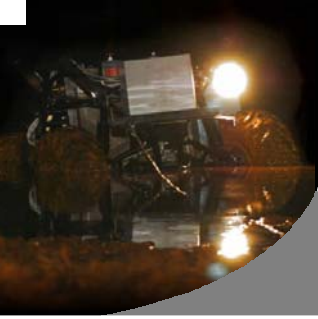## Towards Topological Exploration of Abandoned Mines

Aaron Morris, David Silver, Scott Thayer

acmorr@ri.cmu.edu
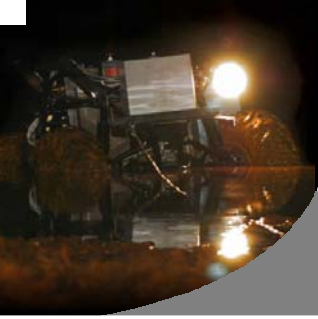
Robotics Institute
Carnegie Mellon University
5000 Forbes Ave.
Pittsburgh, PA 15213

Subterranean Robotics

- Motivation

- Background

- Key challenges

- Topologies, intersections, and navigation

- Experimental Results

- Conclusions
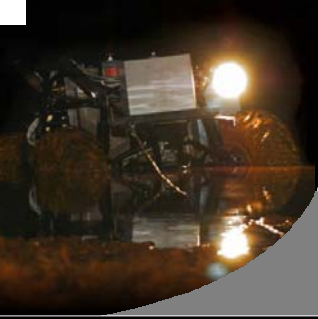
- Things to come…

Subterranean Robotics

Mines   **Caves**   **Sewers**
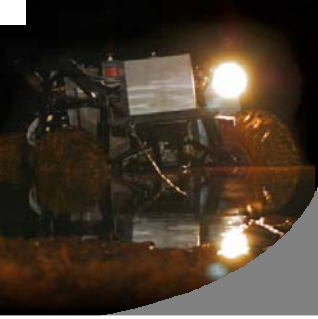
Trouble Below The Surface

Rescue from Quecreek, "All Nine Alive"
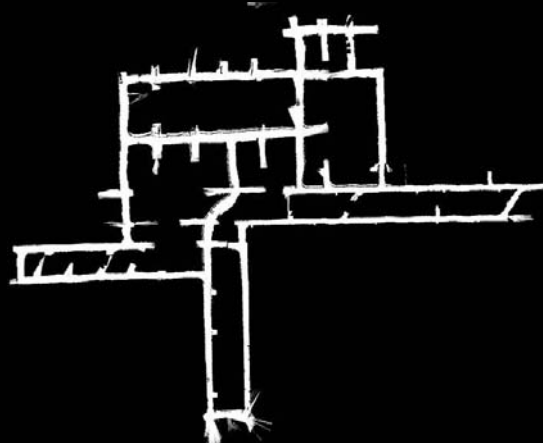
Subterranean Robotics
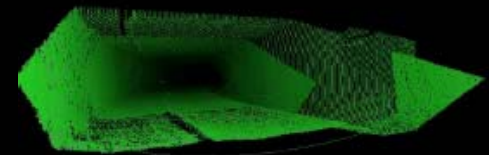
Platforms

SLAM

3D Registration

- C. Baker, Z. Omohundro, S. Thayer, W. Whittaker, M. Montemerlo, and S. Thrun. "A case study in robotic mapping of abandoned mines." Proceedings from FSR 2003.
- S. Thrun, D. Hähnel, D. Ferguson, M. Montemerlo, R. Triebel, W. Burgard, C. Baker, Z. Omohundro, S. Thayer, W. Whittaker. "A System for Volumetric Robotic Mapping of Abandoned Mines." *Proceedings of ICRA 03*.
- D. Silver, D. Ferguson, A. Morris, and S. Thayer. "Feature extraction for topological mine maps." In *IEEE/RSJ Int. Conference on Intelligent Robots and Systems,* 2004.
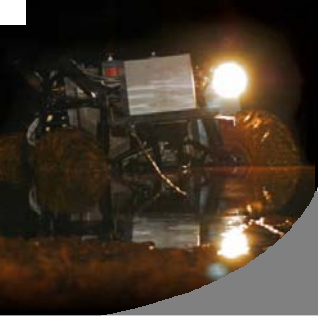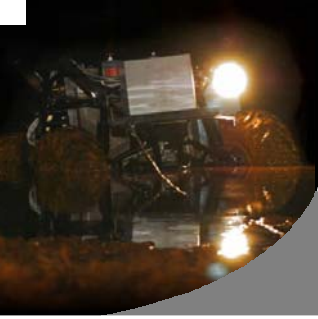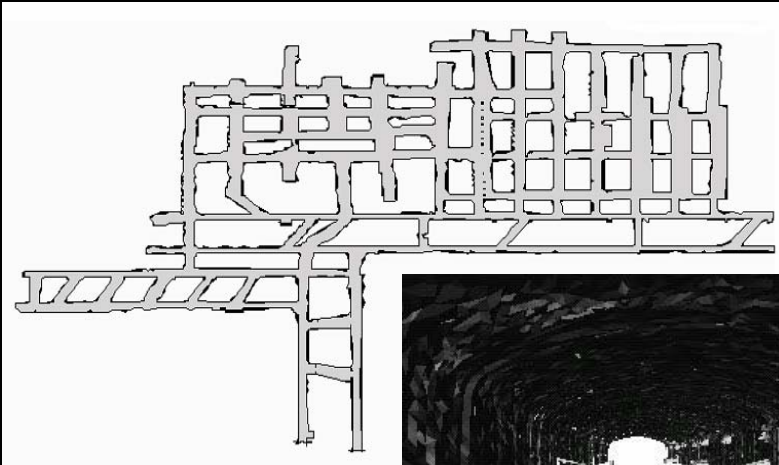
Subterranean Robotics
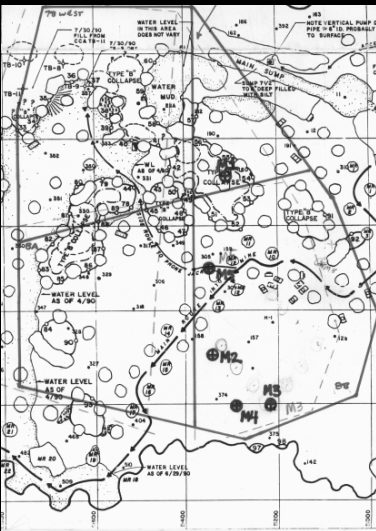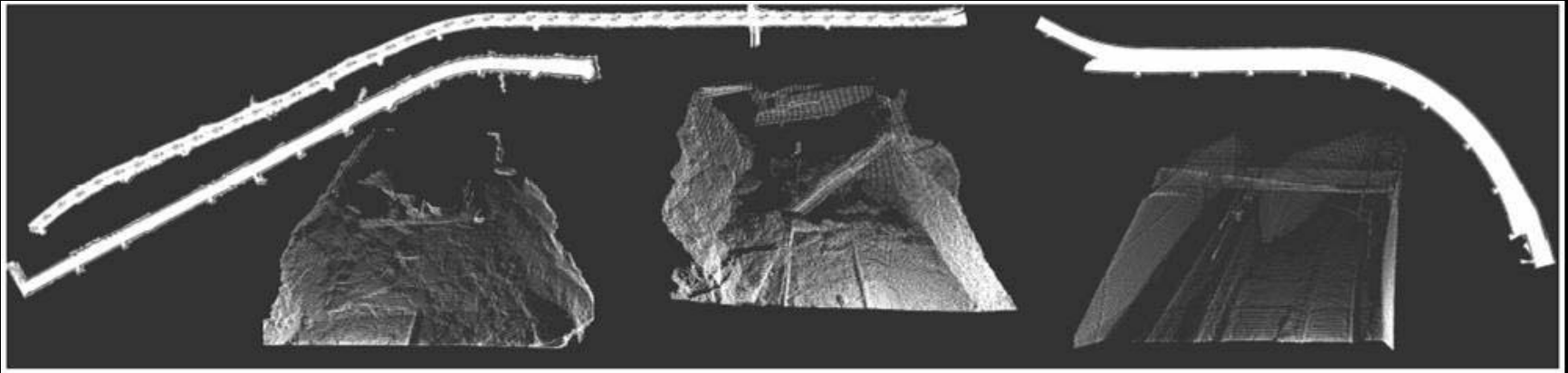
Our mission is to…

- Autonomously explore abandon mines
- Build two-maps and models
- Void verification and adjustment
- Provide information on mine status

Subterranean Robotics
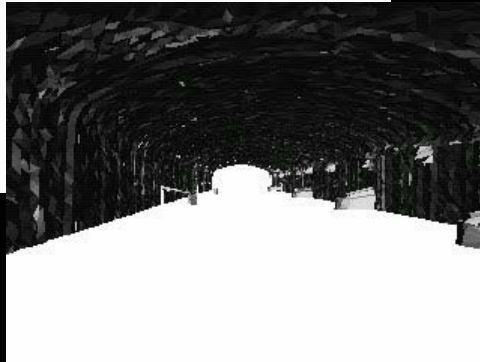
Key Challenges

Large area to explore

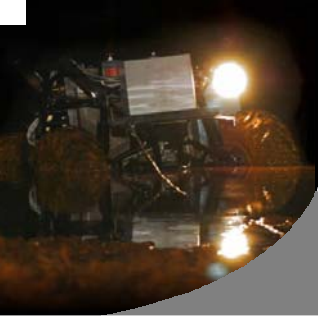**Highly cyclic… maze-like**

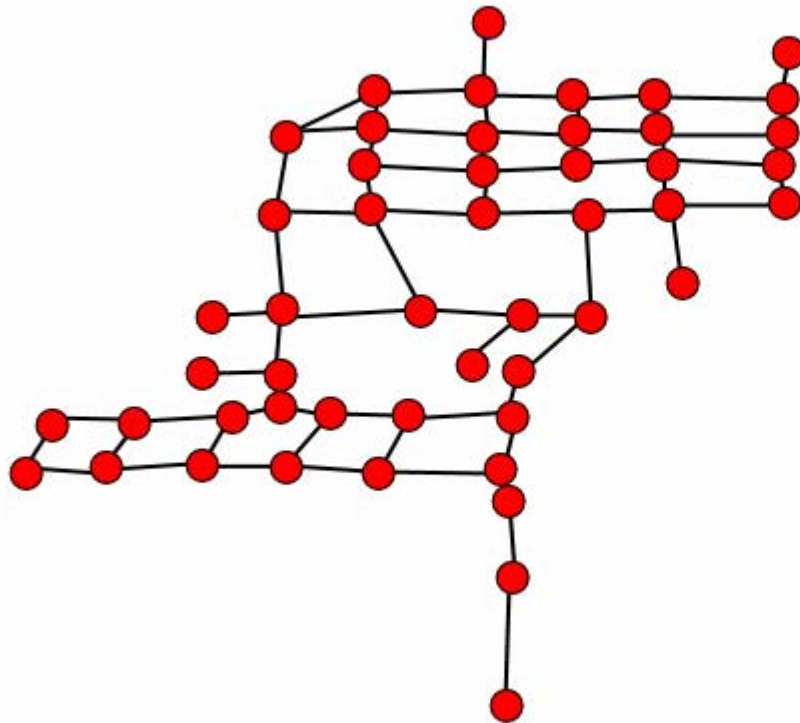**Abandoned for one year …**

Roof beams

Rubble

Cables

Water

Thus, we are challenged to…

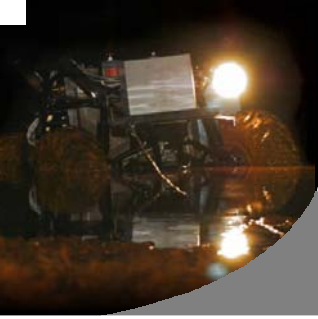*(1) Explore as much as possible (2) Don't get lost and (3) Don't destroy mine or self*

Exploration and localization through topological representations
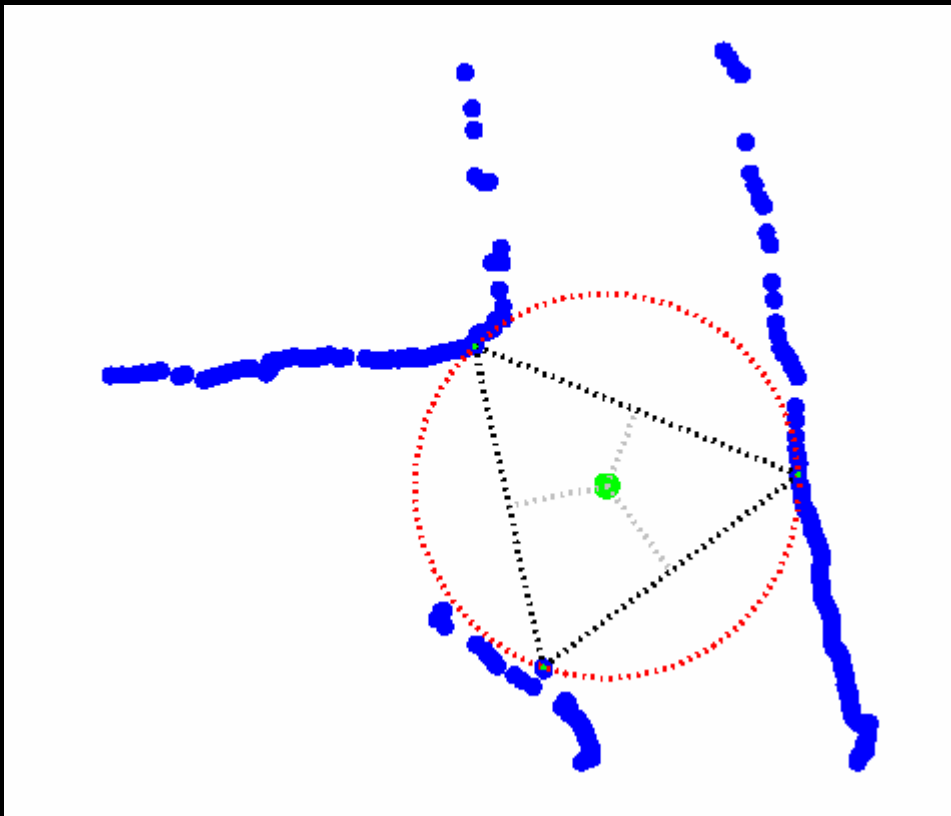
Subterranean Robotics

The "Sense-Think-Act" approach to topological exploration…

- Need a method of extracting topological features from the environment
- Need a way to build and plan topological maps
- Need a method of enacting topological plans
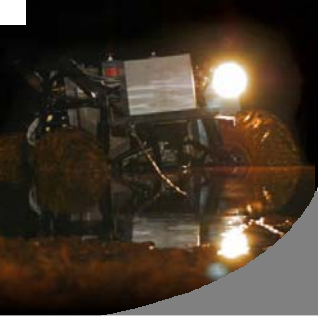
Sense: Intersection Detection
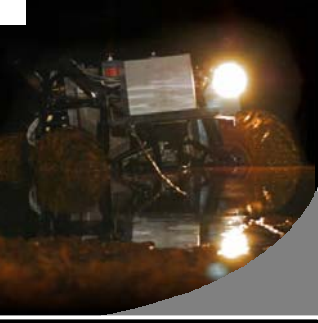

Based up the Generalized Voronoi Diagram

P points

DT - Delaunay Triangulation

T triangles

DT(P)→T:
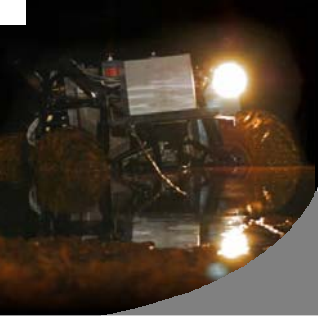**∃t_{ijk} has corners**
p_i, p_j, p_k and edges
e_{ij}, e_{ik}, e_{jk}

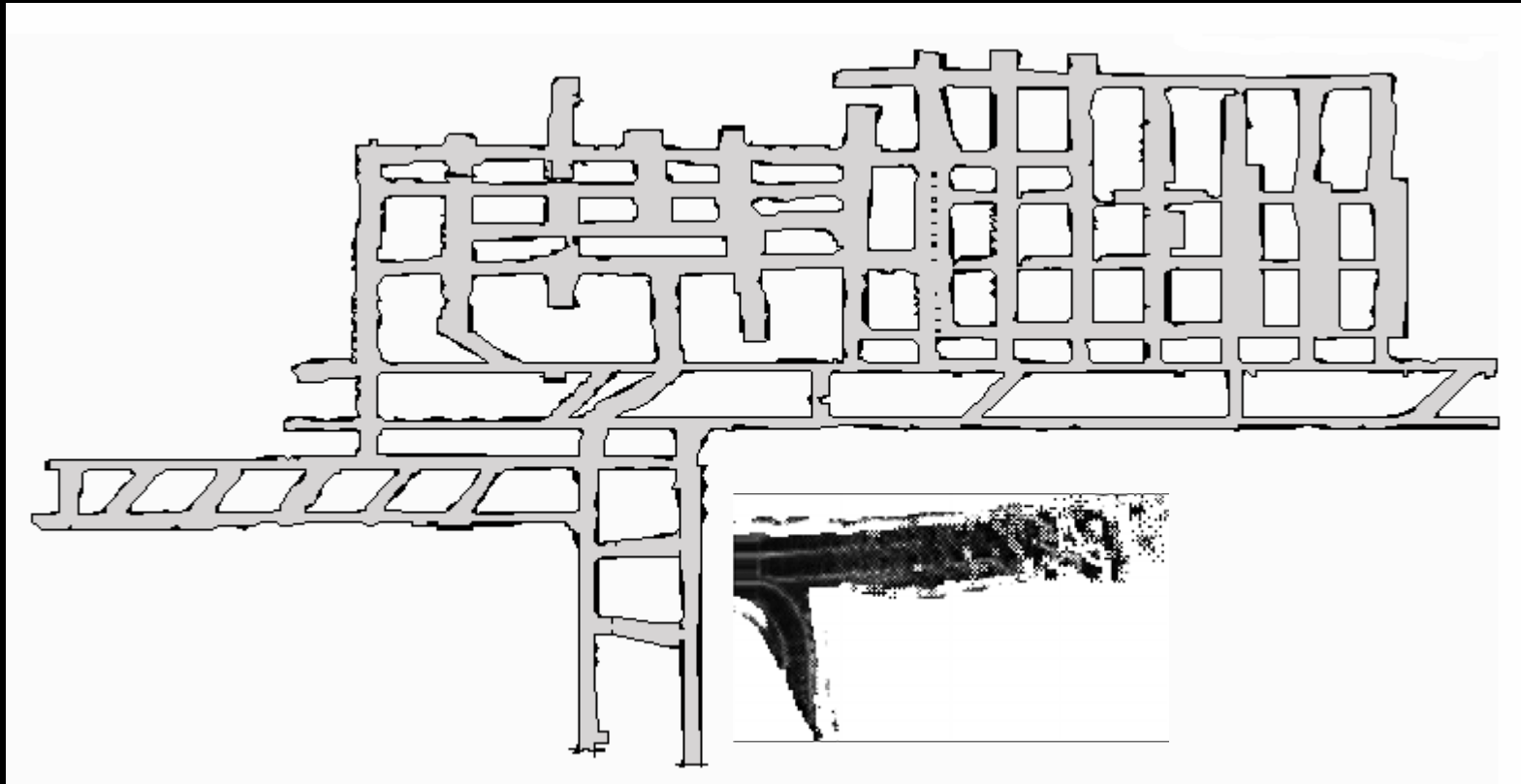## *Think: Topological Planning*
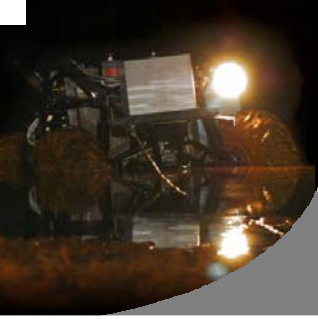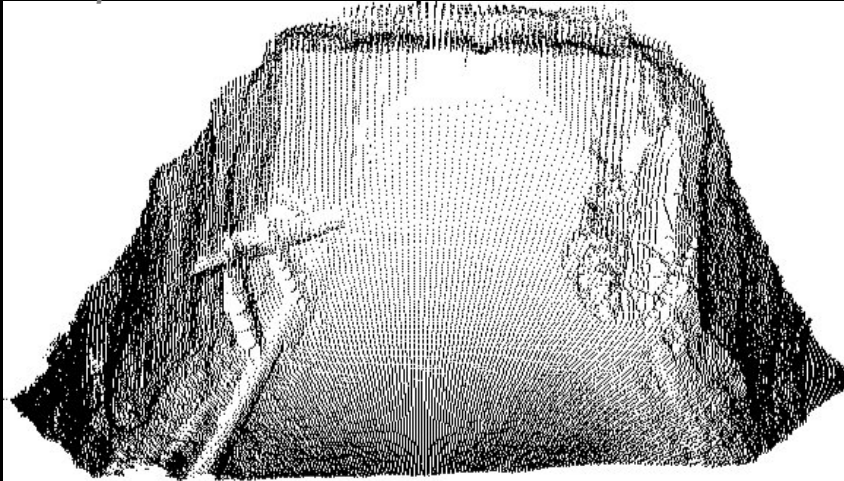
Act: Intersection Navigation

No two intersections are alike. Path plans are likely not to be identical.

Subterranean Robotics
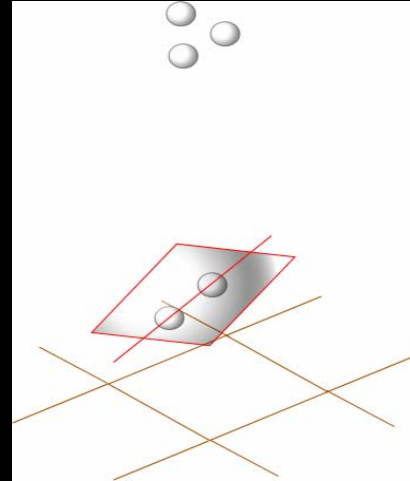
Workspace Computation

3D point set

Local Gradient

Cost map

```
for each p in 3D_Point_Cloud
    map_cell_max[p.x, p.y] = MAX(p.z, map_cell_max[p.x, p.y])
    map_cell_min[p.x, p.y] = MIN(p.z, map_cell_min[p.x, p.y])
end for
for each r in Number_Map_Cell_Rows
    for each c in Number_Map_Cell_Columns
        if map_cell_min[r,c] > Max_Traverse_Height or
          map_cell_max[r,c] < Platform_Height + Safety_Margin or
          (map_cell_min[r,c] or map_cell_max[r,c]) == No_Value
            map_cell[r,c] = lethal
        else
            map_cell[r,c] = map_cell_max[r,c] - map_cell_min[r,c]
```
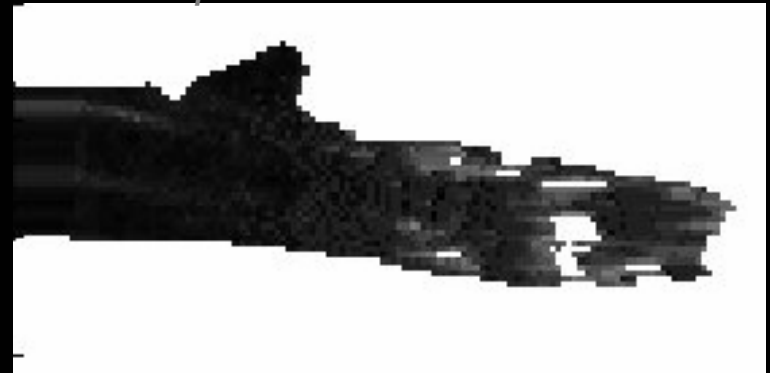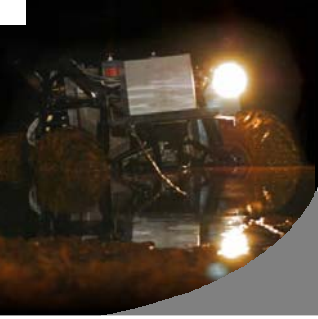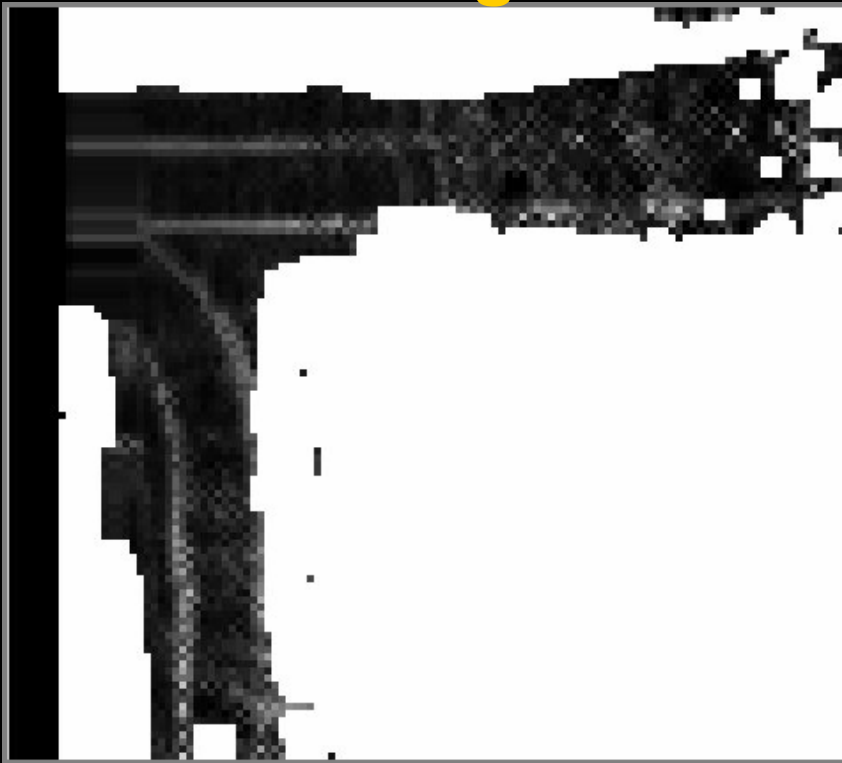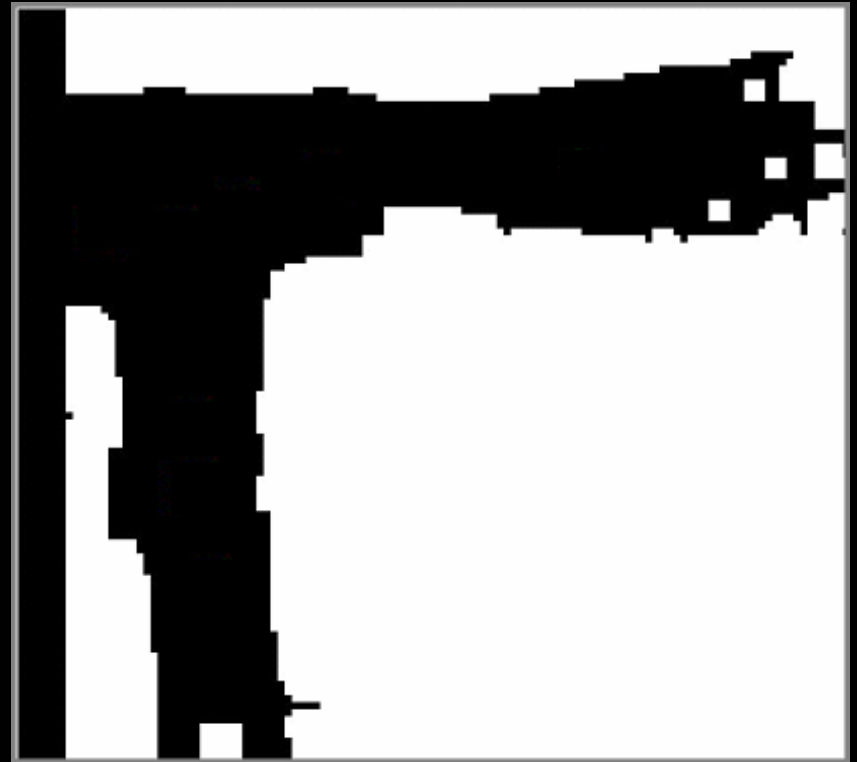
## *Goal Selection*

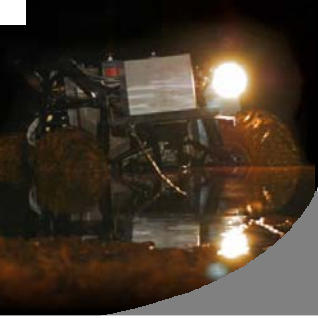**Where do we go next?**



*Cost map*



*Free space*

## *Goal Selection*
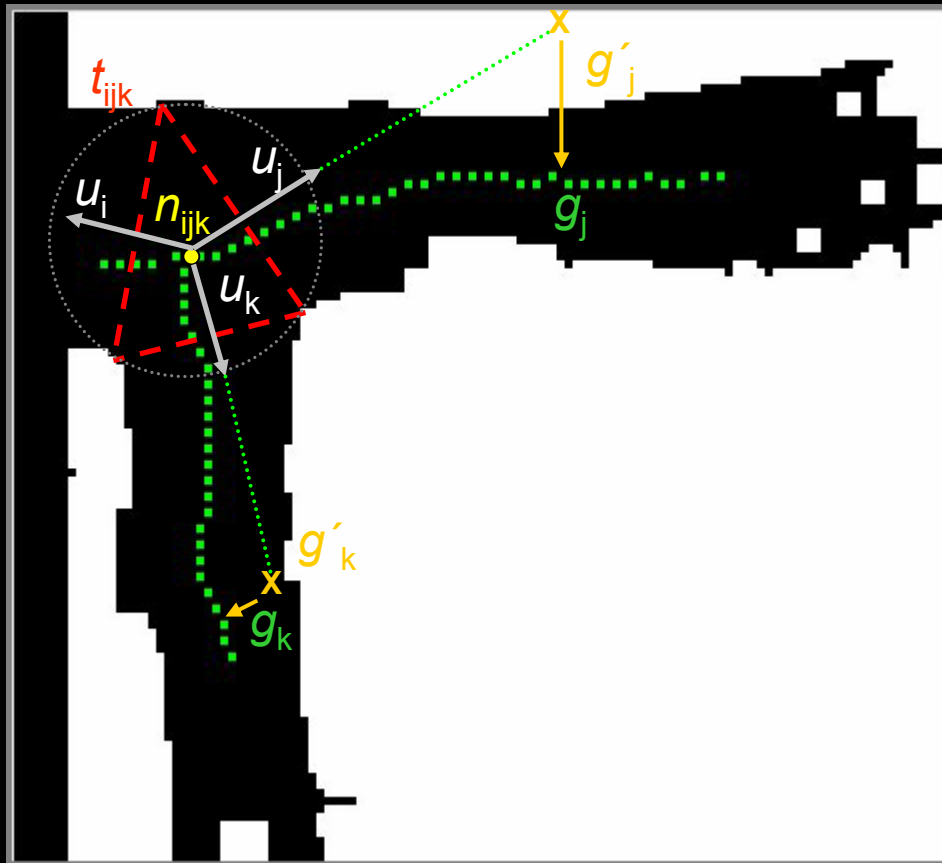


**Given:**
Voronoi node – $n_{ijk}$
Delaunay Triangle – $t_{ijk}$
Potential Goals – P

**Calculate:**
unit vectors – $u_i\, u_j\, u_k$
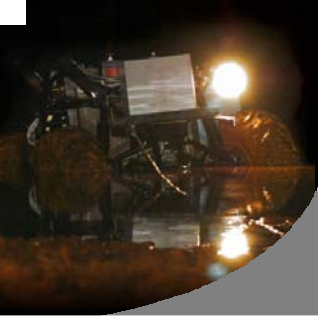goal positions – $g'_j\, g'_k$
$$g'_j = a \cdot u_j + n_{ijk}$$
$$g'_k = a \cdot u_k + n_{ijk}$$

**Choose:**
$g_j\, g_k$ such that
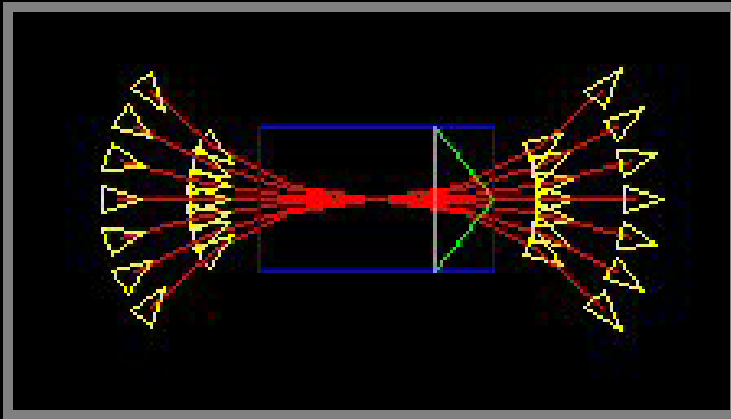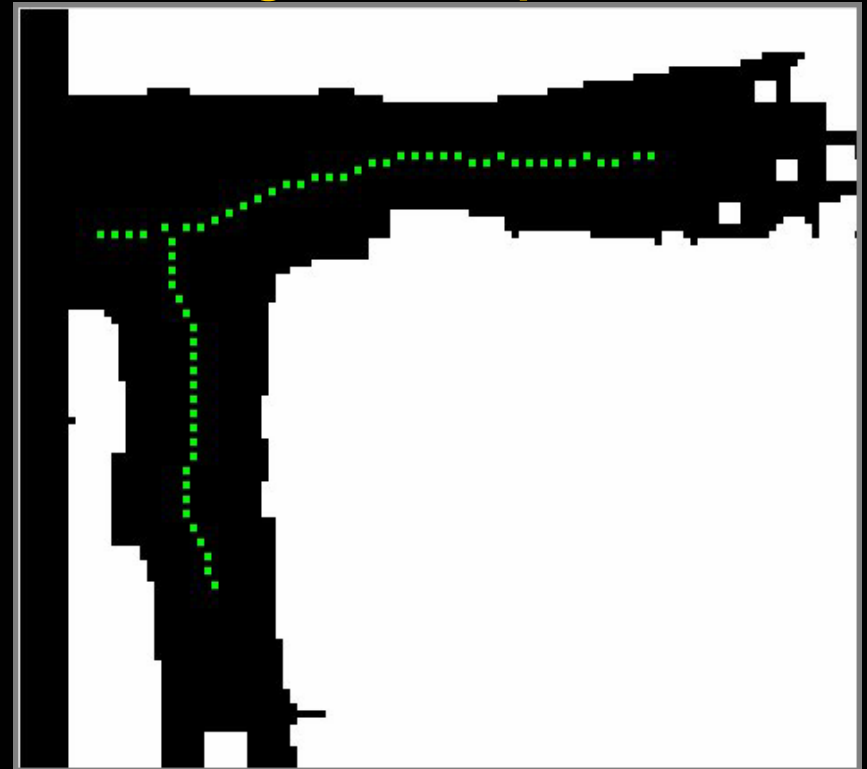$$g_j = \min_{n=1..N}(D(g'_j, P_n))$$
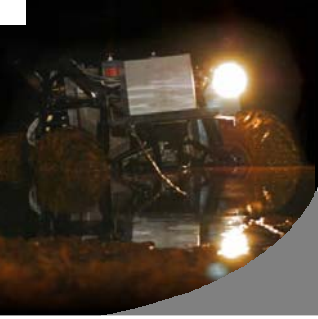$$g_k = \min_{n=1..N}(D(g'_k, P_n))$$

# Subterranean Robotics

**3D Configuration Space**

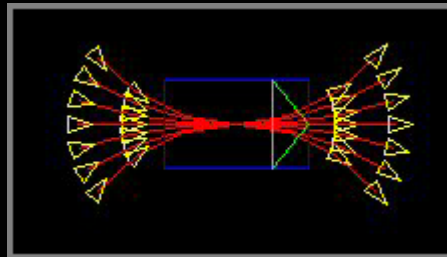**Nonholonomic Motions**

## *Nonholonomic Motion Planning - GS*

*Robot Motion Planning*, Jean-Claude Latombe, Kluwer, 1991.

Velocity Parameters

$$\dot{x} = v\cos\theta \qquad \dot{y} = v\sin\theta \qquad \dot{\theta} = \frac{v}{L}\tan\phi$$
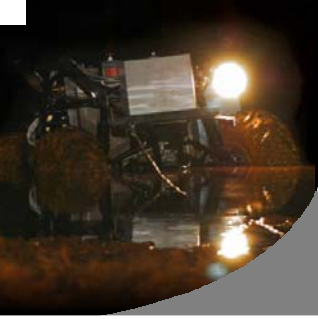
Control Parameters

$$\{-v_0, v_0\} \times \{-\phi_{max}, 0, +\phi_{max}\}$$



*Arc Template*

$$\{-v_0, v_0\} \times \{-\phi_{max}, -\phi_1, ..., 0, ..., +\phi_N, +\phi_{max}\}$$

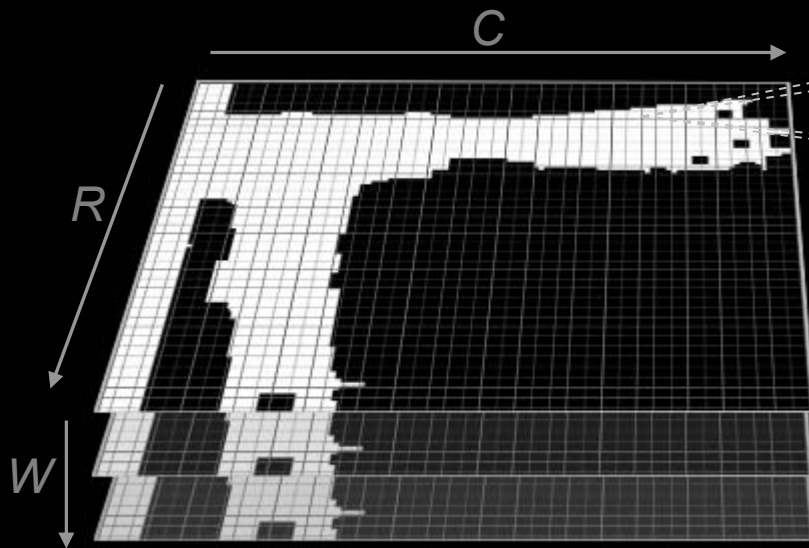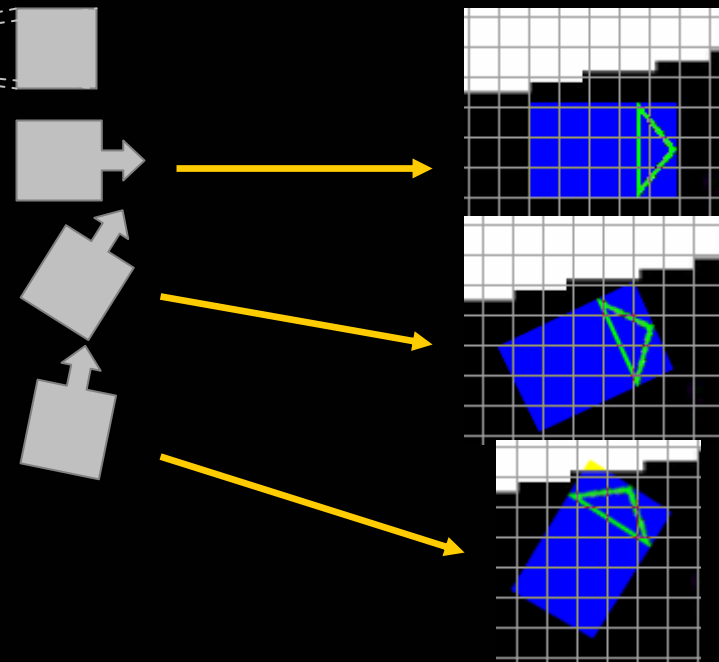$$\text{where } |\phi_{max}| > |\phi_{1..N}| \neq 0$$

## *C-Space*

**3 Dimensional Configuration Space**

**Collision Checking**



$R \times C \times W$ where W is $[-\pi, \pi)$
and cell size is 10cm $\times$ 10cm
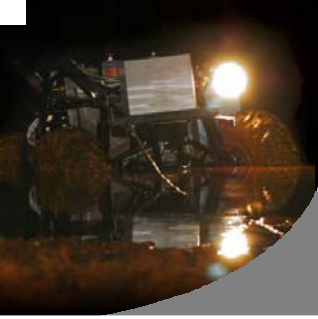
## *The Algorithm*



Priority Queue

$q_i$

$q_i$

$q_{i+1}$ $q_{i+2}$

$q_{i+1}$

$f(c)=g(c)+h(c)$

$q_{i+1}$

Priority Queue

*C-space*

$c_j$

Open

Closed
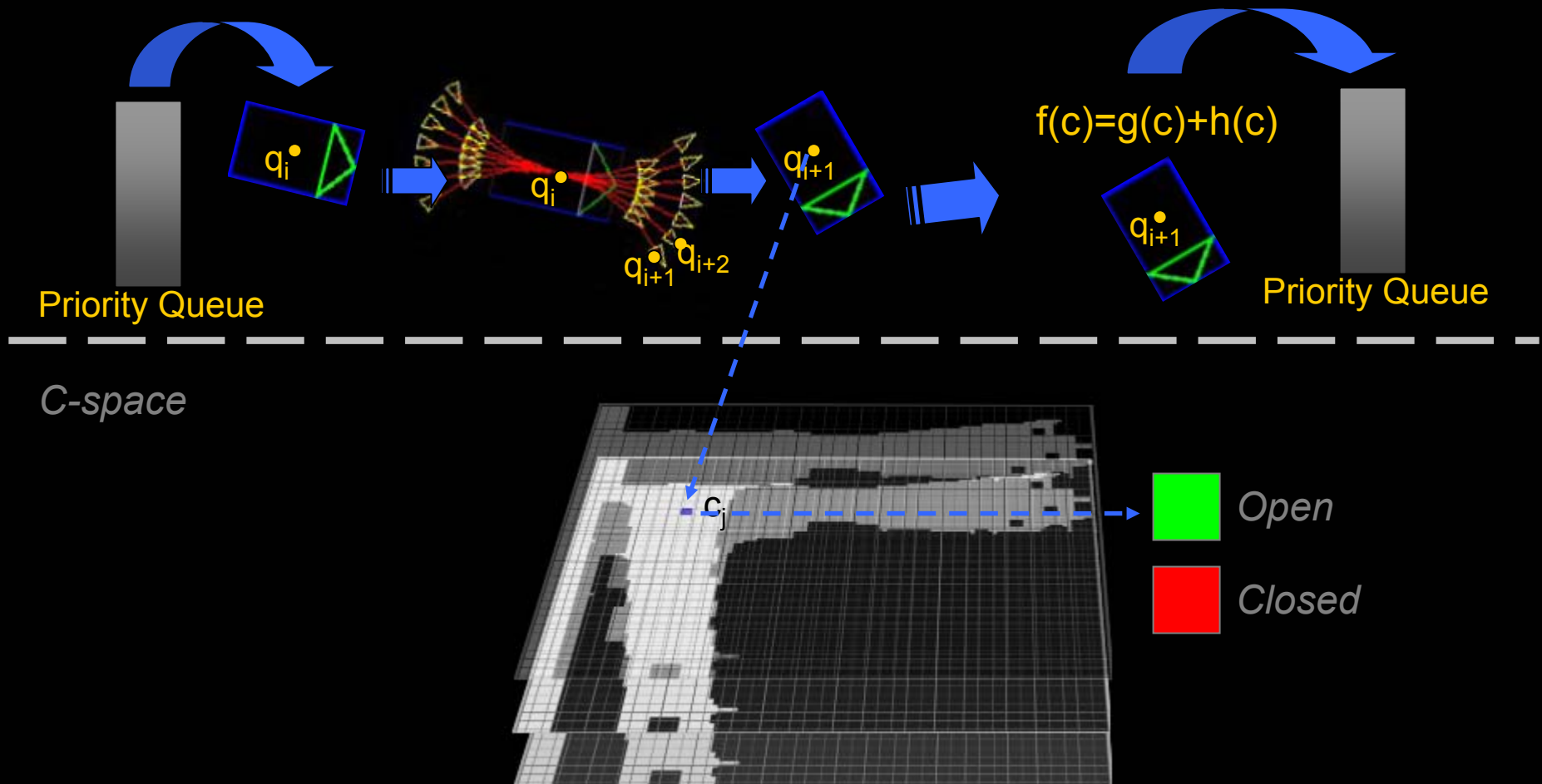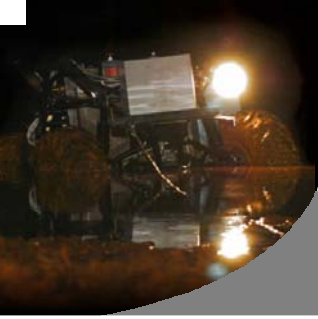
# Subterranean Robotics

| Direct Observation | Remote Observation | Remote Sensing |
|---|---|---|

29 m
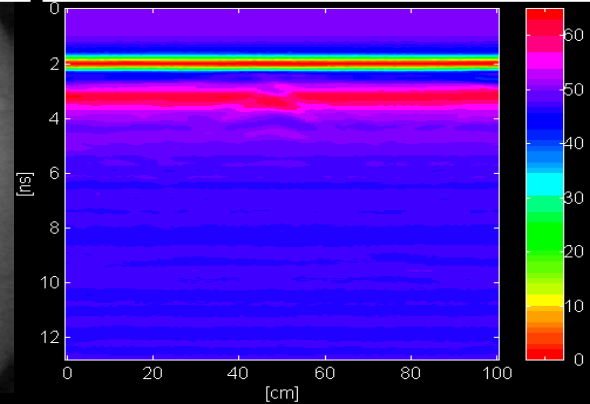
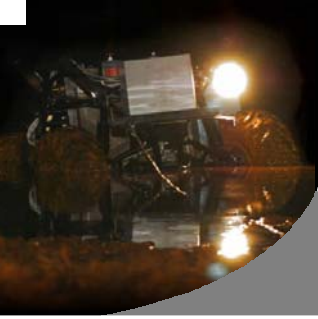- Places inspector into harms way
- Expensive
- Not always an available option
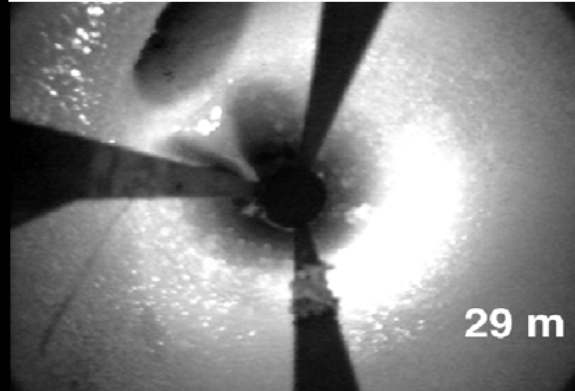
- Requires many holes
  - Expensive
  - Time consuming
- Little quantitative information

- Limited range
- Time consuming
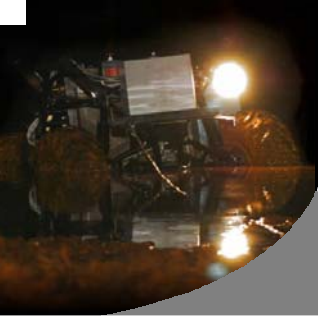- Void must be inferred
- Accuracy?

# Subterranean Robotics

## *Robotic Solutions*

### *Why Robots?*

- Physical presence without human risk

- High fidelity data

- Operation in the harshest of conditions

- Log and recall all sensory input

# Subterranean Robotics

| Condition | Robotic Challenge |
|---|---|
| Harsh environment | Roll, walk, swim, climb, … |
| No communication | Reliable failure recovery, adequate sensing, … |
| Rugged terrain | Recognize and avoid obstacles, surmount everything else |
| Complex 3D obstacles | Recognize and avoid obstacles beyond ground plane |
| Accessibility | Physical constraints for portal entry, borehole, puddle, … |
| Highly cyclic | Reliable localization |
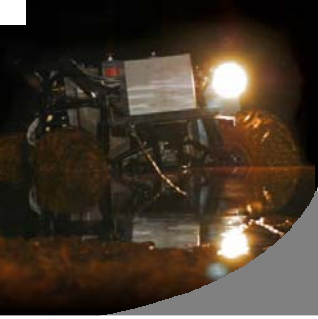
## *Maps and Models*
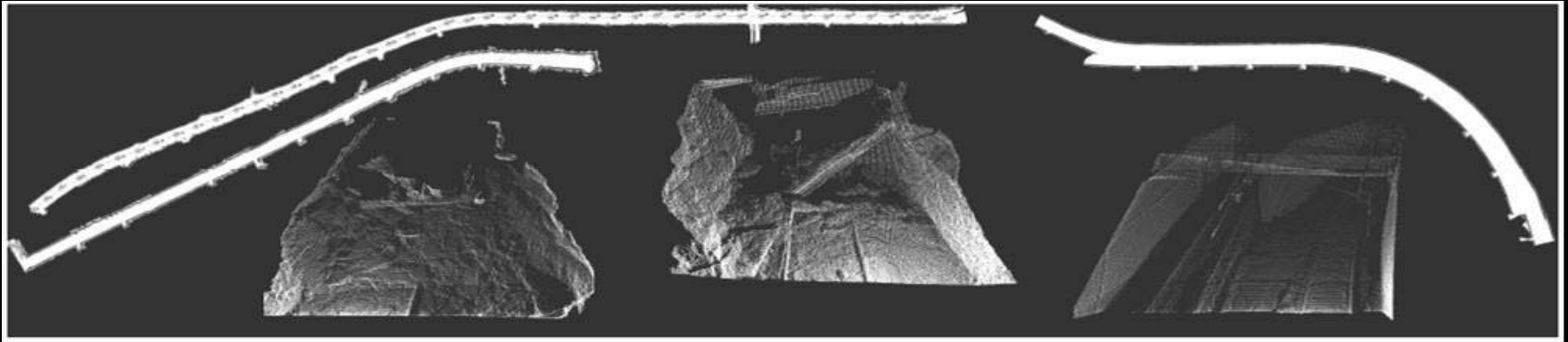


*Mathies Experiments*

[Thrun, Hänel, Montemerlo]
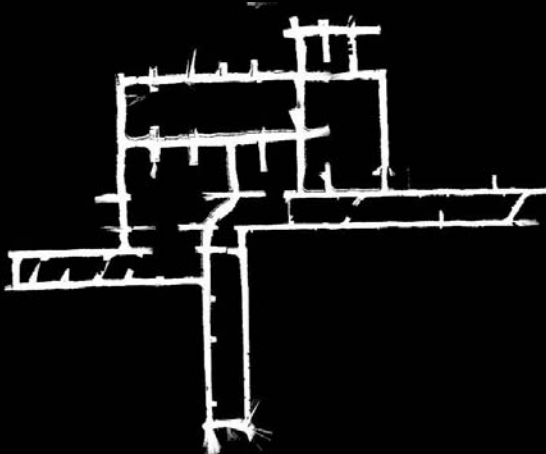


*Bruceton Experiments*
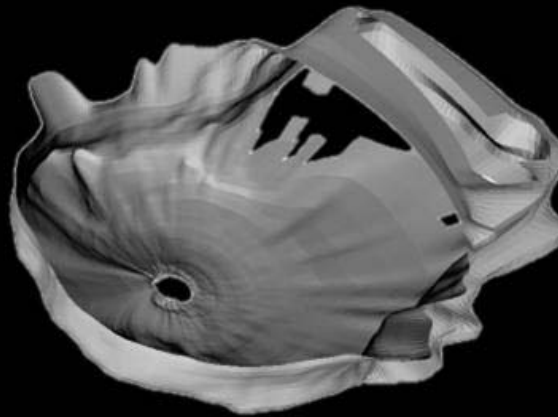
*Kansas City Void*
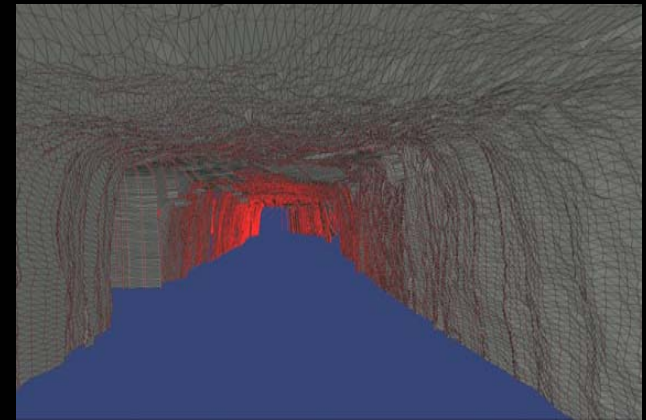
*Bruceton Model*
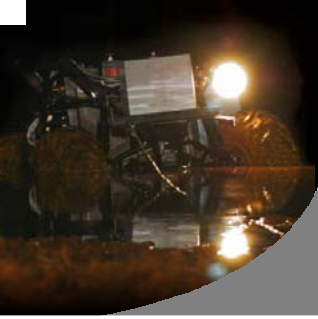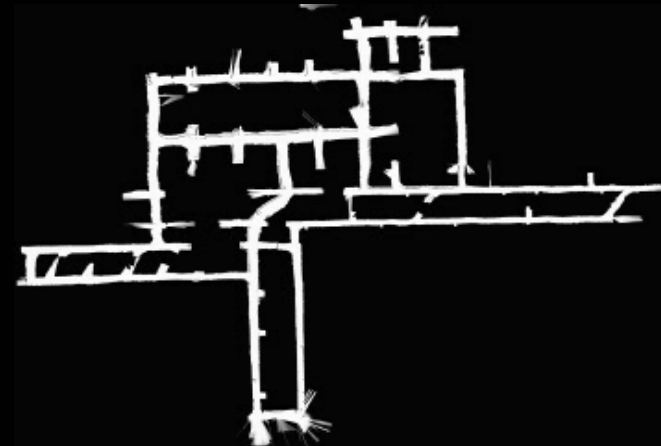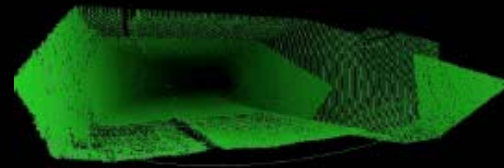
## *Portal Inspection System*
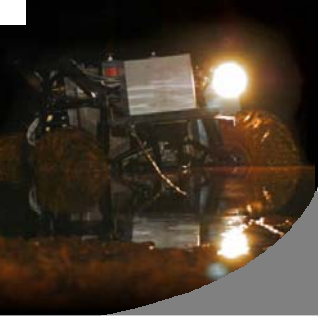
# Subterranean Robotics

- Mobile platform
- Portal Entry
- Robust to certain failures
- Adequate sensor configuration
- Reliable autonomy
- Compelling maps

# Subterranean Robotics

## Summary of Field Deployments in Mathies Mine

| Mission | Date | Port | Goal | Comp | Return Caused By | Duration | Egress | Comments/Results |
|---|---|---|---|---|---|---|---|---|
| 1 | 05/30 | 1 | 500 m | 308 m | Roof-Fall | 2 hr, 35 min | No | Robot Stranded |
| 2 | 10/01 | 2 | 100 m | 100 m | Mission Complete | 48 min | Yes | Complete Success |
| 3 | 10/01 | 1 | 100 m | 100 m | Mission Complete | 43 min | Yes | Complete Success |
| 4 | 10/01 | 3 | 100 m | 60 m | Submergence | 30 min | Yes | Slid Into Drainage Trench |
| 5 | 10/08 | 2 | 500 m | 140 m | Roof-Fall | 1 hr, 21 min | Yes | Hard Drive Failure |
| 6 | 10/22 | 3 | 100 m | 20 m | Software Problems | 20 min | Yes | Navigation Malfunction |
| 7 | 10/22 | 3 | 100 m | 10 m | Software Problems | 9 min | Yes | Navigation Malfunction |
| 8 | 10/30 | 3 | 330 m | 230 m | Fallen Cable | 2 hr 20 min | Yes | Teleoperated Out |
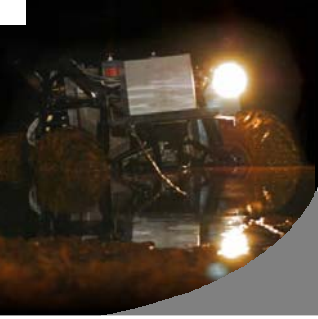
## *The Next Step: Network Exploration*
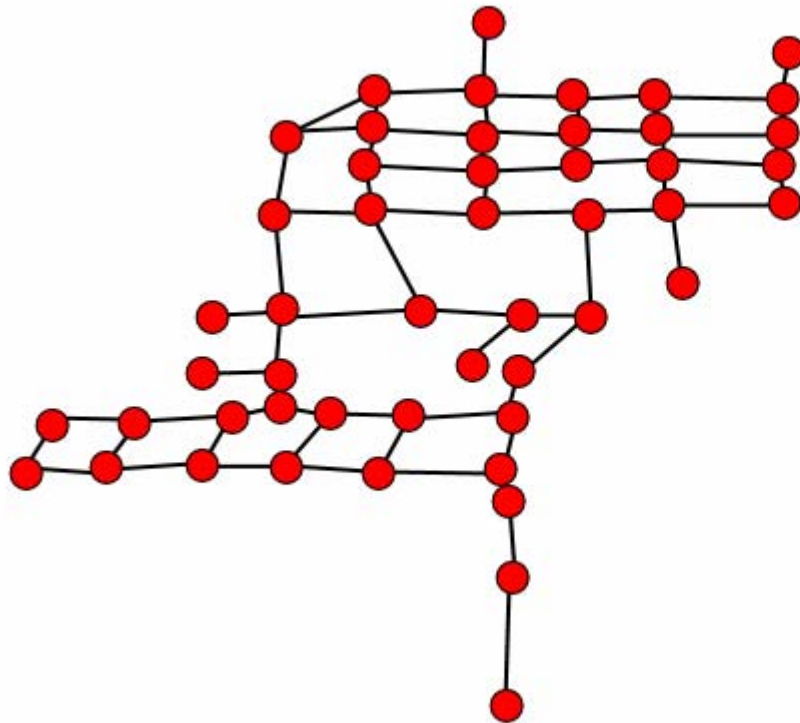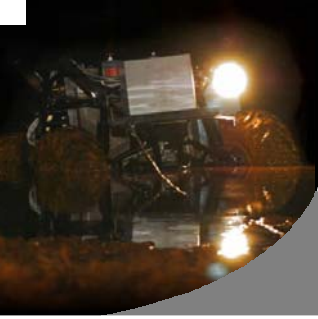


*Exploration and localization through topological representations*

## *Offline ID Results*
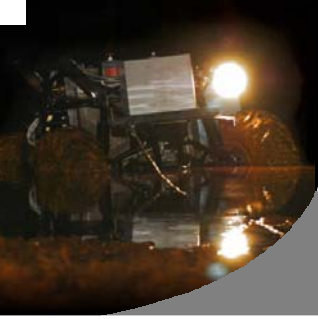
**100 Meters of Mine Corridor**
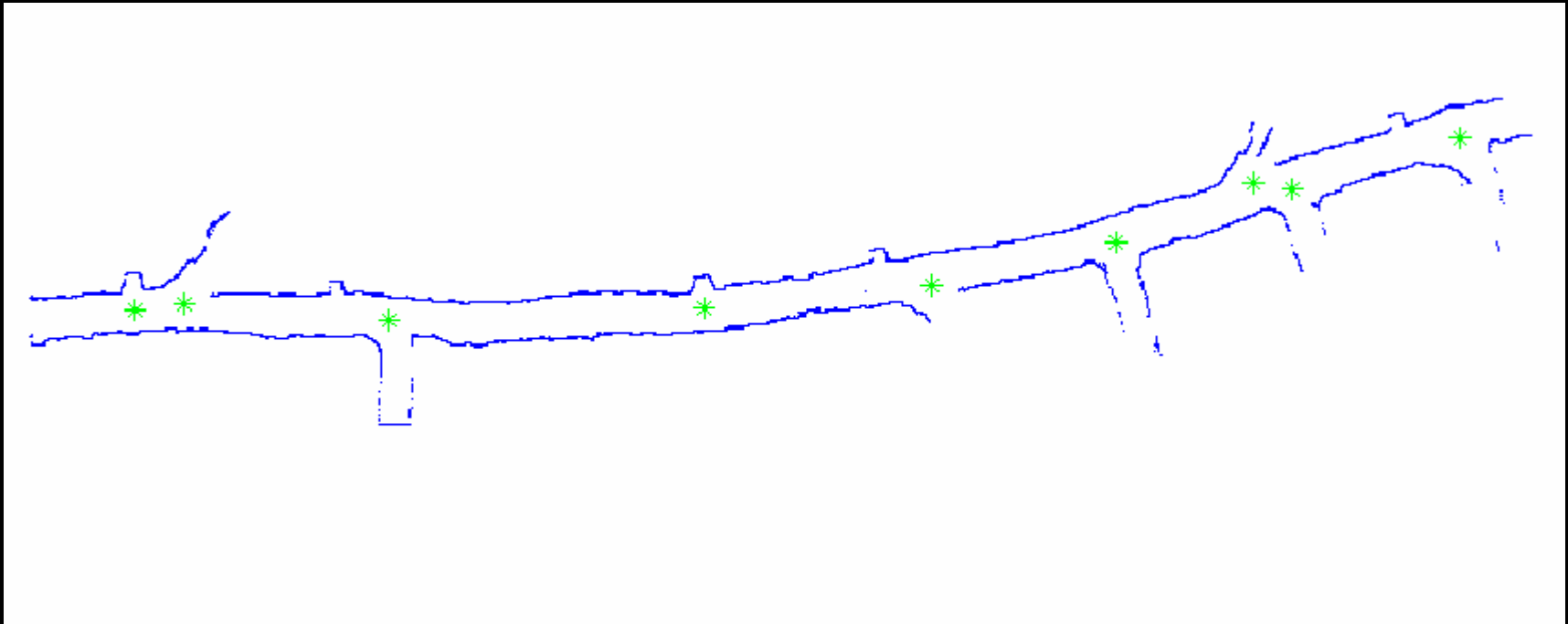


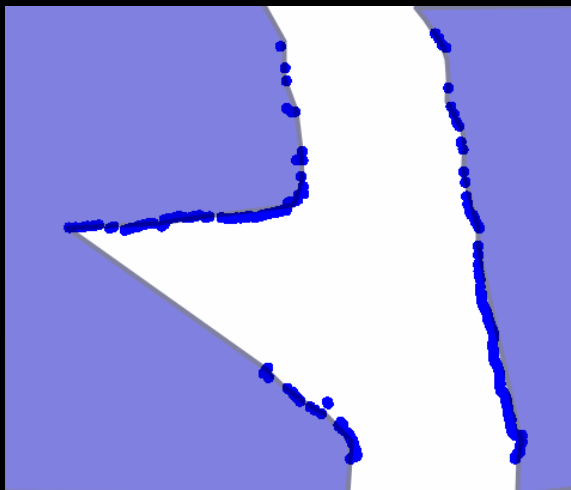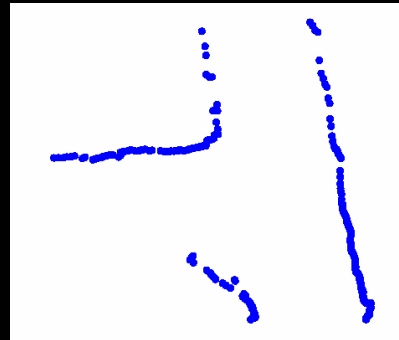*In total, 9 features: 5 intersections and 4 pockets of excavated coal*

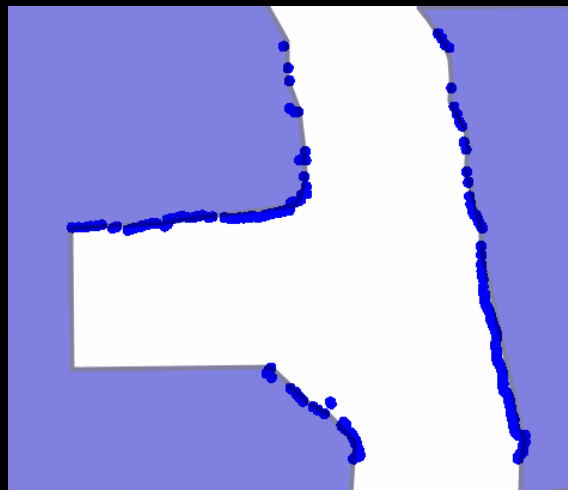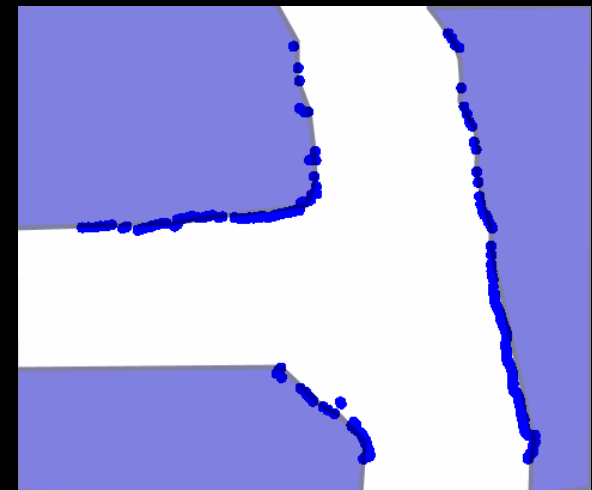## *Node Classification*



Not an intersection          Could be?                    An intersection
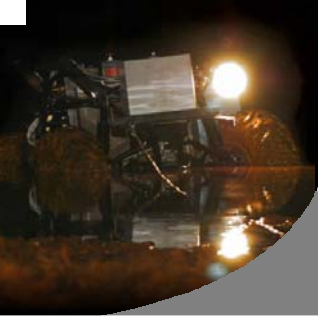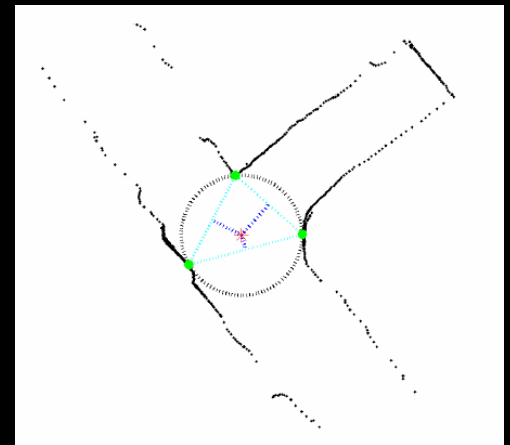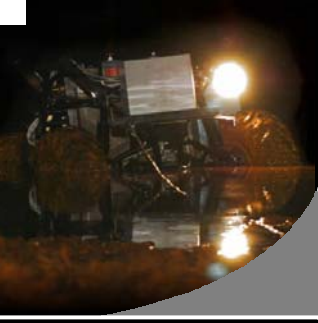
# Subterranean Robotics

- Features selected from DT of range scan, filtered by edge length

- Tracked over multiple scans

- Groundhog sensor configuration requires it to drive through intersection

- Identified as "strong" or "weak" (known as RGVD)
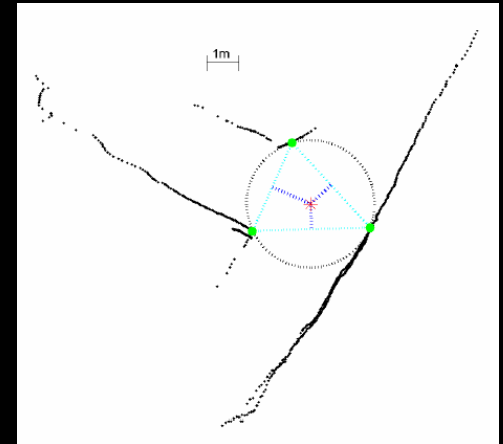


*Strong Node*



*Weak Node*

## *Cost Metric*

$$f(c) = g(c) + h(c)$$
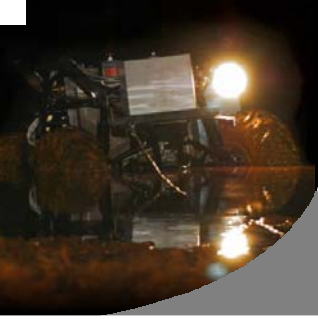
$$h(c) - \text{heuristic value, } D(\{x_c, y_c\}, G)$$

$$g(c) - \text{cost of path from } S \text{ to } c$$

$$g(c) = g(p) + g(p,c)$$
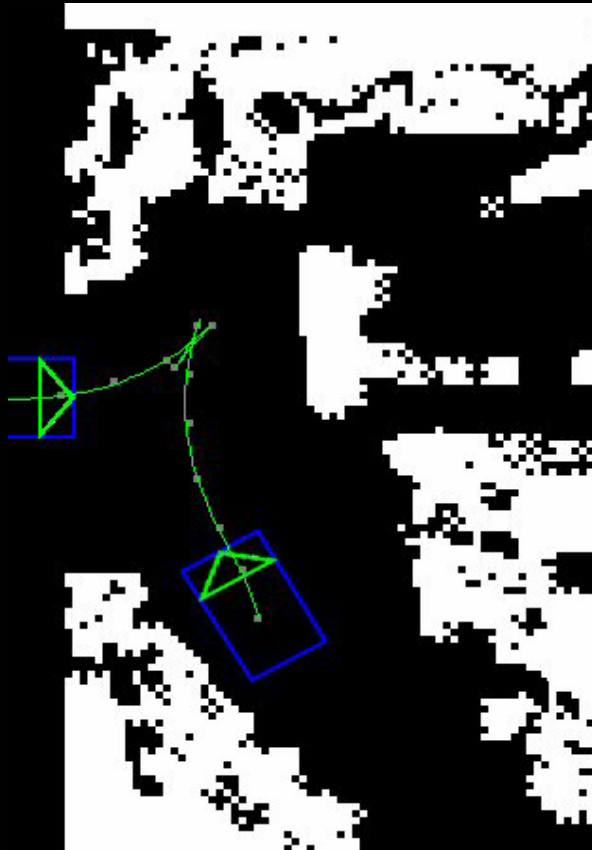
$$g(p,c) = \text{arc\_length}$$

- Best-first search
  - "Obvious" solutions found quickly
  - More complicated maneuvers take longer

- Goal threshold
  - Tighter thresholds longer search times and "quirky" paths
  - Looser thresholds produce worse end poses

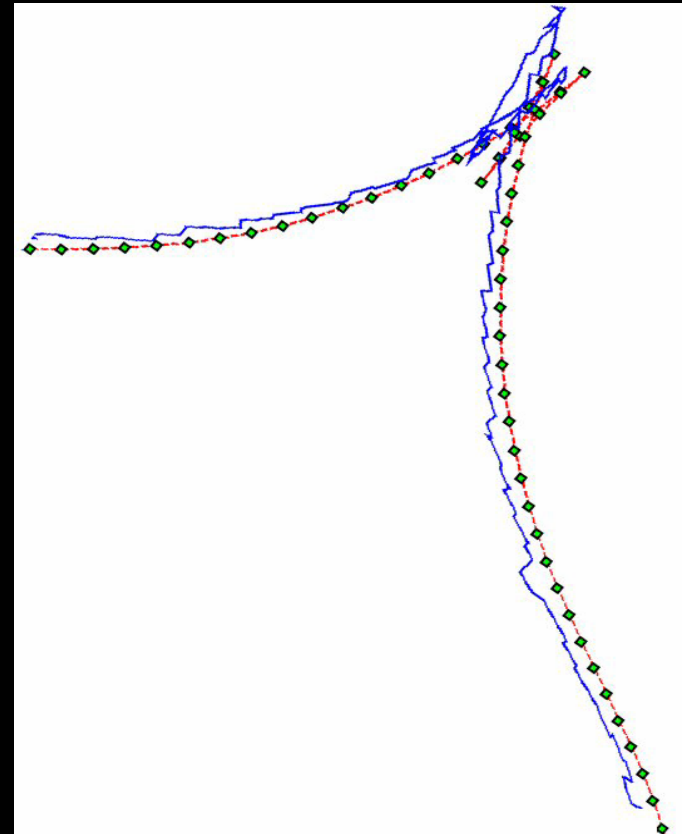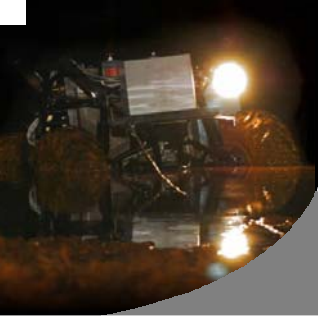- Search time proportional with amount of free space
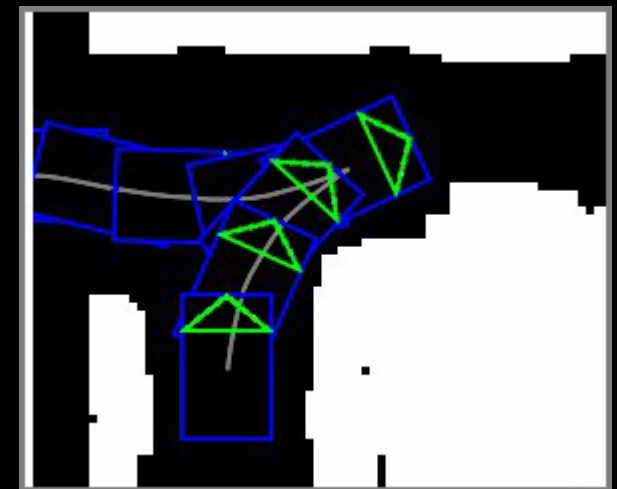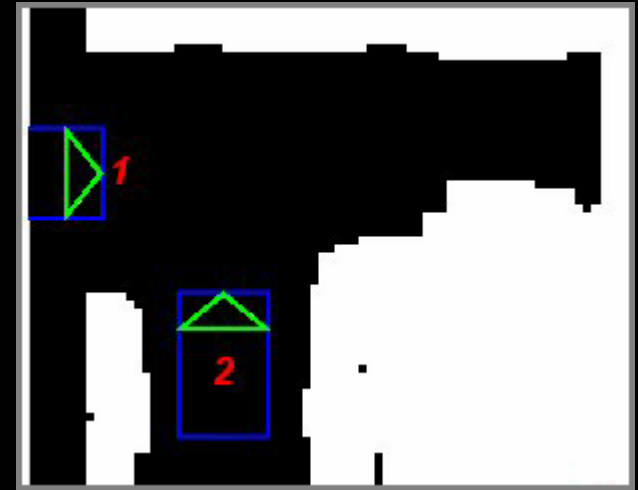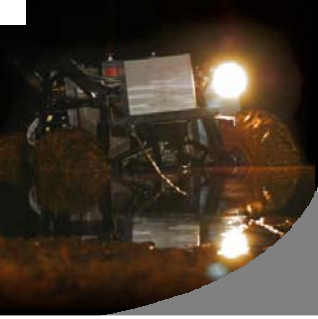
## *Example path*



*Simulated traversal*



*Actual traversal*
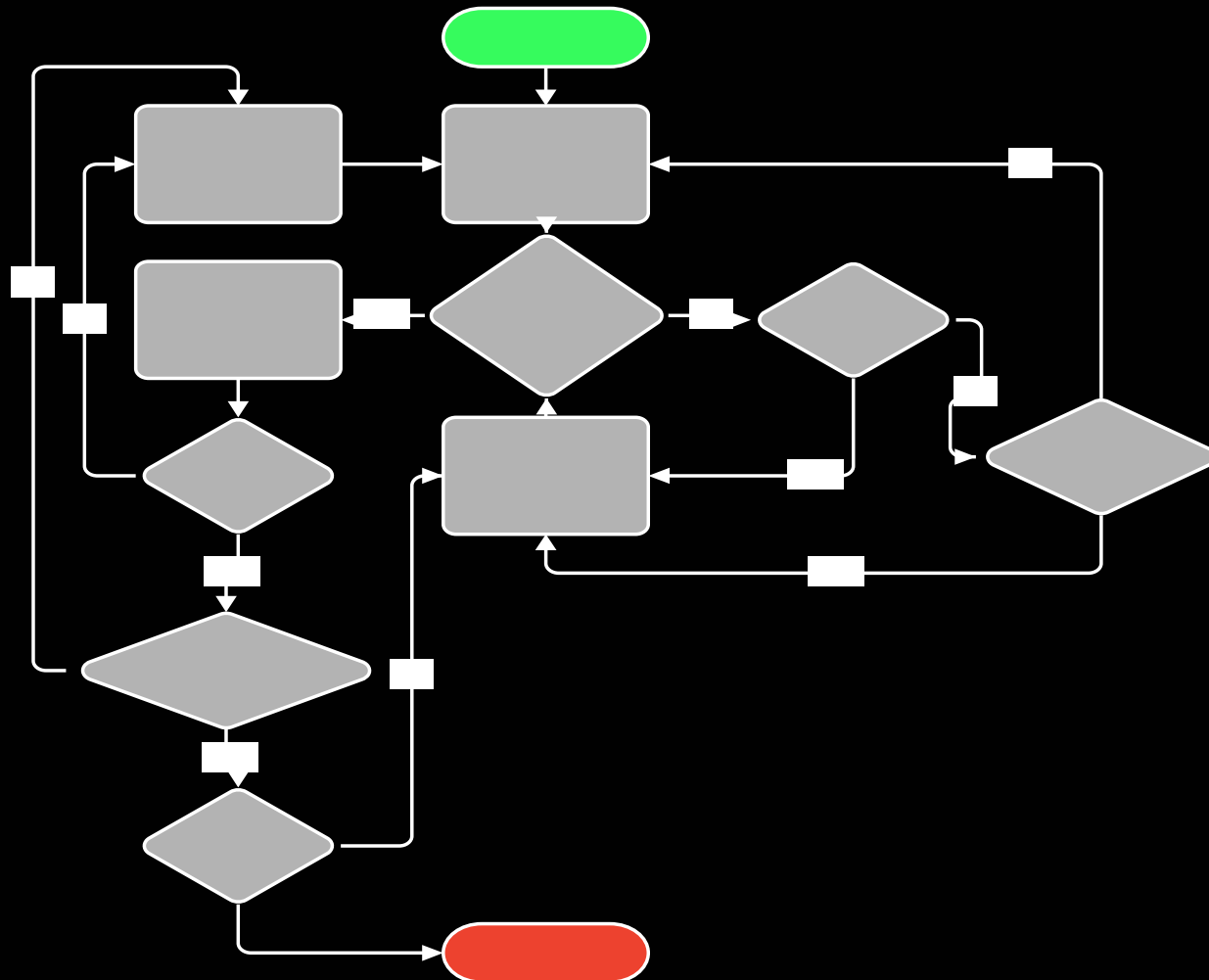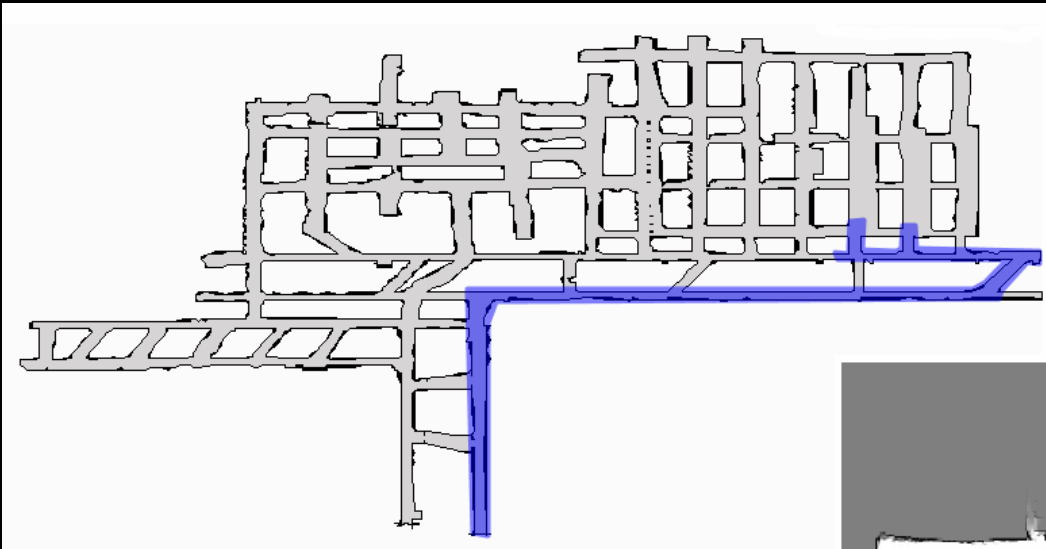
## Phase 3: Topological Planner
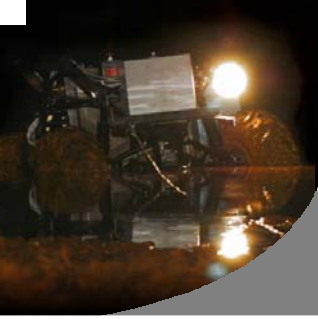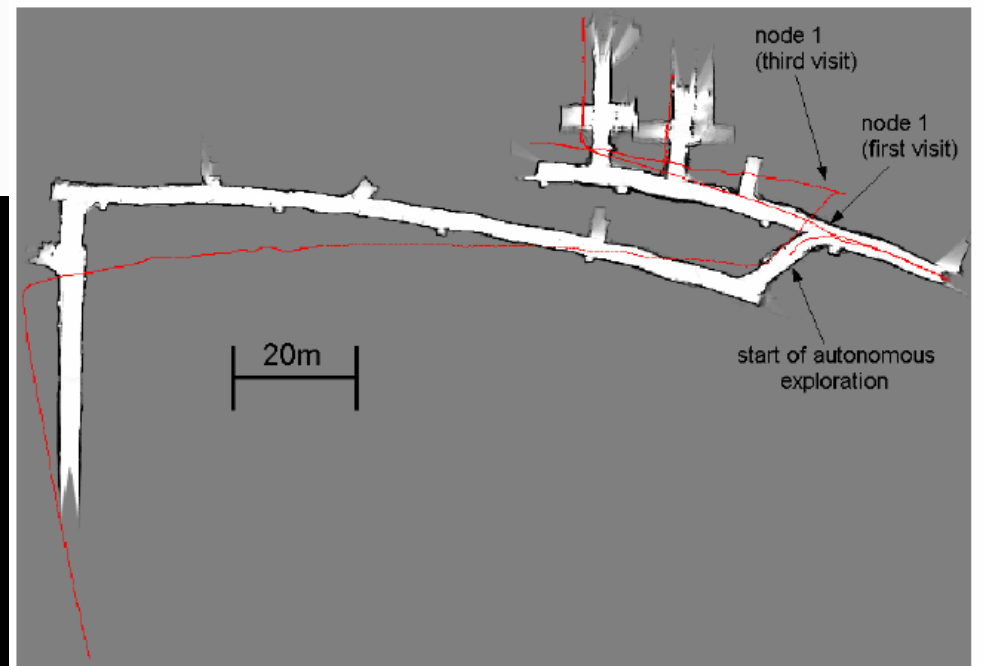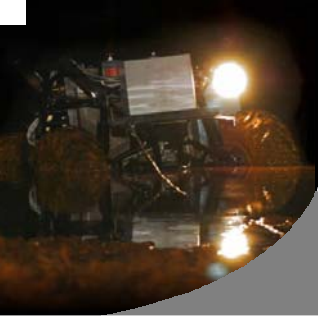
## *Results*



**Longest Autonomous Traverse to Date**

- 2 hours to complete
- Over 400 m
- 8 nodes (3 intersections)



node 1 (third visit)

node 1 (first visit)

start of autonomous exploration

20m

7/7/2005

# Subterranean Robotics

- Over 20 hours of operation, identified 50 intersections

- Strong node identification to total intersections: 100%

- Weak nodes identified as strong: 0

- Average time to calculate motion plan: 10s (vs. 60s with former planner)

- 30s to 60s for complex turning maneuvers

- Complete autonomous tree exploration
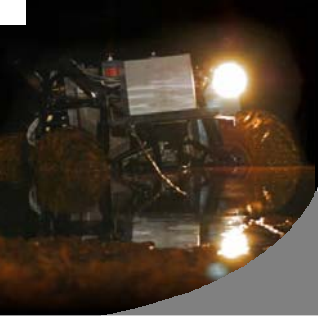
# Subterranean Robotics

## *In the Future…*

- Intersection classification (spin images)
- Probabilistic T-SLAM
- Fault detection and state tracking
- Framework for degraded operation modes
- Implementation on new systems
- Response and rescue
- International endeavors
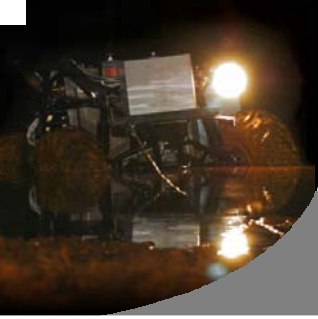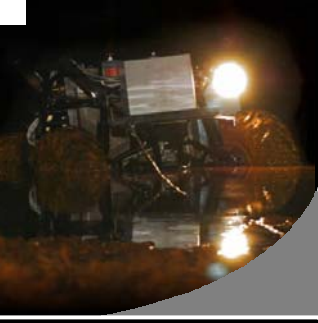
# Subterranean Robotics

**Mine Fire Response and Rescue**

NSH 1109, MW 1:30-2:50PM

# Subterranean Robotics

Subterranean Robotics Online

www.minemapping.org

www.subterraneanrobotics.org

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