Local Metrical and Global Topological Maps in the Hybrid Spatial Semantic Hierarchy

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Overview

- High-resolution, online metrical mapping methods
  - Increasingly more efficient for many environments
  - Difficulties scaling to larger, more complex environments
- Topological mapping methods
  - Scale to environments of great size and structural complexity due to compactness
  - Symbol grounding issues affect map-building efficiency and robustness

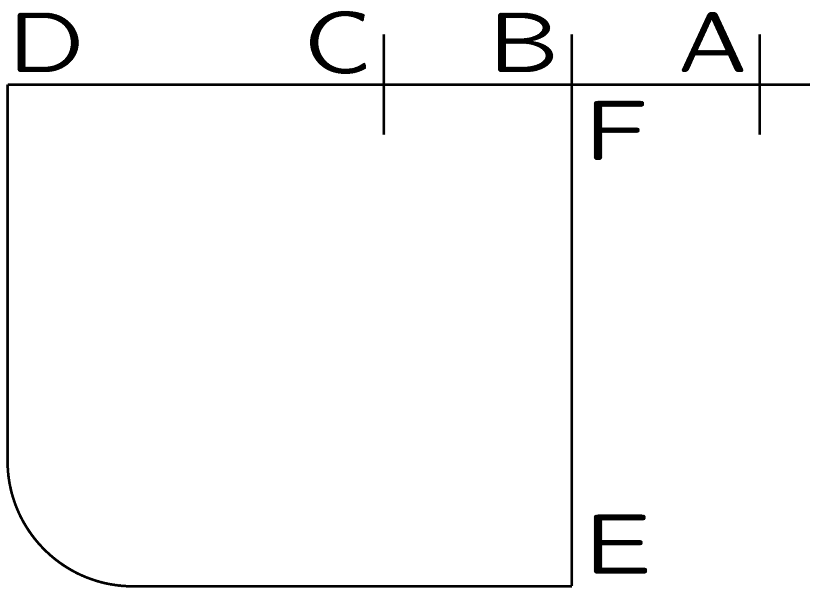
Goal

- Create an online hybrid mapping method that combines the strengths of high-resolution metrical mapping and topological mapping, while avoiding their weaknesses.

Approach

- Factor space into two scales, each providing a different kind of uncertainty.
- Small-scale space
  - Space within the local surround: e.g. this room
  - *Local metrical uncertainty*
    - Incremental localization, obstacle avoidance
  - Occupancy grids
- Large-scale space
  - Space beyond the horizon: e.g. the French Quarter
  - *Structural uncertainty*
    - Loop closing, relocalization
    - Topological maps via Spatial Semantic Hierarchy

Structural Uncertainty Example



- Take a large loop, where global metrical uncertainty becomes very large.
- F=A, F=B, F=C,

  F≠A ∧ F≠B ∧ F≠C
- Larger environments make this scenario more common.
  - Nested loops
  - Spiral structures

Online Loop Closing in Metrical Maps

- Single map hypothesis
  - Incorrect loop closing
    - Overly simple, overly complex maps.
  - If a wrong map is detected,
    - Where was the incorrect loop closure made?
    - How can the map be fixed?

State-of-the-Art Online Metrical Mapping

- Multiple map hypotheses
  - N particles, each with its own high-resolution map
  - K structural loop closing hypotheses
  - Cost vs. particle depletion
    - Fixed number of particles *O(N)*: particle depletion problems
    - Increasing particles with structural uncertainty *O(NK)*: resource limitations
      - Nested loops cause all K hypotheses to branch.

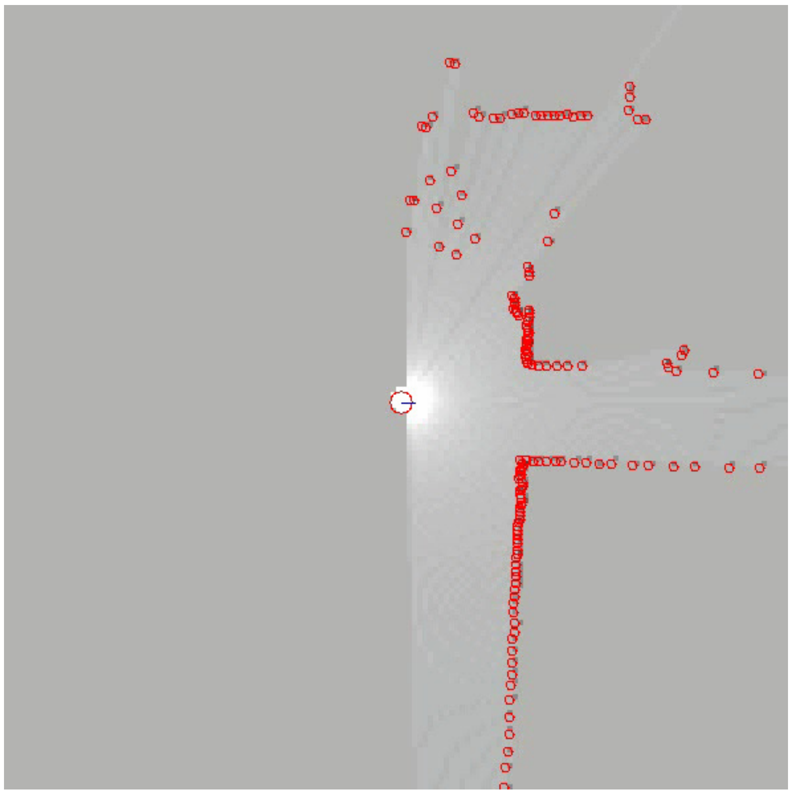
Our Approach to Loop Closing

- Topological maps represent the global structure as a graph of places and paths.
  - Factored from metrical uncertainty.

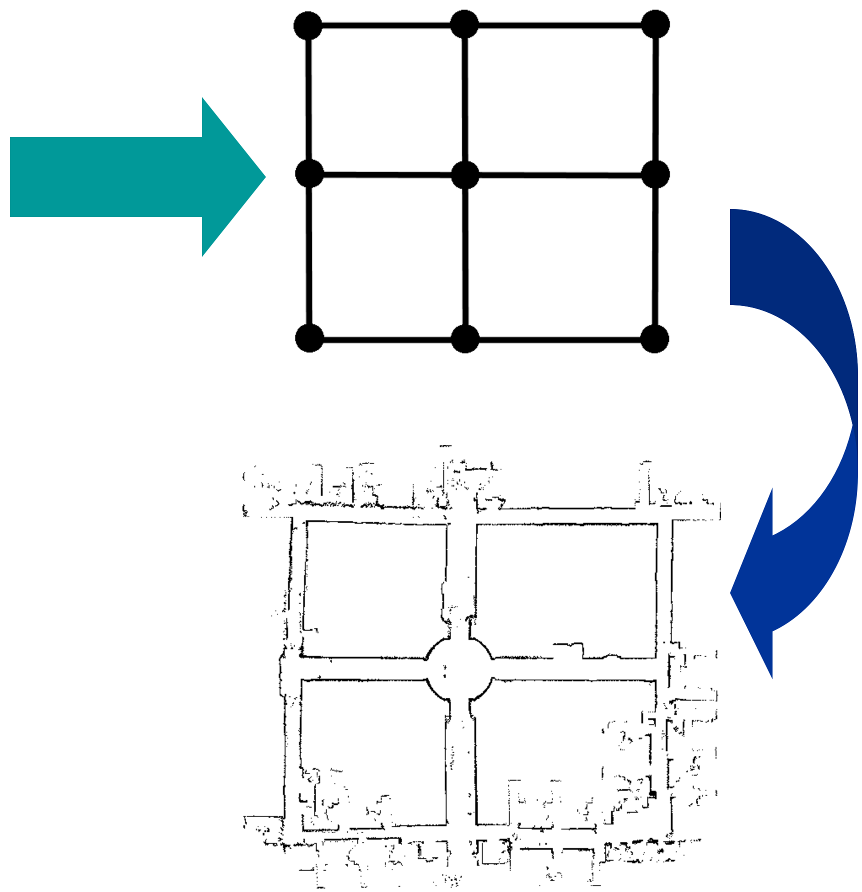
Factored Approach

- To aid in symbol grounding and low-level control, we still use metrical maps as models to describe the "scrolling" local surround.
  - M particles in local metrical map for incremental localization.
  - $M << N$
- Factoring structural uncertainty from local metrical uncertainty: *O(M+K)*.
  - Loop closing hypotheses are efficiently computed by tree of topological maps.

Combining Mapping Methods



Video

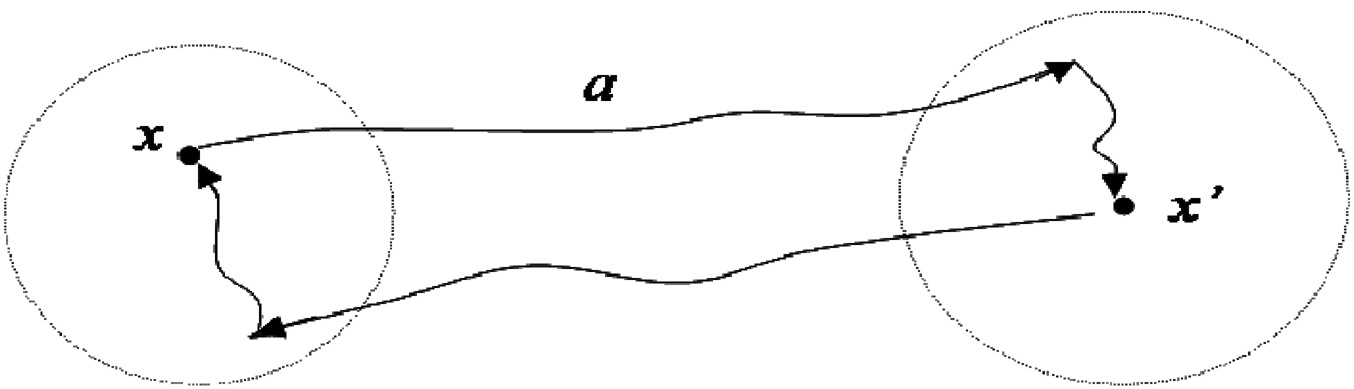


Spatial Semantic Hierarchy

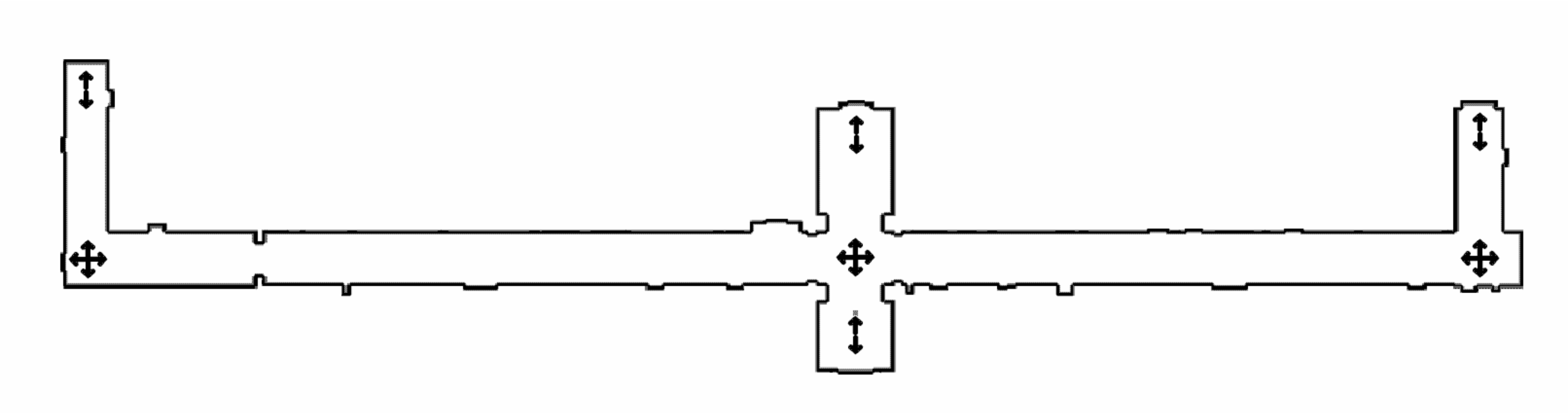
- SSH is a theory of knowledge of large-scale space: the "cognitive map" [Kuipers, AIJ, 2000]
  - Control, Causal, Topological, Metrical
- Formal, non-monotonic logical theory for topological map-building [Remolina and Kuipers, AIJ, 2004]
  - Axioms to generate map hypotheses, check maps for consistency, order maps by minimality criterion.

Abstracting the Continuous World

- SSH has weak assumptions about sensors
- Trajectory-following control through qualitatively uniform regions.
  - e.g. corridor-following, wall-following
- Hill-climb to distinctive state (x,y,θ) at a place.
  - e.g. Voronoi point with orientation
- Each *distinctive state* has a single *view,* abstracted from sensory snapshot.
  - Multiple **dstates** may share same view: perceptual aliasing.



Causal Map-Building



- When arriving at a dstate with view *v*, every previously visited dstate with same view is considered.
  - This dstate could also be novel.
  - Done for every map hypothesis.
  - Many of these hypotheses are discarded due to axioms of the formal logic.

Topological Map Building Overview

- Topological map (places, paths, order, connectivity, containment) built on top of causal map (dstates and actions).
  - Dstates connected by turns define a place and the paths that intersect at that place.
  - Dstates connected by travels define an order of places along a path.

Extending the Basic SSH

- Use information about the local metrical surround.
- Eliminate the need for hill-climbing
  - Localization is handled incrementally
- Local topology of place can be extracted from the local metrical map.
- Local topology is a reliable view of a place.
  - Places have “views” instead of dstates.
  - Matching places instead of dstates creates far fewer maps.

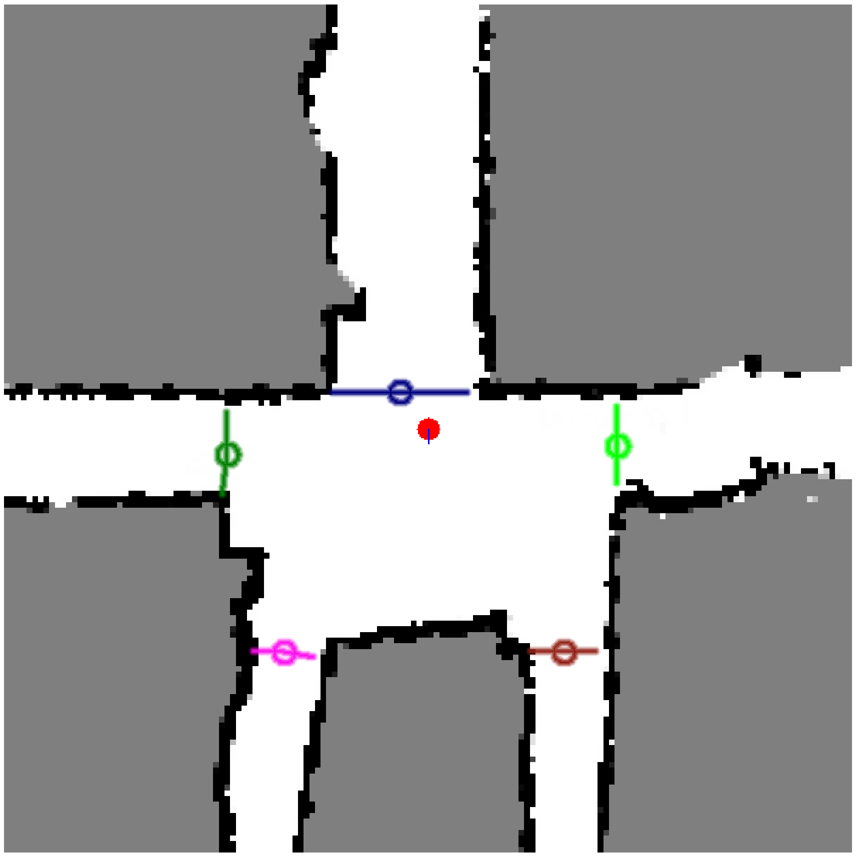
Plan Overview

- Use scrolling, local metrical maps for description of local surround.

- At a place:
  1. Extract local topology from metrical map
     - Gateways, path fragments, small-scale star
  2. Use local topology to ground large-scale space semantics
     - Large-scale star, dstates, places, paths

Gateways

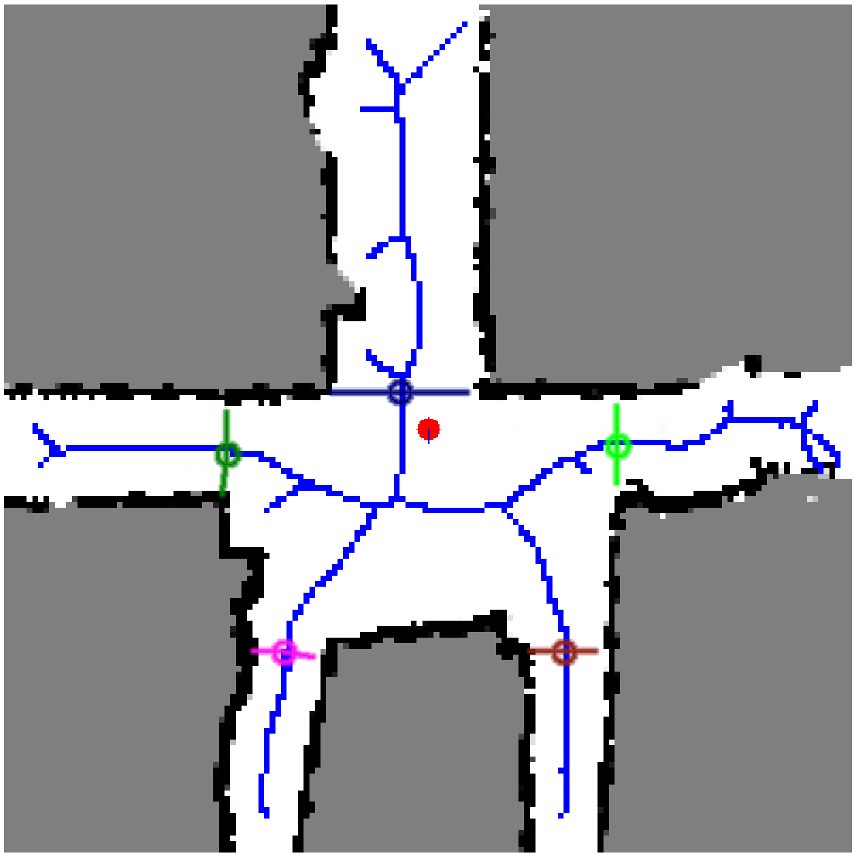
- Boundaries between qualitatively different regions of the environment
  - Boundaries between trajectory-following and hill-climbing applicability
  - Each gateway has two directions, inward and outward.



Current Implementation

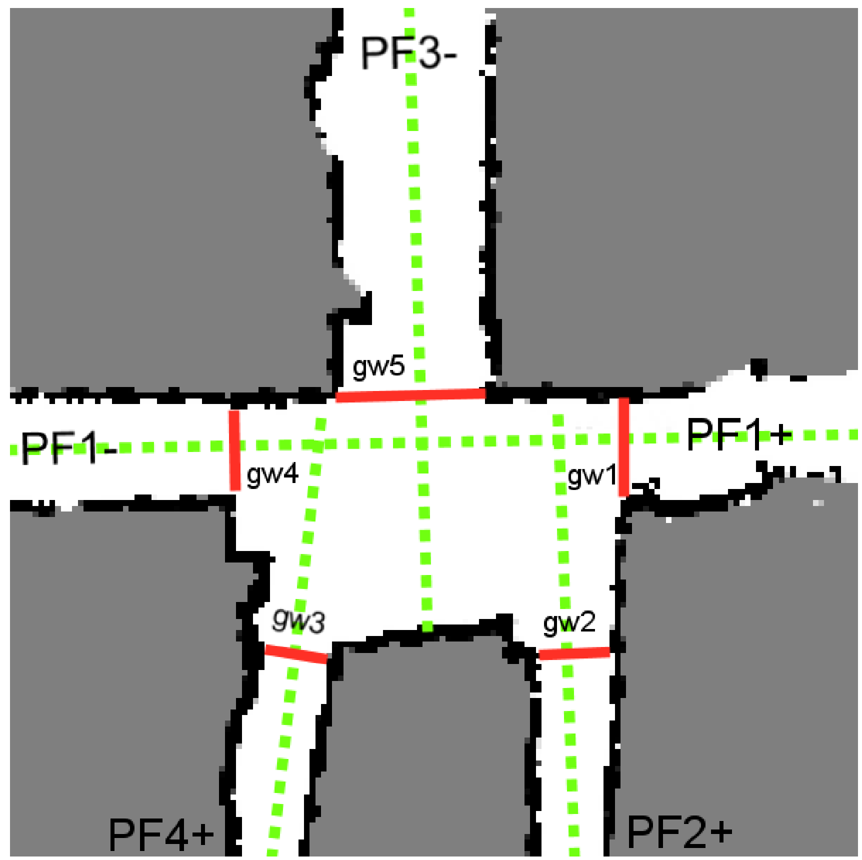
- Gateways are "constrictions" in the Medial Axis of place neighborhoods
  - Corridor environments

- In non-enclosed environments, generalize gateways based on other control laws.



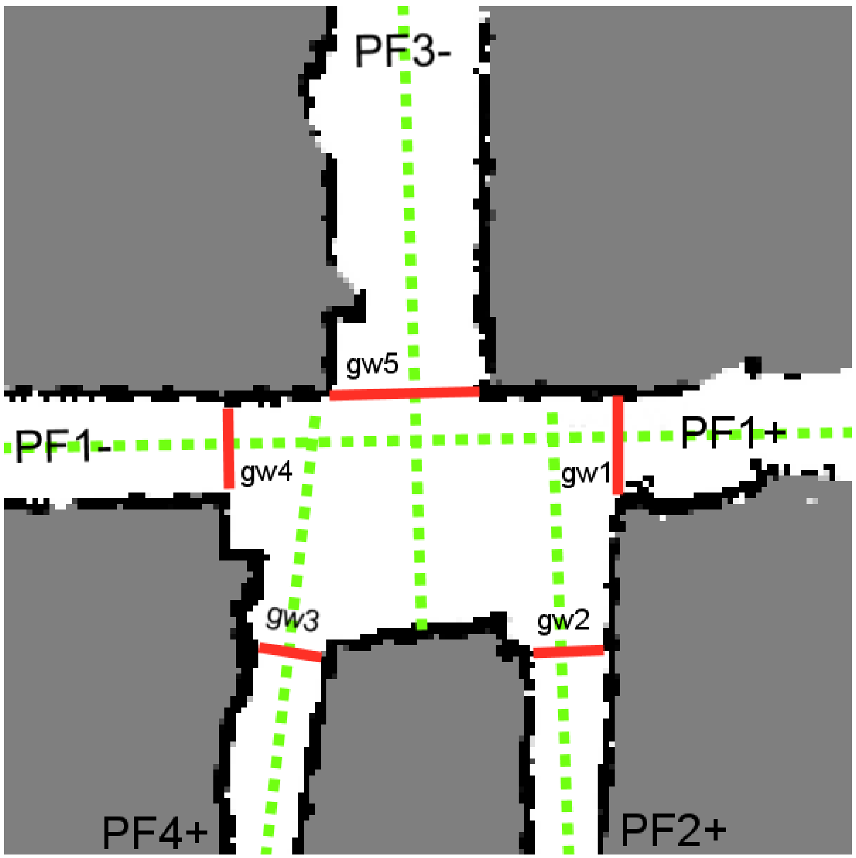
Path Fragments

- Portions of large-scale topological paths that are grounded in small-scale space
- Each path fragment is associated with one or two gateways



Small-Scale Star

- Symbolic description within the small-scale ontology



PF1+	(gw1,out) & (gw4,in)	Midline
PF2+	(gw2,out)	Midline
PF3+	(gw5,in)	DeadEnd
PF4+	(gw3,out)	Midline
PF1-	(gw4,out) & (gw1,in)	Midline
PF4-	(gw3,in)	DeadEnd
PF3-	(gw5,out)	Midline
PF2-	(gw2,in)	DeadEnd

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Binding Small-scale to Large-scale

Small-scale star → Large-scale star

PF1+	(gw1,out) & (gw4,in)	Midline	ds1	Pa1, +	
PF2+	(gw2,out)	Midline	ds2	Pa2, +	
PF3+	(gw5,in)	DeadEnd	ds3	Pa3, +	Endpoint
PF4+	(gw3,out)	Midline	ds4	Pa4, +	
PF1-	(gw4,out) & (gw1,in)	Midline	ds5	Pa1, -	
PF4-	(gw3,in)	DeadEnd	ds6	Pa4, -	Endpoint
PF3-	(gw5,out)	Midline	ds7	Pa3, -	
PF2-	(gw2,in)	DeadEnd	ds8	Pa2, -	Endpoint

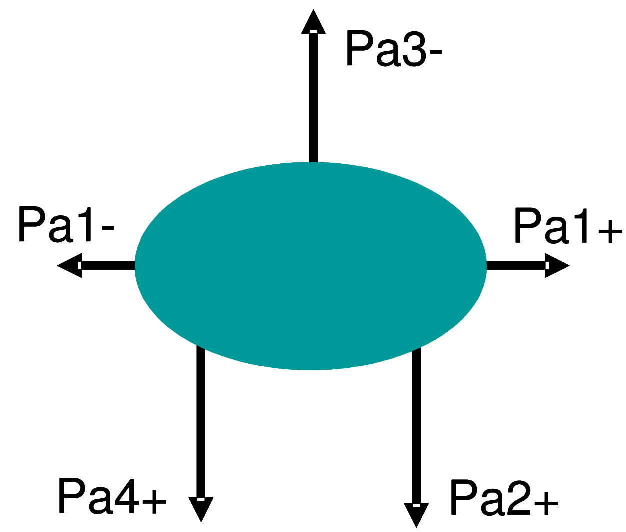
Overview of New Topological Map Building

1. Identify gateways and path fragments

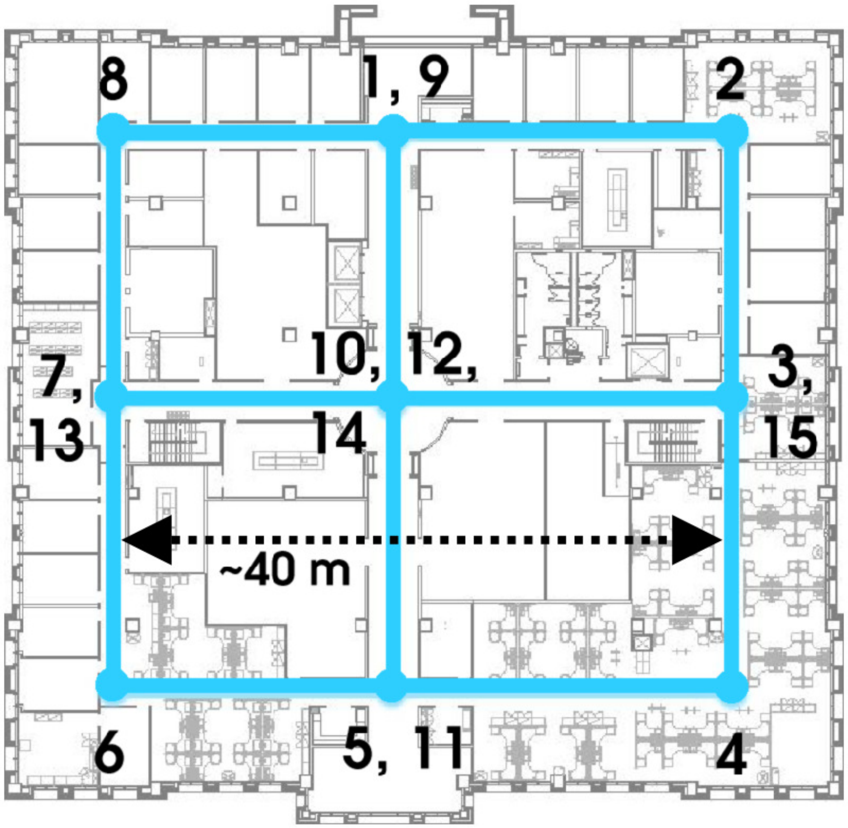
2. Generate small-scale star

3. Match current place to any previously visited places that have the same small-scale star.
   - Metrical map may provide more information to eliminate some models.
   - Creates large-scale star bindings.
   - Causal map falls out of topological map.

Large-scale Local Topology



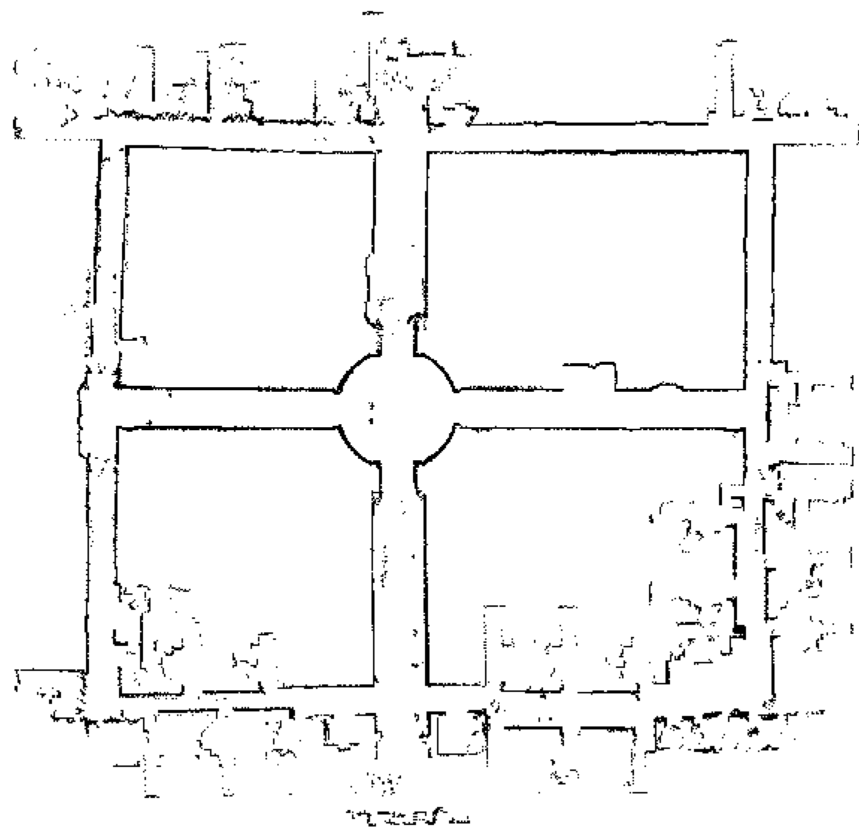
Real World Experiment



- 9 places, 6 paths, 14 actions
- Multiple nested loops
- 4 unique small-scale stars (local topologies)
- 46 possible topological maps, given the experience
  - 136 maps in entire tree
- Minimality ordering identifies the correct topological structure.
- Calculated in ~200 ms on Pentium III 450 MHz

Global Metrical Representation

- If desired, a global metrical map is efficiently computed when using a topological map as a skeleton
  - [Modayil, Beeson, and Kuipers, submitted]
- Minutes to complete



Recap of Previous Work

- High-resolution metrical maps (sensors → global metrical description)
  - Work well in local, simple regions
  - Loop closing in increasingly large environments can miss the correct structural layout of the environment.
- Previous SSH implementations (sensors → global symbolic description)
  - Hill-climbing to dstates, views generated from images at dstates
  - Move directly from sensors and effectors to large-scale space semantics
  - Efficiently determine correct topological layout

The Hybrid SSH: The Best of Both Worlds

- Local metrical maps for metrical uncertainty
  - Factors metrical uncertainty out of global structural uncertainty
  - Localization w/out physical hill-climbing
  - Low-level obstacle avoidance

- Topological maps for structural uncertainty
  - Local topology descriptions that serve as views are created reliably
  - Views of places reduces model search
  - Active exploration for hypothesis elimination
  - Hierarchical implementations

- sensors → local metrical description → local symbolic description → global symbolic description → global metrical description

The End