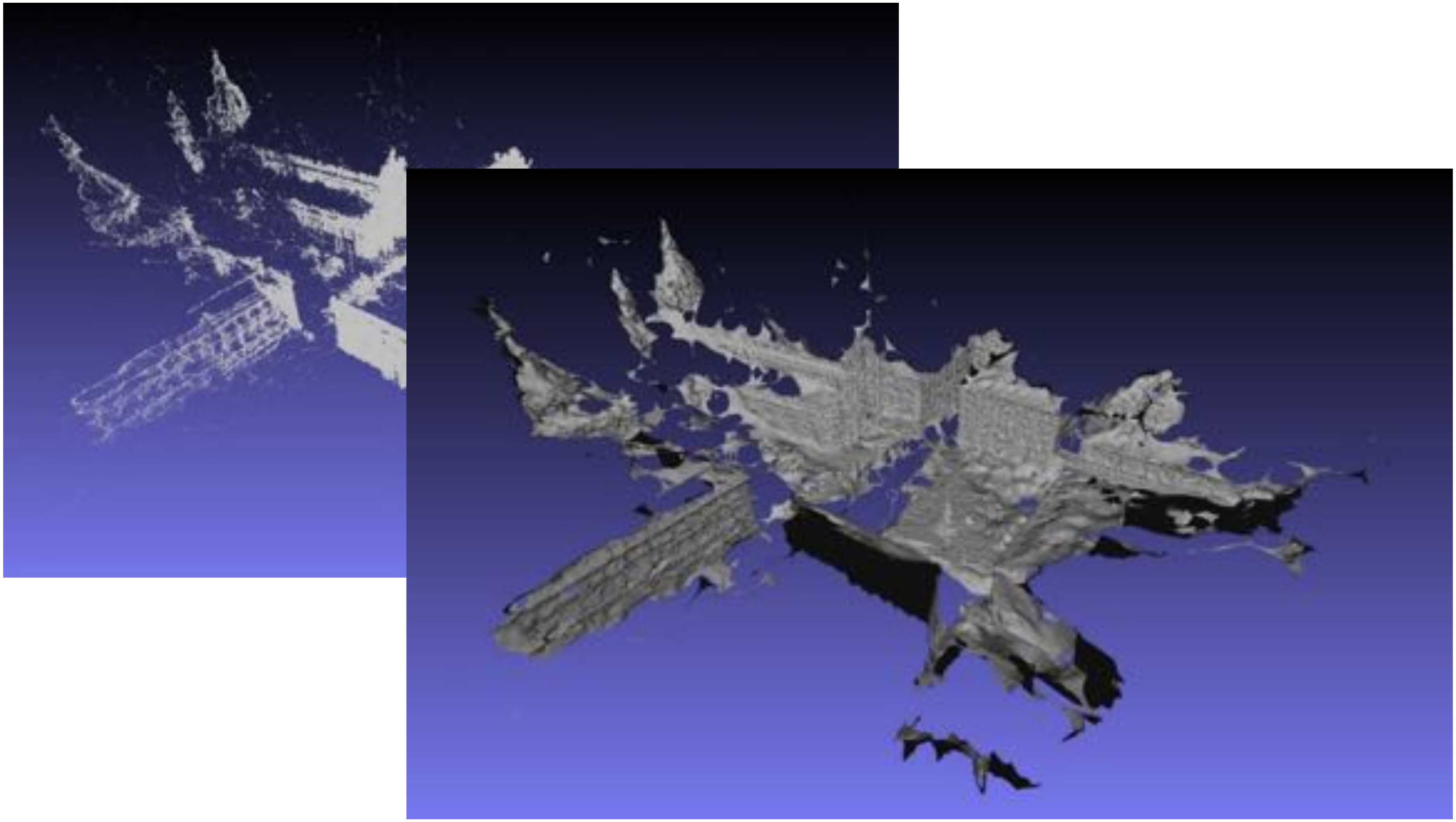
(credit to the course material of *ETH Computer Vision*)

Delaunay method: visibility-consistent



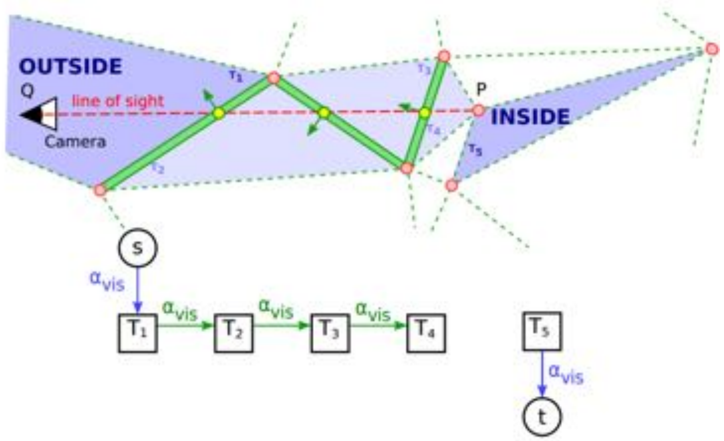
THE DEPARTMENT OF
COMPUTER SCIENCE & ENGINEERING
計算機科學及工程學系

Delaunay method: visibility-consistent

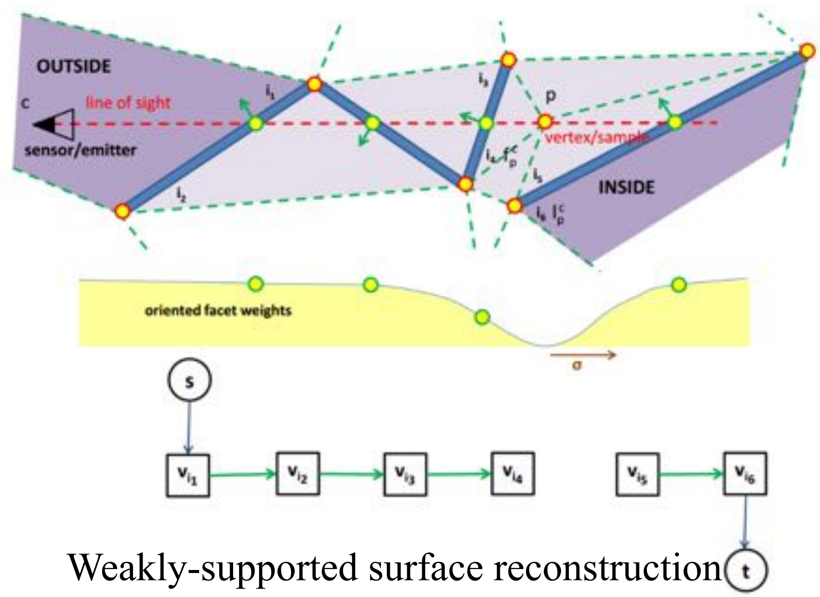


Delaunay method: visibility-consistent EXT

Preserving weakly supported surface



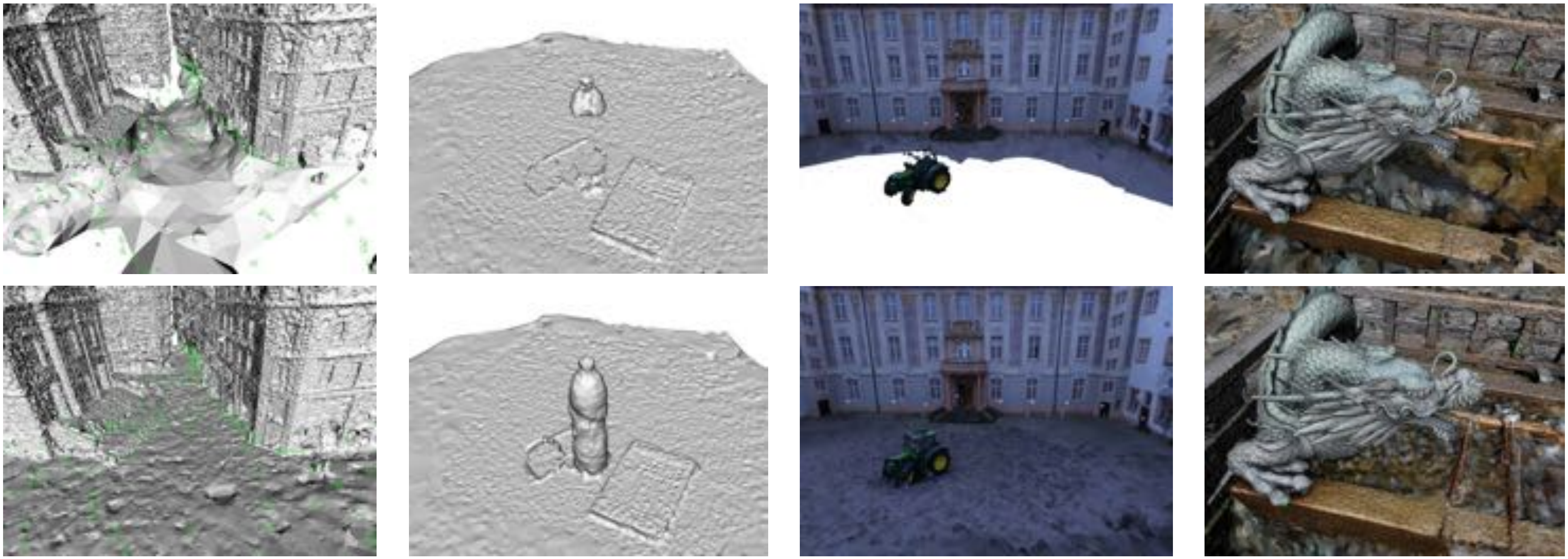
Visibility-consistent surface reconstruction
Vu et.al. PAMI2012



Weakly-supported surface reconstruction
Jancosek & Pajdla. CVPR2013

THE DEPARTMENT OF COMPUTER SCIENCE & ENGINEERING 計算機科學及工程學系

Surface extraction from point cloud

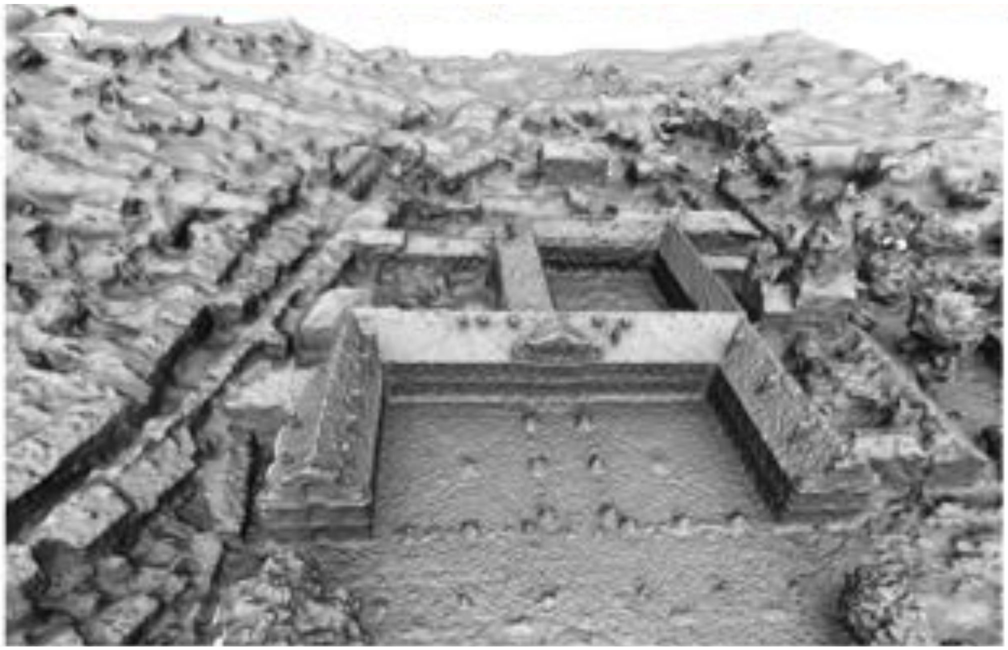


Weakly-supported surface reconstruction
Jancosek & Pajdla. CVPR2013
Visibility-consistent surface reconstruction
Vu et.al. PAMI2012

THE DEPARTMENT OF COMPUTER SCIENCE & ENGINEERING 計算機科學及工程學系

Surface refinement: crucial to high accuracy!

input images



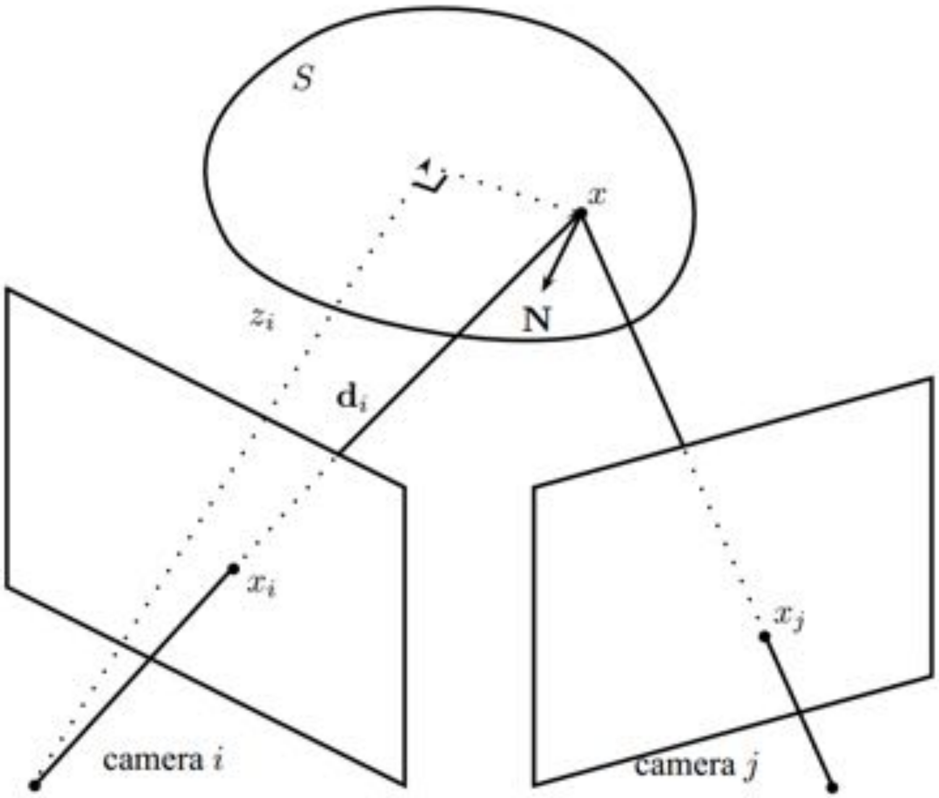
initial surface

Refined surface

dataset: Cluny-161-Small

Variational surface refinement
Vu et.al. PAMI2012

Surface refinement: formulation



Minimizing the error between the observed **image *i*** and **reprojection of image *j***:

$$\mathrm{E}_{\mathrm{error}}(S) = \sum_{i,j} \int_{\Omega_{ij}^S} h(I_i, I_{ij}^S)(x_i)\, \mathrm{d}x_i$$

- Ill-posed, difficult to solve directly
  - Local minima
  - Bad initialization
- Can be modeled via *variational methods*

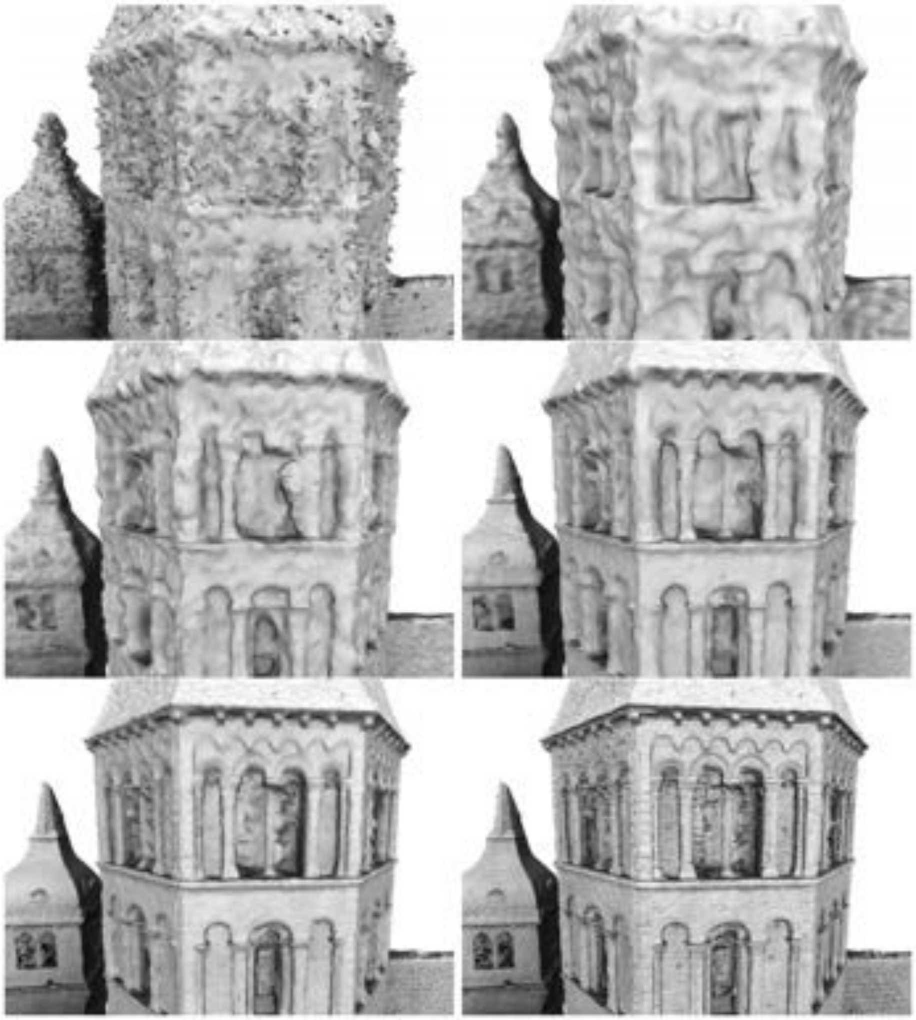
Variational surface refinement
Vu et.al. PAMI2012

THE DEPARTMENT OF COMPUTER SCIENCE & ENGINEERING 計算機科學及工程學系

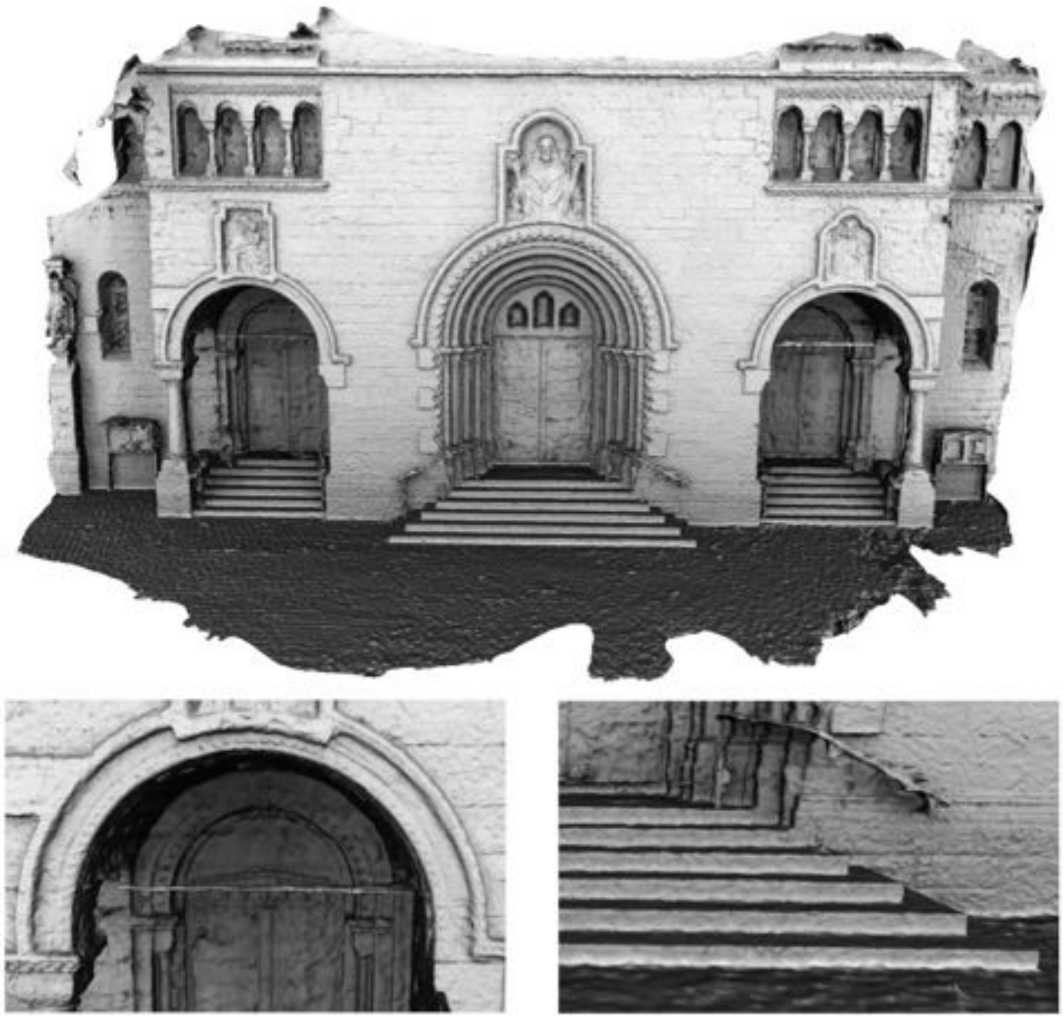
Surface refinement: formulation

	Continuous (level-set)	Discretized (triangular mesh)
Energy formulation	$\mathcal{M}(S) = \sum_i \sum_{j \neq i} \mathcal{M}_{ij}(S)\,,$ $\mathcal{M}_{ij}(S) = \underbrace{M}_{\text{similarity measure}}\vert_{\Omega_i \cap \Pi_i(S_j)} \left(\underbrace{I_i}_{\text{observed image } i}\,,\ \underbrace{I_j \circ \Pi_j \circ \Pi_{i,S}^{-1}}_{\text{reprojection image } j} \right).$	$\mathrm{E}_{\mathrm{error}}(S) = \sum_{i,j} \int_{\Omega_{ij}^S} \overbrace{h}^{\text{similarity measure}}(\underbrace{I_i}_{\text{observed image } i}, \underbrace{I_{ij}^S}_{\text{reprojection image } j})(x_i)\,\mathrm{d}x_i$
Variations/ derivative	$\left.\frac{\partial \mathcal{M}_{ij}(S + \epsilon\,\delta S)}{\partial \epsilon}\right\vert_{\epsilon=0} = -\int_{S_i \cap S_j} \left[\partial_2 M(\mathbf{x}_i) D I_j(\mathbf{x}_j) D\Pi_j(\mathbf{x}) \frac{\mathbf{d}_i}{z_i^3} \right] \left[\mathbf{N}^T \delta S(\mathbf{x}) \right] dx\,.$	$\frac{\mathrm{dE}_{\mathrm{error}}(S)}{\mathrm{d}X} = \int_S \phi(x) \sum_{i,j} \nabla \mathcal{M}_{ij}(x)\mathrm{d}x$ $= \sum_{i,j} \int_{\Omega_{ij}} \phi(x) f_{ij}(x_i)/(\mathbf{N}^T \mathbf{d}_i)\mathbf{N}\mathrm{d}x_i$
Regularization	$\mathrm{E}_{\mathrm{fair}}(S) = \int_S (\kappa_1^2 + \kappa_2^2)\,\mathrm{d}S$	Umbrella operator on mesh
	Pons et.al. IJCV2007	Vu et.al. PAMI2012

Surface refinement: results



Top to bottom: evolution of iterative refinement



Refinement recovers the fine details of the scene

Variational surface refinement
Vu et.al. PAMI2012

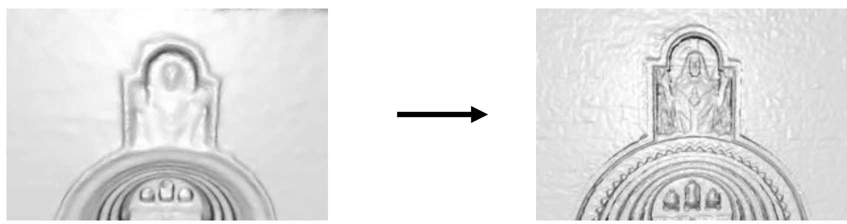
THE DEPARTMENT OF
COMPUTER SCIENCE & ENGINEERING
計算機科學及工程學系

Surface refinement: problems?

- Iterative, repeated computations of
  - visibility
  - image reprojection
  - image similarity

Surface refinement: problems?

- Iterative, repeated computations of
  - visibility
  - image reprojection
  - image similarity
- Not all regions contribute equally
  - Potential regions may gain details



  - A flat plane is still a flat plane

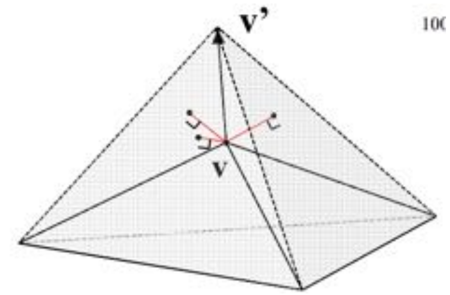
Surface refinement: adaptive refinement

1. Evaluate the importance of a vertex movement

$$gc_{\mathbf{v}} = max_{\mathbf{p} \in planes(\mathbf{v}')}\{(\mathbf{p}^t\mathbf{v})^2\}$$

$$gc_t = \frac{1}{3}\sum^{3} gc_{\mathbf{v}_i},$$

where $\mathbf{p} = [a\ b\ c\ d]^t$ represents a plane and $\mathbf{v}' = [v'_x\ v'_y\ v'_z\ 1]$.

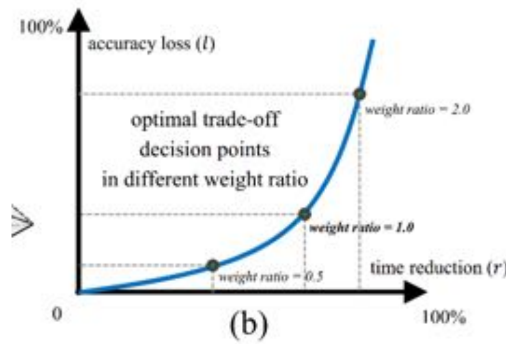


2. Optimal trade-off between accuracy & efficiency

$$u(r_o, l_o) = max_{(r,l)\in curve} u(r, l)$$

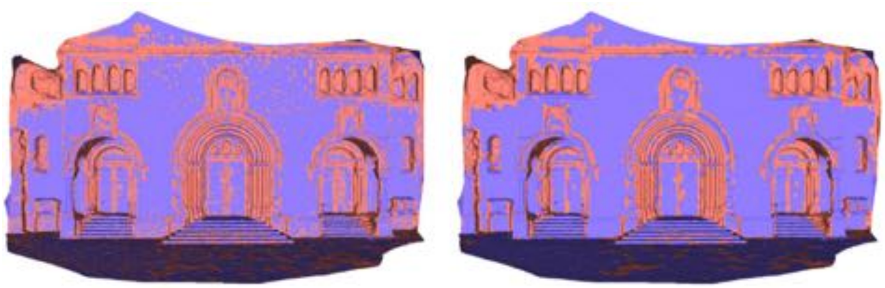
$$u(r, l) = u(r) + u(l)$$

$$= w_r \cdot r + w_l \cdot (1 - l)$$



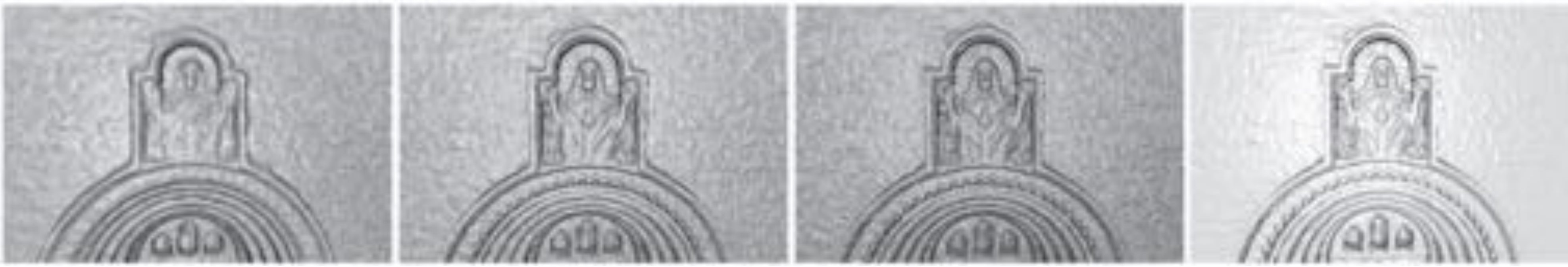
3. Graph cuts optimization

$$\mathbf{E}(f) = \mathbf{E}_{optimality}(f) + \mathbf{E}_{smoothness}(f) + \mathbf{E}_{prior}(f).$$

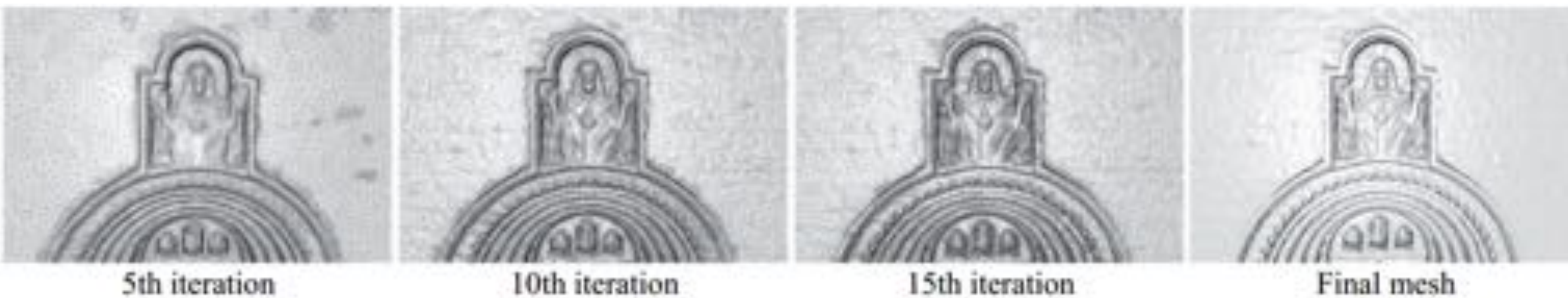


THE DEPARTMENT OF COMPUTER SCIENCE & ENGINEERING
計算機科學及工程學系

Surface refinement: adaptive refinement



Uniform refinement, Vu et.al. PAMI2012

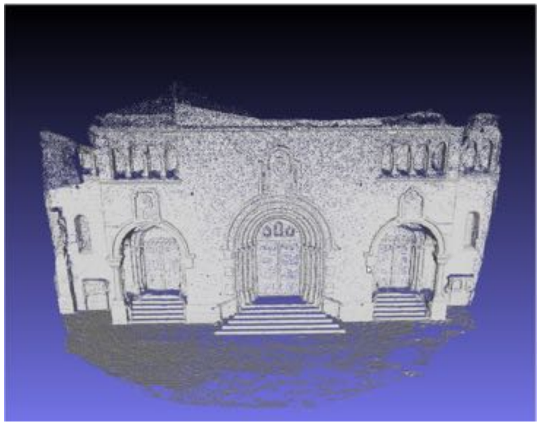


Adaptive refinement, our method

- Adaptive refinement
  - **~5x more efficient** that uniform refinement
  - much more compact mesh
  - Similar reconstruction details.

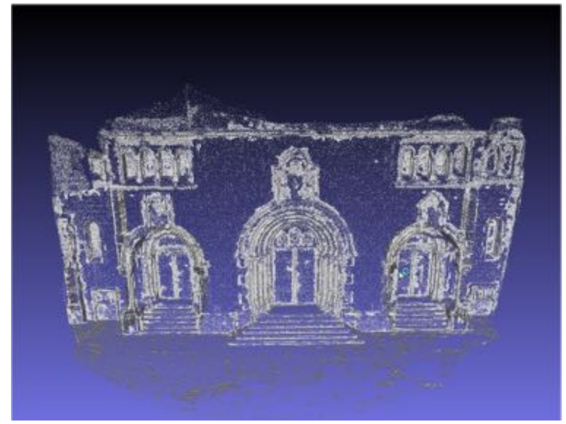
Surface refinement: adaptive refinement

Uniform refinement



2,414,767 #vertex, 4,829,450 #triangle

Adaptive refinement



817,254 #vertex, 1,592,022 #triangle

Herz-Jesu-P25

THE DEPARTMENT OF
COMPUTER SCIENCE & ENGINEERING
計算機科學及工程學系

Content

- Multi-view Stereo
  - Pairwise Stereo
  - Propagation Stereo

- Surface generation
  - Surface extraction
  - Surface refinement

- Texture mapping
  - View selection
  - Color adjustment and blending

THE DEPARTMENT OF COMPUTER SCIENCE & ENGINEERING
計算機科學及工程學系

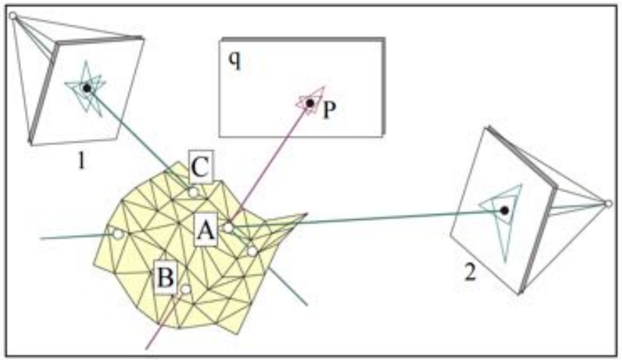
Texture mapping (for 3D reconstruction)

- Texturing a point cloud
  - Trivial, directly fetch color from image for every 3D point
- Texturing a triangular mesh surface
  - Non-trivial
  - Triangle view selection
    - For each triangle, select its best image for texture (data term)
    - Minimize number of texture seam (smoothness term)
  - Color adjustment and blending
    - Alleviate the artifacts at seams between two texture patches (atlas), due to inaccurate camera or imbalance illumination

Texture mapping: Triangle view selection

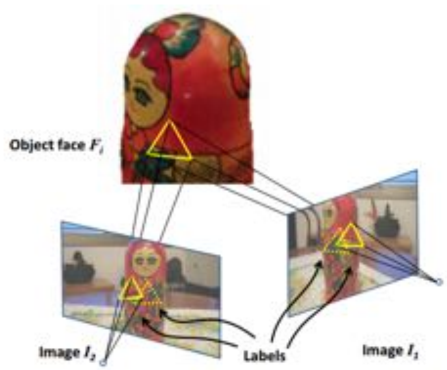
- For each triangle, select multiple view

blending multiple image
Callieri et.al. CG2008

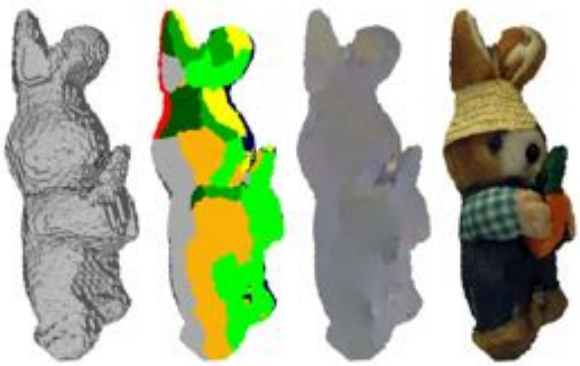


Color interpolation
Grammatikopoulos et.al. ISPRS2007

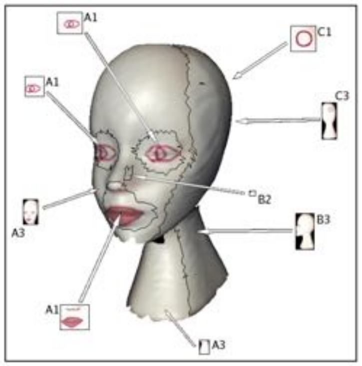
- For each triangle, select one best view



Seam optimization
Gal et.al. CG2010



MRF+Poisson blending
Lempitsky & Ivanov. CVPR2007



Continuous color optimization
Velho & Sossai. CVPR2007

THE DEPARTMENT OF
COMPUTER SCIENCE & ENGINEERING
計算機科學及工程學系

Texture mapping: Triangle view selection

- Triangle view selection as a MRF problem

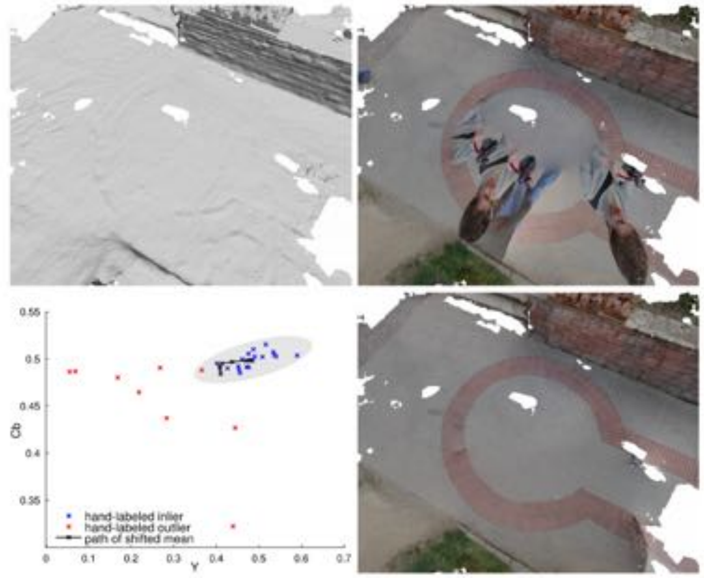
$$E(l) = \sum_{F_i \in Faces} E_{data}(F_i, l_i) + \sum_{(F_i, F_j) \in Edges} E_{smooth}(F_i, F_j, l_i, l_j),$$

  - Each triangle selects a best view
  - Neighboring triangles select same view

- Solved by alpha expansion

Texture mapping: Triangle view selection

- Difficulties:
  - dynamic objects



Handle by photo-consistency check and outlier removal

  - out-of-focus image

Handle by weighting the gradient magnitude

Large-scale texturing. Waechter et.al. ECCV2014

Texture mapping: Color adjustment and blending

- Let f be the original intensity, g be the adjustment (gain)

$$\arg\min_{g} \sum_{v_{left/right}} (f_{v_{left}} + g_{v_{left}} - (f_{v_{right}} + g_{v_{right}}))^2 + \frac{1}{\lambda}\sum_{i,j}(g_i - g_j),$$

•Minimize the difference of neighboring intensity
•Minimize the imposed adjustment (be as much original as possible)

- Blending
  - Alpha blending causes ghosting effect
  - Poisson blending:

Poisson Image Editing
Perez et.al. SIGGRAPH2003

THE DEPARTMENT OF COMPUTER SCIENCE & ENGINEERING 計算機科學及工程學系

Unsolved problems and future work

- **local camera optimization** for MVS
  - SfM computes globally optimized camera, which is not locally optimized
  - Inaccurate camera is detrimental
  - Related work: (Zhu et.al. CVPR2014)
- Simultaneously surface **refinement** + **texturing**
  - Repeated computations of depth, visibility, etc.
  - Not and end-to-end optimization
  - Optimize the surface **geometry** and **textures,** for the rendering photo-realism
- **Fine-scale object** reconstruction (such sticks, wire)
  - Due to sparse point cloud at that objects
  - Can be improved by more structural point cloud, such as adding connectivity information