3D Wireless Sensor Networks: Challenges and Solutions

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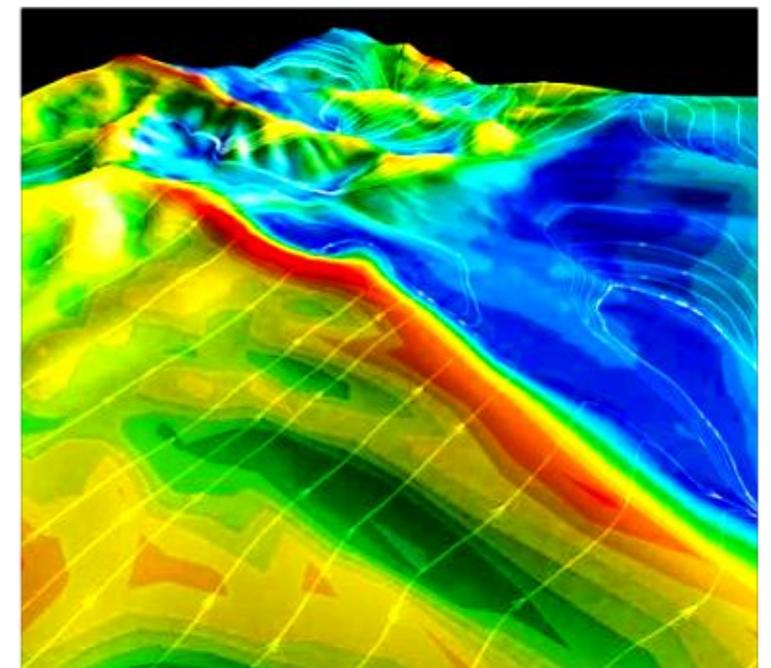
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2D PLANE, 3D VOLUME, AND 3D SURFACE SENSOR NETWORKS

- Sensor network settings
  - 2D plane: crop sensing in fields or wildlife tracking on plains
  - 3D volume: underwater or space reconnaissance
  - 3D surface: seismic monitoring on ocean floors or in mountainous regions

HTTP://WWW.ROBAID.COM/

What's New in 3D?

The First Example: Deterministic Routing with Constant Overhead (DISCO)

[MOBIHOC'11] Su Xia, Xiaotian Yin, Hongyi Wu, Miao Jin, and Xianfeng David Gu, "Deterministic Greedy Routing with Guaranteed Delivery in 3D Wireless Sensor Networks", in ACM MobiHoc, 2011. (Acceptance rate: 10%)

[MOBIHOC'14] Su Xia, Hongyi Wu, and Miao Jin, "Trace-Routing in 3D Wireless Sensor Networks: A Deterministic Approach with Constant Overhead", in ACM MobiHoc, 2014. (Acceptance rate: 10%)

GREEDY ROUTING

☐ What is greedy routing?

    ☐ A node always forwards a packet to one of its neighbors, which is the closest to the destination of the packet

☐ Why greedy routing?

    ☐ Both computation complexity and storage space bounded by a small constant, thus scalable to large networks with stringent resource constraints on individual nodes

    ☐ Deterministic: the distance to destination is reduced in each step

LIMITATIONS OF CURRENT GREEDY ROUTING SCHEMES

- Face routing (alternatives/enhancements)
  - Exploit the fact that a void in a 2D planar network is a face with a simple line boundary
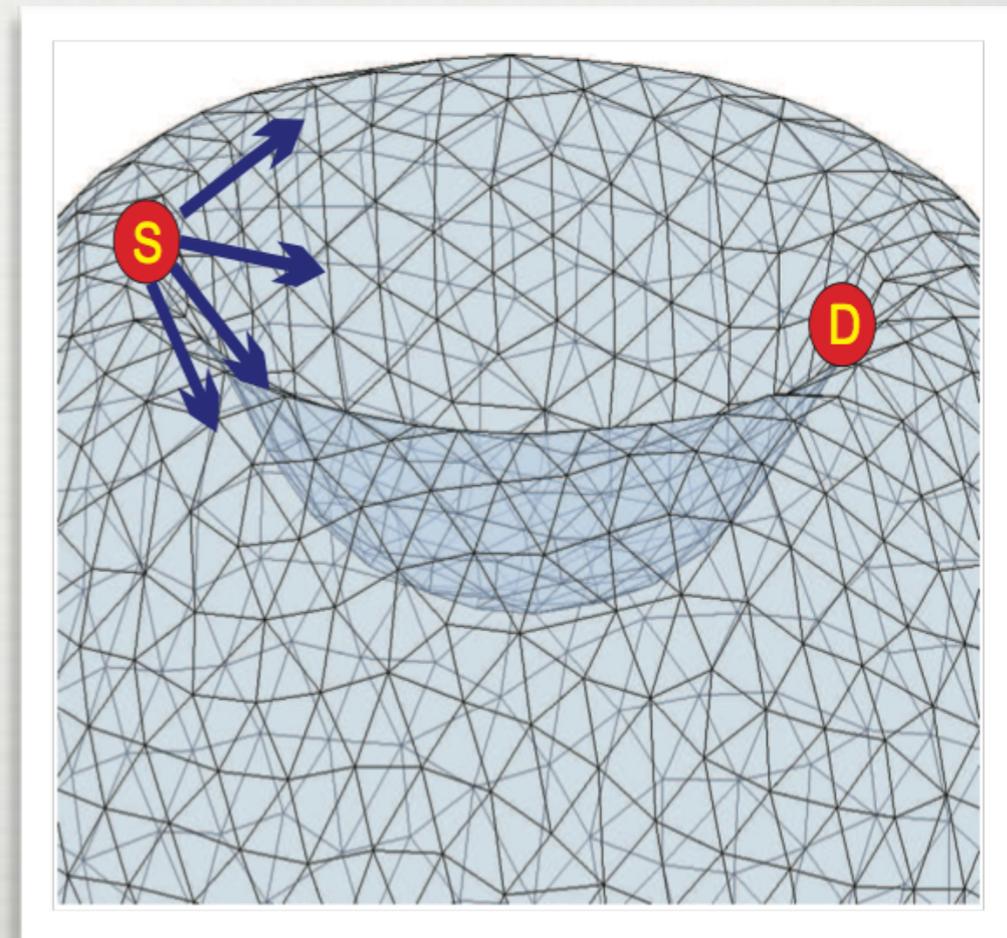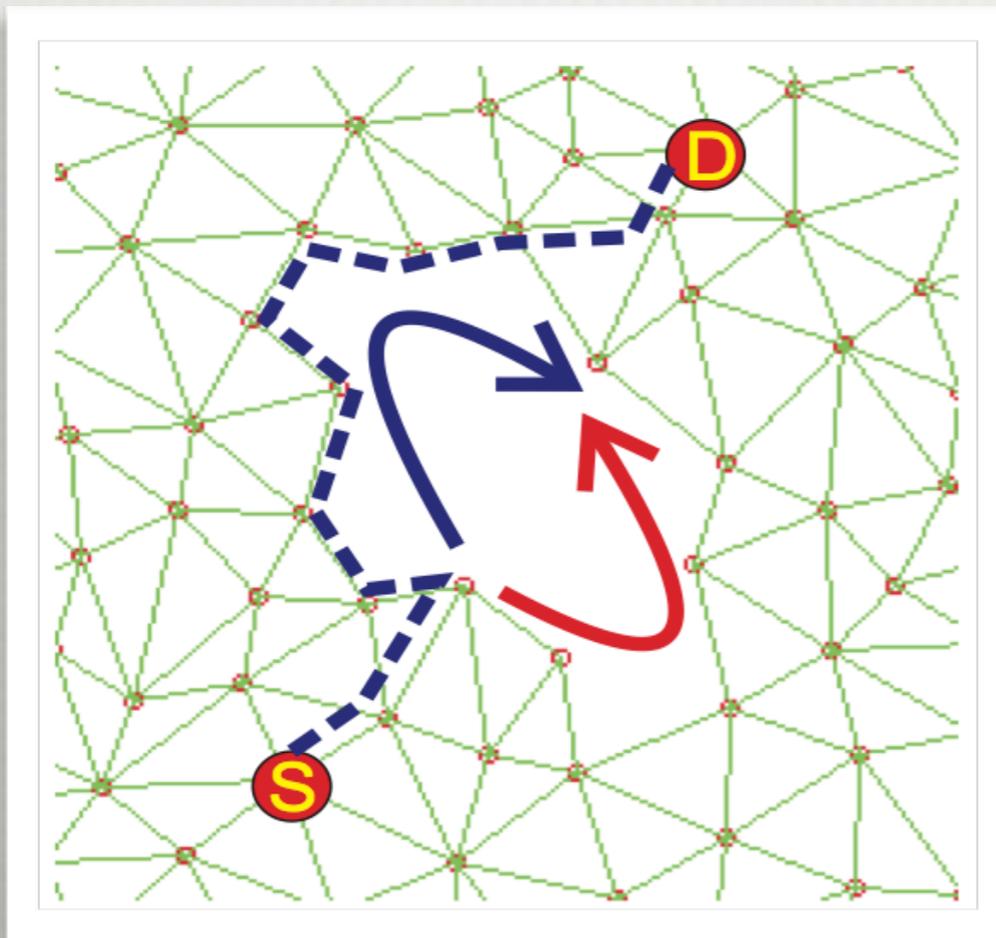
LIMITATIONS OF CURRENT GREEDY ROUTING SCHEMES

- Structures-based

  - 3D partial unit Delaunay triangulation [5]: divide the network into closed subspaces such that a local minimum recovered within a few subspaces only

  - GDSTR-3D [10]: If a local minimum is reached, forward packet along a spanning tree of convex hulls

  - Distributed multi-dimensional tree structure [30]

  - Random walk under a spherical dual graph structure [8]

  - Certain structure must be maintained by individual sensors, which are often non-locally-deterministic [8][5] or requires non-constant storage space [10][30]

LIMITATIONS OF CURRENT GREEDY ROUTING SCHEMES

☐ Topology control — a critical communication range is suggested to avoid local minimum [29]: theoretically sound but the critical communication range is often too large for practical sensor networks

☐ Dimension reduction—project to a 2D plane to apply face routing [6,7]: <u>no guarantee</u> (face routing on projected plane does not ensure a packet to actually move out of void in the 3D network)

☐ Proven results [28]

☐ There does not exist a deterministic algorithm that can guarantee delivery based on local information only in general 3D networks
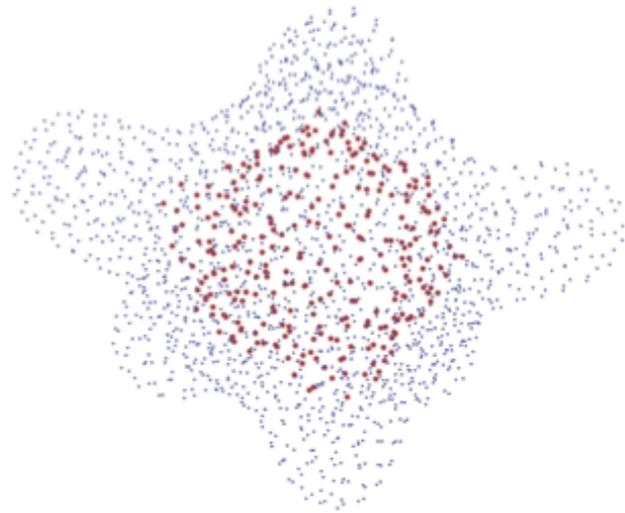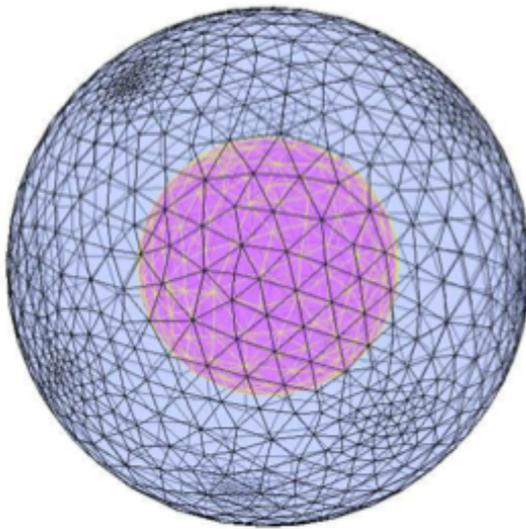
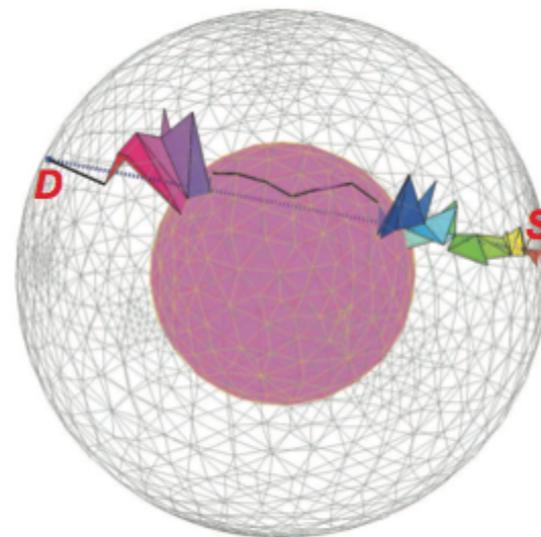(a) A 3D sensor network (Network model 1).
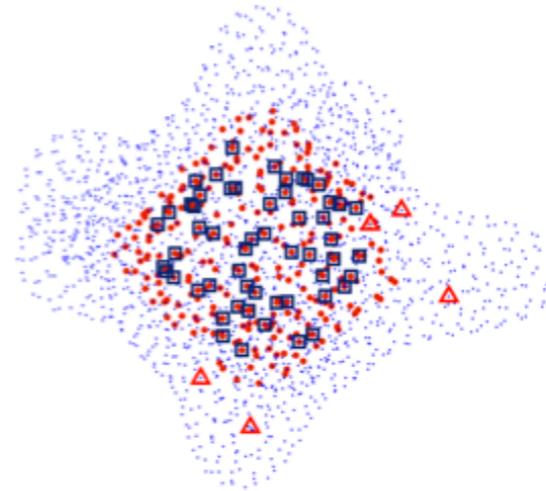
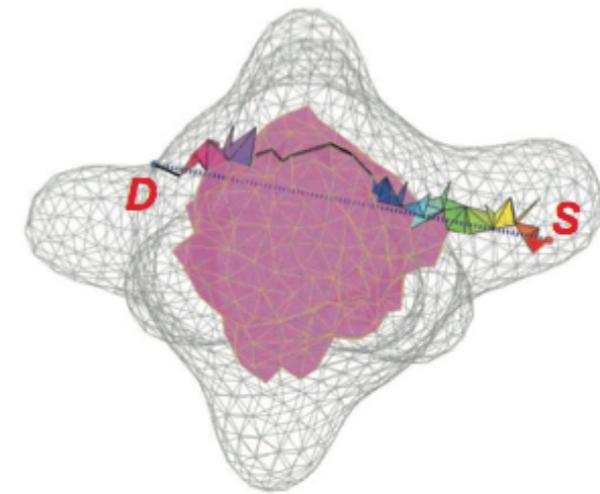(b) Local minimums in nodal greedy routing.
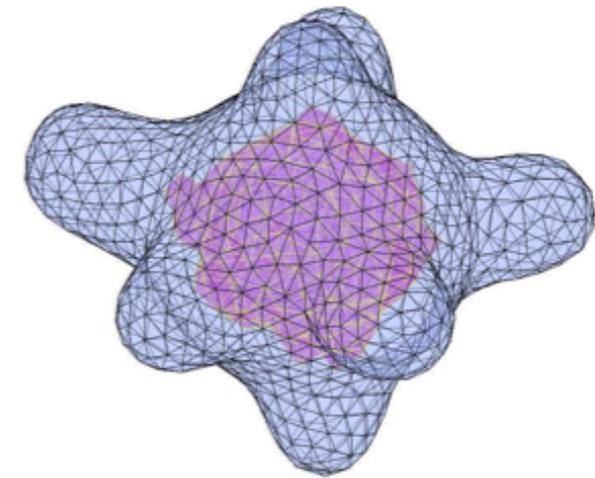
(c) Unit tetrahedron cells (UTCs).

(d) Volumetric Harmonic mapping.

(e) A greedy routing path in mapped domain.

(f) A greedy routing path in original network.

ROUTING AT BOUNDARY UTCS

☐ How to do the mapping?

☐ <u>Spherical harmonic map</u>: first map the boundary of the 3D network continuously and one-to-one to a unit sphere by minimizing spherical harmonic energy

☐ <u>Volumetric harmonic map</u>: next minimize the volumetric harmonic energy under the spherical boundary condition computed in the first step

☐ We design distributed algorithms to realize such mapping

☐ Both algorithms are distributed; a node needs to communicate with its one-hop neighbors only

☐ Lemma 2: The iterative algorithms are proved convergent

☐ The number of iterations is $O(n^2)$

LIMITATION

- DISCO Property
  - Each node only maintains two coordinates
  - Computation is constant-bounded
  - Routing is deterministic
- Conflicts with the proven result?
  - Works for network with no or one hole only

TRACE-ROUTING ALGORITHM (MOBIHOC'14)

- ☐ Trace routing:

  - ☐ When geometric greedy routing reaches a local minimum p_{min} on Boundary B_i, construct a virtual cutting plane that is determined by p_{min}, Destination d, and a random point p.

  - ☐ The plane intersects B_i, yielding a trace that contains p_{min}.

  - ☐ Advances along the trace in clockwise or counterclockwise direction until it reaches a point closer to d than p_{min} is. Then greedy routing follows.

(c) Proposed trace-routing.
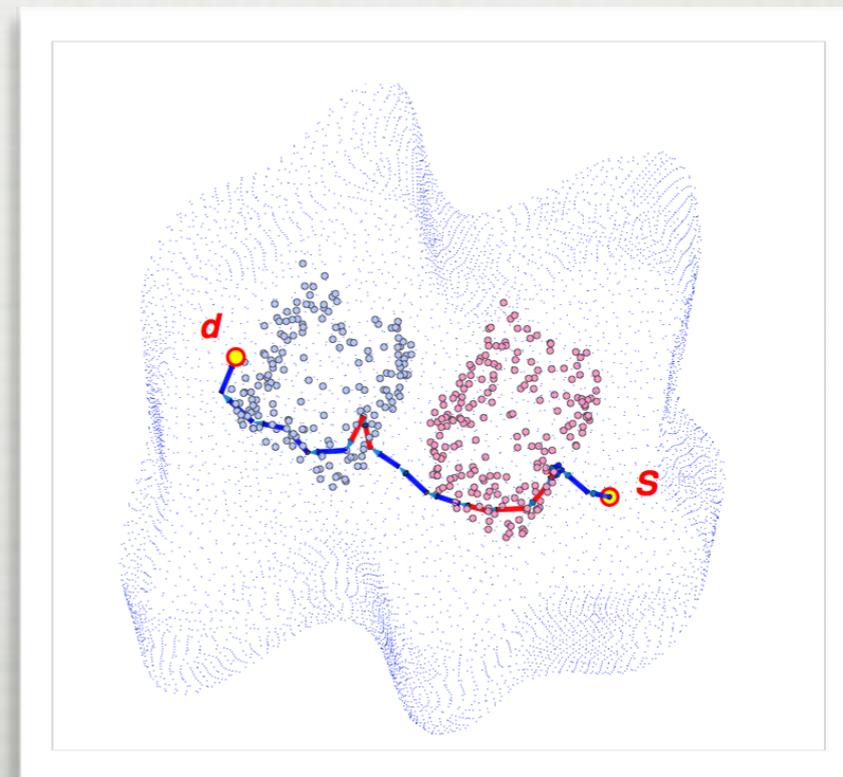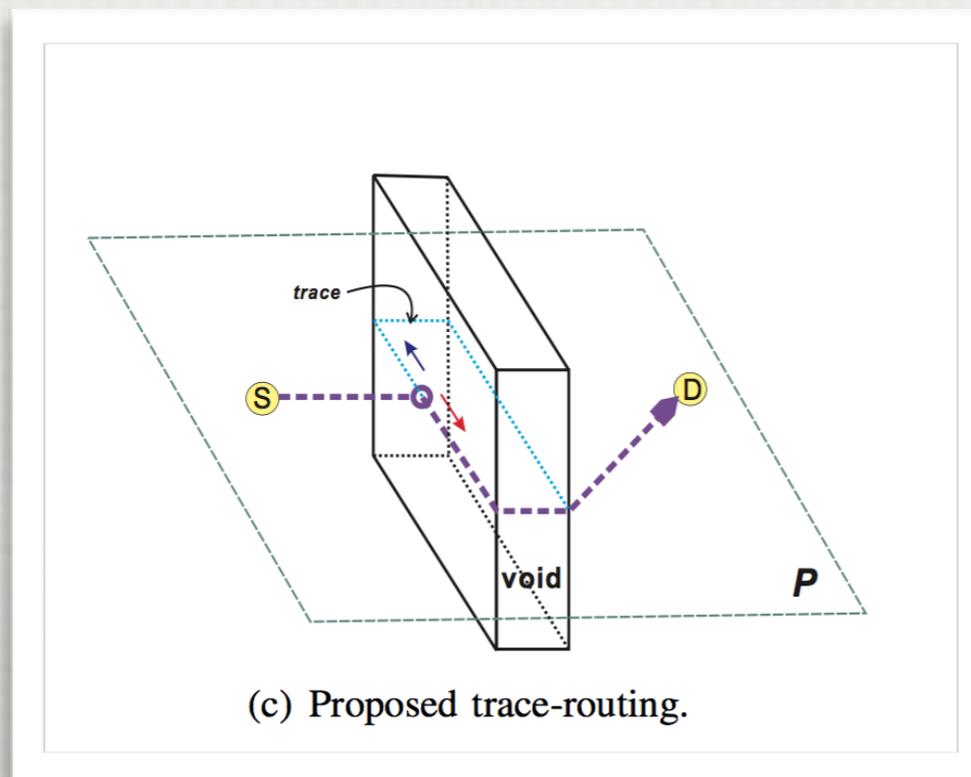
TRACE-ROUTING ALGORITHM

- ☐ Work for all networks? No!

- ☐ Definition: A 3D volume U is s-con (Strong-CON-nected), if and only if the intersection of any plane and U is a connected graph on the plane

- ☐ Theorem: There exists a deterministic algorithm with constant storage, communication and computation overhead, which can successfully navigate the routing path out of local minimums in an s-con volume.

  - ☐ A closed-loop trace with no self-intersection can be constructed deterministically.

  - ☐ There exists at least one node on the trace, which is closer to the destination than the local minimum

  - ☐ Storage, communication and computation overhead are constant

SUMMARY—FIRST EXAMPLE

- Investigate DISCO routing in 3D wireless sensor networks
  - Fundamentally different and more challenging than 2D
  - None of the 2D schemes can be applied
  - Does not exist a DISCO algorithm for general 3D networks
- Consider two spacial but representative network settings
  - Network with no or one internal hole: map boundary to sphere via Volumetric Harmonic mapping
  - S-Con network: trace-routing

The Second Example: Autonomous Localization in 3D Surface Networks

[INFOCOM'12] Yao Zhao, Hongyi Wu, Miao Jin, and Su Xia, "Localization in 3D Surface Sensor Networks: Challenges and Solutions", in IEEE INFOCOM, 2012. (Acceptation rate: 18%)

[MOBIHOC'13] Yao Zhao, Hongyi Wu, Miao Jin, Yang Yang, Hongyu Zhou, and Su Xia, "Cut-and-Sew: A Distributed Autonomous Localization Algorithm for 3D Surface Wireless Sensor Networks", in ACM MobiHoc, 2013. (Acceptation rate: 10%)

[INFOCOM'14] Yang Yang, Miao Jin, and Hongyi Wu, "3D Surface Localization with Terrain Model", in IEEE INFOCOM, 2014. (Acceptation rate: 19%)

AUTONOMOUS LOCALIZATION ON 2D PLANE

- ☐ Input: Euclidean distance
- ☐ Principle: search the solution space to discover optimal sensor coordinates that minimize the average distance error
- ☐ Methodology: multidimensional scaling, neural networks, nonlinear optimization, differential geometry
- ☐ Bottom line: distance information is sufficient to localize sensor nodes on a 2D plane (except for non-rigid shapes)
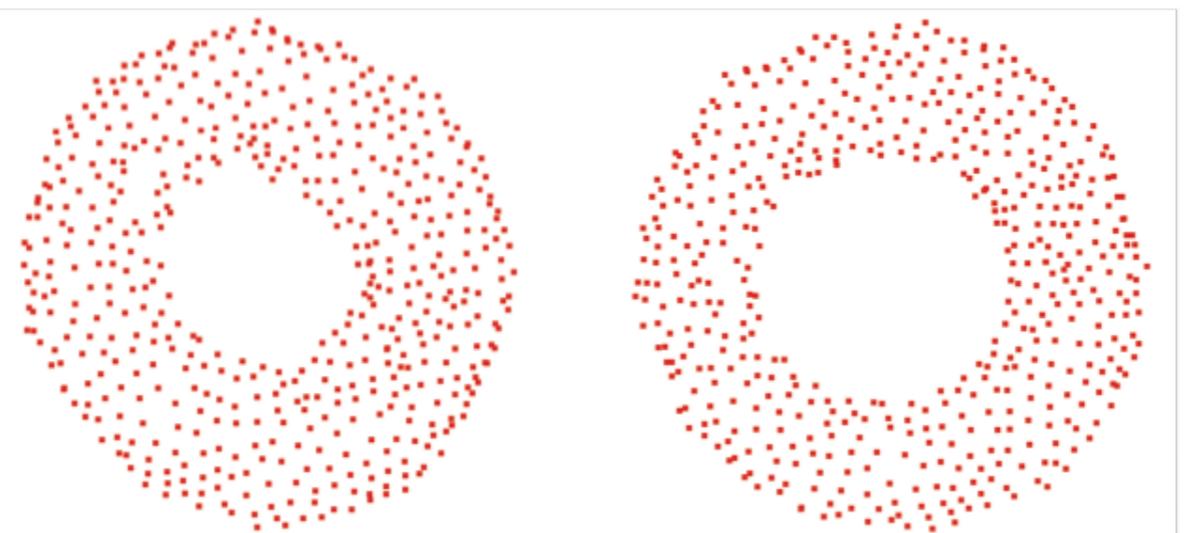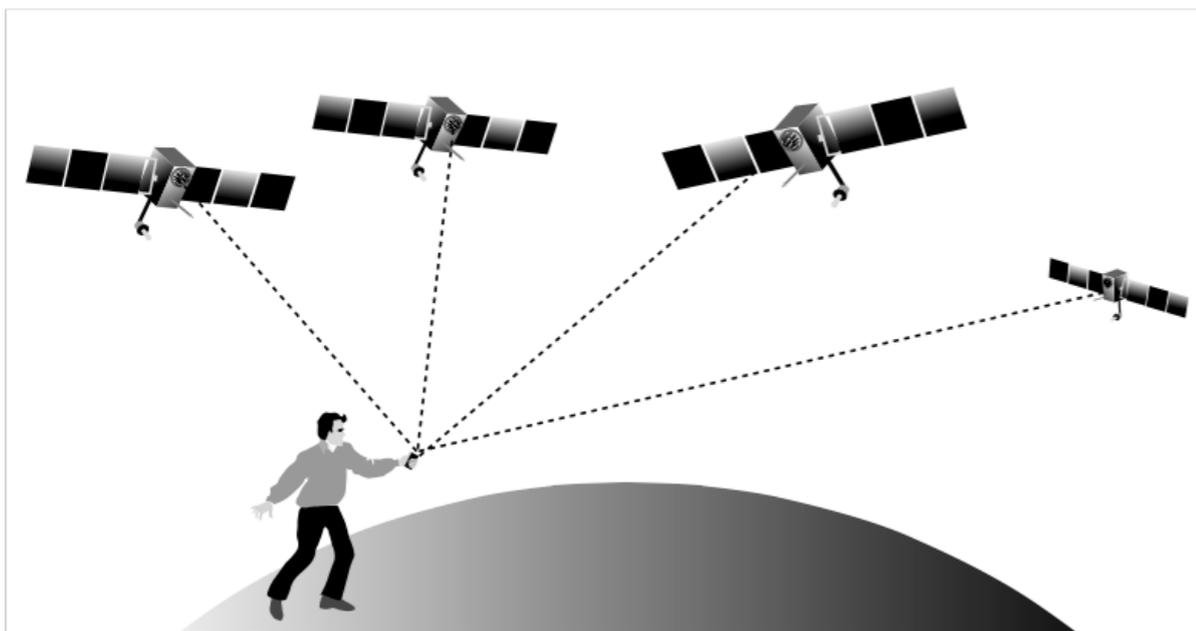
(a) A 2D network.   (b) 2D MDS result.

AUTONOMOUS LOCALIZATION IN 3D VOLUME

- ☐ Introducing the third dimension does not substantially increase the hardness of the problem
- ☐ It is straightforward to extend most 2D localization algorithms to 3D volume
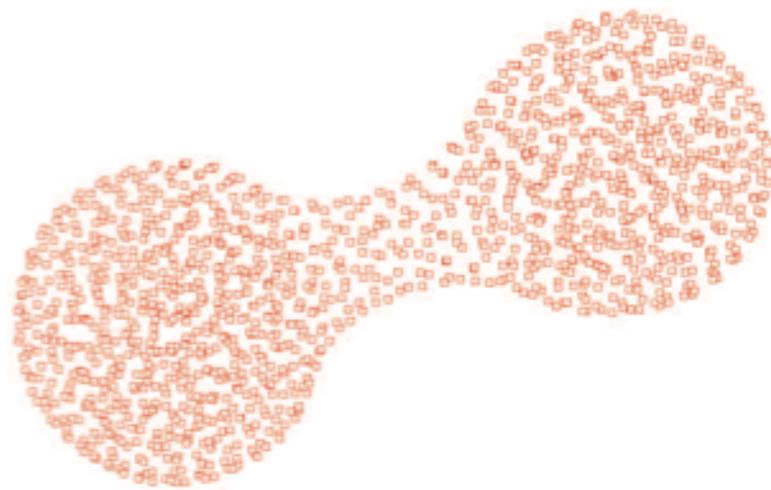
(c) A 3D volume network.   (d) 3D MDS result.
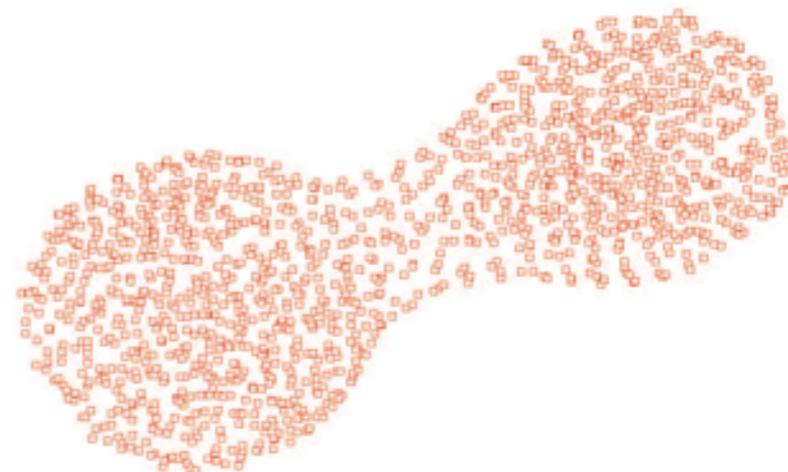
CHALLENGES IN 3D SURFACE LOCALIZATION

☐ First glance: a 3D surface appears to be a special case of 3D volume or a generalization of 2D plane

☐ Surprising challenges: existing algorithms not applicable

    ☐ Hardness: lack of correct Euclidean distance estimation between remote nodes
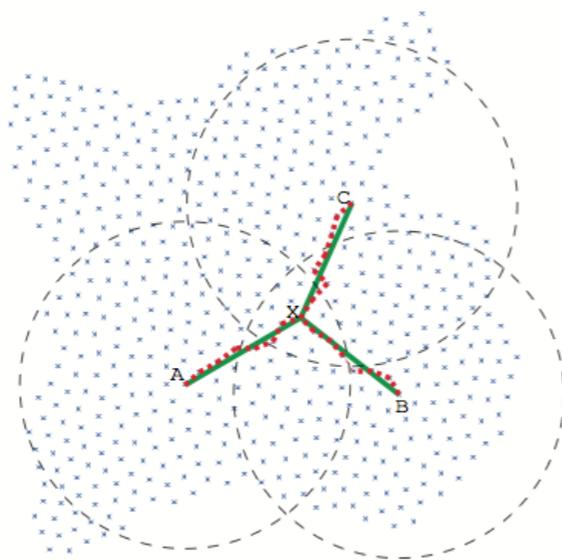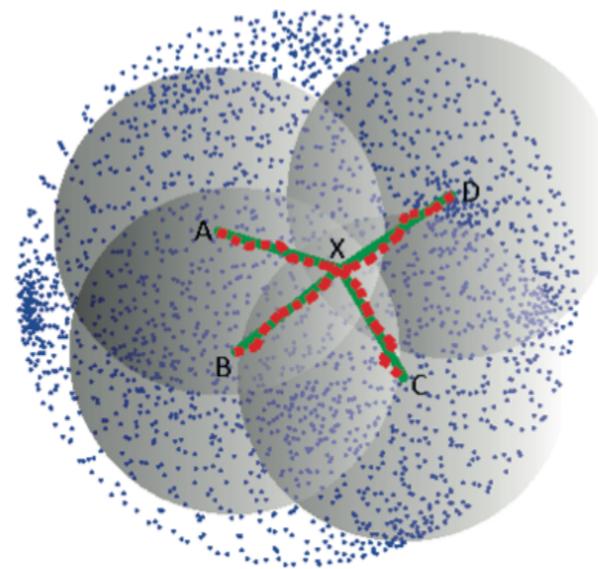
(a) 2D network.   (b) 3D volumetric network.   (c) 3D surface network.
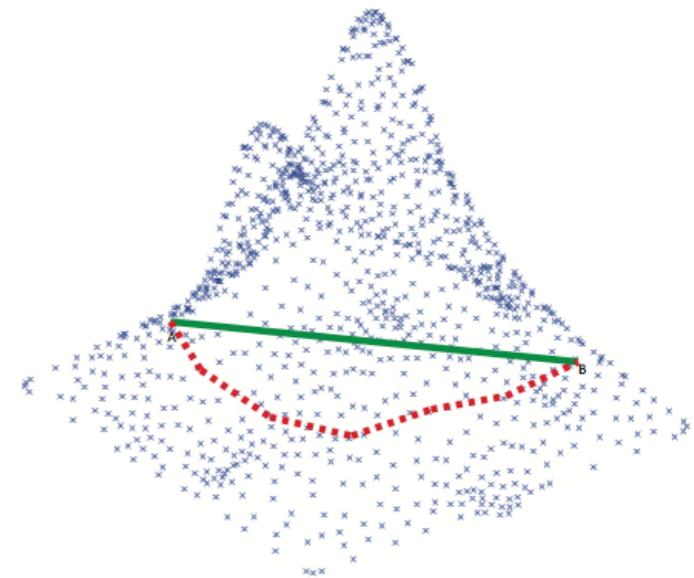
CHALLENGES IN 3D SURFACE LOCALIZATION

☐ Proven result: a general 3D surface network is not localizable, given surface distance constraints only
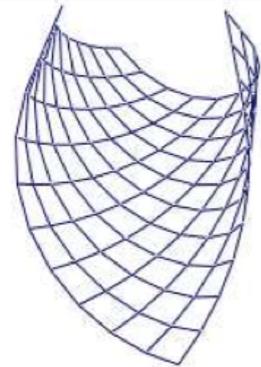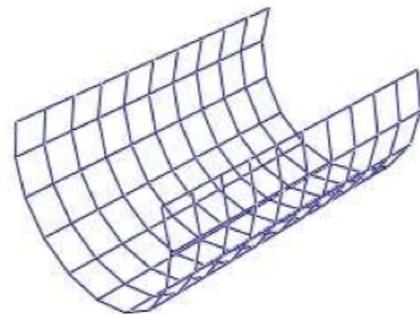
(a) A 3D surface.   (b) Deformation of the surface.   (c) A 3D surface network.   (d) MDS result of (c).
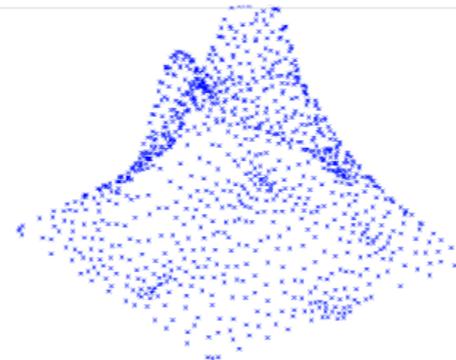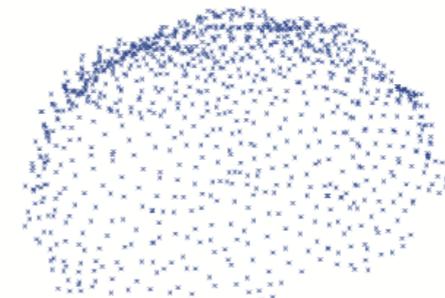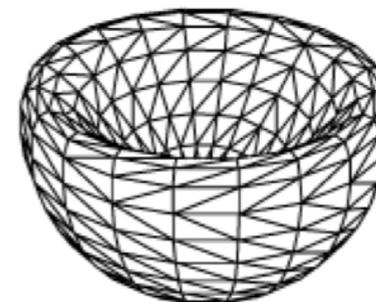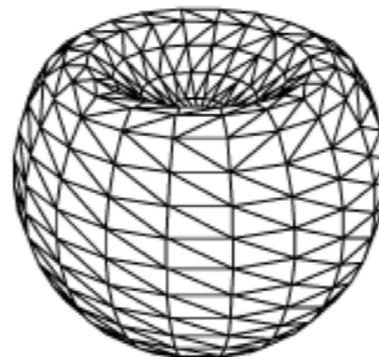
PROPOSED APPROACH

☐ Observation:

  ☐ Sensor network on single-value (SV) 3D surface is localizable

☐ Proposed approach: divide-and-conquer

  ☐ Partition a general 3D surface network into SV patches

  ☐ Localize individual patches

  ☐ Merge them into unified coordinates system
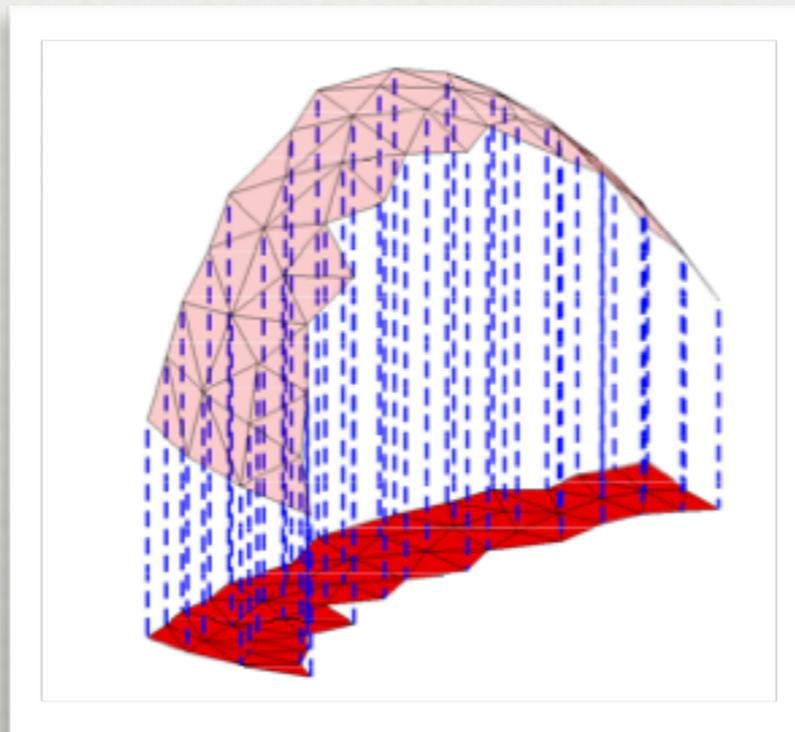
OPTIMIZATION GOAL

- ☐ Observation:
  - ☐ Many options to partition a network
  - ☐ Theoretically infinite solution space to be explored
- ☐ Optimization goal: discover the minimum SV partition
  - ☐ All patches must be SV to ensure their localizability
  - ☐ The number of patches should be minimized to avoid unnecessary partitioning and merging, which are subject to linear transformation errors
- ☐ How to achieve minimum SV partition?
  - ☐ Identify Non-Single-Value (NSV) edges
  - ☐ Partition the network according to NSV edges
  - ☐ Proven to be minimum SV partition

ALGORITHM OVERVIEW
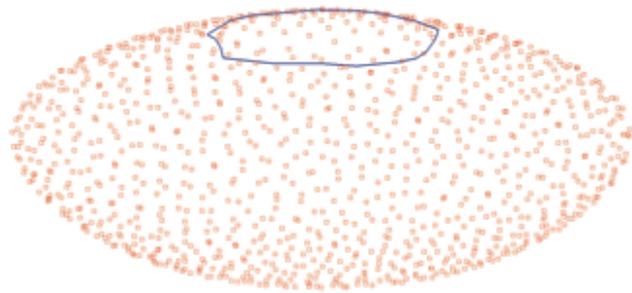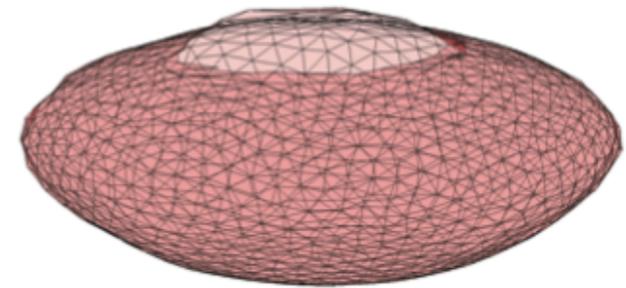

(a) A 3D surface network.
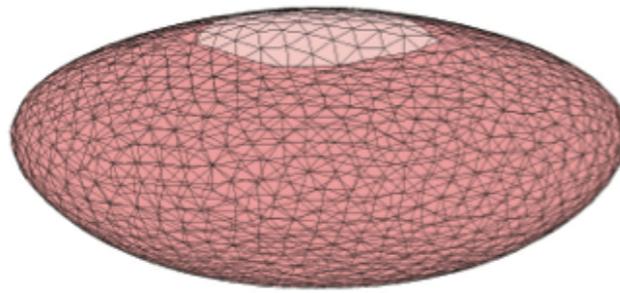
(b) Triangulation mesh.
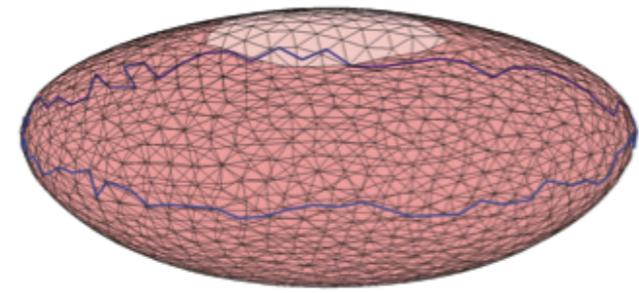
(c) Identified NSV edges.
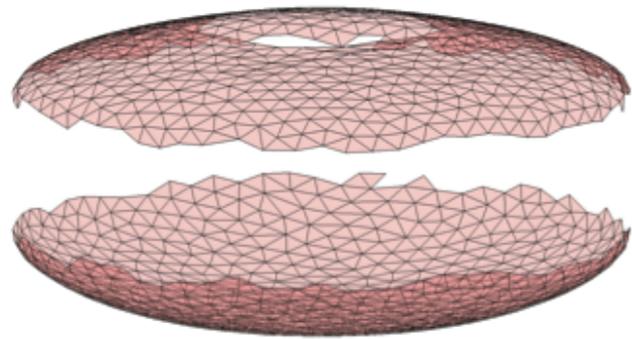
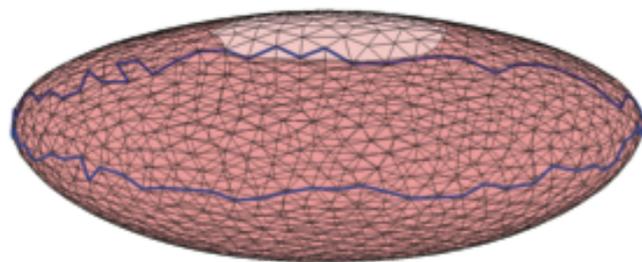(d) Partitioned SV pieces.
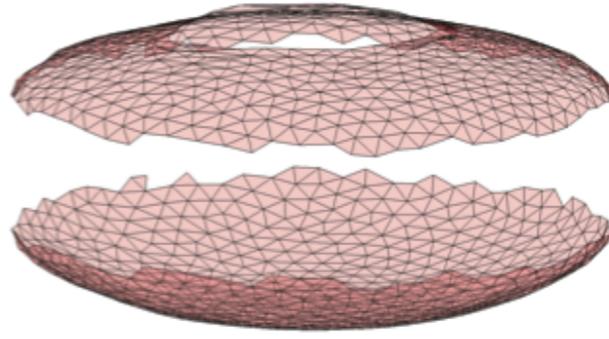
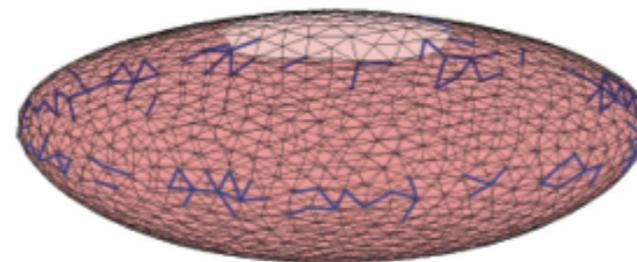(e) Localization of individual pieces.

(f) Final localization result.
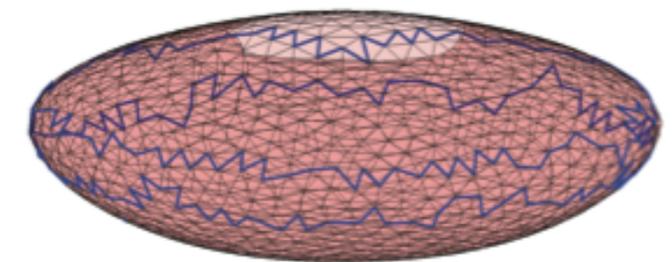
PRACTICAL SOLUTION WITH NOISY INPUTS

- Distance and height measurements can be noisy
- Inaccurate inputs directly affect identification of NSV edges
  - NSV edges become isolated, deviating from true NSV edges
  - Impossible to partition the network directly
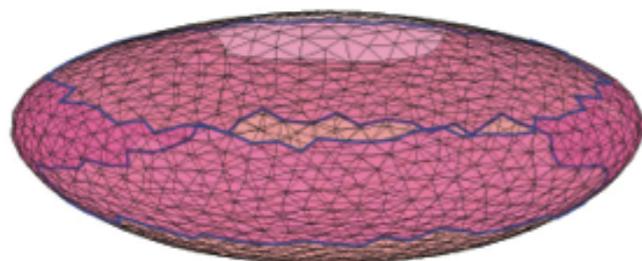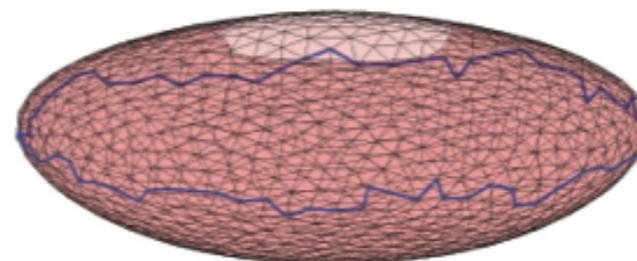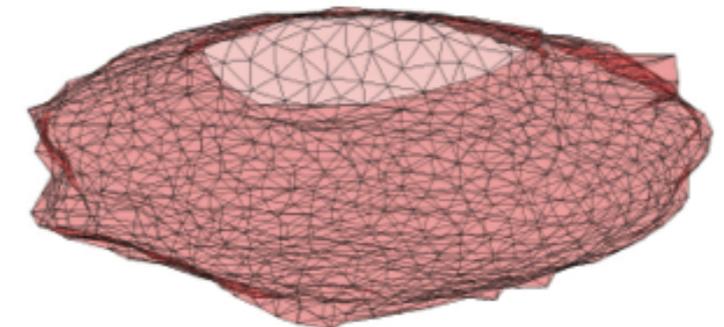

(a) True NSV edges.

(b) Detected NSV edges.

(c) Coalescence of isolated NSV edges.

(d) Formation of NSV band.

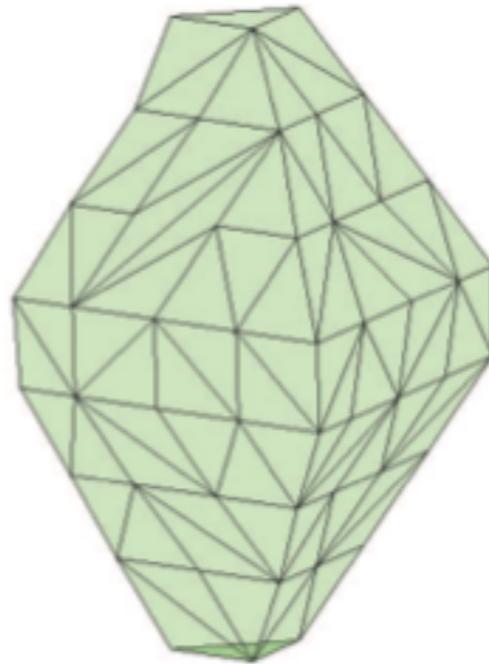(e) Partition along medial axis.
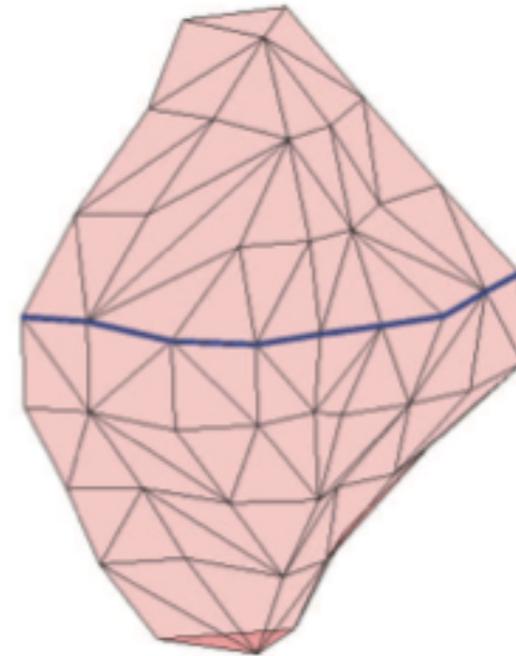
(f) Final localization result.

PROTOTYPING

- Built indoor testbed models
- Forty eight Crossbow MICAz motes are attached to its surface
- RSSI is used to estimate the length of links (about 20% errors)
- Ground truth is manually measured
- Average location error around 14%

(a)　　　　　(b)　　　　　(c)

SUMMARY—2ND EXAMPLE

- ☐ Unique challenge in 3D surface localization
- ☐ A divide-and-conquer approach, named cut-and-sew
  - ☐ Achieve minimum SV partition
  - ☐ Localize individual patches
  - ☐ Merge patches
- ☐ Introduce a practically-viable solution for real-world sensor network settings where the inputs are noisy
- ☐ Implement and evaluate via simulations and indoor testbed experiments

Boundary Detection and Surface Construction

[ICDCS'10] Hongyu Zhou, Su Xia, Miao Jin, and Hongyi Wu, "Localized Algorithm for Precise Boundary Detection in 3D Wireless Networks", in IEEE ICDCS, 2010.

[INFOCOM'11] Hongyu Zhou, Hongyi Wu, Su Xia, Miao Jin and Ning Ding, "A Distributed Triangulation Algorithm for Wireless Sensor Networks on 2D and 3D Surface", in IEEE INFOCOM, 2011.

[INFOCOM'12] Hongyu Zhou, Hongyi Wu, and Miao Jin, "A Robust Boundary Detection Algorithm Based on Connectivity Only for 3D Wireless Sensor Networks", in IEEE INFOCOM, 2012.

[MOBIHOC'13] Hongyu Zhou, Miao Jin, and Hongyi Wu, "A Distributed Delaunay Triangulation Algorithm Based on Centroidal Voronoi Tessellation for Wireless Sensor Networks", in ACM MobiHoc, 2013.
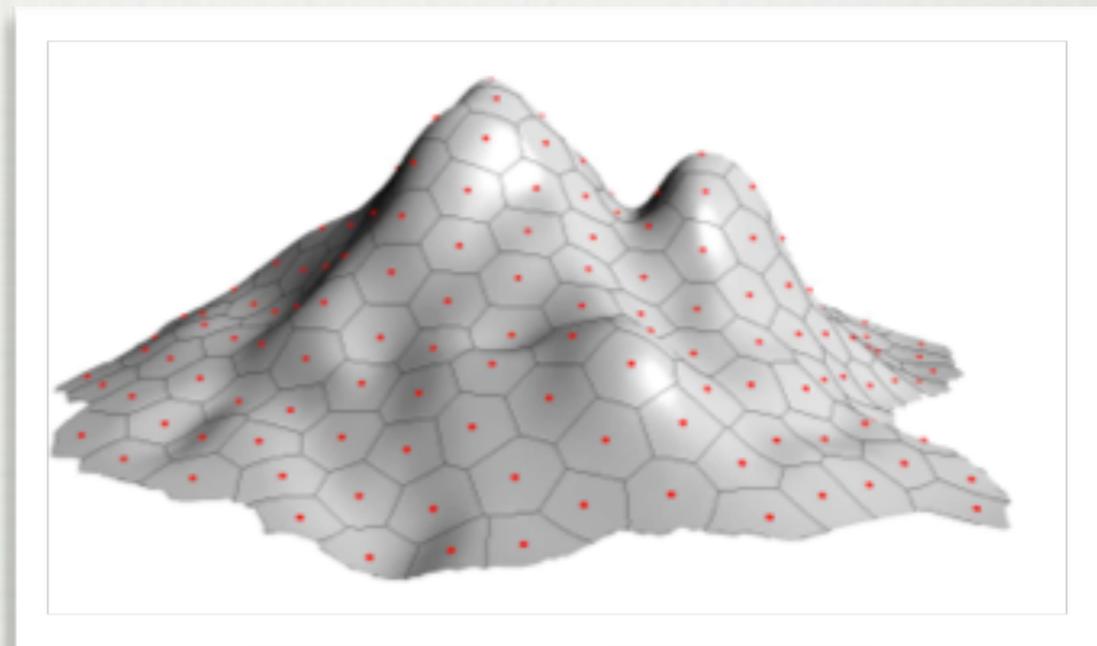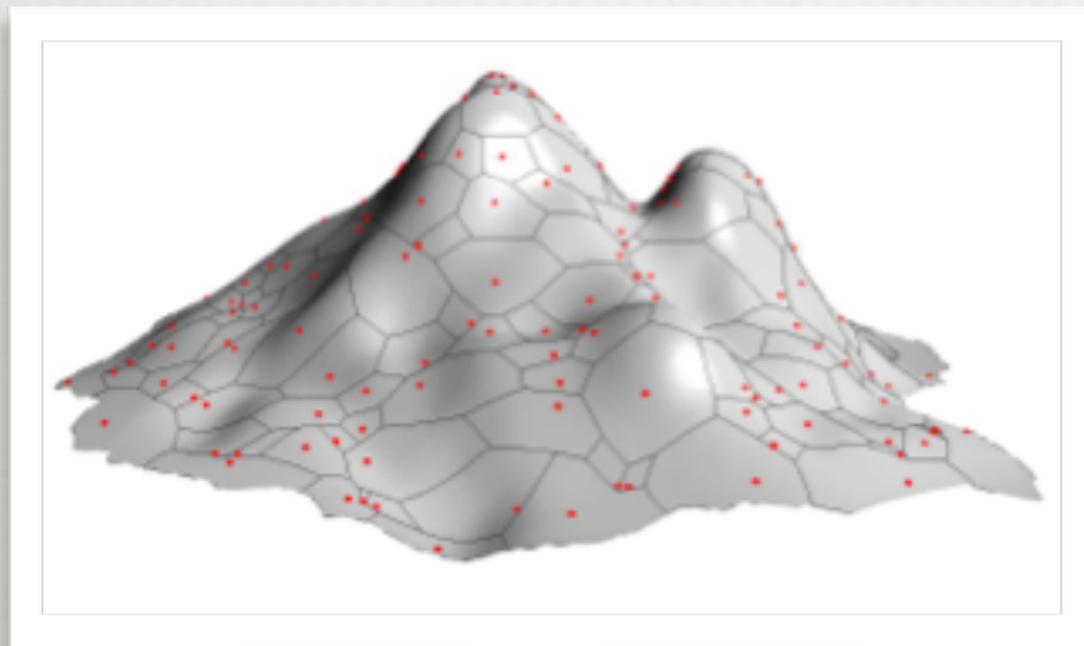
[ToN'15] Hongyu Zhou, Su Xia, Miao Jin and Hongyi Wu, "Localized and Precise Boundary Detection in 3D Wire- less Sensor Networks", in IEEE/ACM Transactions on Networking, Vol. 23, No. 6, pp. 1742-1754, 2015.

BOUNDARY DETECTION

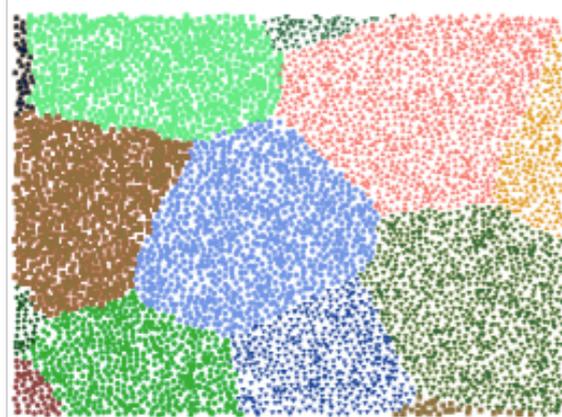- Boundary detection: identify nodes on boundaries of a 3D network
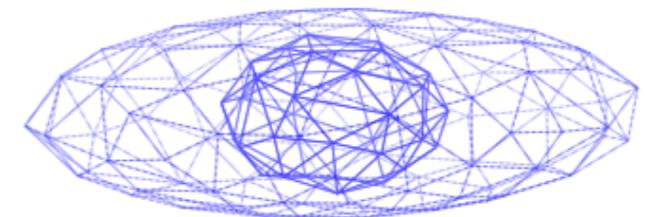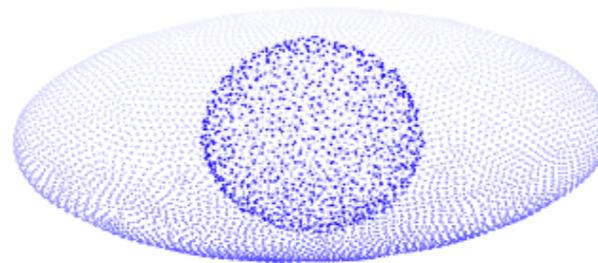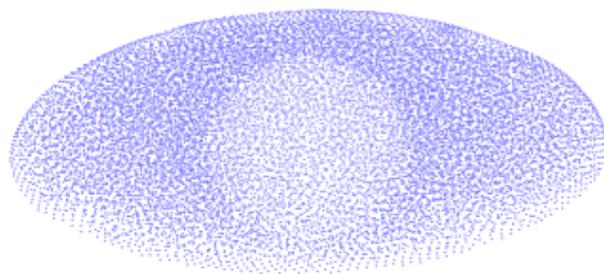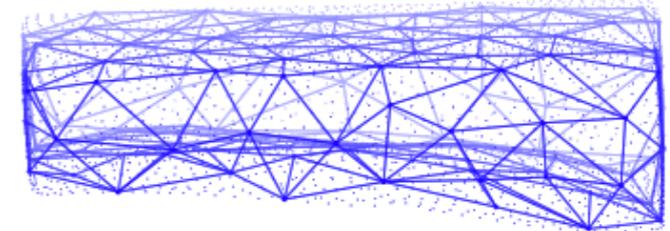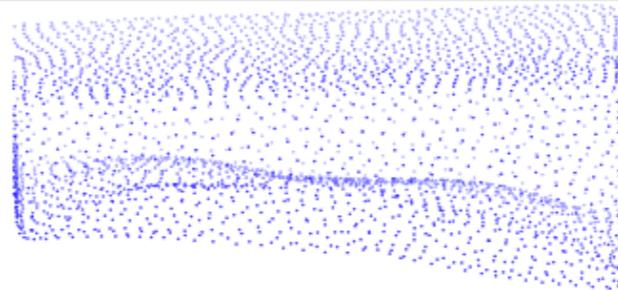
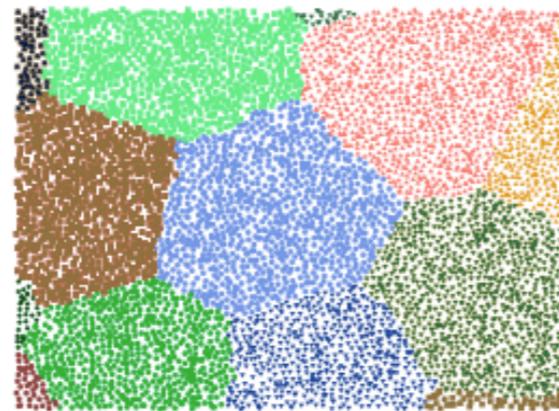# Distributed Sensor Deployment on 3D Surface Networks

[INFOCOM'12] Miao Jin, Guodong Rong, Hongyi Wu, Liang Shuai, and Xiaohu Guo, "Optimal Surface Deployment Problem in Wireless Sensor Networks, in IEEE INFOCOM, 2012.
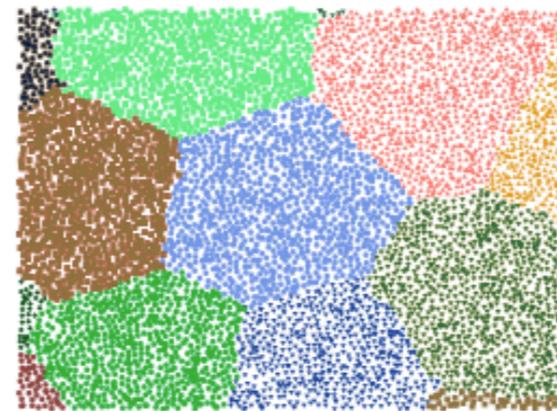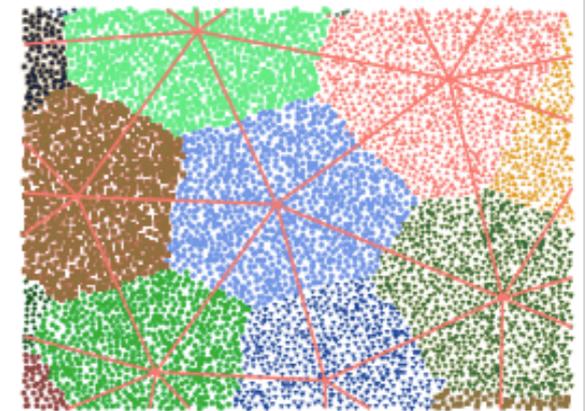
DELAUNAY TRIANGULATION (MOBIHOC'13)

(a) Initial Voronoi diagram. (b) Result after two iterations. (c) Result after four iterations. (d) Final result.

☐ A distributed algorithm for Delaunay triangulation

   ☐ Performs centroidal Voronoi tessellation

   ☐ Constructs dual graph to yield Delaunay triangulation

☐ Proven convergence of centroidal Voronoi tessellation in sensor networks

☐ Proven to succeed in constructing a Delaunay triangulation, if the CVT cell size is greater than a constant

Distributed Data Storage and Retrieval

[INFOCOM'13] Yang Yang, Miao Jin, Yao Zhao, and Hongyi Wu, "Cut Graph Based Information Storage and Retrieval in 3D Sensor Networks with General Topology", in IEEE INFOCOM, mini-conference, 2013.

[ToN'14] Yang Yang, Miao Jin, Yao Zhao, and Hongyi Wu, "Distributed Information Storage and Retrieval in 3D Sensor Networks with General Topologies", accepted for publication in IEEE/ACM Transactions on Networking, 2014.
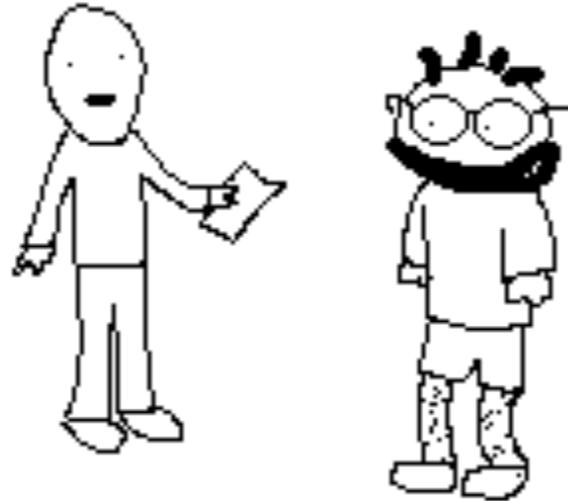
Medial Axis Construction in 3D Sensor Network

[INFOCOM'13] Su Xia, Ning Ding, Miao Jin, Hongyi Wu, and Yang Yang, "Medial Axis Construction and Applications in 3D Wireless Sensor Networks", in IEEE INFOCOM, 2013.

Optimal Marching of Autonomous Mobile Sensors

[ICDCS'16] Buri Ban, Miao Jin, and Hongyi Wu, "Optimal Marching of Autonomous Networked Robots ", in IEEE ICDCS, 2016.

QUESTIONS ?