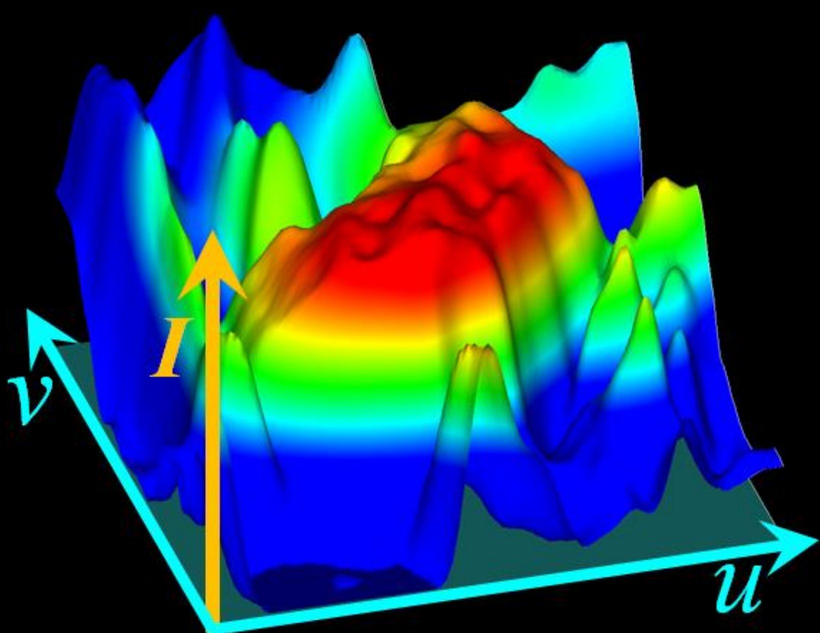
Eurographics 2013
May 6-10, Girona (Spain)

Bilateral Hermite Radial Basis Function for Contour-based Volume Segmentation



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1. RIKEN
2. National Cancer Center

Introduction

- Volume segmentation is fundamental
  - Extract information / Construct models

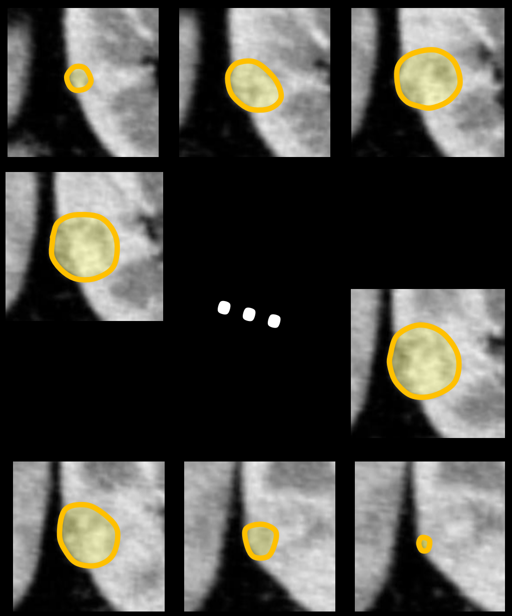
User interaction is necessary to segment ambiguous regions

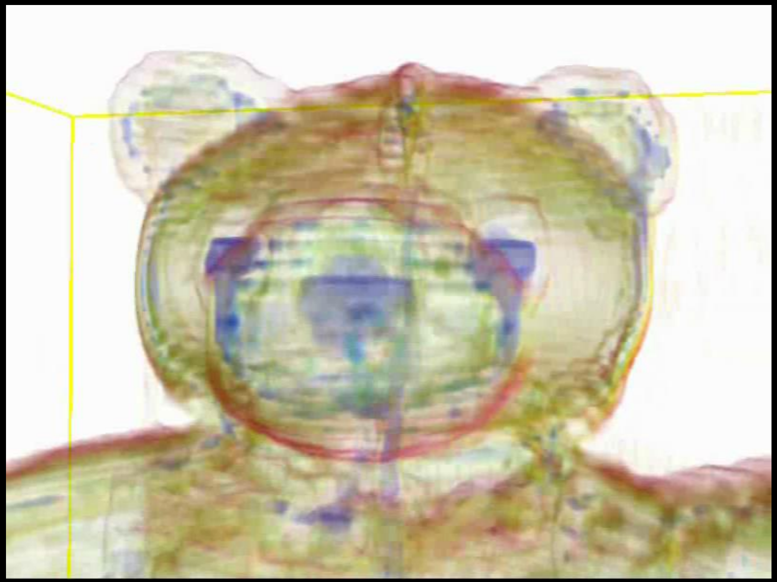
Tumor in CT

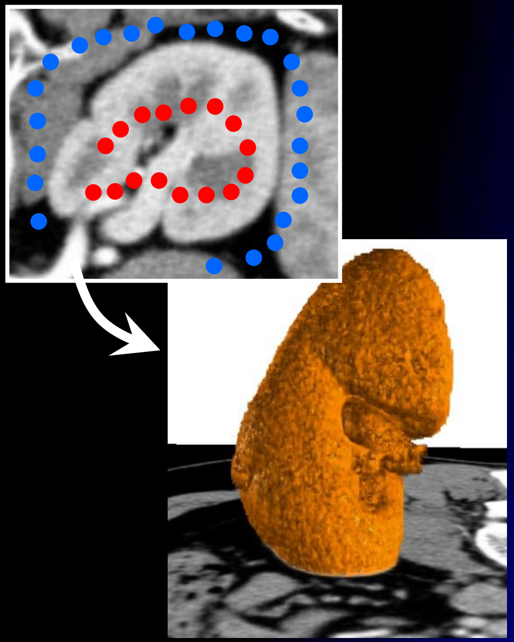
Muscle in MRI

Organs in ISM

Interactive volume segmentation approaches







GraphCut, Region Growing, Active contours

Slice-by-slice

Time consume☹

Accurate

Contour-based

Moderate time

Accurate

Seed-based

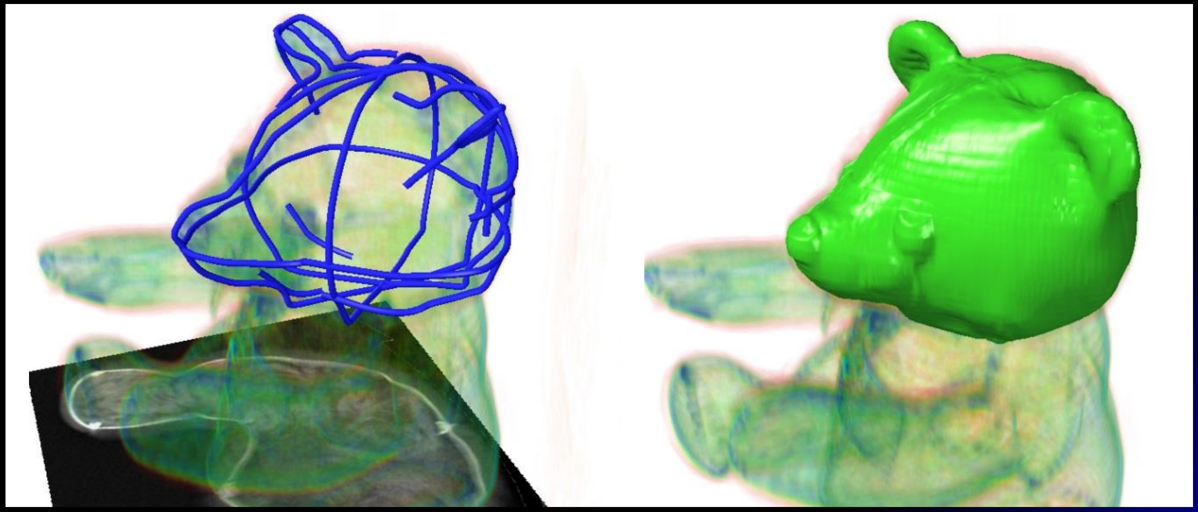
Easy & quick

May cause error☹

Our goal

- Present a contour-based segmentation technique for ambiguous ROIs

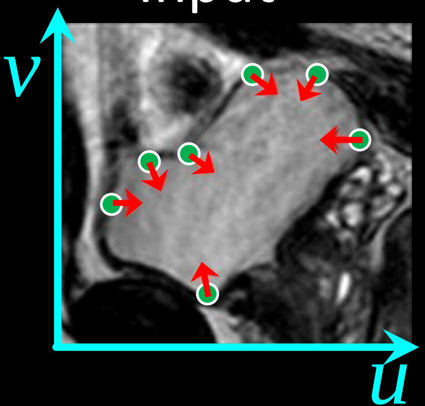
- Generate segmentation boundary that
  - -- pass through all contours
  - -- have smooth shape around blurred image area
  - -- fit to image edges around area with clear edges



Our approach

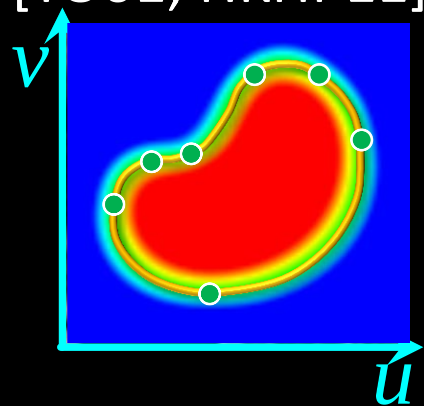
- New technique based on implicit surface reconstruction

Input



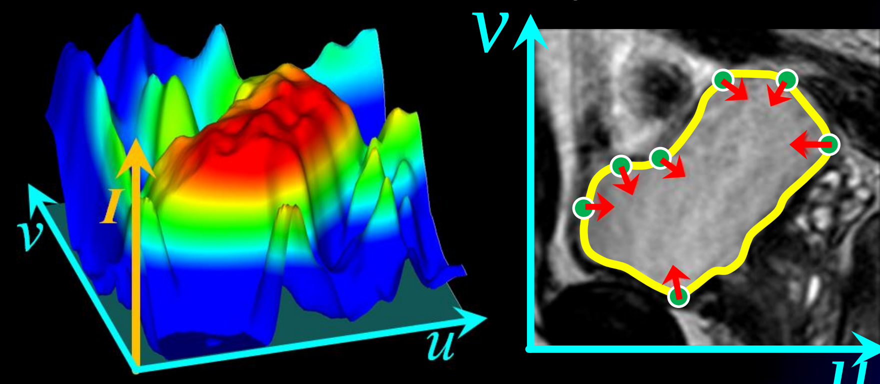
Constraints on 2D image

[TO01; HKHP11]



Scalar field on image

Our technique



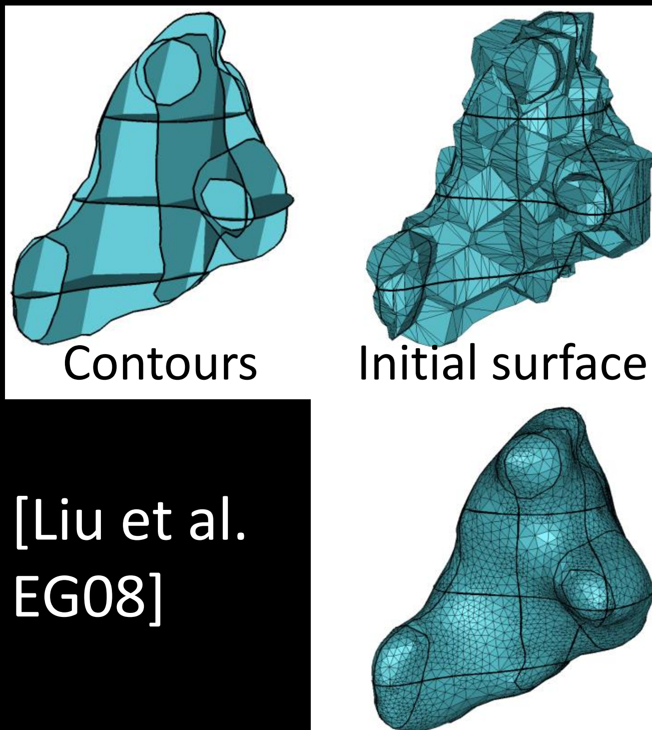
Scalar field on image manifold in bilateral domain

- B-HRBF: New formulation to compute scalar field in bilateral domain

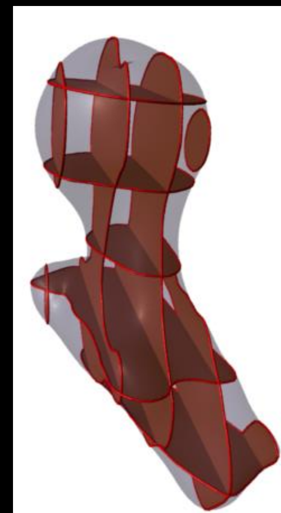
$$f(\bar{\mathbf{p}}_i) = 0, \quad \nabla f(\bar{\mathbf{p}}_i) = \mathbf{normal}$$

$$f(\bar{\mathbf{x}}) = \sum_i \left(\alpha_i \phi(\bar{\mathbf{x}} - \bar{\mathbf{p}}_i) - \boldsymbol{\beta}_i \cdot \nabla\phi(\bar{\mathbf{x}} - \bar{\mathbf{p}}_i)\right) + \mathbf{a} \cdot \bar{\mathbf{x}} + b$$

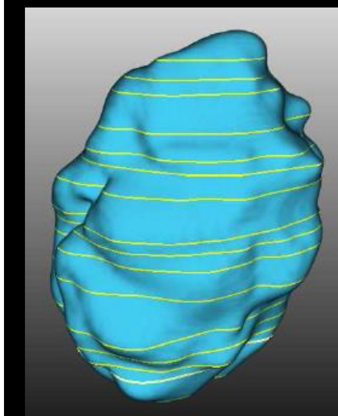
Previous contour-based technique



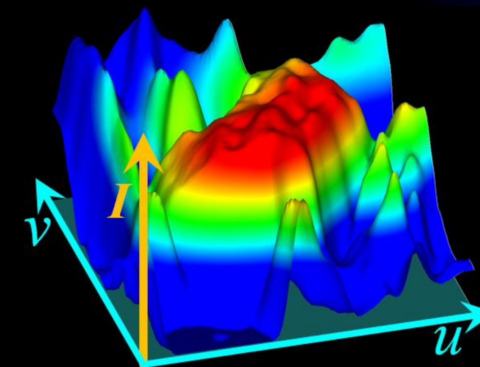
[Liu et al. EG08]



[Turk et. al. SIGGRAPH 01]



[Heckel *et. al.* VCBM 11]

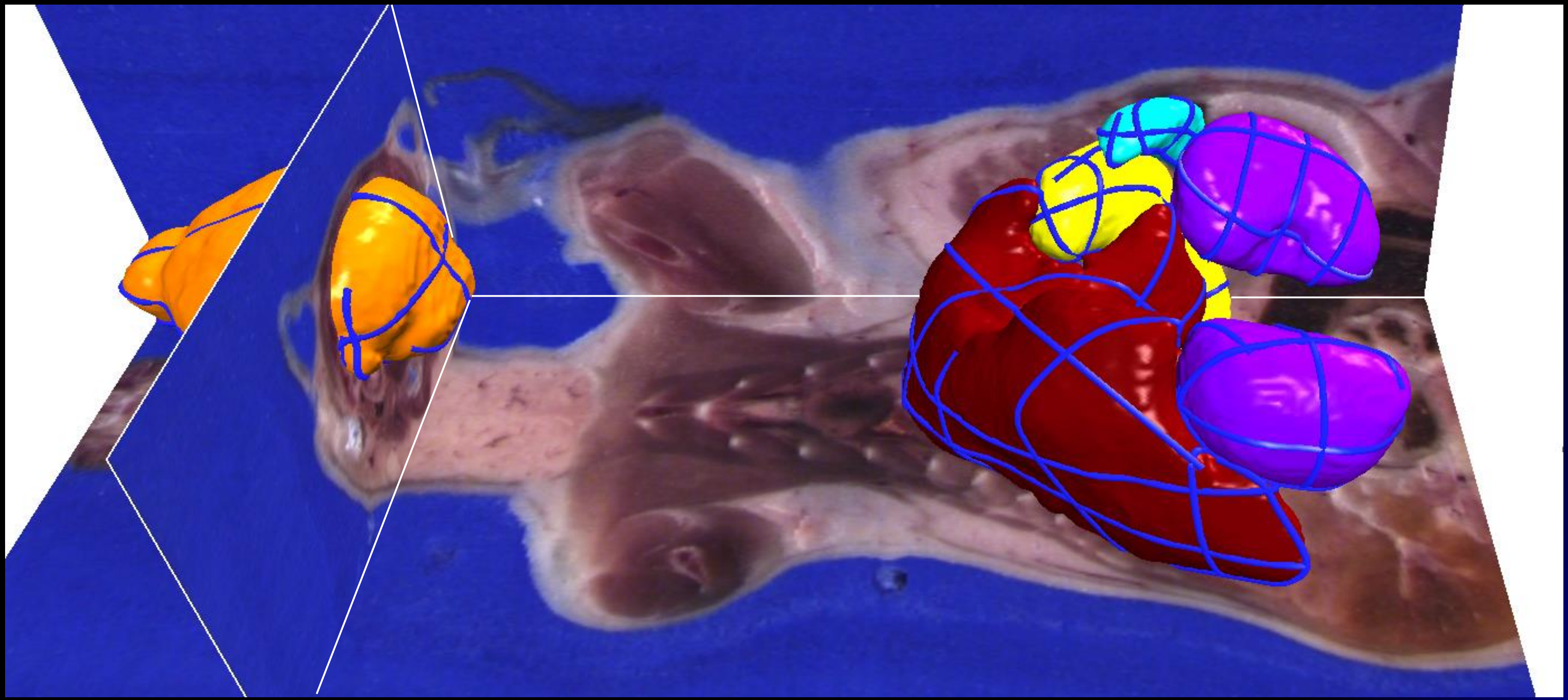


Generalized Volonoi Diagram

Implicit surface reconstruction

Our B-HRBF

	Generalized Volonoi Diagram	Implicit surface reconstruction	Our B-HRBF
Pass contours	✓	✓	✓
Smooth shape	✓	✓	✓
Fit image edge	☹	☹	✓



Demo

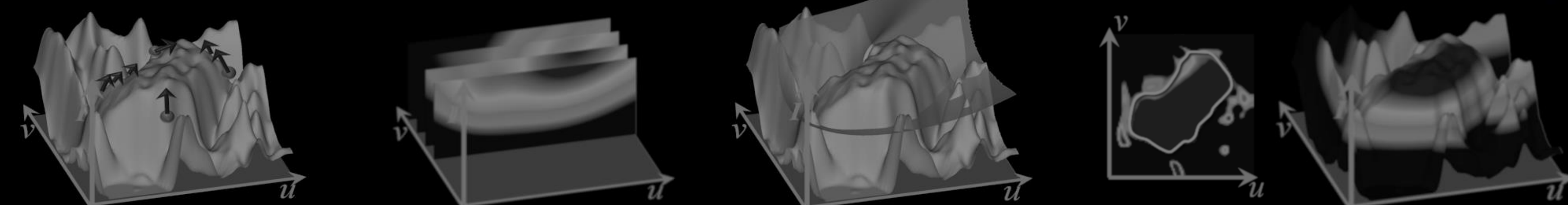
Video
(backup)

B-HRBF segmentation

$\boxed{\text{Overview}}$

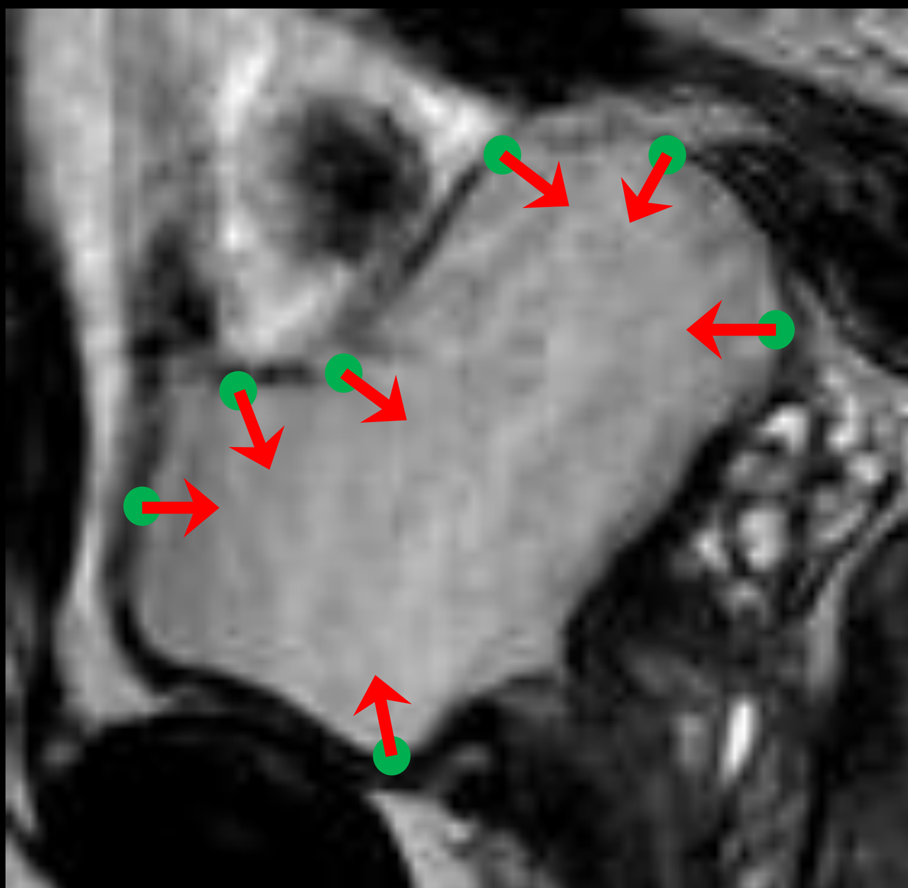
Gradient constraint

Contours → constraint points & normals



1. Image Manif　2. B-HRBF　3. Intersection　4. Zero-set on IM

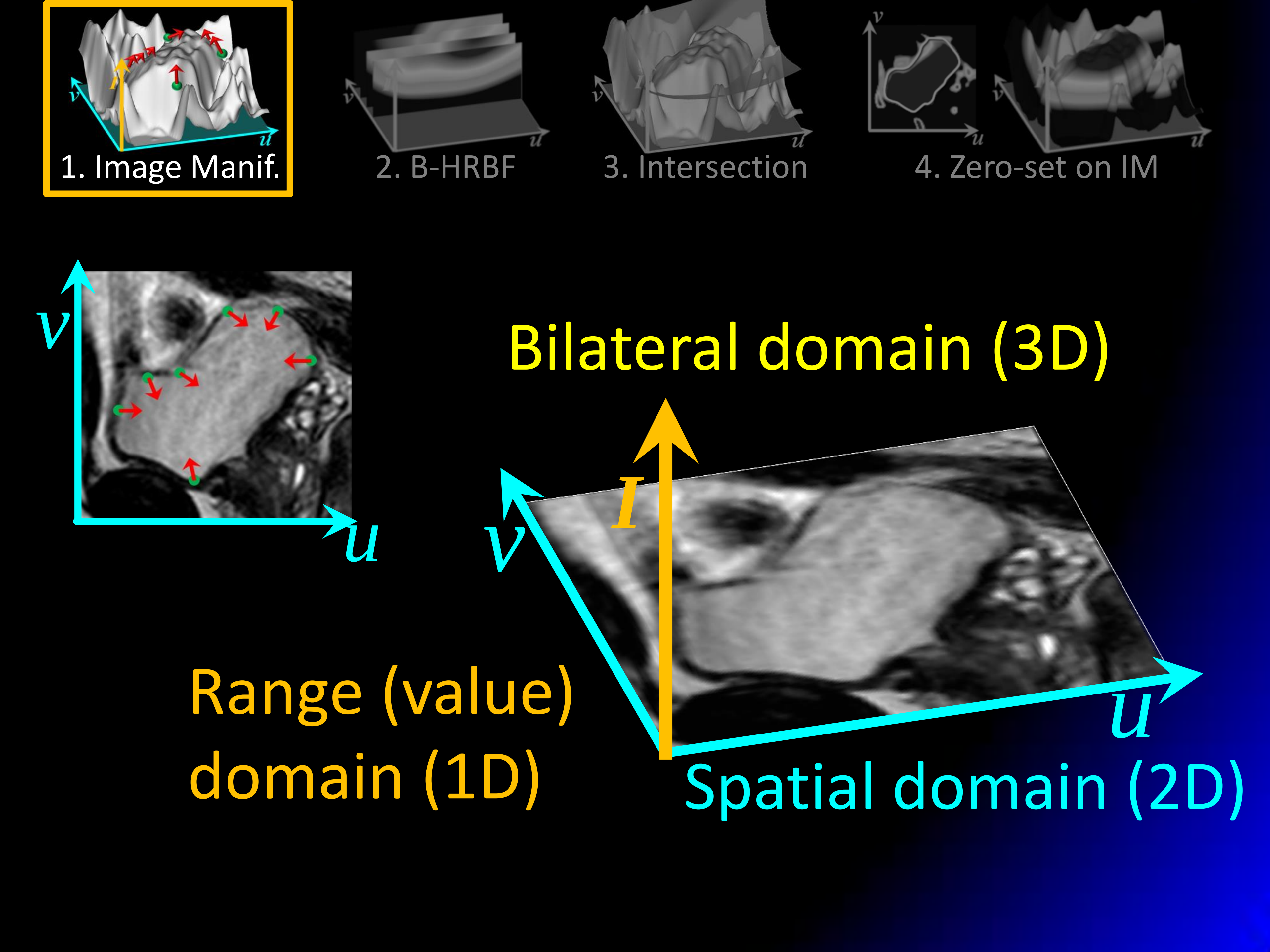
2D gray scale image



Constraint

- points $\mathbf{p}_i$
- normals $\mathbf{n}_i$

of boundary surface
(curve in 2D)



1. Image Manif.
2. B-HRBF
3. Intersection
4. Zero-set on IM
v
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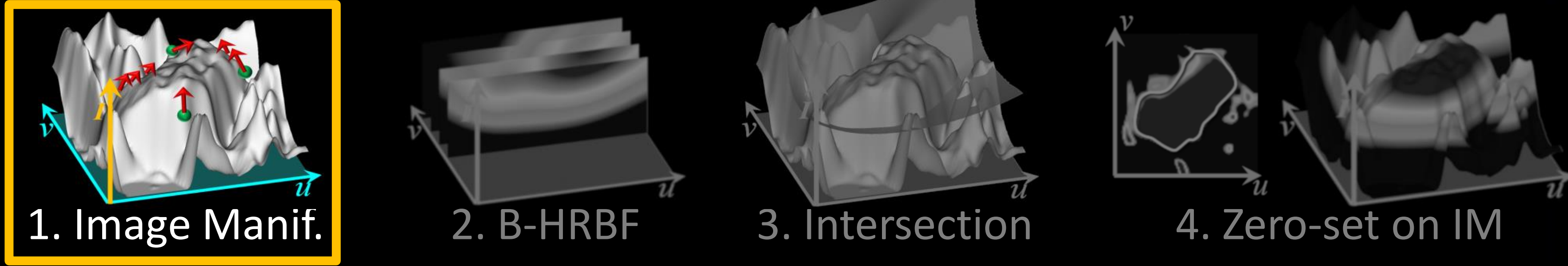
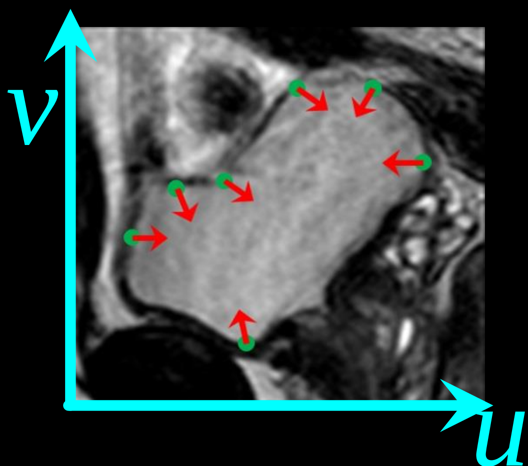
Bilateral domain (3D)
I
v
u
Range (value)
domain (1D)
Spatial domain (2D)





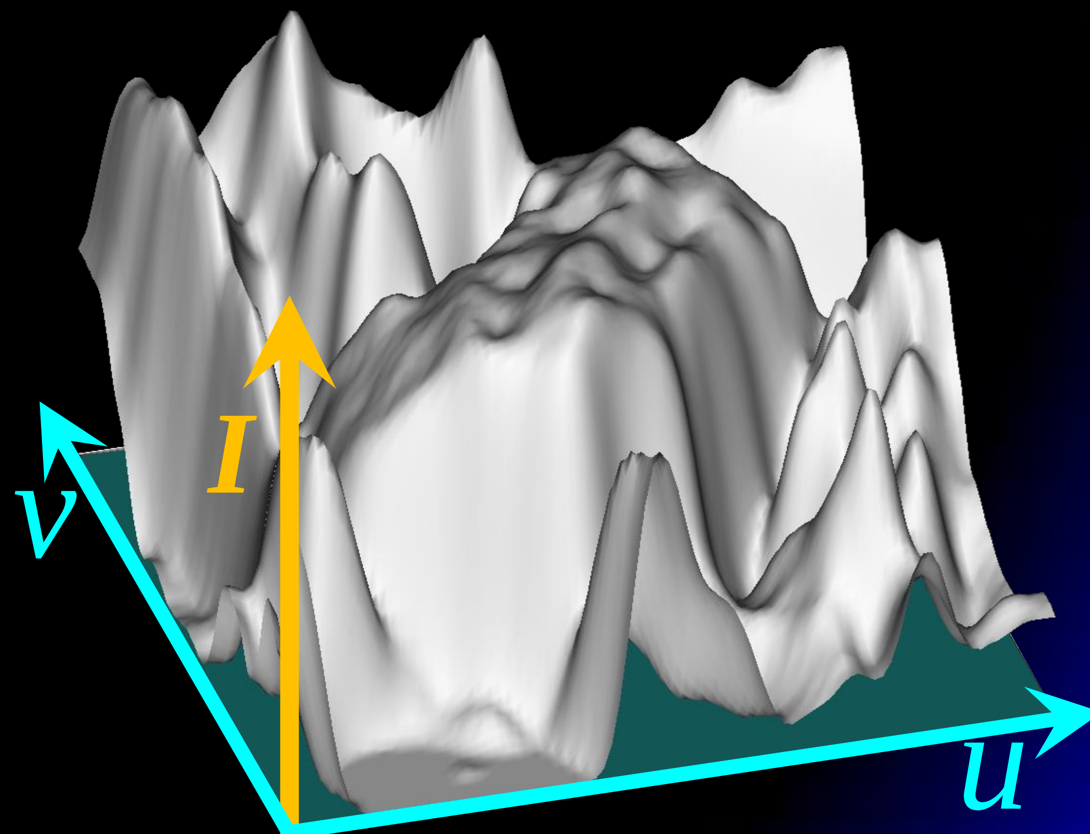
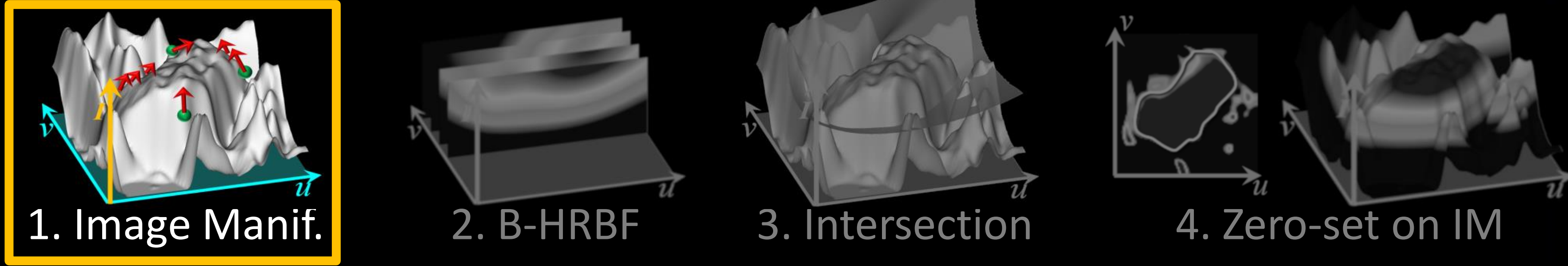
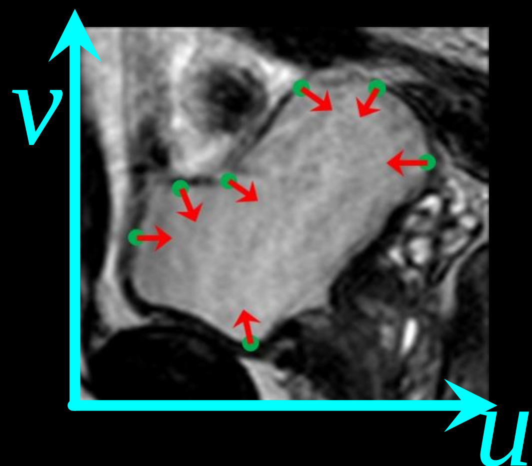
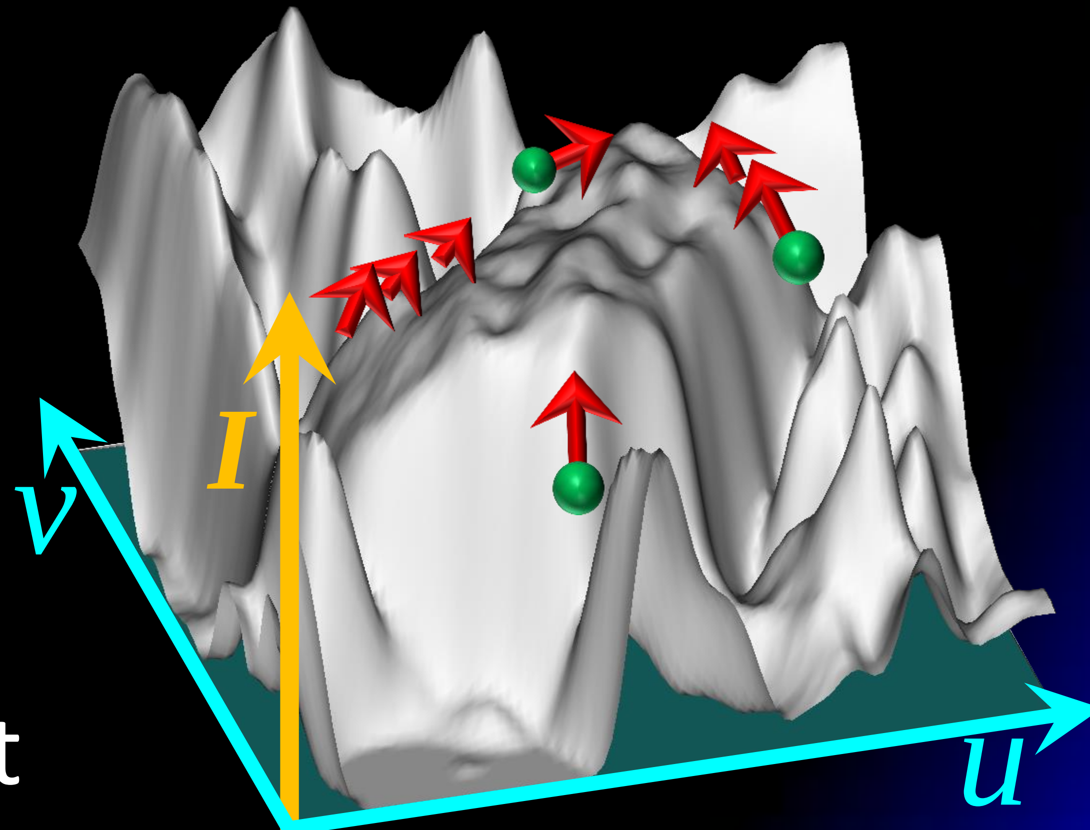


Image Manifold $\mathbf{r}(\mathbf{x}) = \begin{pmatrix} \mathbf{x} \\ w^c I(\mathbf{x}) \end{pmatrix}$





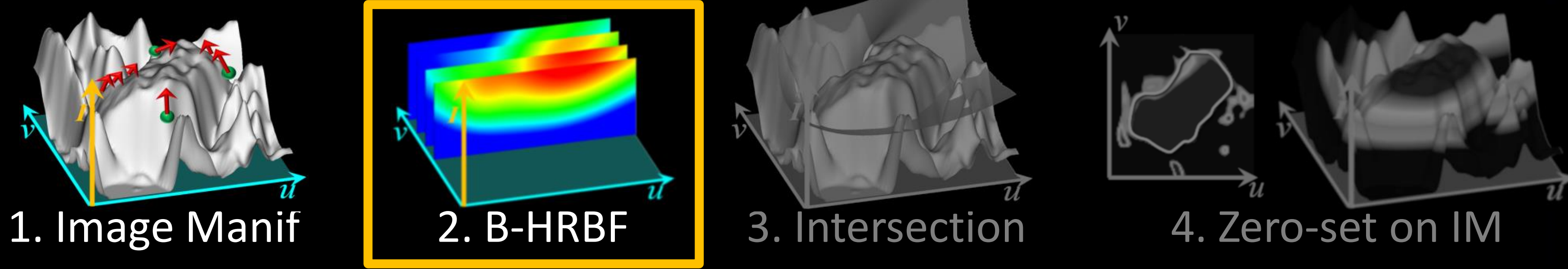


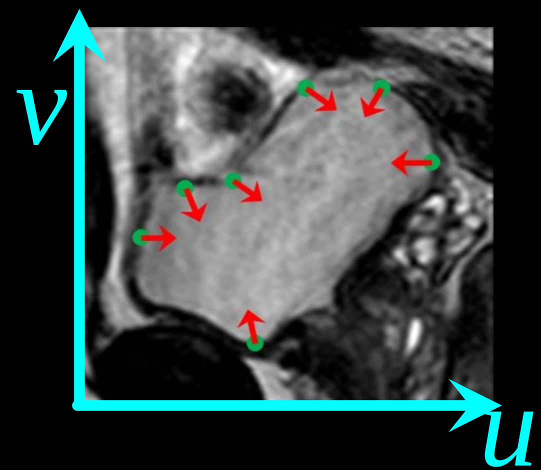
Map constraint

points $\mathbf{p}_i \rightarrow \bar{\mathbf{p}}_i = \mathbf{r}(\mathbf{p}_i)$

normals $\mathbf{n}_i \rightarrow \bar{\mathbf{n}}_i = \mathbf{J}\mathbf{n}_i / ||\mathbf{J}\mathbf{n}_i||$

J : Jacobian of r

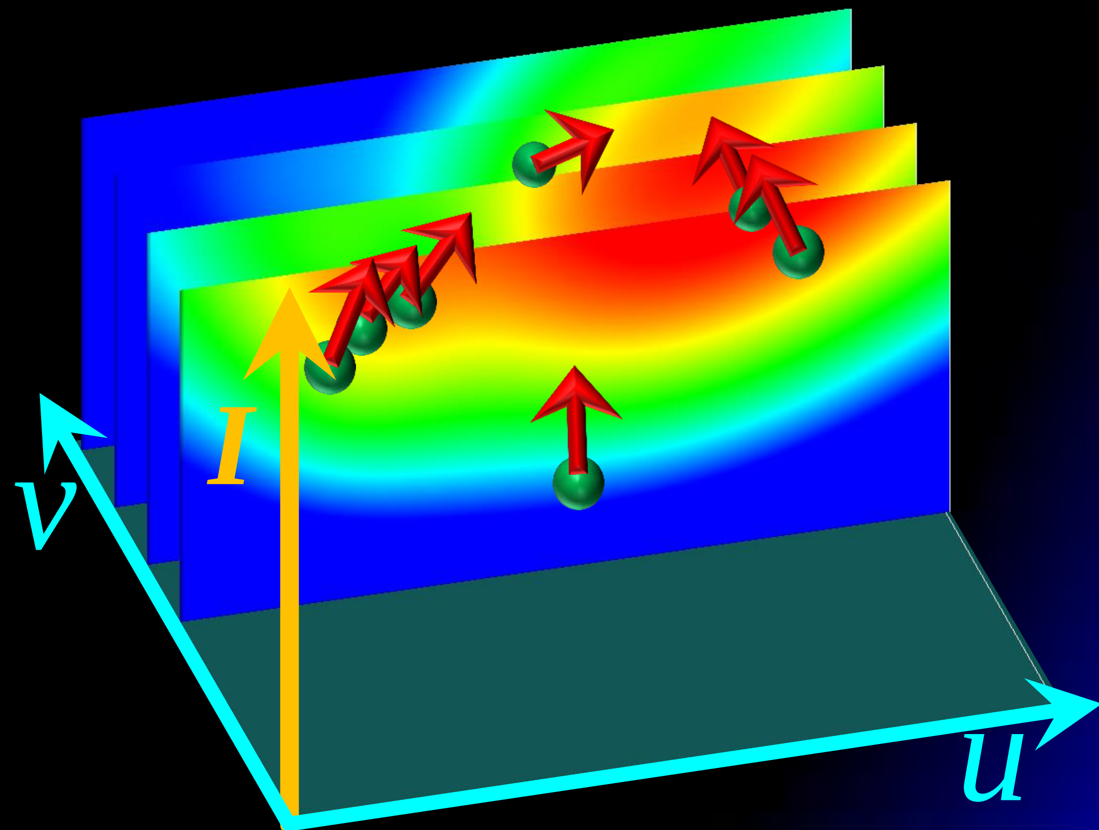




Scalar field $f(\bar{\mathbf{x}})$

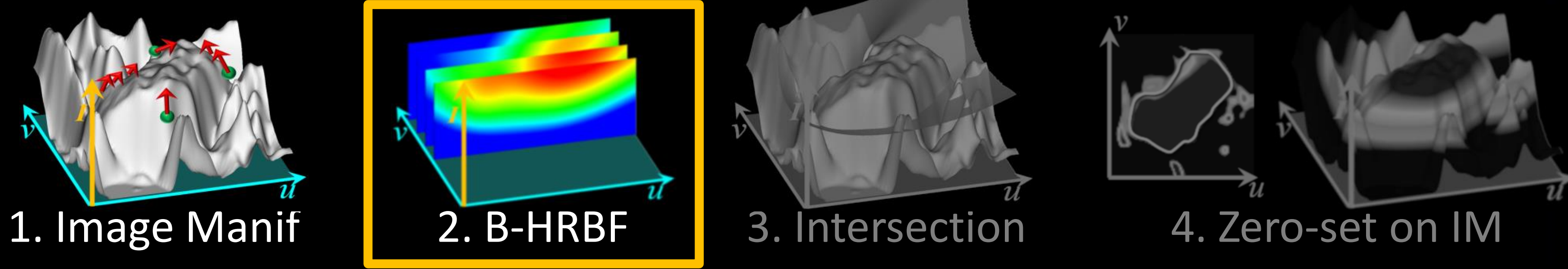
$$f(\bar{\mathbf{p}}_i) = 0$$

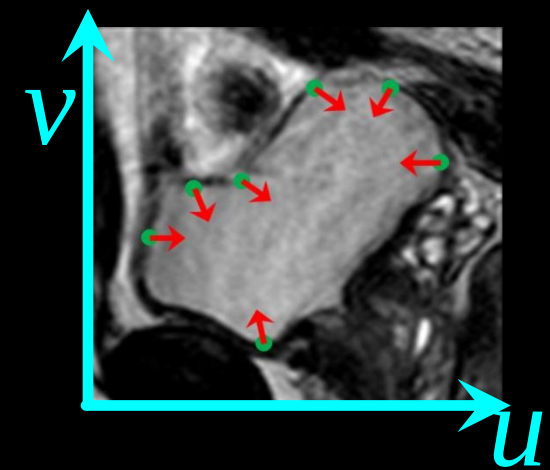
$$\nabla f(\bar{\mathbf{p}}_i) = \textbf{normal}$$



Bilateral-HRBF

$$f(\bar{\mathbf{x}}) = \sum_i \left(\alpha_i \phi(\bar{\mathbf{x}} - \bar{\mathbf{p}}_i) - \boldsymbol{\beta}_i \cdot \nabla\phi(\bar{\mathbf{x}} - \bar{\mathbf{p}}_i)\right) + \mathbf{a}\bar{\mathbf{x}} + b$$

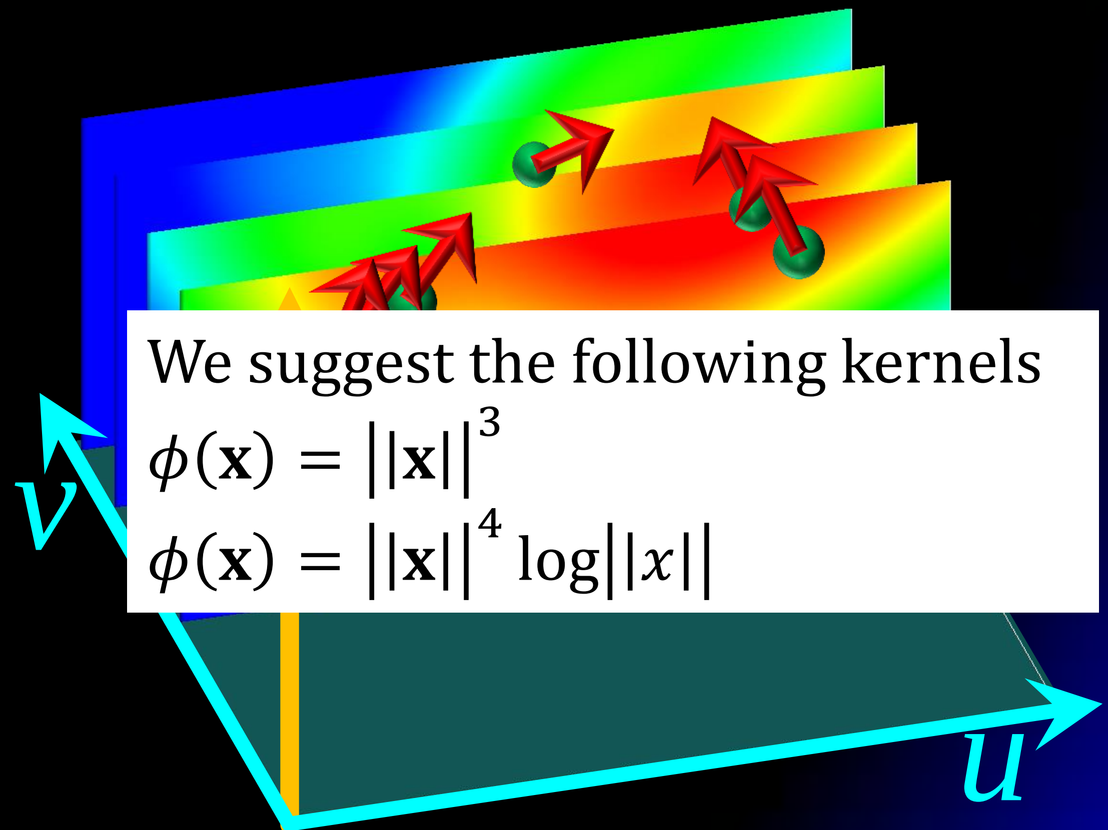




Scalar field $f(\bar{\mathbf{x}})$

$$f(\bar{\mathbf{p}}_i) = 0$$

$$\nabla f(\bar{\mathbf{p}}_i) = \mathbf{normal}$$



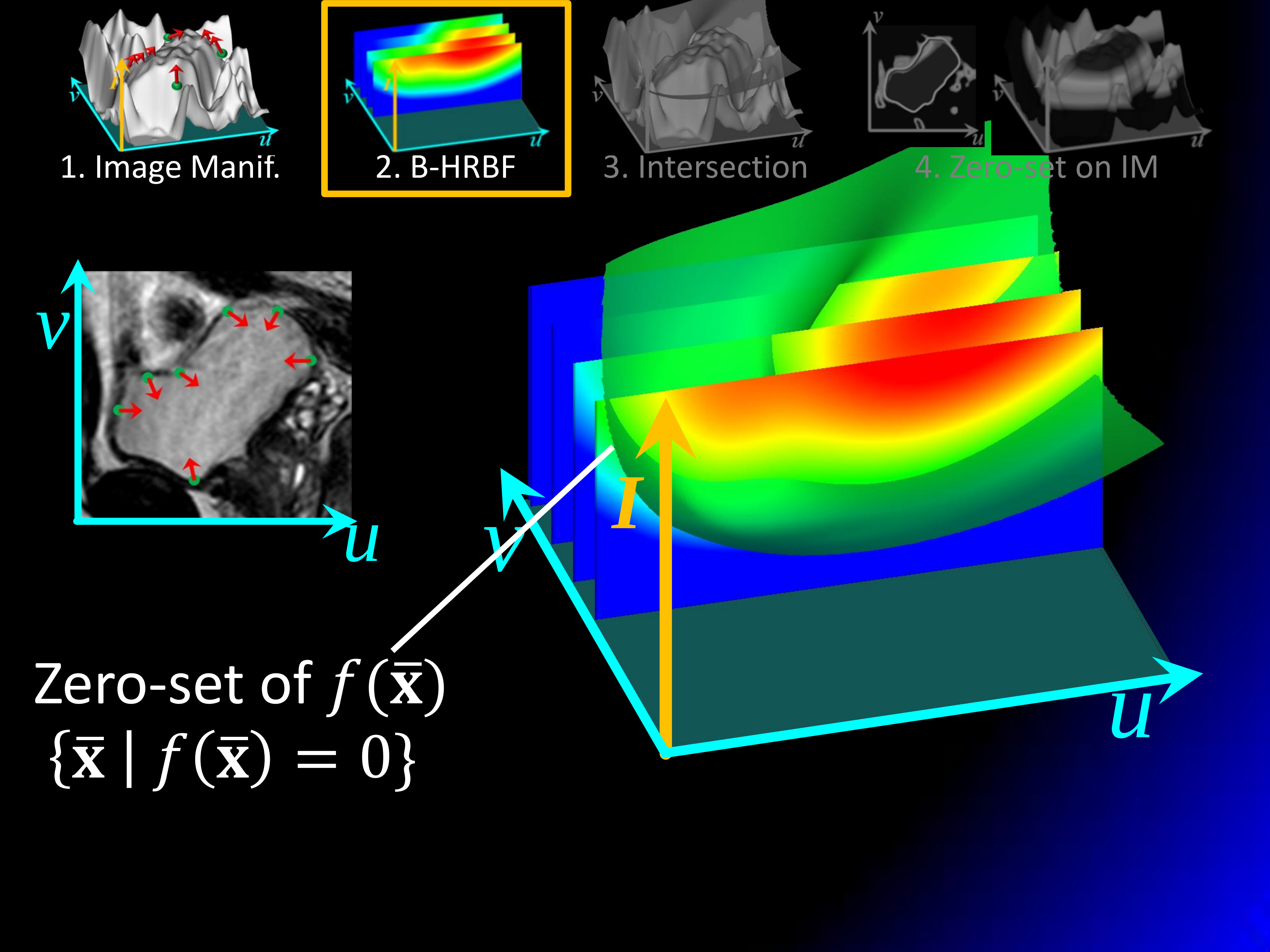
We suggest the following kernels

$$\phi(\mathbf{x}) = ||\mathbf{x}||^3$$

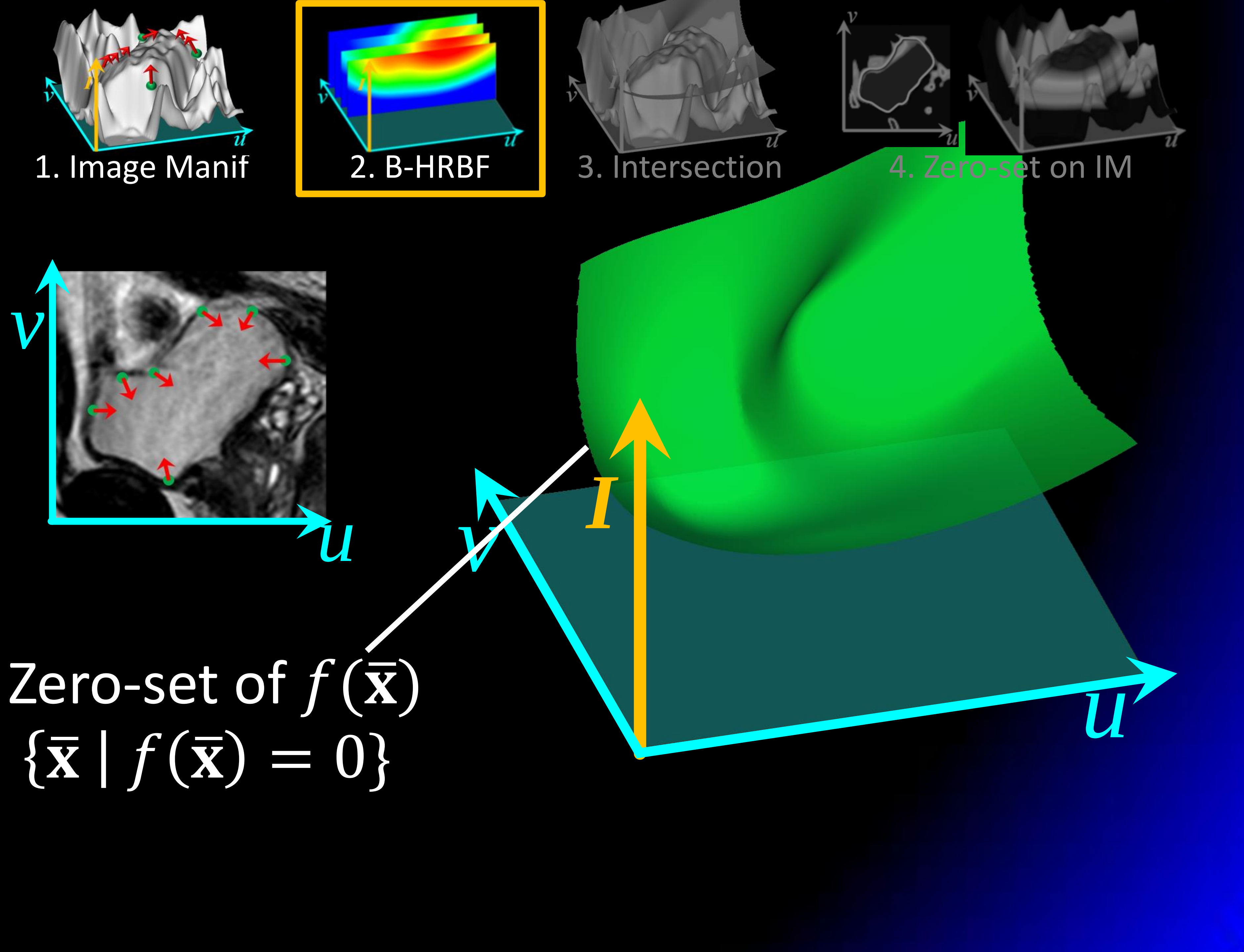
$$\phi(\mathbf{x}) = ||\mathbf{x}||^4 \log||x||$$

Bilateral-HRBF

$$f(\bar{\mathbf{x}}) = \sum_i (\alpha_i \phi(\bar{\mathbf{x}} - \bar{\mathbf{p}}_i) - \boldsymbol{\beta}_i \cdot \nabla\phi(\bar{\mathbf{x}} - \bar{\mathbf{p}}_i)) + \mathbf{ax} + b$$



1. Image Manif.
2. B-HRBF
3. Intersection
4. Zero-set on IM
v
u
I
Zero-set of $f(\bar{\mathbf{x}})$
$\{\bar{\mathbf{x}} \mid f(\bar{\mathbf{x}}) = 0\}$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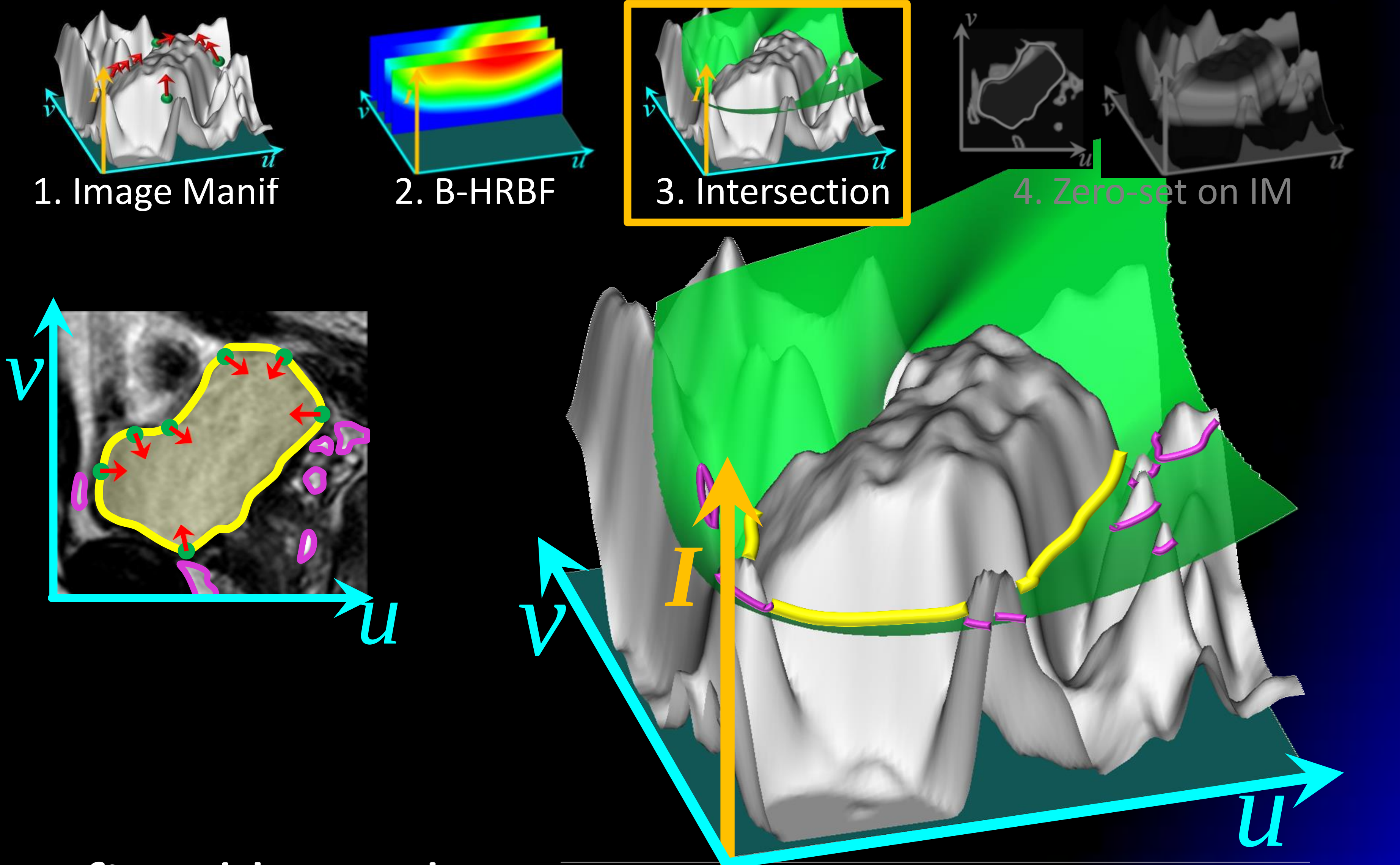
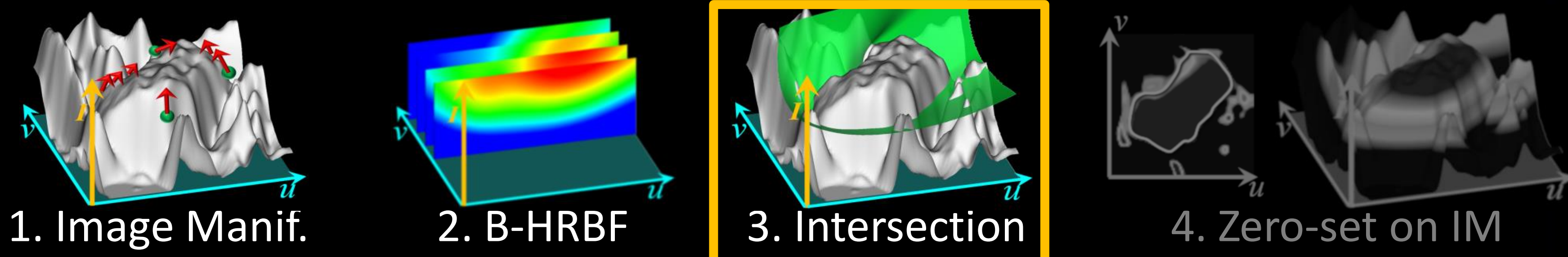
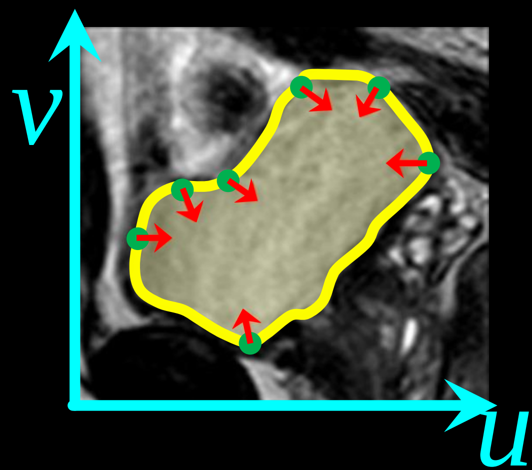
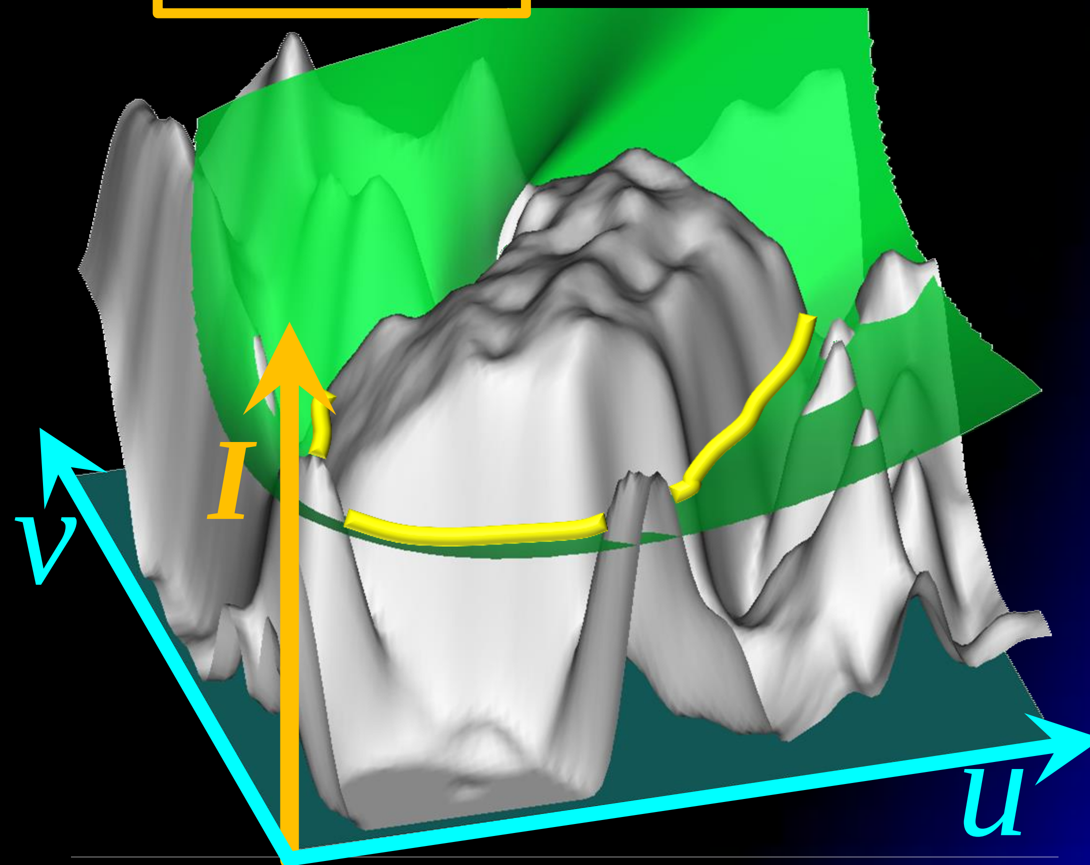


Defined boundary as intersection zero-set of $f(\bar{\mathbf{x}})$ & Image manifold



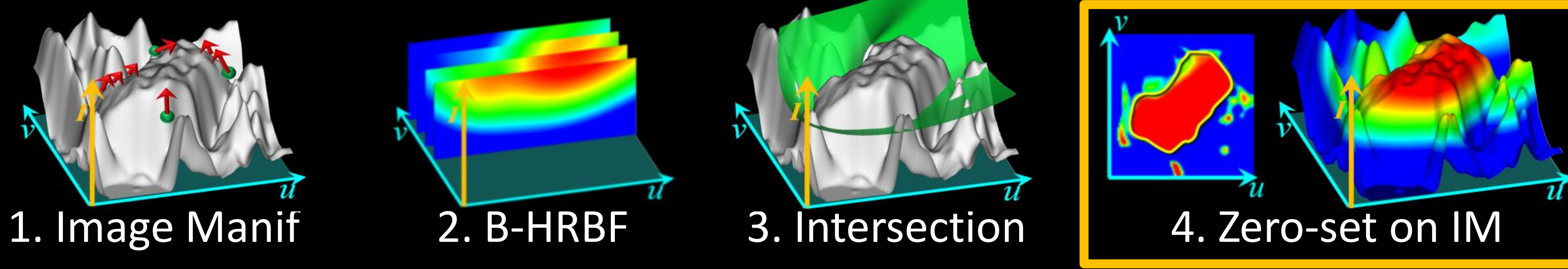


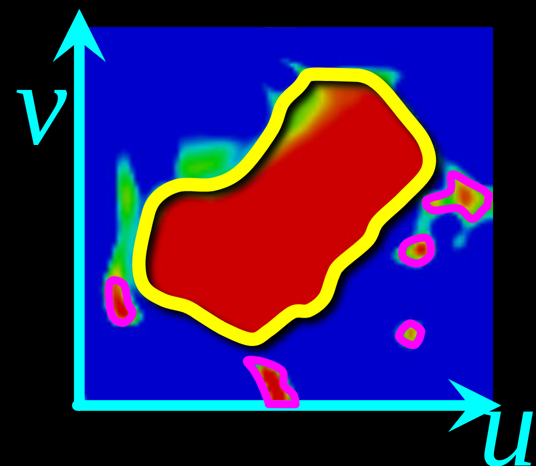


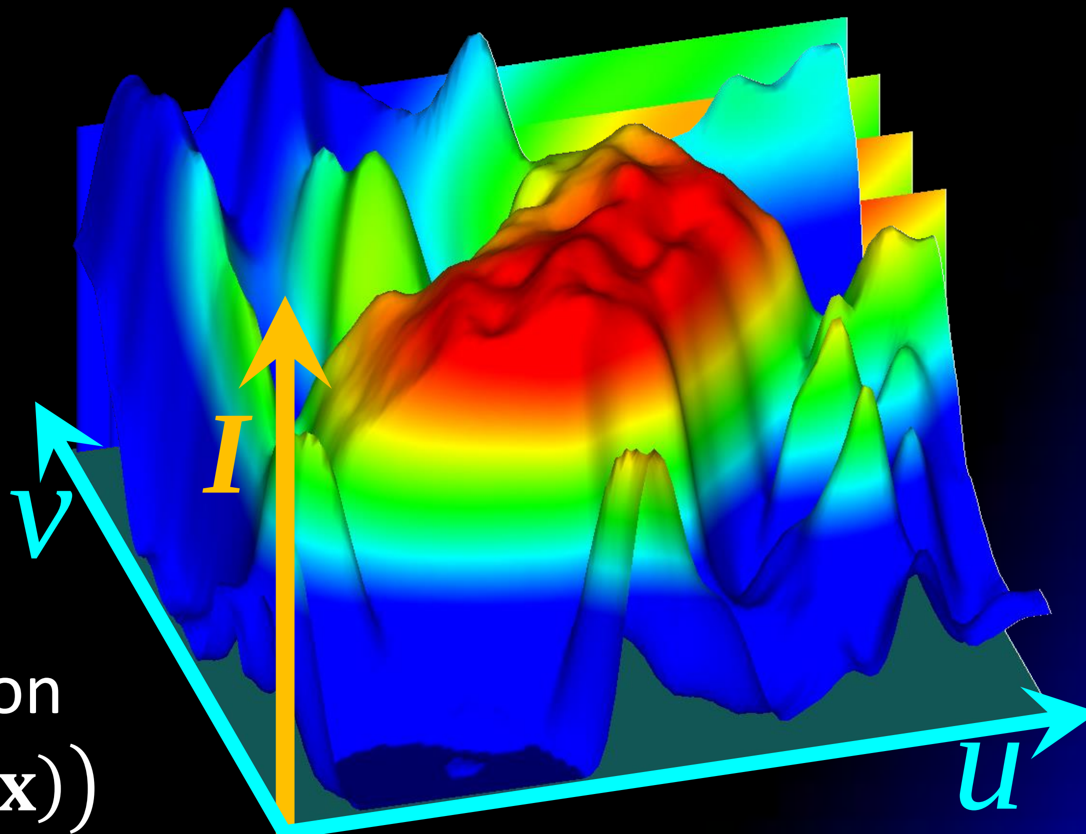
Edge fitting effect

Image edges form steep slopes in image manifold

Intersection of zero-set and image manifold often occur





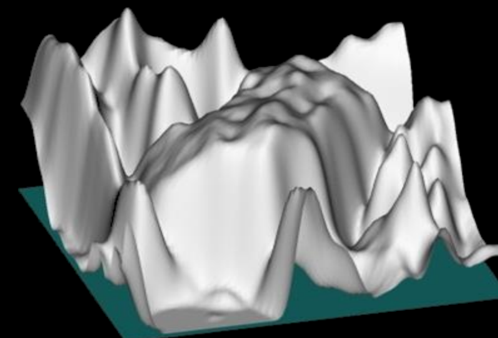


+ Evaluate scalar field on image manifold $f\big(\mathbf{r}(\mathbf{x})\big)$

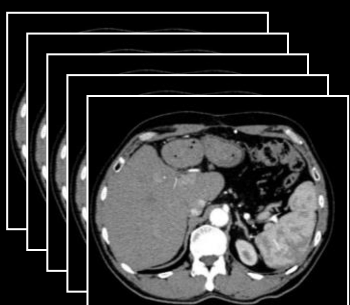
+ Extract zero set on image manifold $\{\mathbf{x}|f\big(\mathbf{r}(\mathbf{x})\big)=0\}$

+ Apply surface tracking marching cubes [SFYC*96]

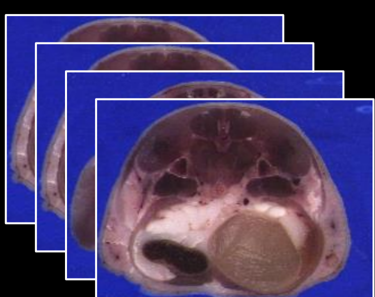
s-D r-ch Image → s-manifold in s+rD



2D grayscale → 2-manifold in (2+1)D



3D grayscale → 3-manifold in (3+1)D



3D RGB → 3-manifold in (3+3)D

B-HRBF segmentation

Overview

$\boxed{\text{Gradient constraint}}$

Contours → constraint points & normals

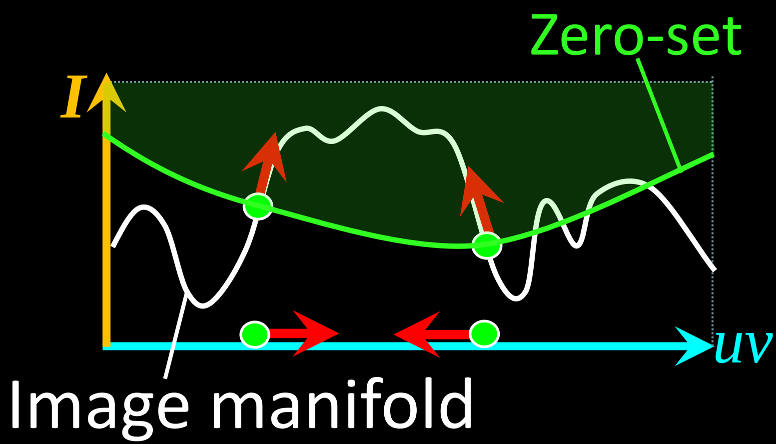
$$f(\bar{\mathbf{p}}_i) = 0$$

$$\boxed{\nabla f(\bar{\mathbf{p}}_i) = \mathbf{normal}}$$

B-HRBF

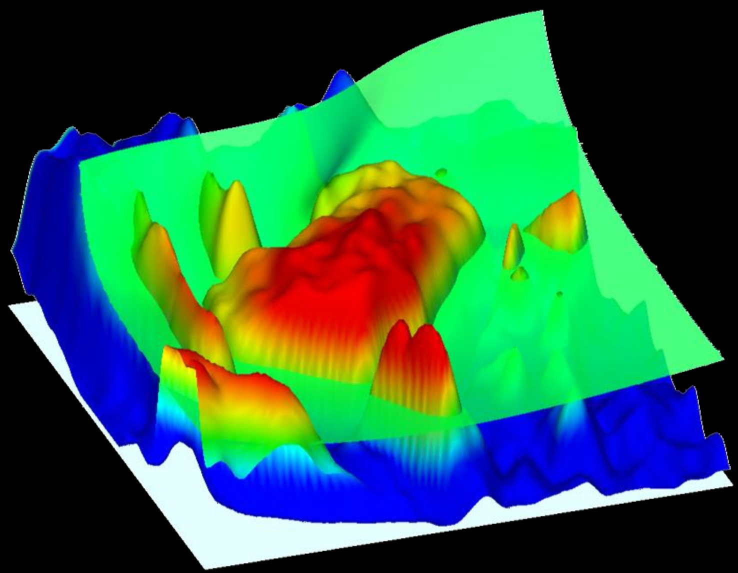
$$f(\bar{\mathbf{x}}) = \sum_i \left(\alpha_i \phi(\bar{\mathbf{x}} - \bar{\mathbf{p}}_i) - \boldsymbol{\beta}_i \cdot \nabla\phi(\bar{\mathbf{x}} - \bar{\mathbf{p}}_i)\right) + \mathbf{a}\bar{\mathbf{x}} + b$$

$$\nabla f(\bar{\mathbf{p}}_i) = \frac{\mathbf{J}\mathbf{n}_i}{||\mathbf{J}\mathbf{n}_i||}$$



- Normal is on tangent plane of image manifold
- Zero-set becomes near orthogonal to steep slopes of image manifold
- Intersection between zero-set and slopes of image manifold often occur

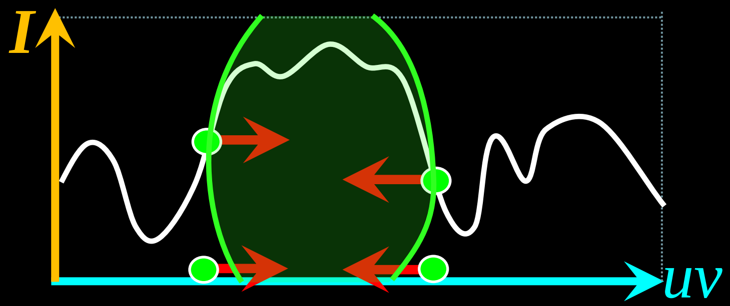
→ Edge fitting effect

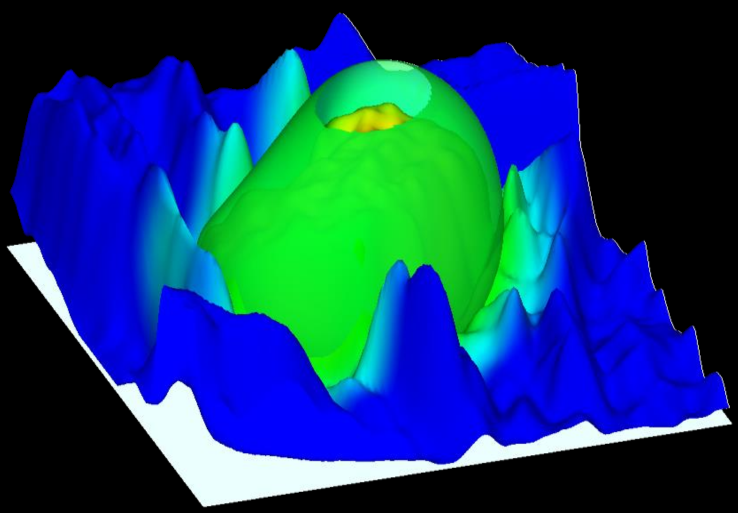


$$\nabla f(\overline{\mathbf{p}}_i) = \begin{pmatrix} \mathbf{n}_i \\ \mathbf{0} \end{pmatrix}$$

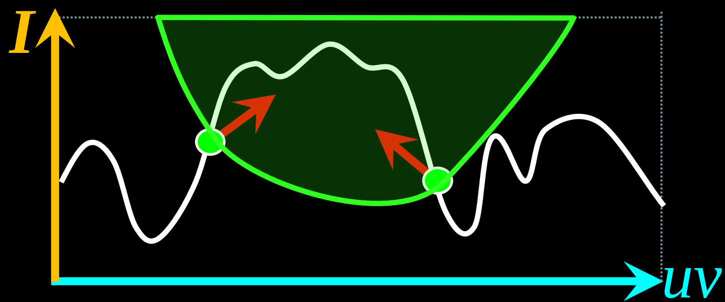
- Translate the spatial domain normal
- Zero-set is near orthogonal to spatial domain
- The shape of image manifold is unimportant

→ Smoothing effect



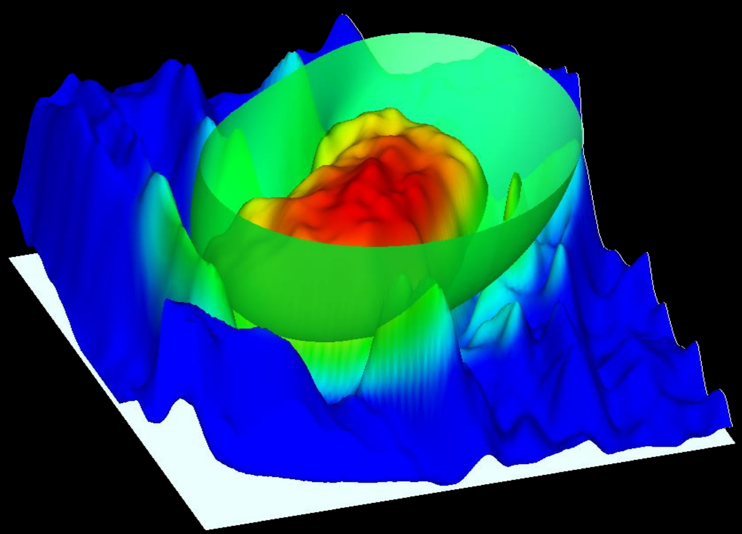


$$\nabla f(\bar{\mathbf{p}}_i) = \alpha \frac{\mathbf{J}\mathbf{n}_i}{||\mathbf{J}\mathbf{n}_i||} + (1-\alpha)\begin{pmatrix}\mathbf{n}_i \\ \mathbf{0}\end{pmatrix}$$



- Blend the two types of normals

→ Balance smoothing and edge fitting effects

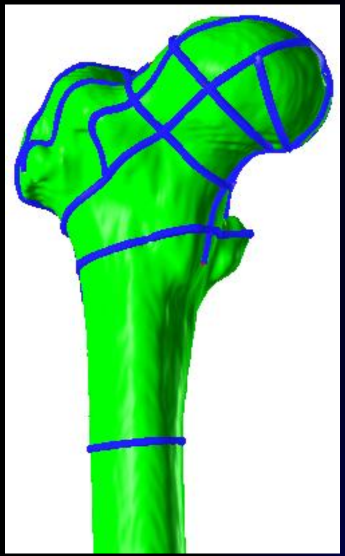


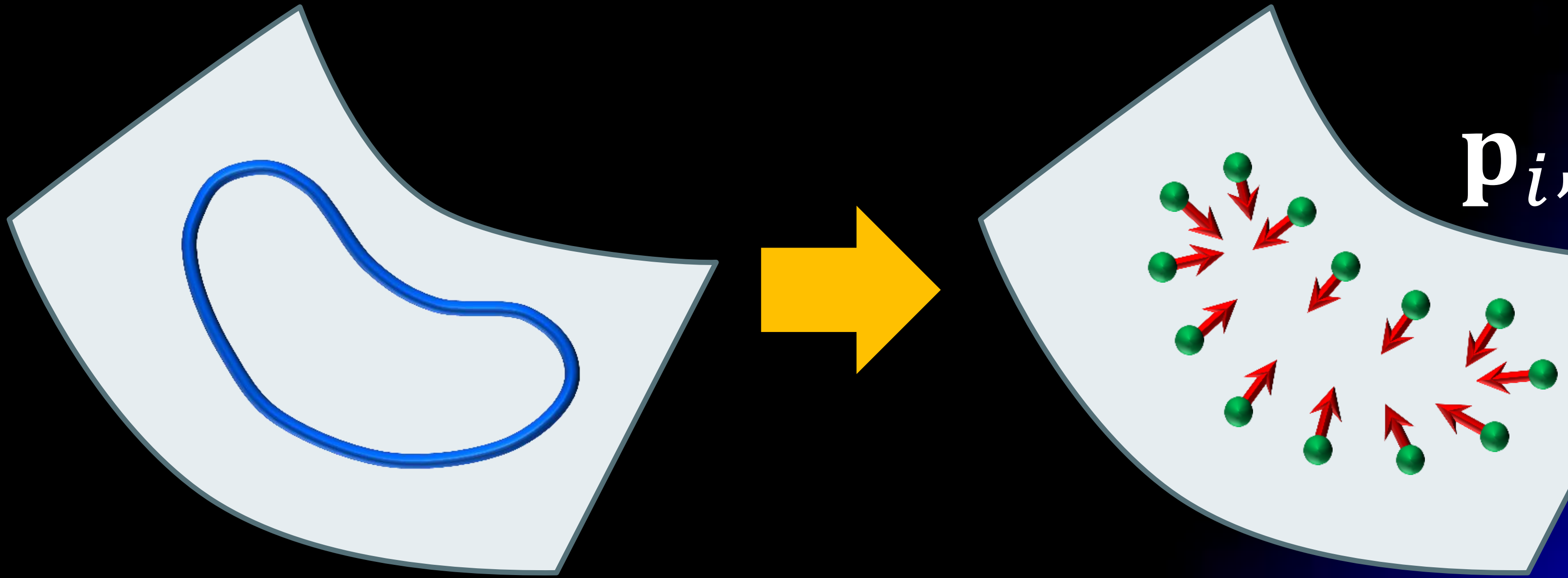
B-HRBF segmentation

Overview

Mapping normals

Contours → constraint points & normals



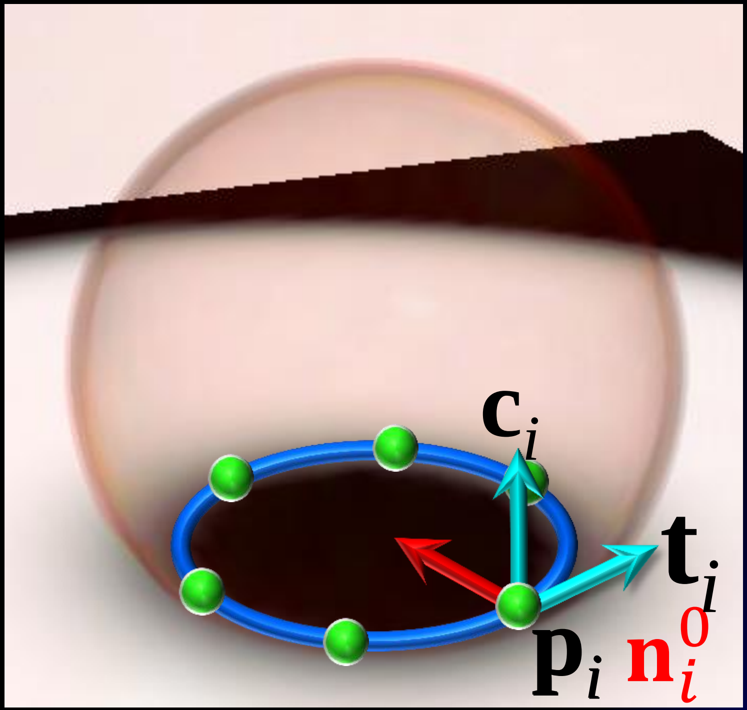


$\mathbf{p}_i, \mathbf{n}_i$

Contour → $\mathbf{p}_i$ $\mathbf{n}_i$

0. Cross section & contour
1. Resample with an interval - $\mathbf{p}_i$
2. Compute base normal as -

   $\mathbf{n}_i{}^0 = \mathbf{t}_i \times \mathbf{c}_i / ||\mathbf{t}_i \times \mathbf{c}_i||$ [HKHP11]

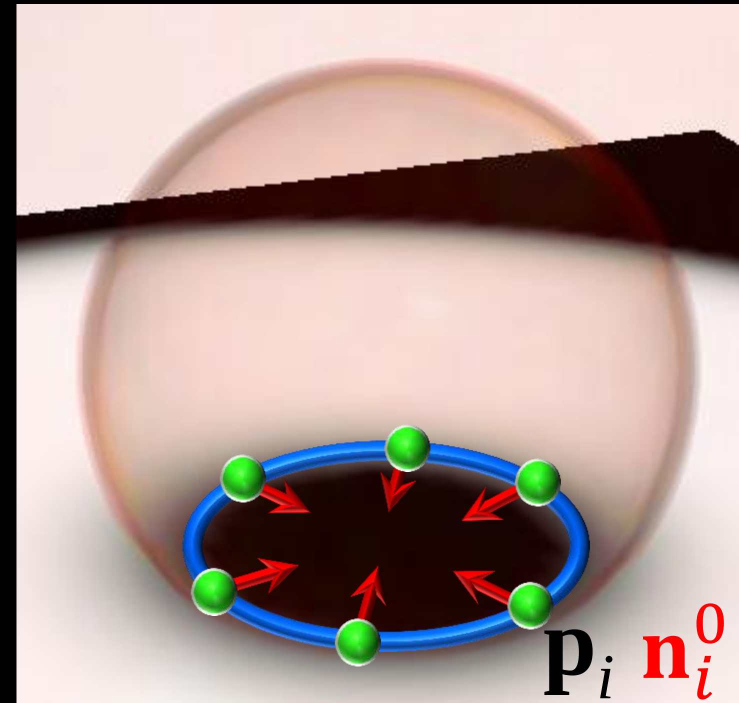


$\mathbf{t}_i$: tangent of contour

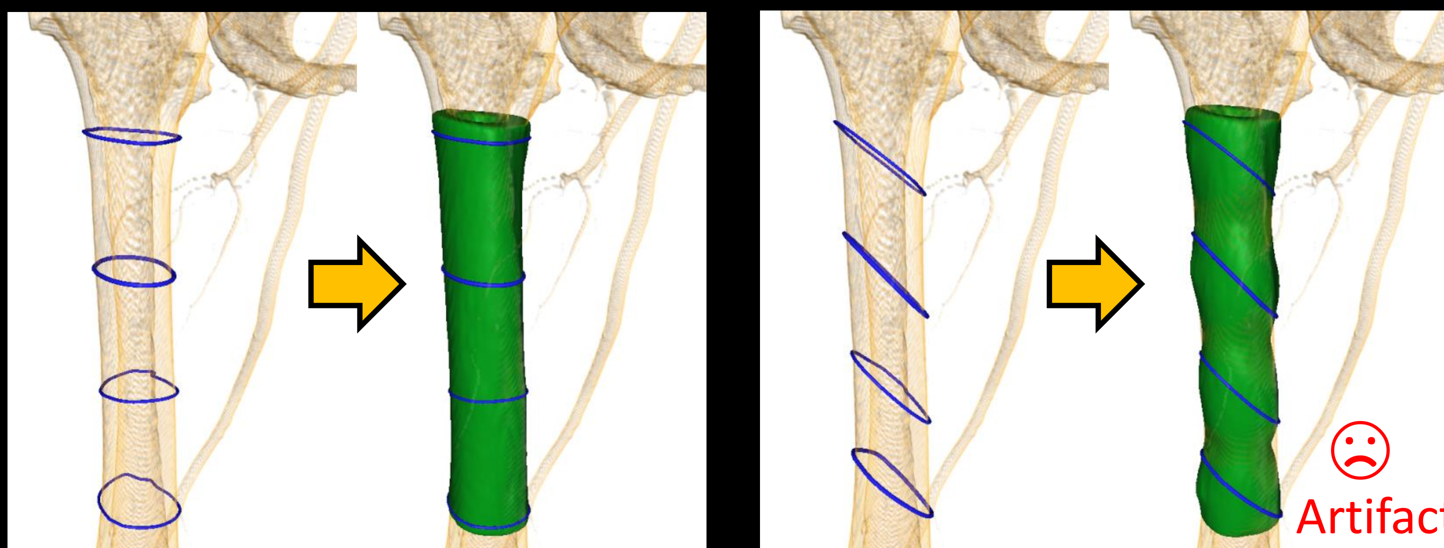
$\mathbf{c}_i$: normal of cross section

Contour → $\mathbf{p}_i$ $\mathbf{n}_i$

0. Cross section & contour
1. Resample with an interval - $\mathbf{p}_i$
2. Compute base normal as -
   $\mathbf{n}_i{}^0 = \mathbf{t}_i \times \mathbf{c}_i / ||\mathbf{t}_i \times \mathbf{c}_i||$ [HKHP11]



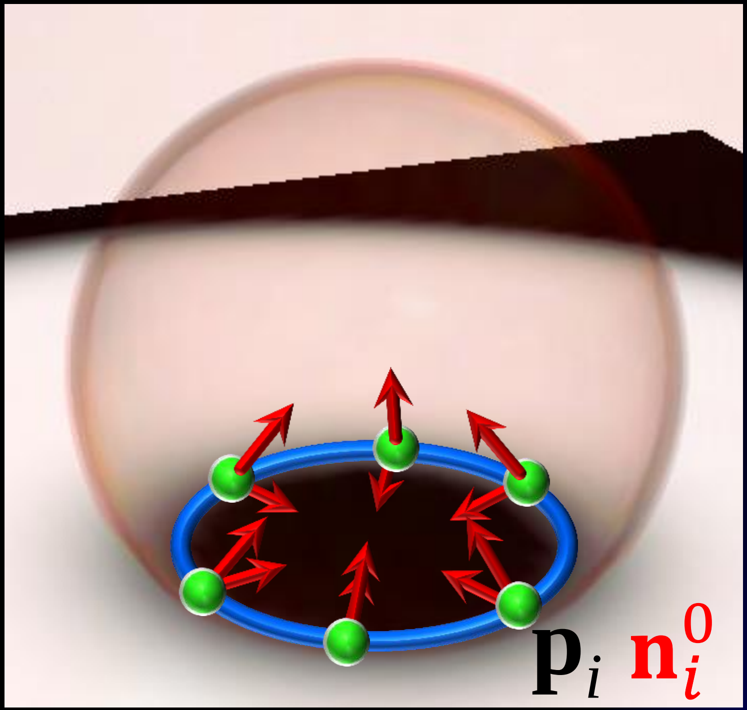
The base normal has problem

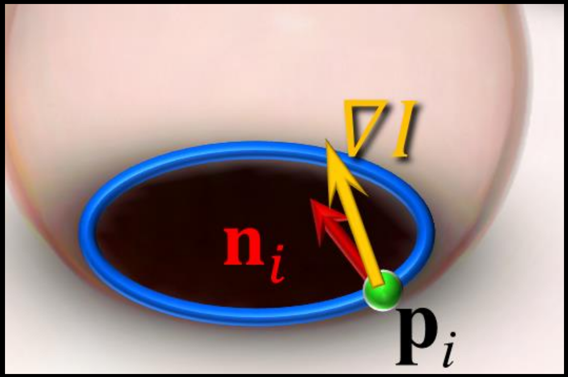


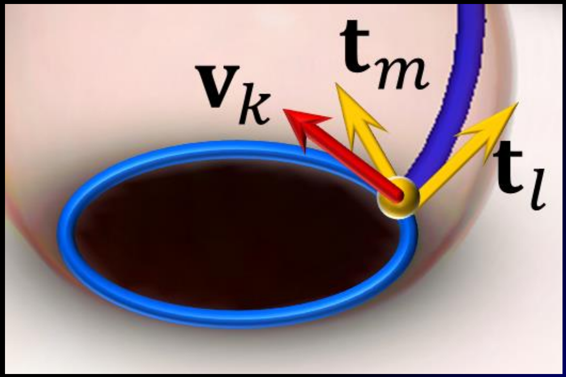
Contours are orthogonal / slanted to target region

Contour → $\mathbf{p}_i\ \mathbf{n}_i$

0. Cross section & contour
1. Resample with an interval - $\mathbf{p}_i$
2. Compute base normal as -
   $\mathbf{n}_i{}^0 = \mathbf{t}_i \times \mathbf{c}_i / ||\mathbf{t}_i \times \mathbf{c}_i||$
3. Modify $\mathbf{n}_i{}^0 \rightarrow \mathbf{n}_i$ with heuristics





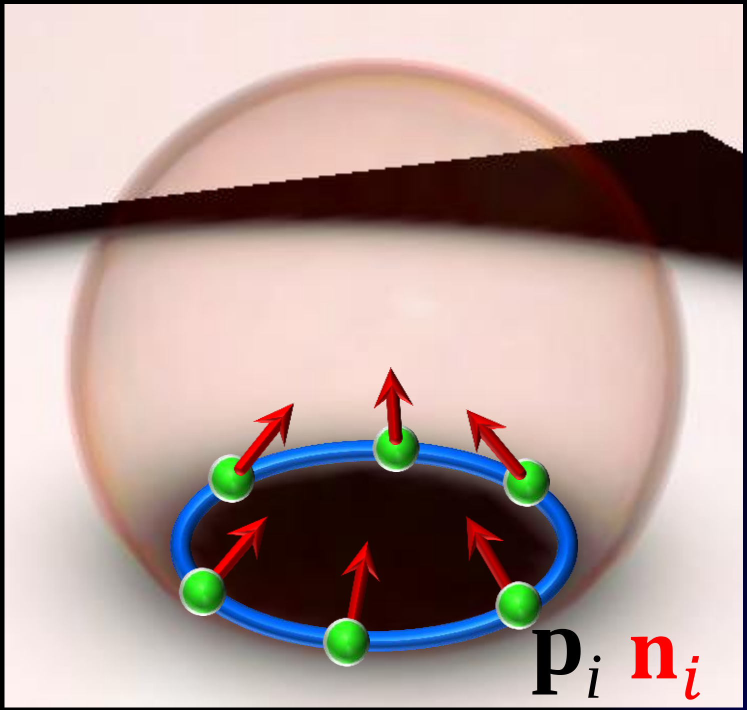


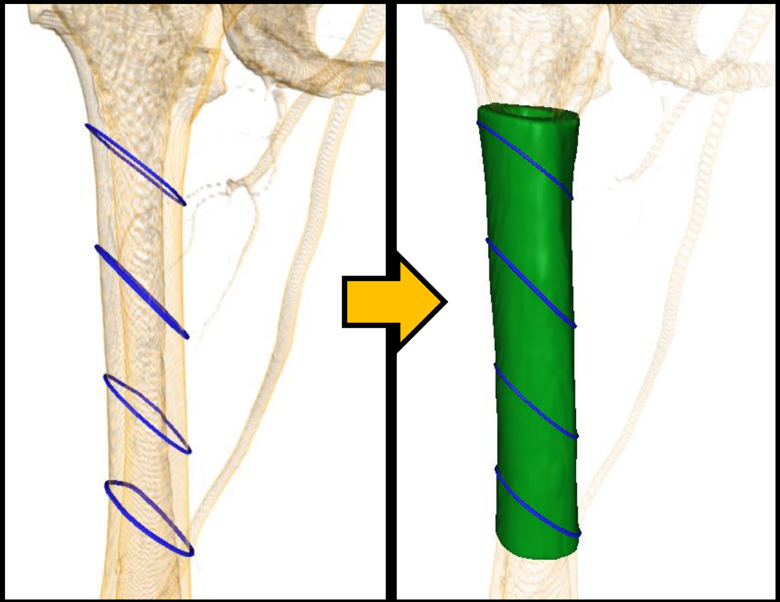
- Use image gradient ∇I
- Align base normal to ∇I

- Use intersection of contours
- Desired normal is $\mathbf{t}_l \times \mathbf{t}_m$

Contour → $\mathbf{p}_i$ $\mathbf{n}_i$

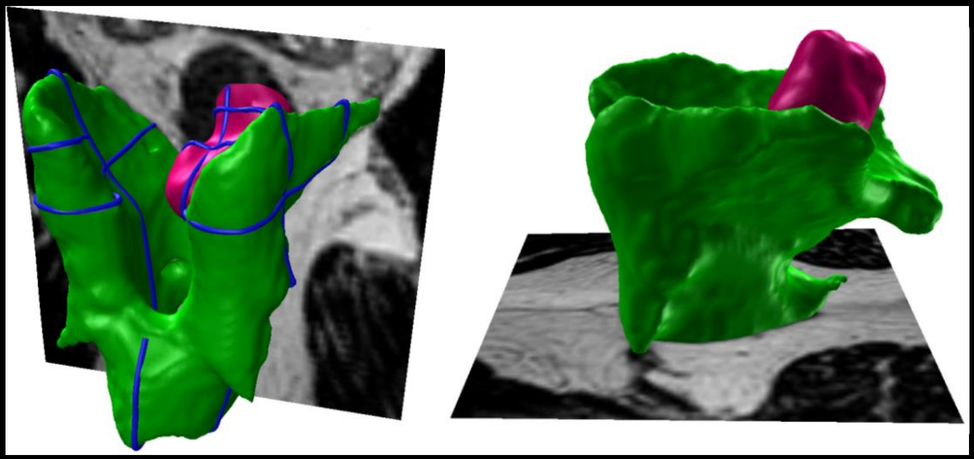
0. Cross section & contour
1. Resample with an interval - $\mathbf{p}_i$
2. Compute base normal as -
   $\mathbf{n}_i{}^0 = \mathbf{t}_i \times \mathbf{c}_i / ||\mathbf{t}_i \times \mathbf{c}_i||$
3. Modify $\mathbf{n}_i{}^0$ → $\mathbf{n}_i$ with heuristics

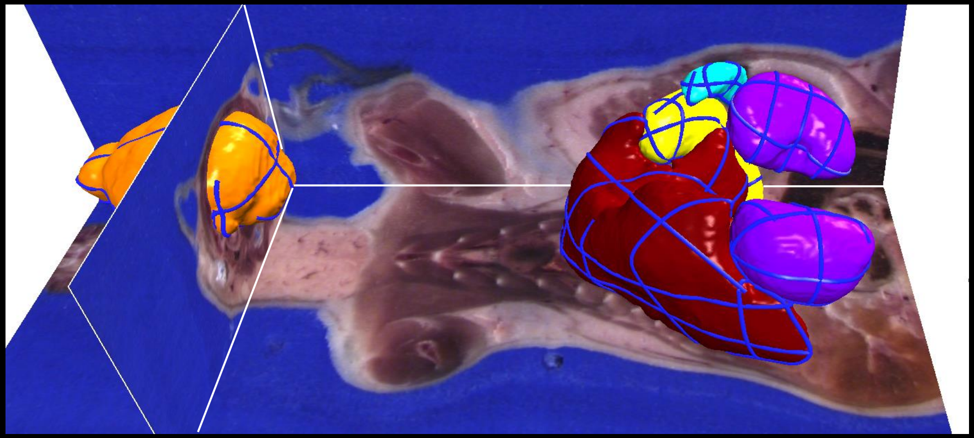


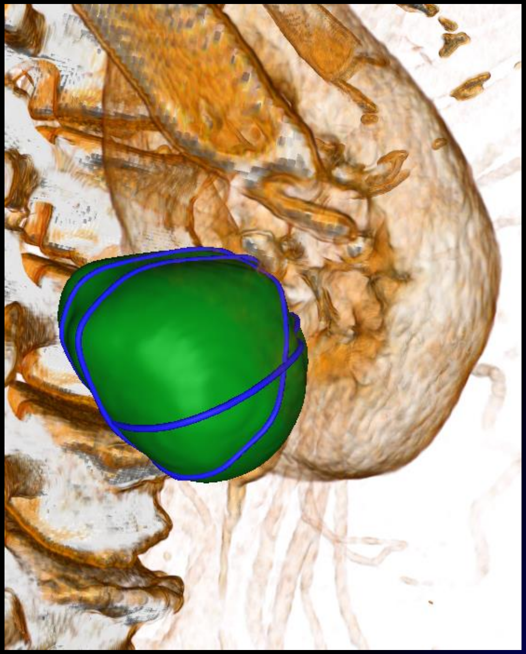


Normal $\mathbf{n}_i$ avoid artifact even with slanted contours

Results

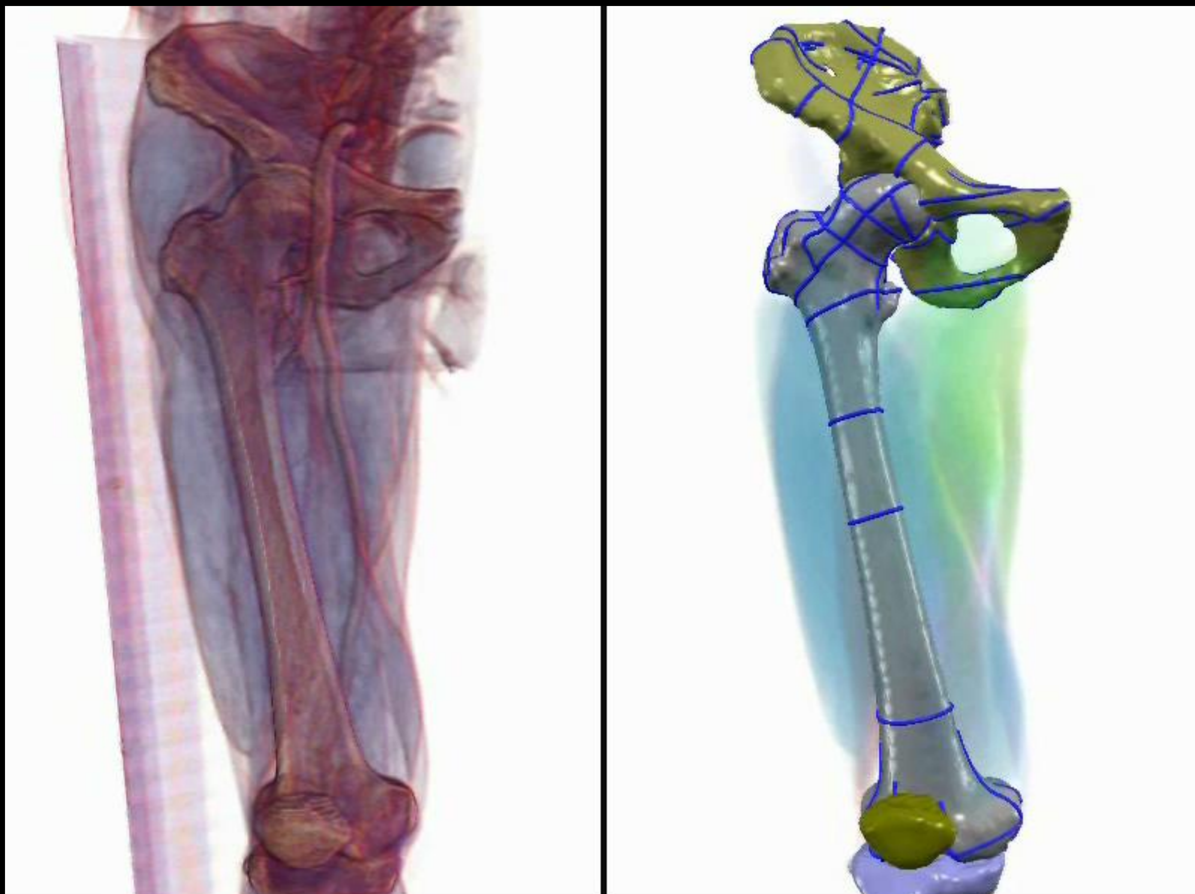




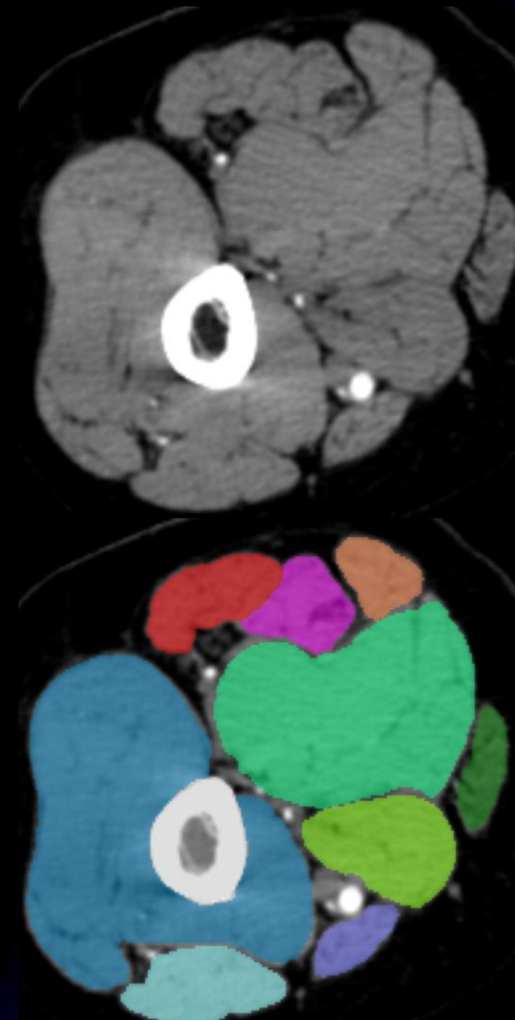


- We applied our technique to biomedical images
- Results were evaluated from experts

Right thigh segmentation (CT)

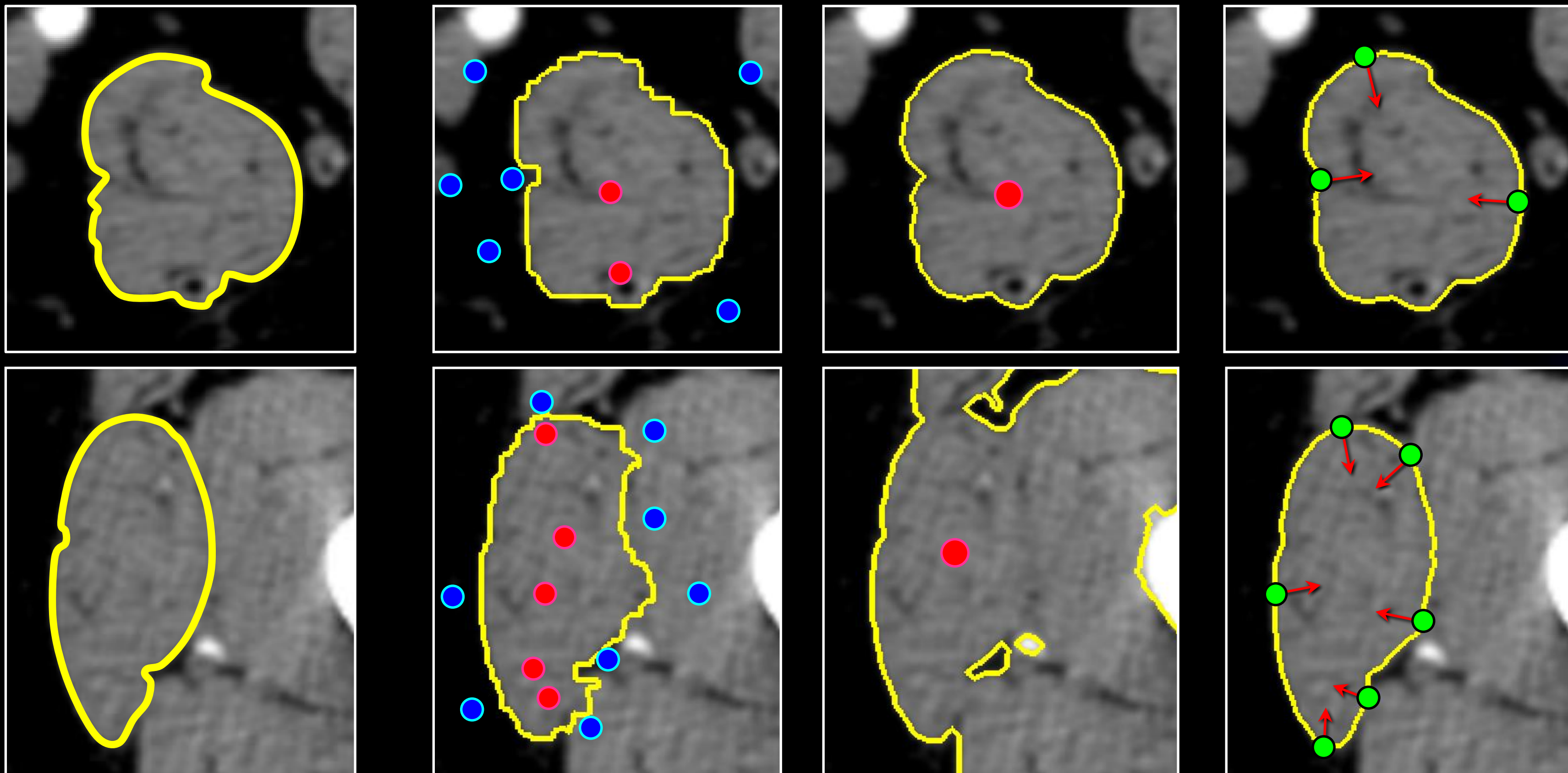


Cross section



- 5 bones & 9 muscles
- Less than 30 min to segment each

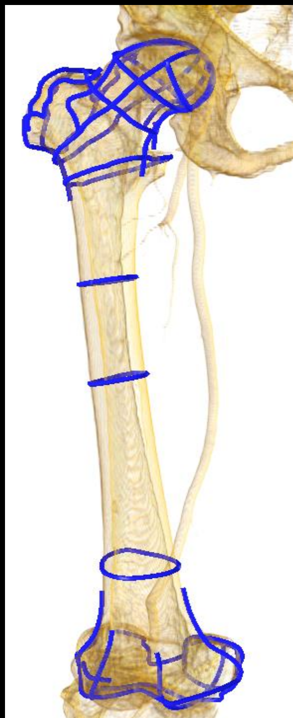
Comparison with previous seed-based methods

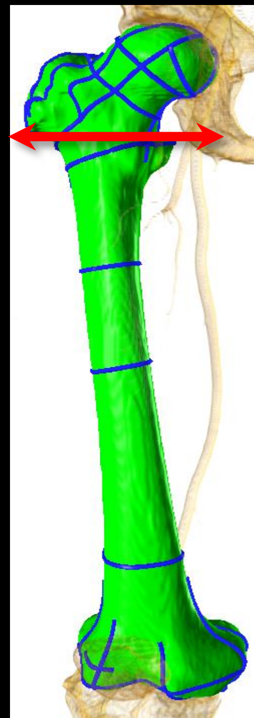


Ground truth | Graph cut | Region grow | Our B-HRBF

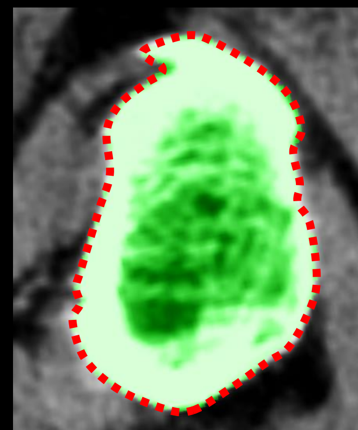
- Tried to obtain same segmentation with three methods
- ROI has clear boundary (top) : all methods worked well
- ROI has blurred boundary (bottom): seed based methods failed

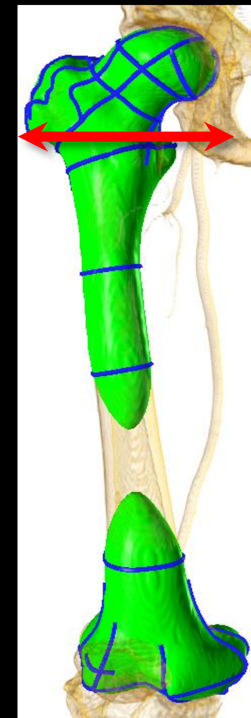
Comparison with previous contour-based method



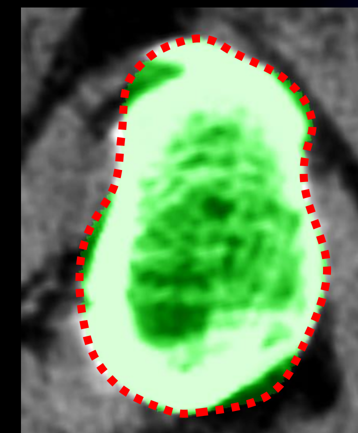


Cross section





Cross section



[TO02; HKHP11]

Input contours

Our method

Previous method

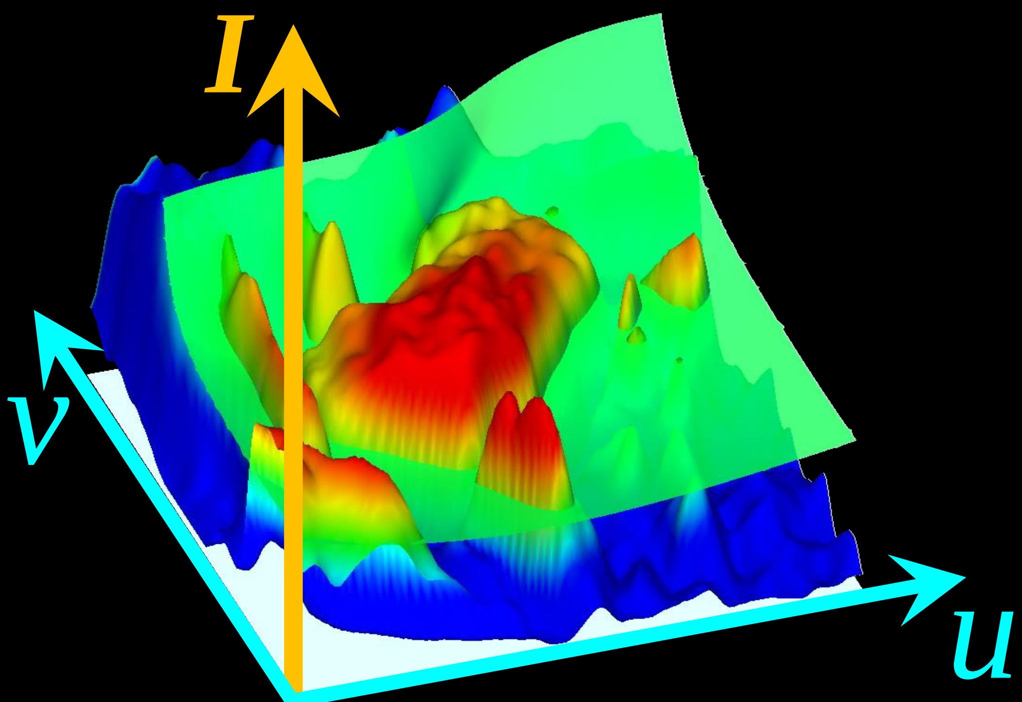
Implicit-surface reconstruction

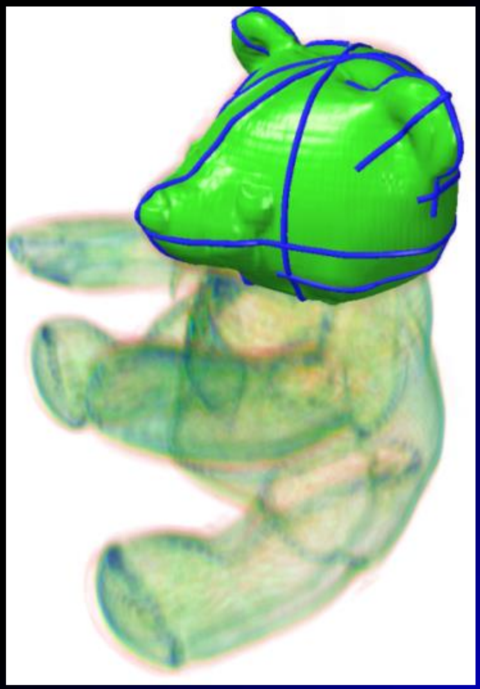
Prev. method

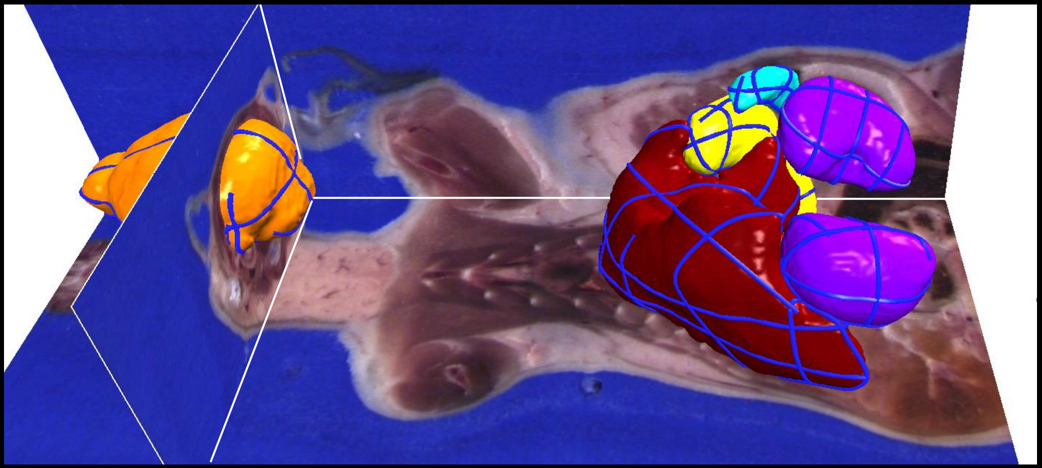
- Separated surfaces around shaft
- miss edges around joint

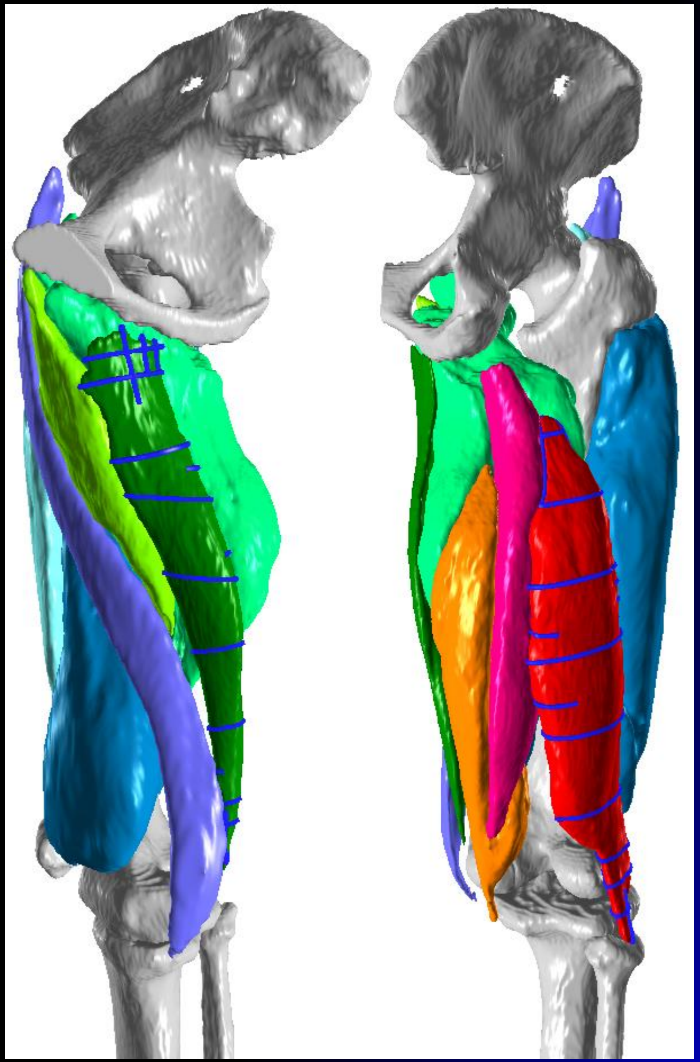
Conclusion

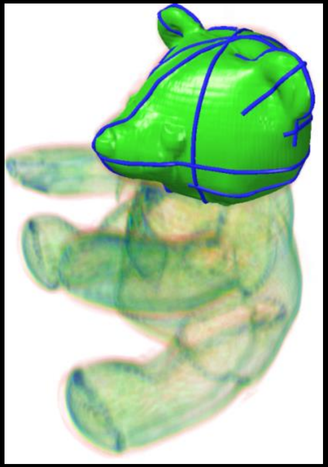
- New volume segmentation technique
  - Compute scalar field in bilateral domain with B-HRBF
  - Define boundary as Intersection of zero-set and image manifold
- Acceleration scheme of B-HRBF (omitted)
- An contour-based user interface for segmentation

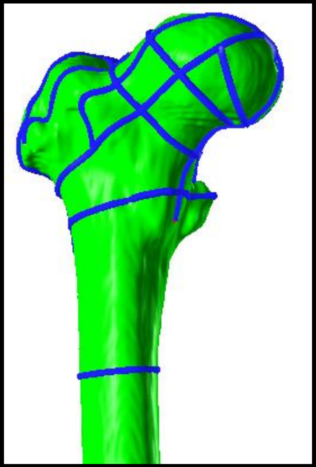


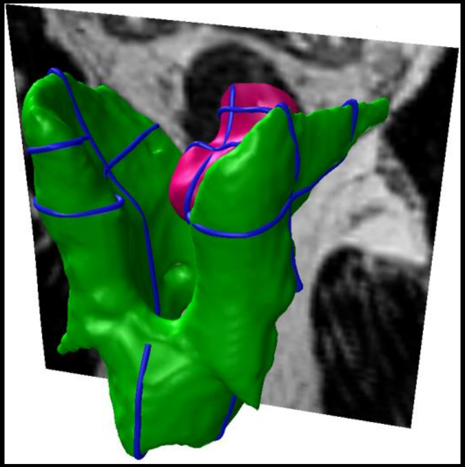










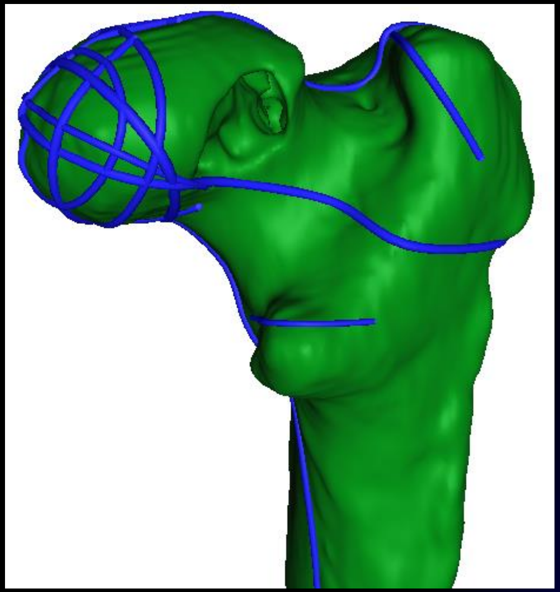


Thank you for your attentions

Limitation & future work

- To find good arrangement of contours is difficult for novices

→ To support to find nice contour arrangement



Bad example

+ unnecessary contours exist
+ additional contours required

- Contour-based user interface is only for 3D

→ User interface for higher dimensional volume

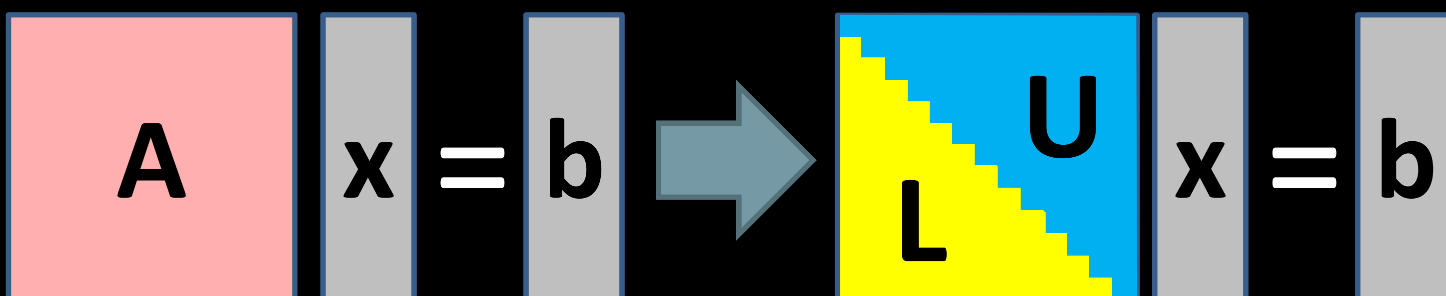
Main bottleneck of algorithm

- When computing BHRBF

$$f(\bar{\mathbf{x}}) = \sum_i (\alpha_i \phi(\bar{\mathbf{x}} - \bar{\mathbf{p}}_i) - \boldsymbol{\beta}_i \cdot \nabla\phi(\bar{\mathbf{x}} - \bar{\mathbf{p}}_i)) + \mathbf{a}\bar{\mathbf{x}} + b$$

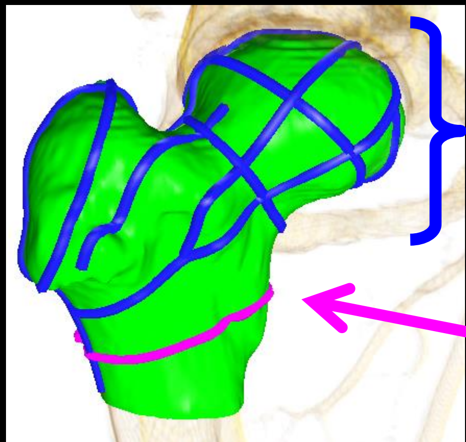
$$f(\bar{\mathbf{p}}_i) = 0, \qquad \nabla f(\bar{\mathbf{p}}_i) = \mathbf{normal}$$

- We have to solve dense and large linear system



- We solve the linear system by LU-factorization based method ← this is the main bottleneck

Acceleration of LU factorization

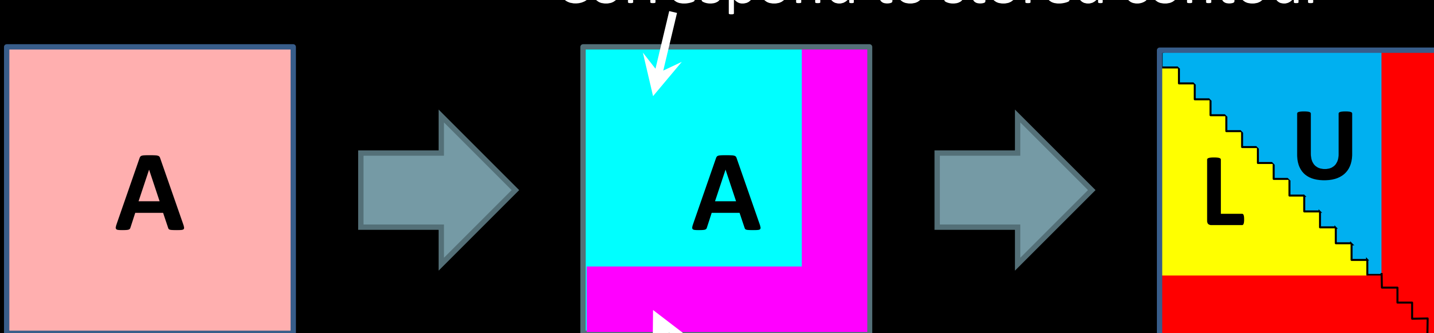


stored contour (fixed)

Active contour (can be change)

- User edits only one contour at a time
- Matrix consists of 2 parts (correspond to active/stored contour)
- Pre-compute LU factorization of stored contour part
- Compute LU factorization only a part correspond to active contour

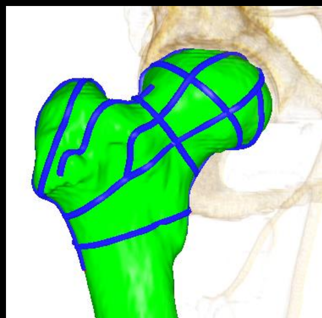
Correspond to stored contour

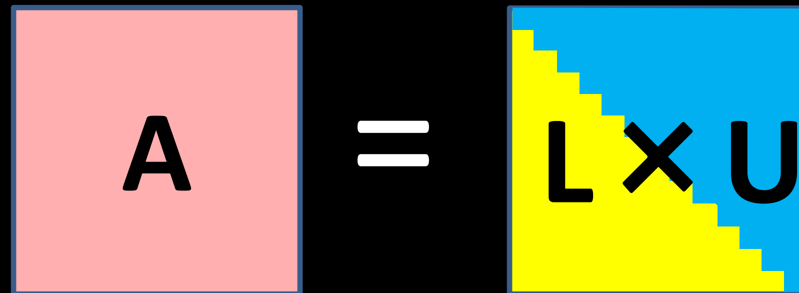


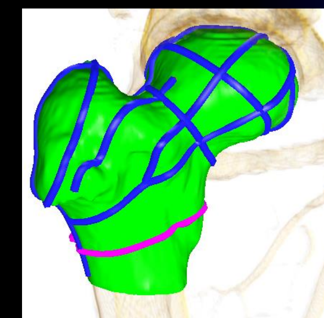
active contour

Acceleration of LU factorization

- All contours are stored and we factorized HRBF matrix in LU form







  - The user may select a contour to activate (to re-edit)
  - HRBF matrix consists of two part
    - Correspond to activated contour / stored contour
  - We sweep a part correspond to active contour to right・bottom keeping a the LU form [Gondzio's algorithm]