Reliable Path for Virtual Endoscopy:

Ensuring Complete Examination of Human Organs

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Reliable Path for Virtual Endoscopy: Ensuring Complete Examination of Human Organs; Taosong He, Lichan Hong, Dongqing Chen, and Zhengrong Liang;
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Endoscopy

- method that enables us to examine interior of human organs using camera
- **Virtual endoscopy**
  - integration of medical imaging and computer graphics
  - uses model of human organ based on data from CT or MRI
  - noninvasive, cost-effective, free of risks

Navigation

- Navigation is a crucial component of virtual endoscopy
- Common navigation techniques:
  - pre-defined fly-through path
  - free navigation
  - combination of both

Motivation

- **How can we ensure that physician visualized all the existing abnormalities in the organ?**
- **Reliable Path**: Path that guarantees us visibility of each interior surface area

Reliable Path

- **definition:** set of connected points inside the model from which the entire interior surface can be seen
- advanced restrictions to make path usable:
  - never penetrate the surface
  - as short as possible
  - as smooth as possible
  - stay away from surface as far as possible

Optimal Reliable Path

- **definition:** minimal set of connected points inside the model from which the entire interior surface can be seen
- given an organ model *D*, its interior region *R*, boundary area ∂D, we get $D=R+\partial D$; then optimal path is a curve $P \subset R$ of minimal length where

$$\forall(v_0 \in \partial D) \rightarrow \exists((v_1 \in P) \wedge (v_0 v_1 \in R \cup \{v_0\}))$$

Optimal Reliable Path (in discrete space)

- data used for virtual endoscopy are discrete
- **definition in discrete space:**
  - given an 3D volume *V* split into surface voxel set *B*, internal voxel set *I* and exterior voxel set *E*;
  - for each voxel $v \in I$ there is a set of visible voxels $S_v \in B$ (which can be seen from *v*)
  - reliable path: connected set $C^* = \{v_o, v_1, \ldots, v_{n-1}\}$ with minimum *n* so that each voxel $x \in B$ belongs to at least one visible voxel set S_v

Near-Optimal Reliable Path

- there may be more OR paths for one model *V*
- optimal reliable path problem is **NP-complete**
- it is required to find some near-optimal reliable path
- all reliable paths can be classified into 3 categories:
  - **optimal** (can't afford to compute them)
  - **feasible** (usable, they meet restrictions as defined earlier)
  - **impractical**

Skeleton

- **definition:** set of centers of maximal balls. Maximal ball is a ball in region *P* which is itself not enclosed in another ball in *P*.
- has some nice properties:
  - its points stay in center of the model
  - union of max. balls is interior region
- **Q: Is skeleton reliable?**
- **Q: Is skeleton feasible?**

Is skeleton reliable?

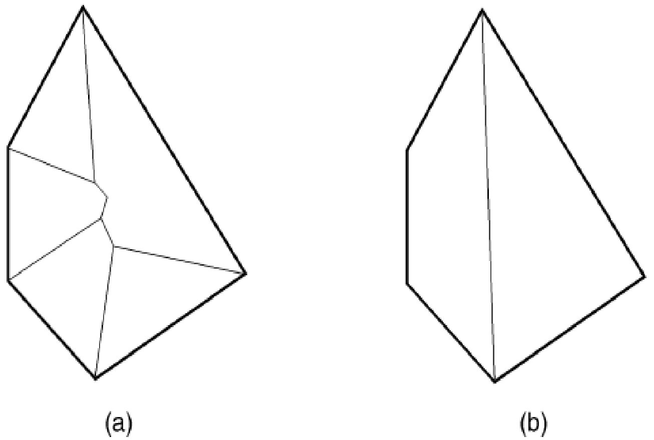
- Reliability of skeleton *S* can be proven by contradiction:
- Given *D*, its boundary area ∂D and its interior area *R* where $D = \partial D + R$
- Lets assume that

  $$\exists \mathbf{v_0} \in \partial \mathbf{D} \land \exists \mathbf{v_1} \neq \mathbf{v_0} \land \mathbf{v_1} \in \mathbf{c v_o} \rightarrow \mathbf{v_1} \in \partial \mathbf{D}$$

  where *c* is a center of maximal ball *B* enclosing v_0
- Since *B* is convex and both *c* and v_0 are included in *B*, *v1* is inside *B*.
- Interior area of *B* is included in *R* (from definition). Therefore **v1$\in$R.**

Is skeleton feasible?

- definition of skeletons leads to many branches on the path – **path is not smooth enough**



- skeleton is hard to compute for large data sets
- approximation algorithms **do not guarantee reliability**

Efficient Algorithm

- computes path that is near-optimal, smooth, reliable
- main idea: **to repeatedly incorporate new observation points covering maximal areas of previously invisible surface**
- voxels with higher distances from surface are closer to center and have bigger visibility set
- visible set of neighboring voxels could largely overlap – only voxels whose distance values are at local maxima are considered

Efficient Algorithm – stage 1

P – set of points to be included in path U – unrevealed surface
T_v – visible set of voxel v

1. Reconstruct volume V
2. Classify V into: external E, internal I, surface B
3. Compute Euclidean distance on I
4. Initialize L with all the local maximum voxels;
   Sort L in the order of decreasing distance values
5. $P := \emptyset$; $U := B$;
   Repeat until ($L == \emptyset$)
      $v := L.head$; $L := L - v$; compute $\boldsymbol{T_v}$;
      if ($T_v \cup U \neq \emptyset$) then
         $P := P \cup \{v\}$; $U := U - T_v$
6. Connect P into $C \subset I$ using shortest path algorithm

Efficient Algorithm – stage 2

7. $P' := C - P$; $U := U - \bigcup_{(v \in P')} \boldsymbol{T_{v'}}$; $P := \emptyset$
8. Repeat until $(U == \emptyset)$
   select $v \in U$; get $K \subset I$ that is visible from v;
   select $v' \in K$ with highest distance value;
   $P := P \cup \{v'\}$; $U := U - \boldsymbol{T_{v'}}$
9. Connect $C \cup P$ into $C \subset I$ using shortest path algorithm
10. Return C

Efficient Algorithm

- presented algorithm computes reliable path of desired quality
- **stage 1:** establishes a priority list of center voxels and covers a majority of surface using selected center voxels
- **stage 2:** covers the remaining uncovered surface (ensuring reliability)

Efficient Algorithm - Noise

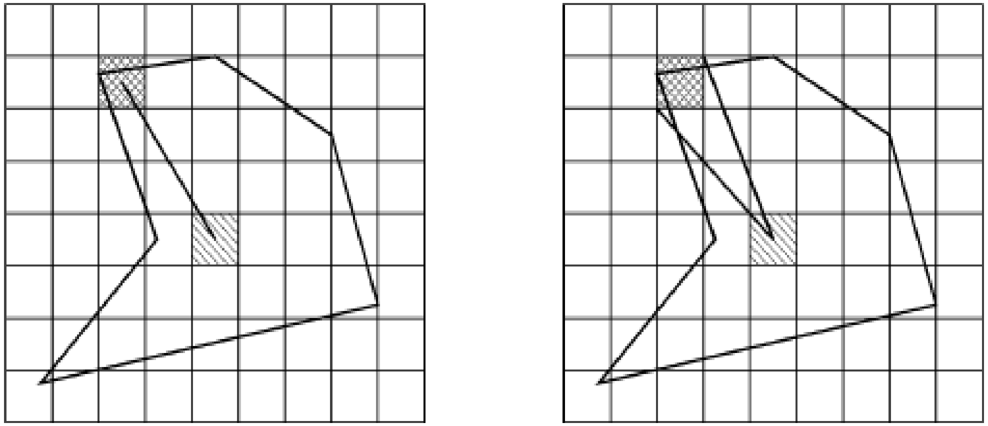
- given algorithm is much less sensitive to noise presented in data set than i.e. skeleton
- this is because **visibility** instead of **geometry** is applied when determining the path voxels
- however some noise treatment in preprocessing is recommended to avoid small turns and forks

Visibility Test

- computing visibility set for voxel is the most time consuming part of algorithm
- for virtual endoscopy each voxel can be represented as a rectangular box

Visibility Test – Definition of visibility

- 2 approaches to definition of visibility:



(a) (b)

  - **liberal (a):** voxels v_o and v_1 are visible to each other if and only if line c_0c_1 does not intersect surface, where c_0 and c_1 are centers of voxels v_0 and v_1
  - **conservative (b)**

Visibility Test – 360° Camera

- it is very hard to predict viewing frustum before actual navigation
- visible voxel set for each voxel *v* on the path is computed **assuming a full 360° field-of-view**
- requires feasible 360° camera control method
  - restricting physician to precomputed path
  - allowing to control speed, direction (F/B) and zoom
  - virtual camera designed for presenting a 360° view

Visibility Test – Range of sight

- to have a clear view of the examined surface – **range of sight** is limited at each voxel
- **1st step:**
  - at center of voxel v_0 a sphere of radius r is created – representing the range of sight for v_0;
  - r is usually **max. voxel-to-surface distance * 3**
- **2nd step: test of visibility**
  - "shoot" a ray $v_0 s$ from v_0's center to each surface voxel s within the sphere

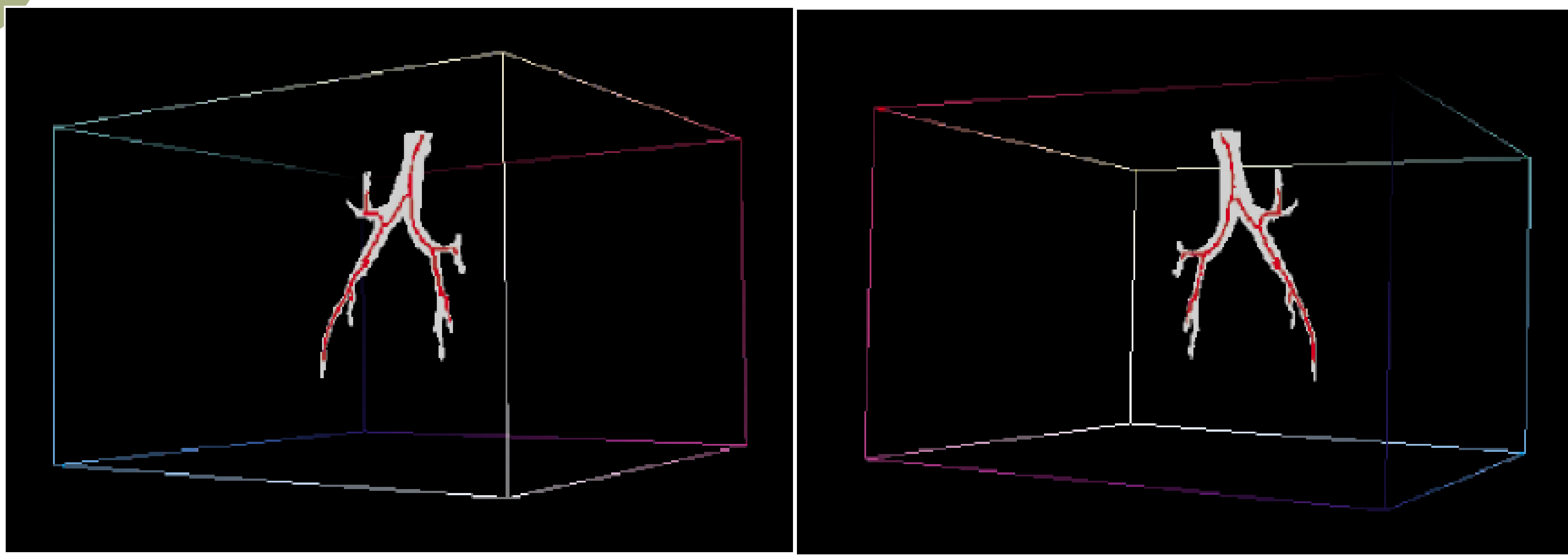
Experimental Result #1

- airway of female patient, age 35
- acquired by spiral CT scanner
- resolution of reconstructed data set:

  512 x 512 x 202
- 24,571 internal and 16,958 surface voxels
- reliable path consist of 363 voxels
- time to count the path: 109 seconds

  (300MHz, 640MB RAM)

Experimental Result #1

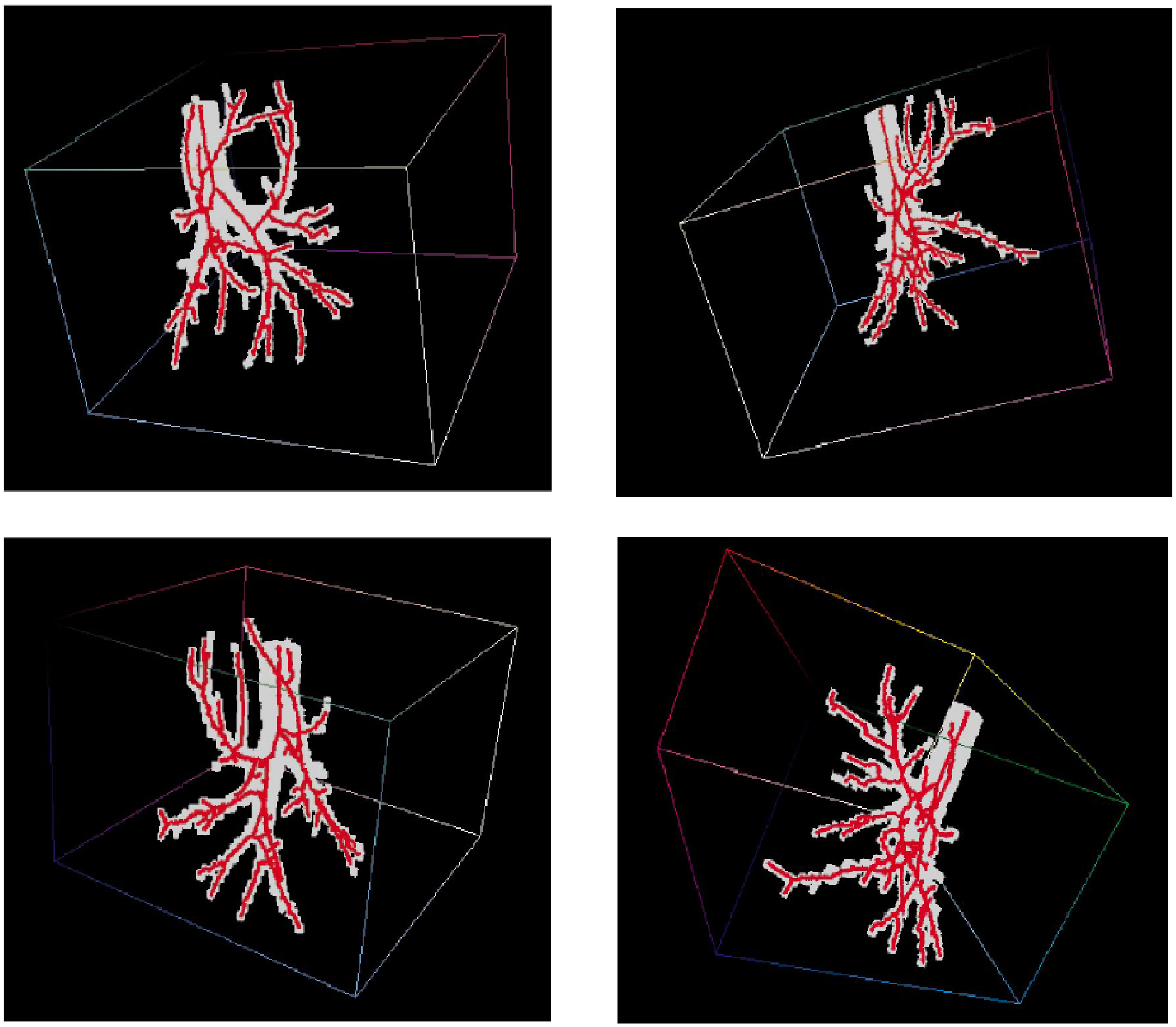


- path is shown in red; surface is shown semitransparent
- path stays in center of model
- restricted range of sight resulted into long branches on the path

Experimental Result #2

- airway (more complicated)
- resolution of reconstructed data set:
  256 x 256 x 166
- 47,225 internal and 39,058 surface voxels
- reliable path consist of 1,378 voxels
- time to count the path: 33 seconds
  (300MHz, 640MB RAM)

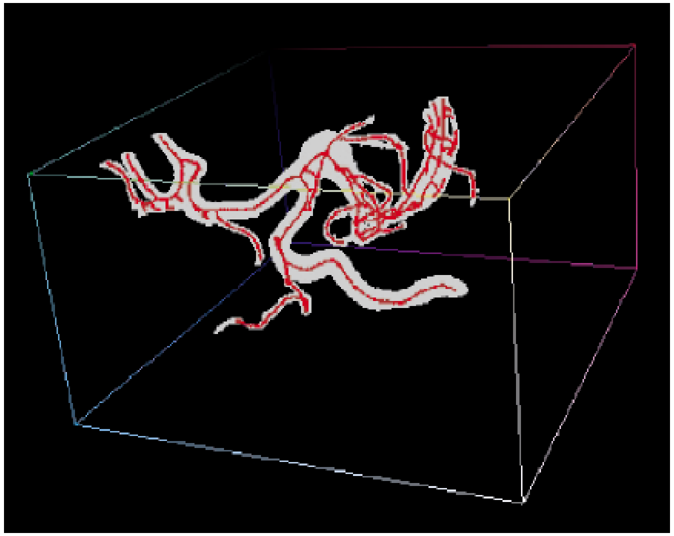
Experimental Result #2

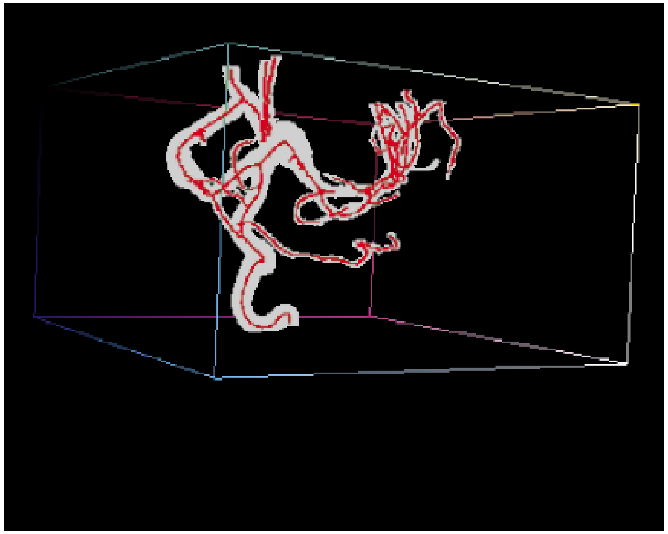


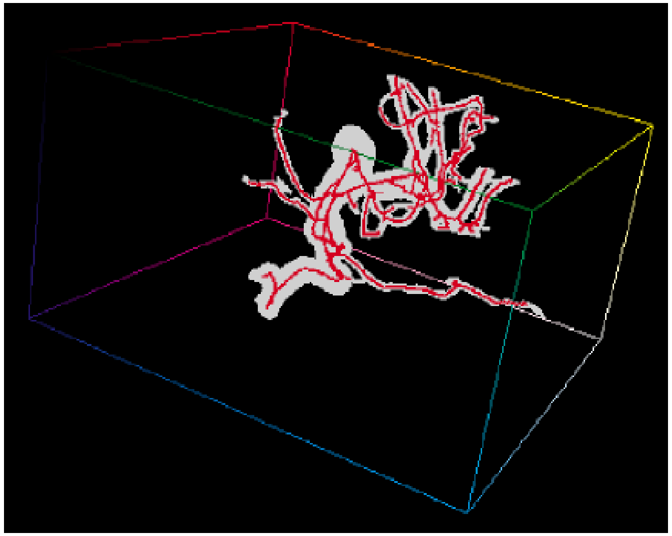
Experimental Result #3

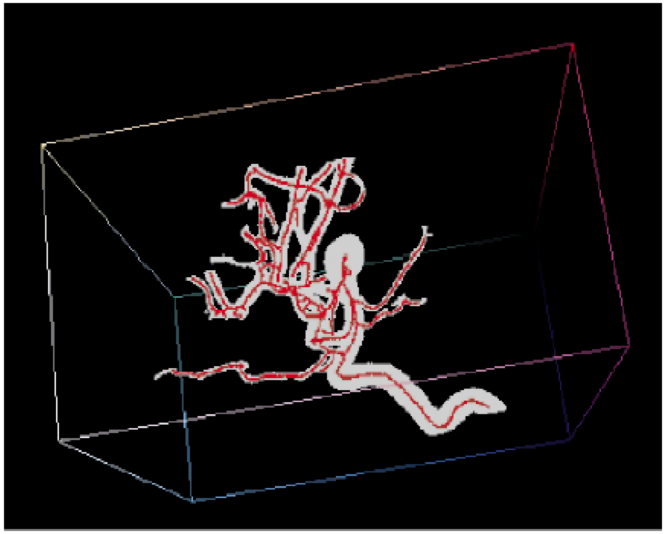
- blood vessel of male patient, age 41
- acquired by angiograph
- resolution of reconstructed data set:
  512 x 512 x 258
- 292,773 internal and 151,064 surface voxels
- reliable path consist of 2,741 voxels
- time to count the path: 270 seconds
  (300MHz, 640MB RAM)

Experimental Result #3









Conclusions

- given algorithm efficiently generates feasible reliable path meeting defined restriction
- reliable path is generally a “road map” for exploring the model
- requires new 360° camera model

Thanks for your listening...