Cut-And-Sew: A Distributed Autonomous Localization Algorithm for 3D Surface Sensor Networks

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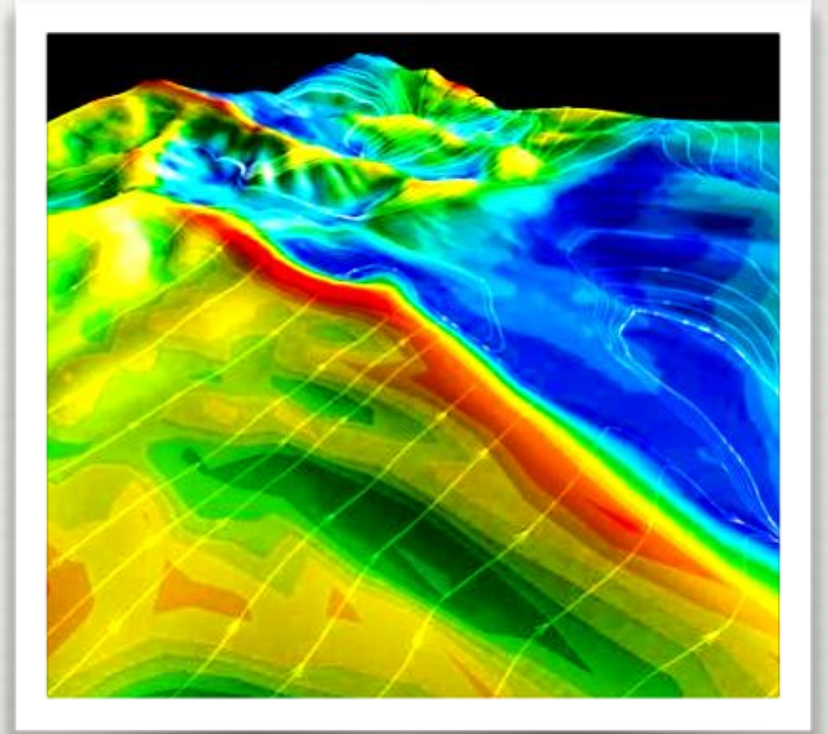
AUTONOMOUS LOCALIZATION IN WIRELESS SENSOR NETWORKS

- Location awareness is of significant importance
  - Sensor deployment
  - Position-aware sensing
  - Geometric routing
  - In-network data storage and retrieval
- Global Navigation Systems
  - Unaffordable due to high cost and lavish energy consumption
  - Unavailable without line-of-sight satellite signals
- **Autonomous localization**
  - GPS-less
  - GPS-free

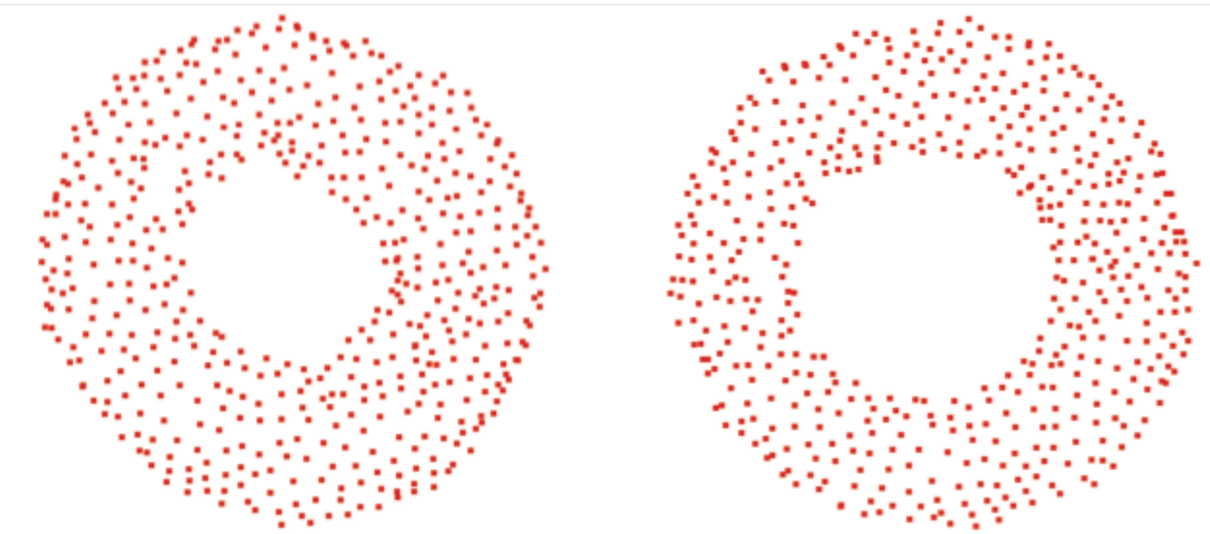
2D PLANE, 3D VOLUME, AND 3D SURFACE SENSOR NETWORKS

- 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



AUTONOMOUS LOCALIZATION ON 2D PLANE

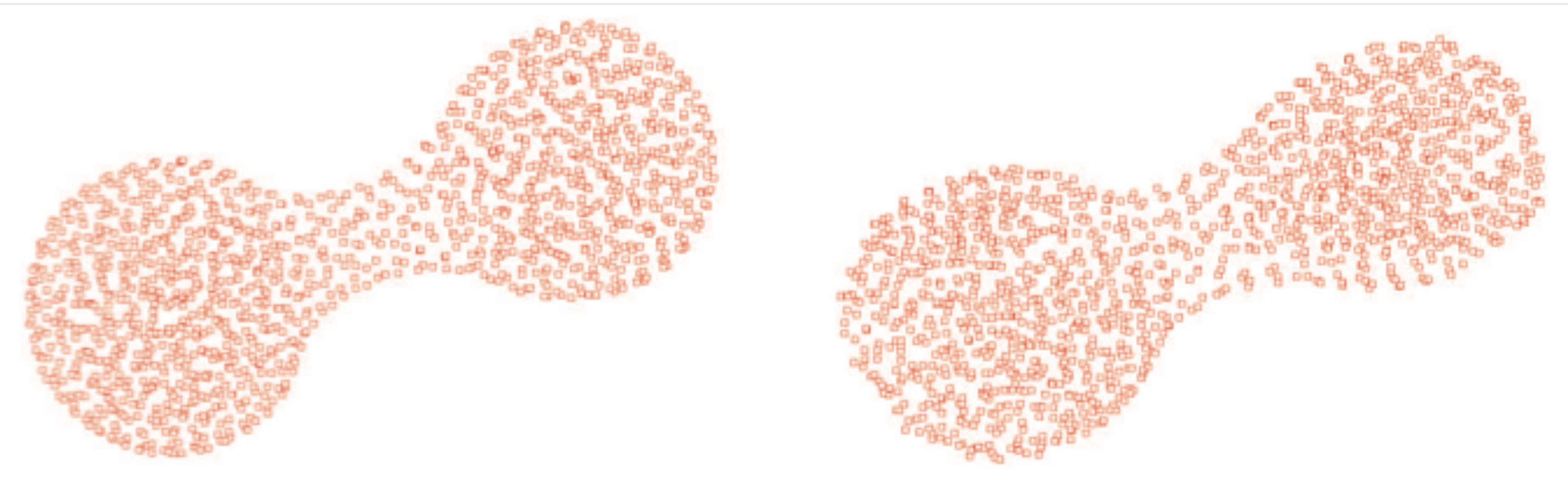
- Input: Euclidean distance
- Principle: search the solution space to discover optimal sensor coordinates that minimize the average distance error
- Methodology: multidimensional scaling, neural networks, nonlinear optimization, differential geometry
- Bottom line: distance information is sufficient 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

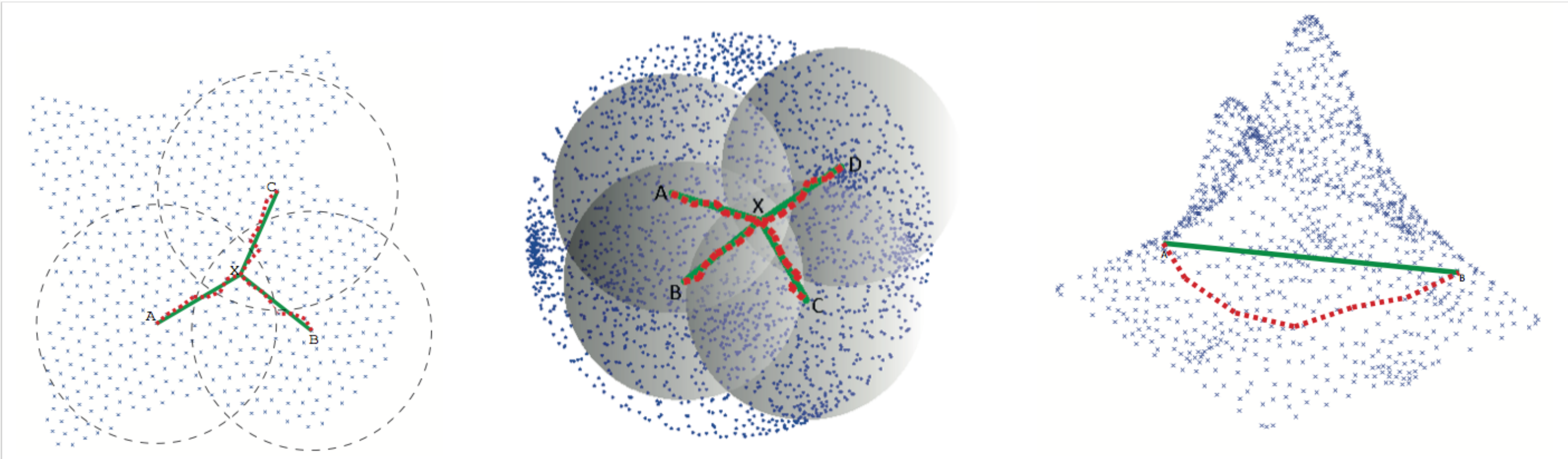


(c) A 3D volume network.

(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

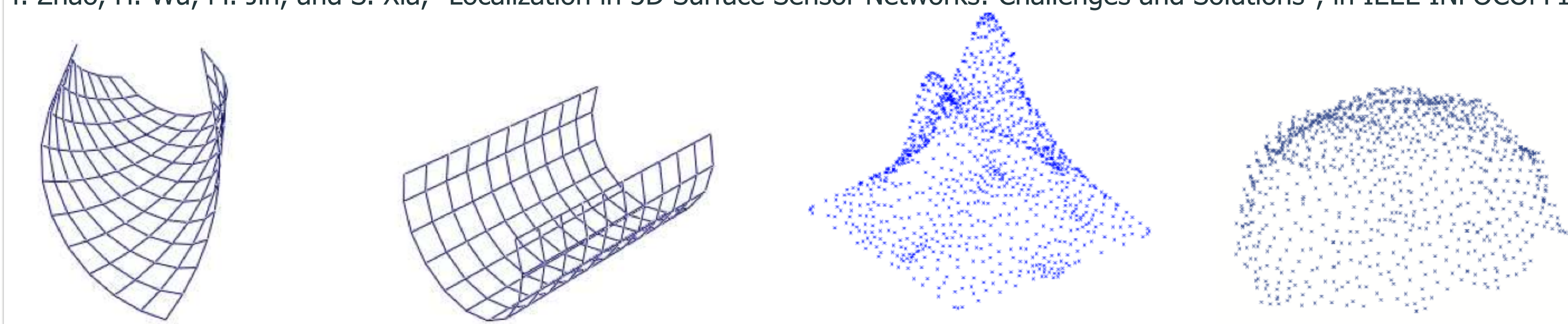


(a) 2D network. (b) 3D volumetric network. (c) 3D surface network.

CHALLENGES IN 3D SURFACE LOCALIZATION

- Proven result: a general 3D surface network is not localizable, given surface distance constraints only

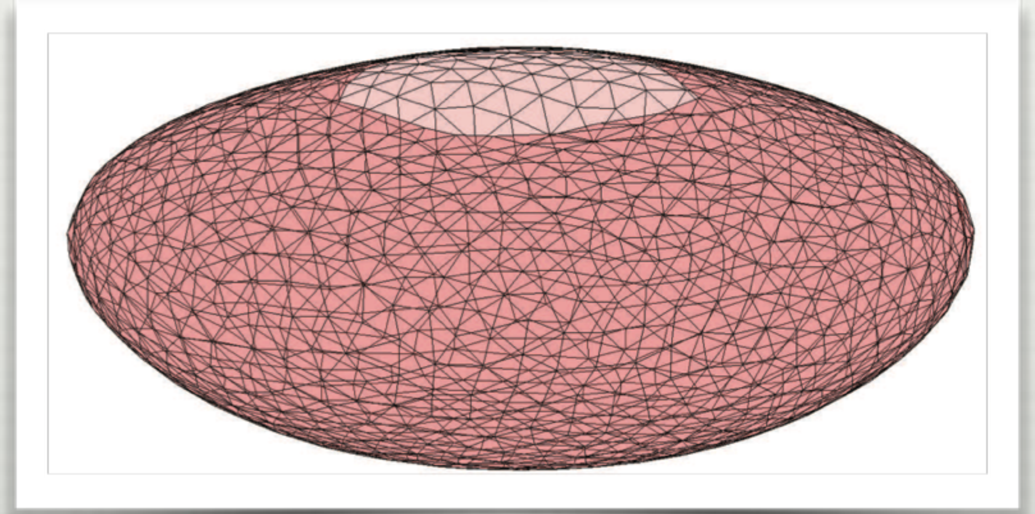
Y. Zhao, H. Wu, M. Jin, and S. Xia, "Localization in 3D Surface Sensor Networks: Challenges and Solutions", in IEEE INFOCOM'12.



(a) A 3D surface. (b) Deformation of the surface. (c) A 3D surface network. (d) MDS result of (c).

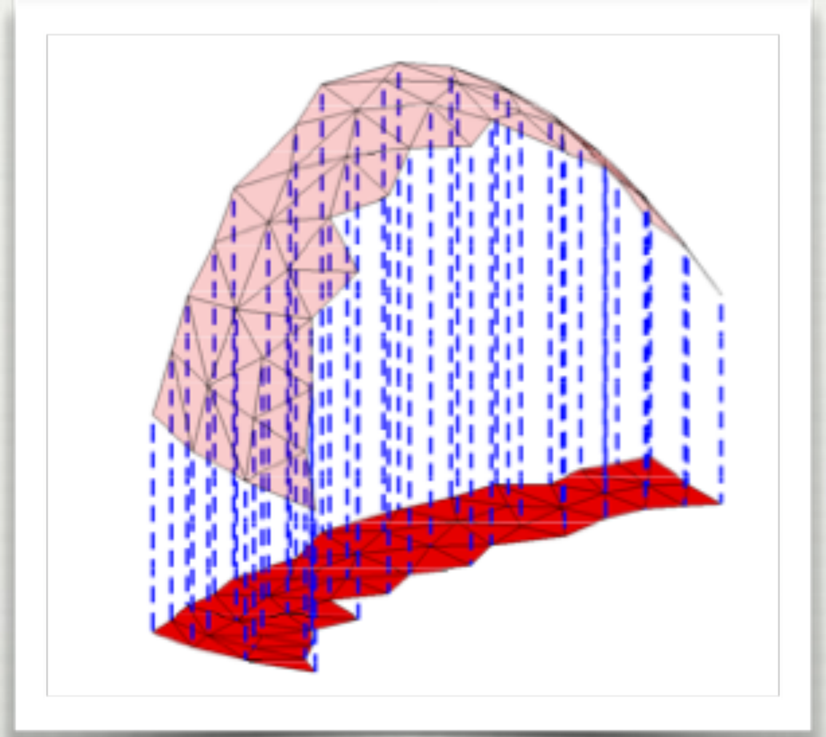
CHALLENGES IN 3D SURFACE LOCALIZATION

- Practical problem formulation:
  - Inputs: local distances and nodal height measurements
- First glimpse: the problem seems to become trivially easy
  - Height: Z-coordinate
  - Project sensors to X- Y plane and then apply 2D algorithms
- This naive approach often fails
  - Projection of a general 3D surface is non-planar
  - 2D localization algorithms either fail or result in extraordinarily large errors in a significantly non-planar graph



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

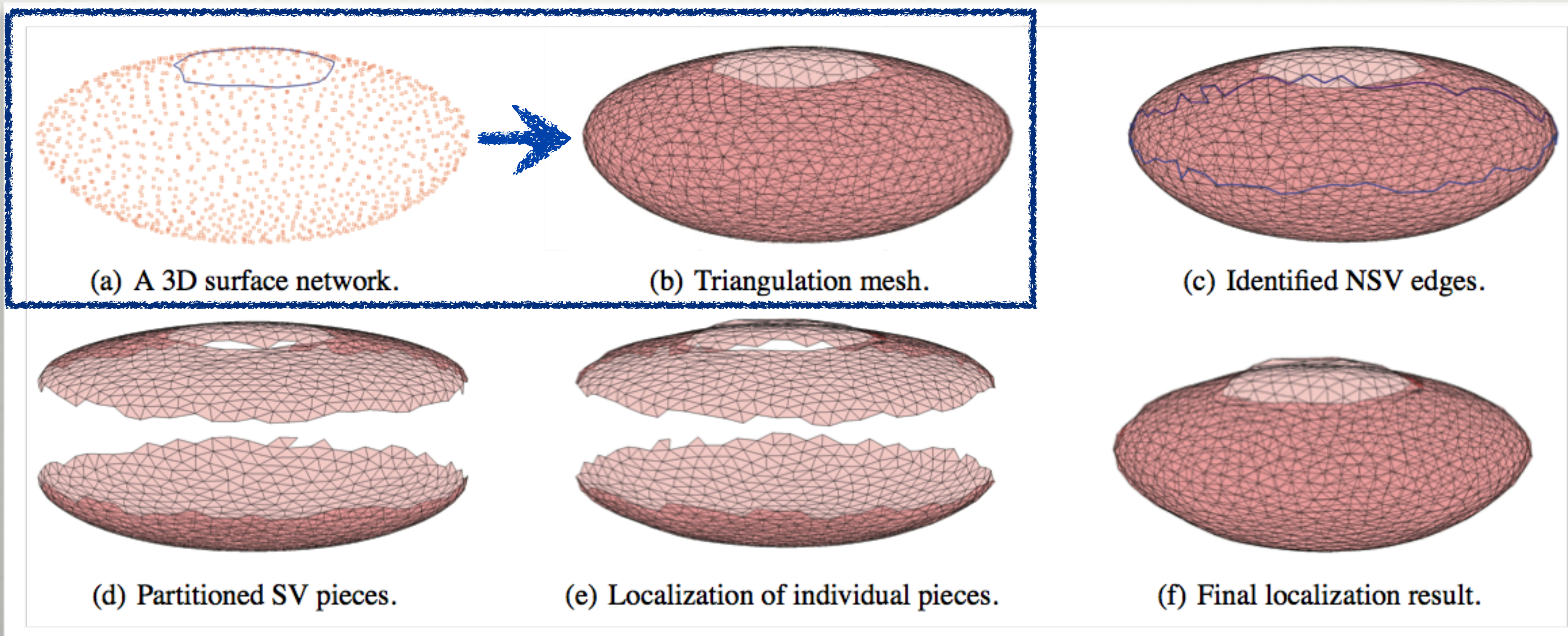


OPTIMIZATION GOAL

- 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

NSV EDGES

- Establish a triangular mesh structure (or triangulation) based on local connectivity and distance information [27]



(a) A 3D surface network. (b) Triangulation mesh. (c) Identified NSV edges.

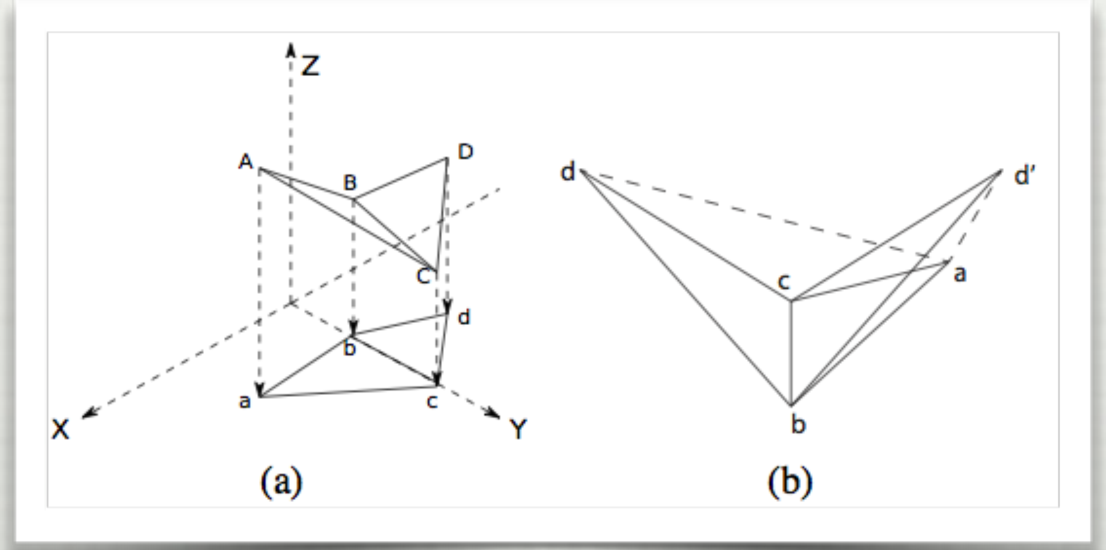
(d) Partitioned SV pieces. (e) Localization of individual pieces. (f) Final localization result.

NSV EDGES

- If an edge in the triangular mesh is not on the boundary, it must be shared by two and only two triangles.

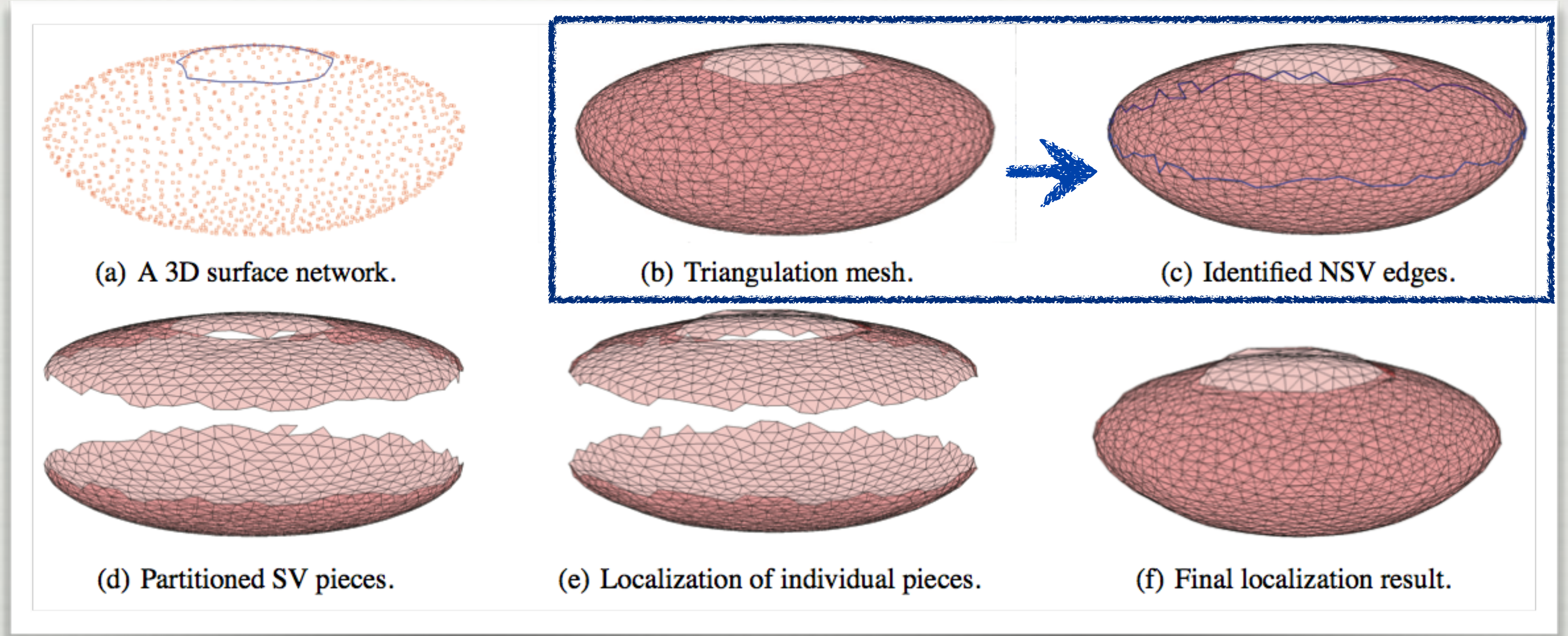
> In the triangulation of a 3D surface network, an edge is locally NSV (or NSV for short) if the projection of its two associated triangles overlap on the X-Y plane.

- LEMMA 1. Given an edge in the triangular mesh of a 3D surface sensor network, its associated local distance information is sufficient to determine whether it is a NSV edge.



NSV EDGES

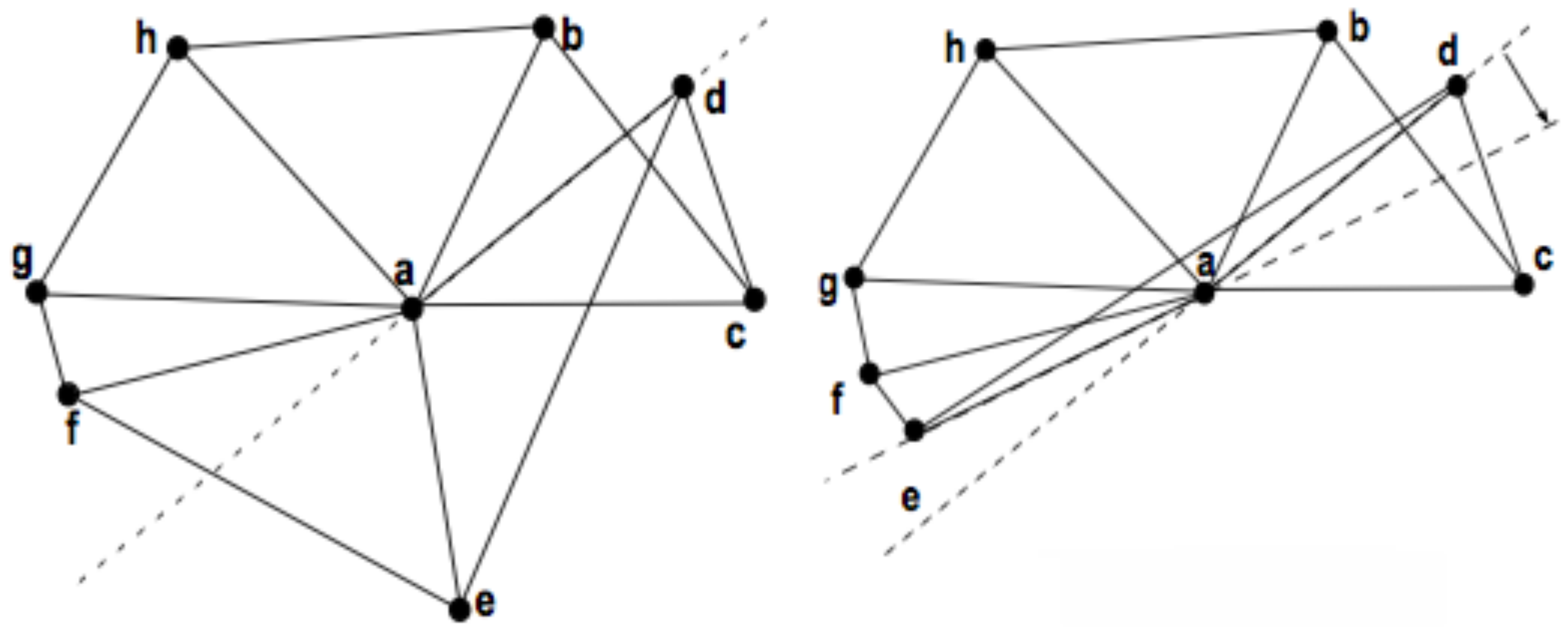
- Identified NSV edges



A 3D surface sensor network is called a NSV (or SV) network if it contains (or does not contain) NSV edges.

NSV EDGES

- LEMMA 2. A NSV edge must connect to other NSV edges or boundary edges.



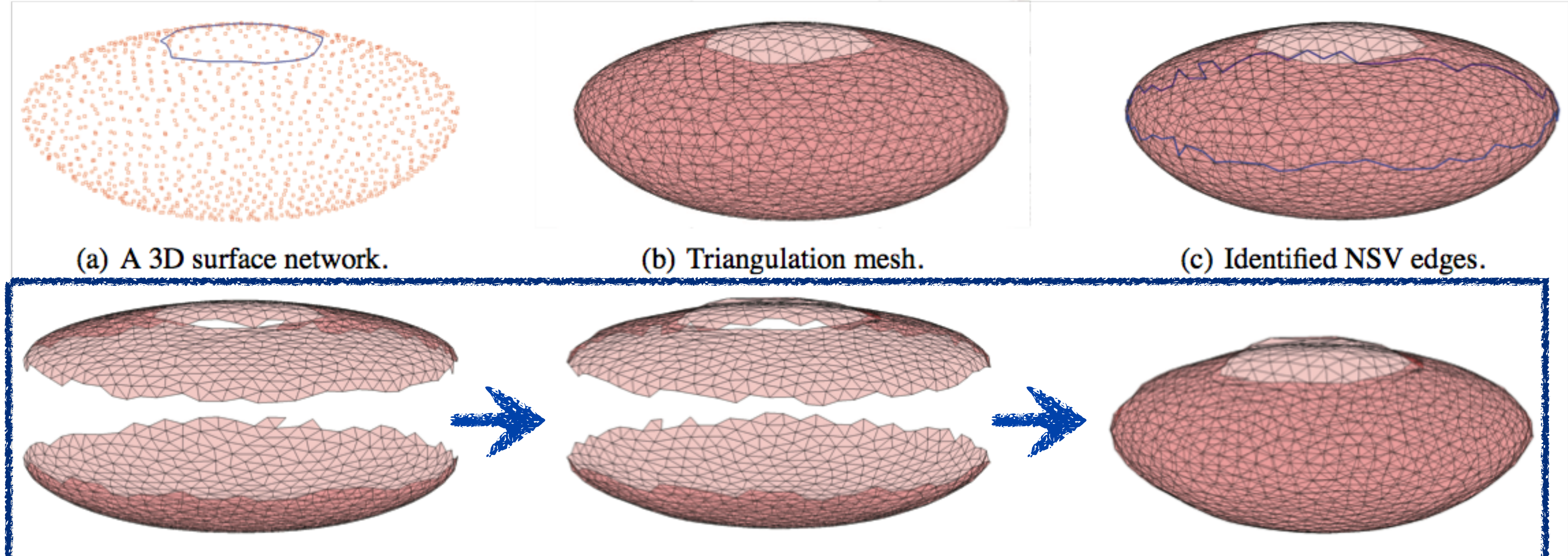
(a) Node *e* on right side of *ad*. (b) Node *e* on left side of *ad*.

NSV EDGES

- THEOREM 1. The minimum SV partition is achieved by dividing the network along NSV edges.
  - Follow a partitioning strategy:
    - Start from any node on an arbitrary NSV edge and cut the network along all of its connected NSV edges
    - NSV edges must connect to each other or to boundary, the cutting process will either form a loop or stop at the boundaries of the network. In either case, the network is partitioned into two or more separated patches.
    - Repeats until no NSV edges exist in the entire network
  - The network is partitioned into patches
  - Patches are SV: none of them contain a NSV edge
  - Partition is minimum: all NSV edges must be cut open, otherwise a patch containing NSV edges must be NSV patch

LOCALIZATION AND COMBINATION

- For each SV patch
  - Project to X-Y plane
  - Apply 2D planar localization to obtain X-Y coordinates
  - Add Z to yield 3D coordinates
- Use distributed least square to "sew" the patches

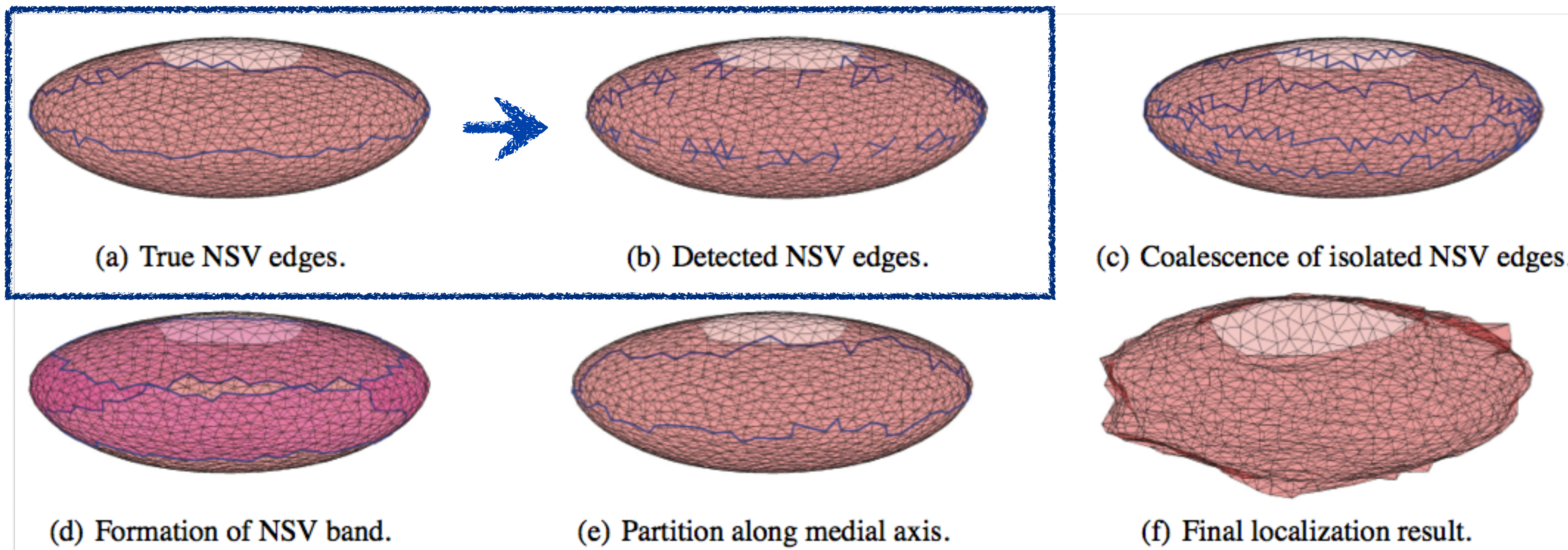


(a) A 3D surface network. (b) Triangulation mesh. (c) Identified NSV edges.

(d) Partitioned SV pieces. (e) Localization of individual pieces. (f) Final localization result.

PRACTICAL SOLUTION WITH NOISY INPUTS

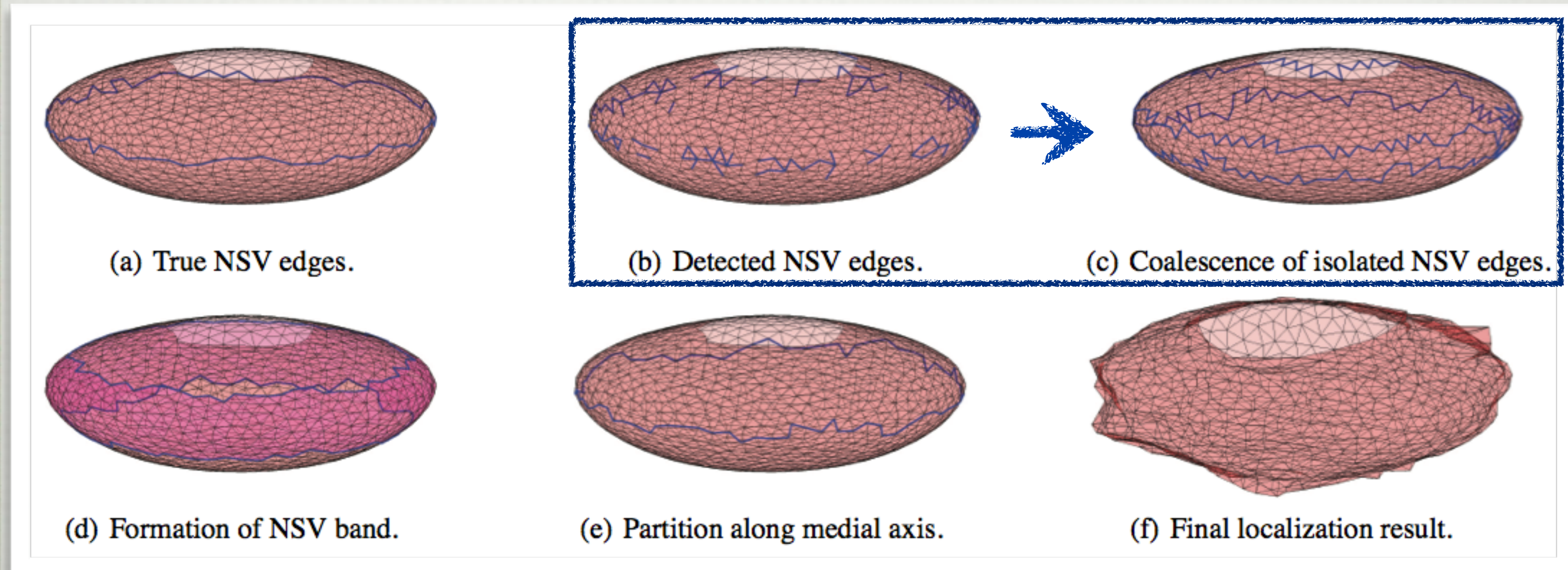
- Distance and height measurements can be noisy
- Inaccurate inputs directly affect identification of NSV edges
  - NSV edges become isolated, deviating from true NSV edges
  - Impossible to partition the network directly



(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.

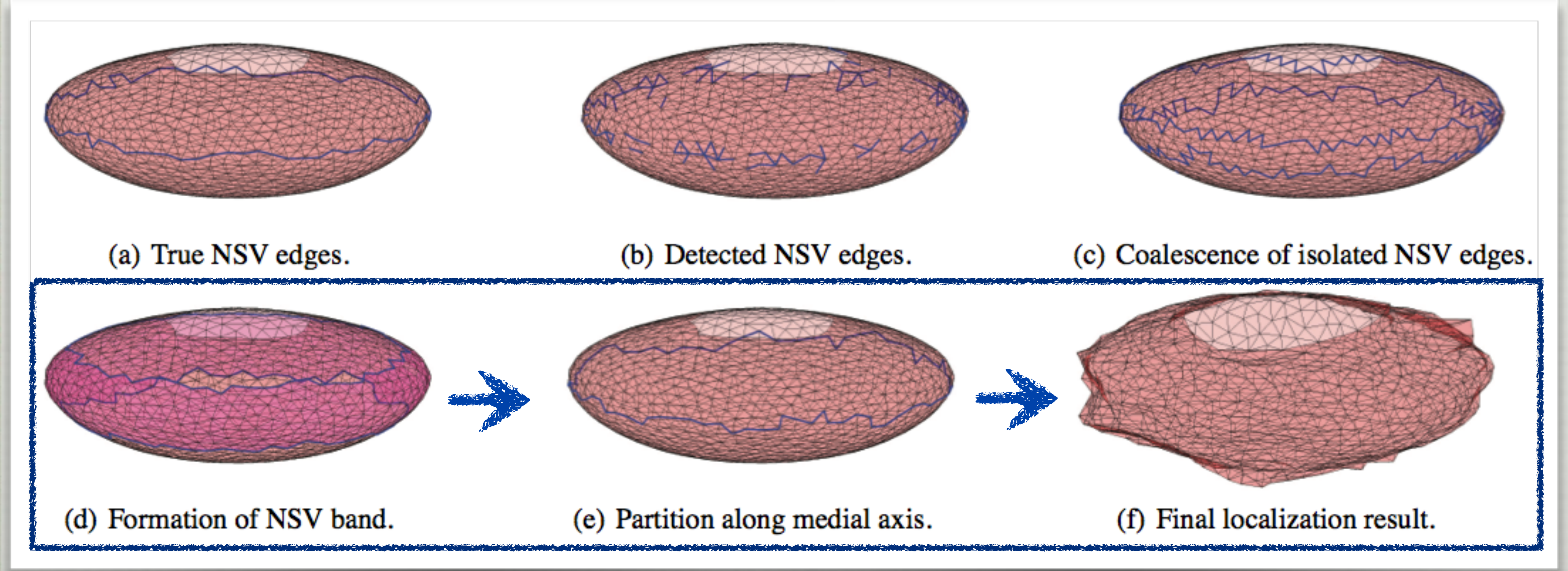
PRACTICAL SOLUTION WITH NOISY INPUTS

- Coalescence of isolated NSV edges
  - If a triangle contains a NSV edge, the triangle marked NSV
  - If two NSV triangles are one-hop away, the edges between them are marked as NSV
  - Two closest clusters are connected by their shortest path



PRACTICAL SOLUTION WITH NOISY INPUTS

- Formation of NSV band
  - Marks the edges within 1-hop of existing NSV edges as NSV
- Partition along medial axises of NSV band
  - Two closest clusters are connected by their shortest path

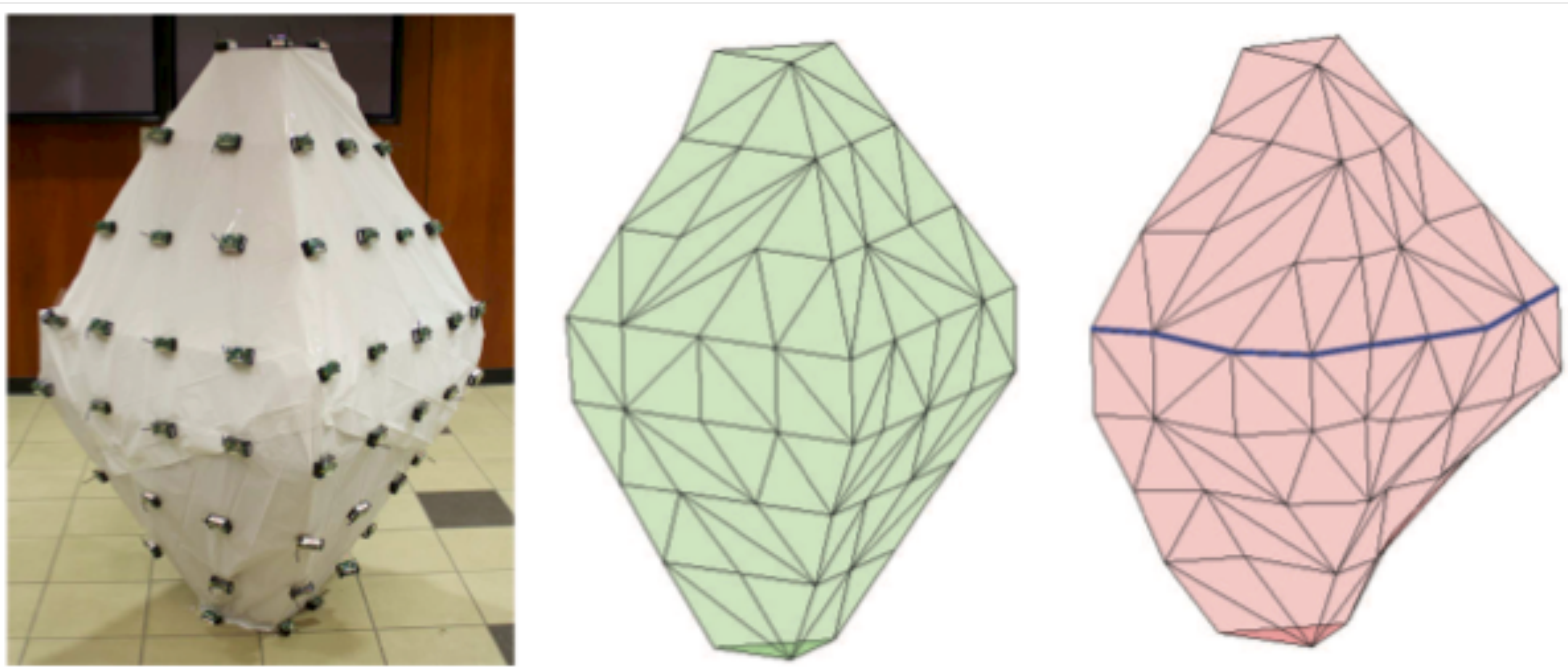


COMPLEXITY AND OVERHEAD

- Overall observation
  - NSV edge identification, network partitioning and projection are all done locally by the individual nodes
  - Complexity and overhead are dominated by localization in each patch and the merge of patches
- Computation complexity: $O(Max\{m^3,n\})$
  - n is the number of nodes in the network
  - m is the maximum number of nodes in a patch.
- Overall communication overhead: $O(n)$

PROTOTYPING

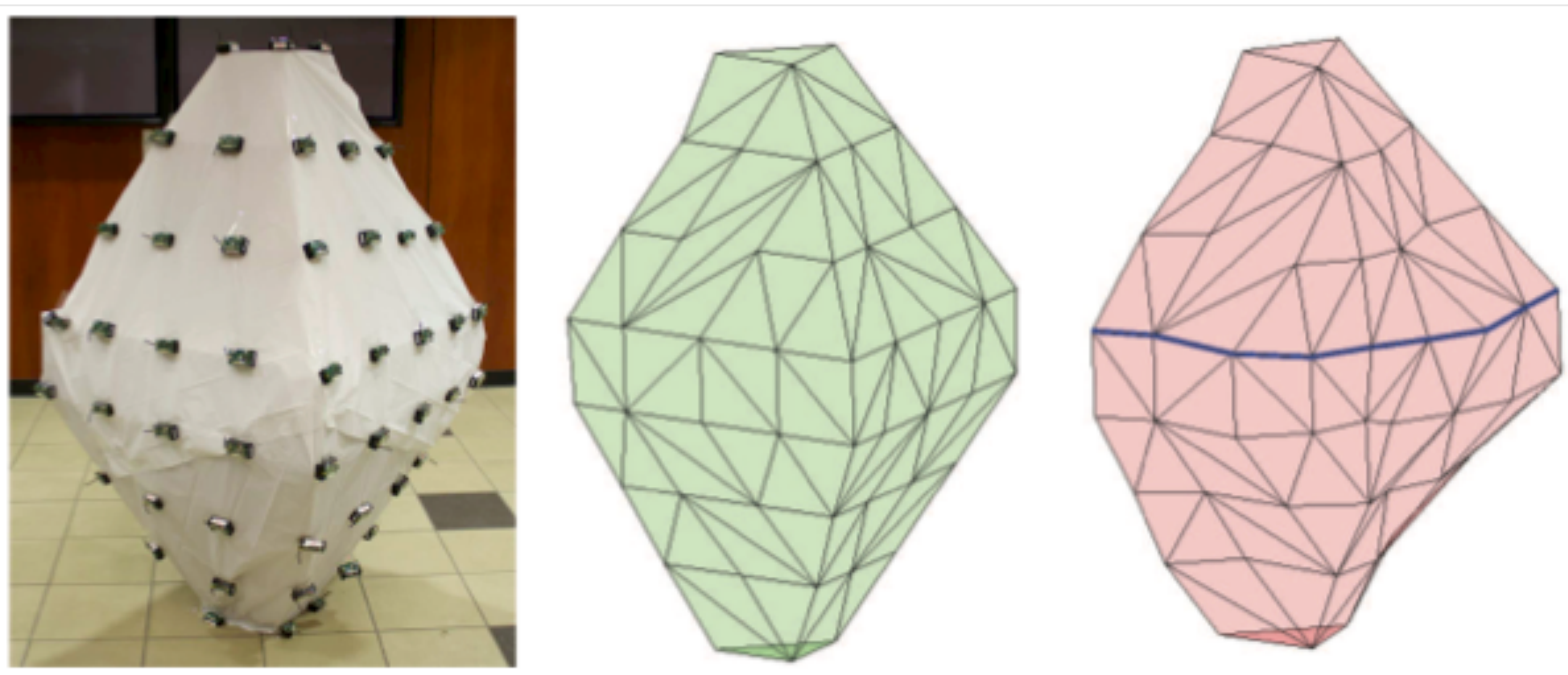
- Built indoor testbed models
- Forty eight Crossbow MICAz motes are attached to its surface
- Sensors use close to minimum radio transmission power
- RSSI is used to estimate the length of links (about 20% errors)
- Ground truth is manually measured



(a) (b) (c)

EXPERIMENTAL RESULTS

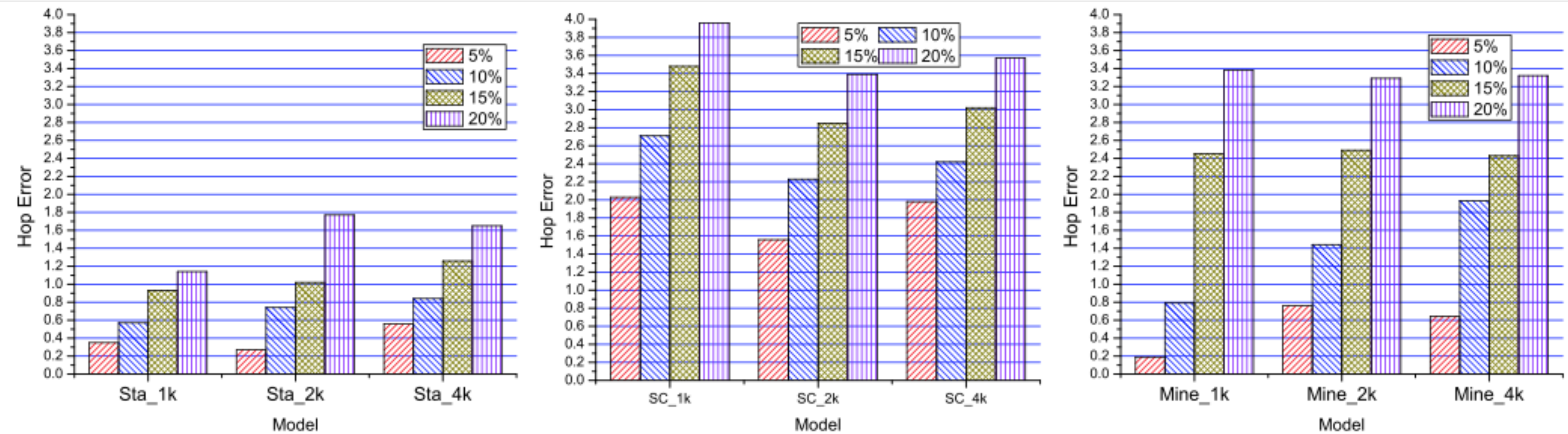
- NSV edges are identified correctly
- Network is thus partitioned into two SV patches
- MDS is applied to localize each of them
- Combined patches largely restore the original 3D surface network
- Average location error around 14%



(a) (b) (c)

SIMULATIONS

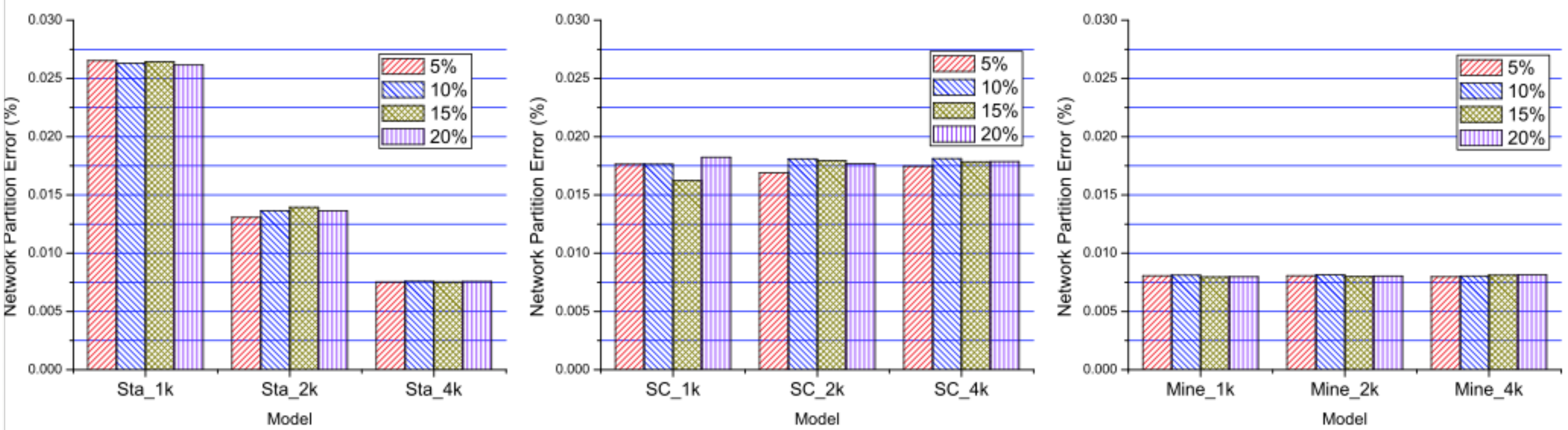
- Three network models, each simulated with 1k, 2k and 4k nodes
- NSV edge detection error
  - Average minimum hop-distance between true NSV edges and identified NSV edges
  - Increases dramatically with higher measurement errors



(a) Stadium model. (b) Sea cave model. (c) Mine pit model.

SIMULATIONS

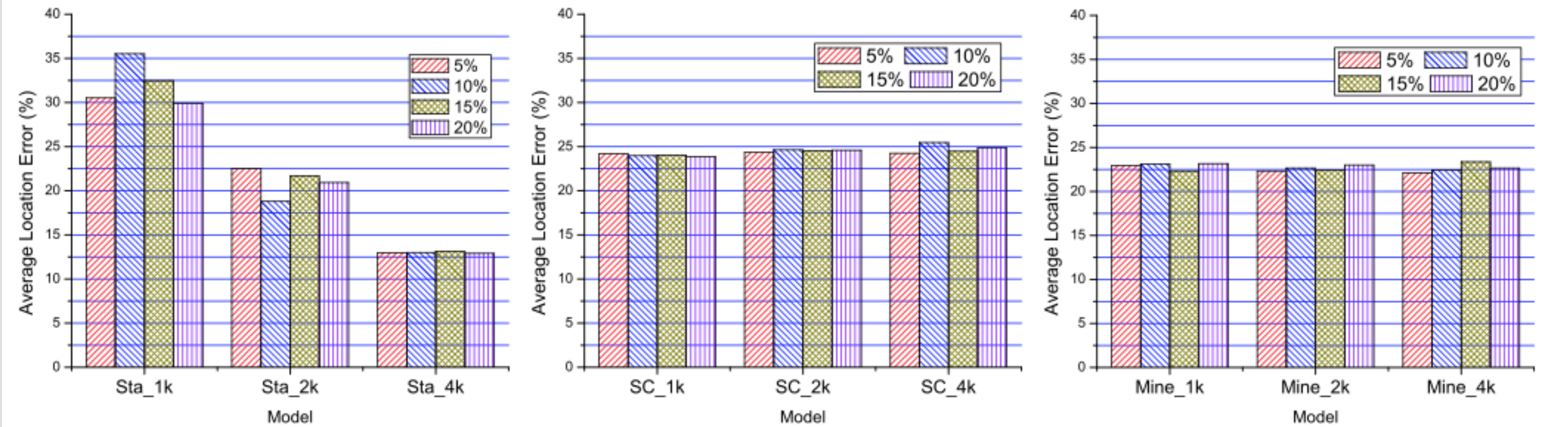
- Network partition error
  - Defined as the maximum deviation between the ideal partition and the identified medial axis of NSV band
  - Insensitive to measurement errors
  - A higher sensor density helps reduce localization errors in stadium model. The effect is not observed in other models.



(a) Stadium model. (b) Sea cave model. (c) Mine pit model.

SIMULATIONS

- Average location error
  - The localization result is not significantly affected by inaccurate distance and height measurements



(a) Stadium model. (b) Sea cave model. (c) Mine pit model.

SIMULATIONS

- Comparison with a slice-based approach [25]
  - Cut the network into layers
  - No guarantee to localize all nodes in the network

Table 1: Localizable Rate

	Stadium	Sea Cave	Mine Pit
Slice-Based [25]	98.8%	90.8%	81.3%
Cut-and-Sew	100%	100%	100%

CONCLUSIONS

- Unique challenge in 3D surface localization
- A divide-and-conquer approach, named cut-and-sew
  - Achieve minimum SV partition
  - Localization 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