Robotic exploration

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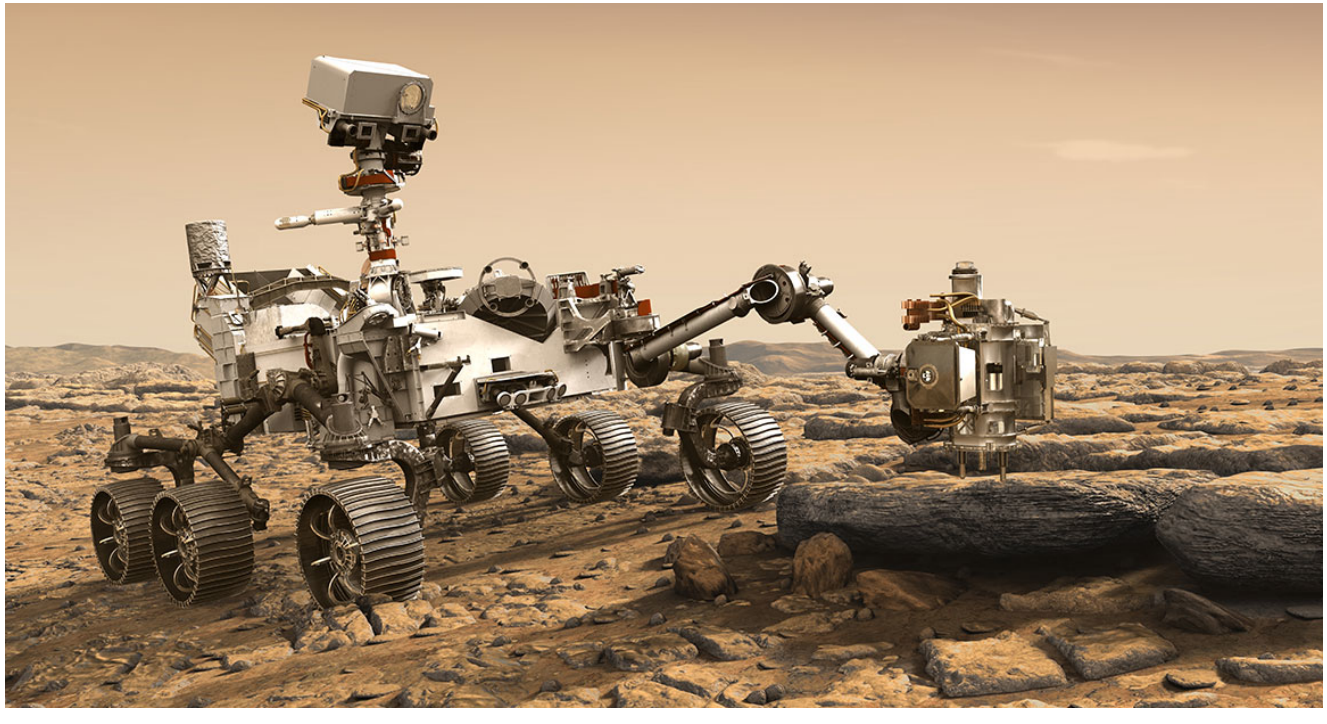


Motivation scenarios

https://www.youtube.com/watch?v=P3uT4gHEFHw

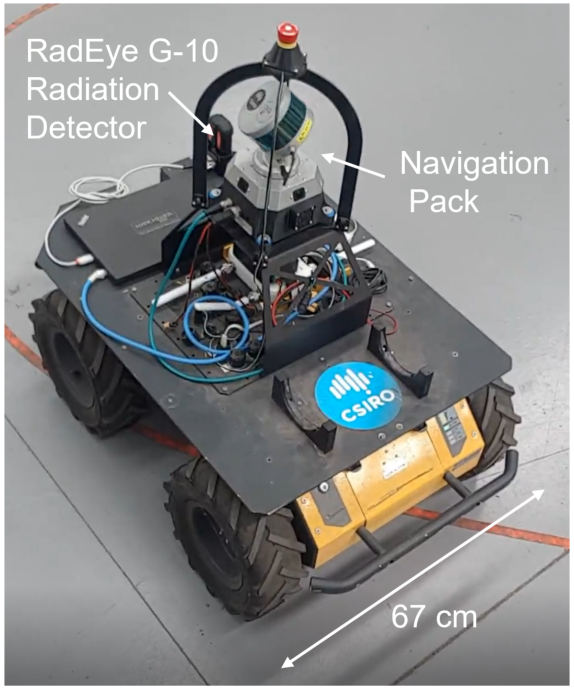
Finding precious metals, water sources, etc.

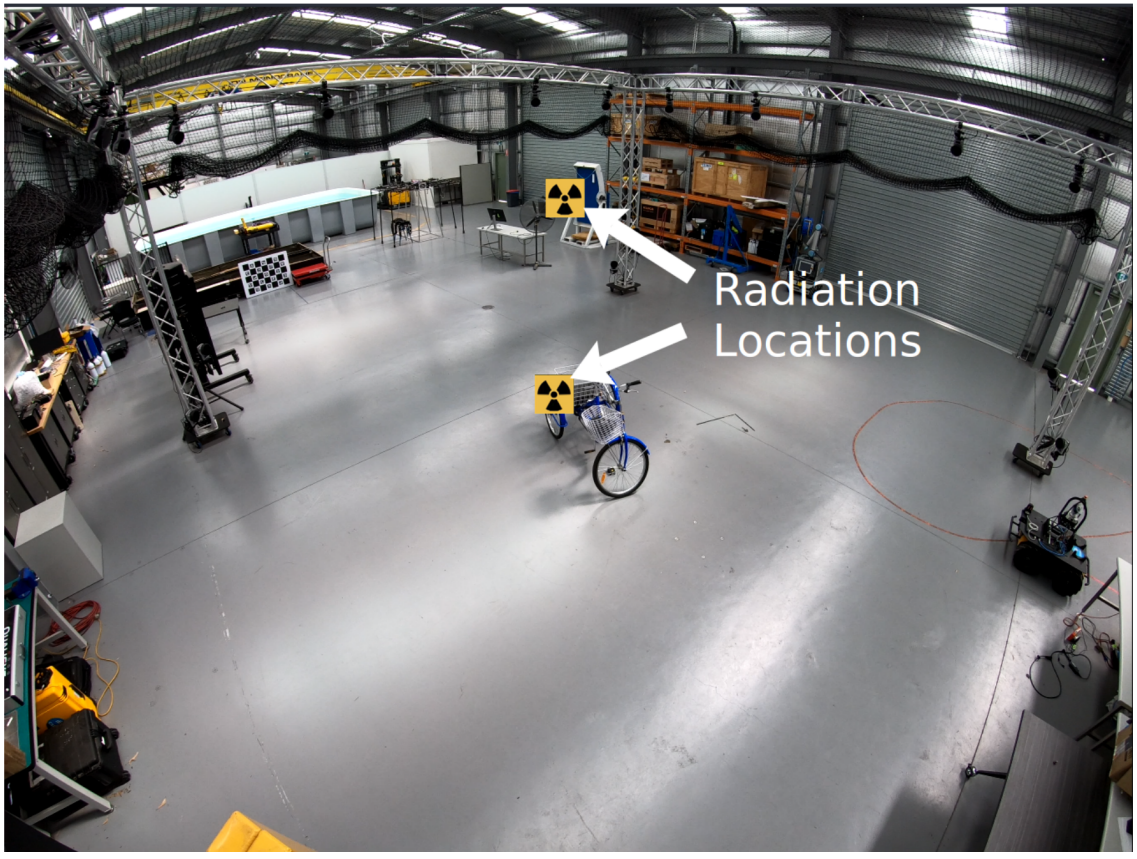
Motivation scenarios

Finding and rescuing people in debris

Source: robohub.org

Motivation scenarios

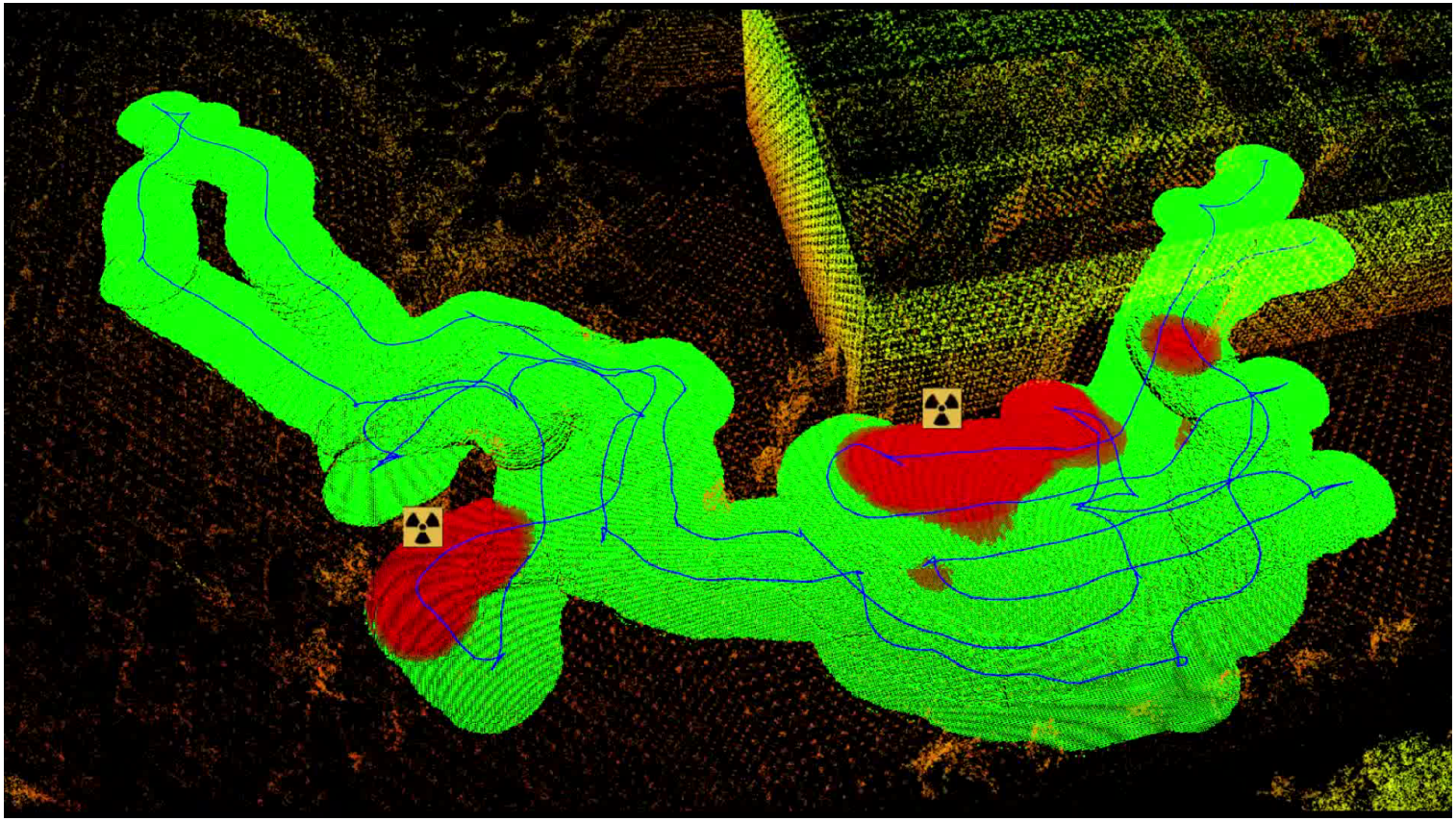




Mapping radioactive zones

☛Groves, K.; Hernandez, E.; West, A.; Wright, T.; Lennox, B. Robotic Exploration of an Unknown Nuclear Environment Using Radiation Informed Autonomous Navigation. Robotics 2021, 10, 78.

Motivation scenarios



www.youtube.com/watch?v=Hj7xt7isOWc

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Exploration

- *the activity of searching and finding out about something* (Cambridge English dictionary)
- *. . . is a trip, but it's more than just a vacation — it's going somewhere to examine and discover new things* (vocabulary.com)

Robotic exploration

- *use a robot to maximize knowledge over a particular area*
  - Is there a precious metal? Where are the victims? Is there a radioactivity?
- Fundamental problem of robotics
- Single robot vs. multi-robot exploration
- Practical problem needed in many applications

How to approach exploration

Reactive

- measure, evaluate, act, measure, evaluate, . . .
- not optimal (e.g., time/energy consuming)
- can lead to cycles

Decision-based

- build a model of the environment
- make decision using the model
- more efficient, can be optimized
- extra effort to make the model of the environment

How to represent/model environment?

- Many approaches
- Model should always be selected according given application

Example of models of environments I

Low-level data

- Raw sensor data (e.g. LIDAR values, images)
- Neural network models (weights+topologies), learned policies (Reinforcement learning), rosbag
- File formats: (txt,bin,SQL,HDF,. . .)
- They are specific to given task/environment
- Hard to interpret by humans
- Poor generalization


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Database Structure | Browse Data | Edit Pragmas | Execute SQL

Table: runs

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3	3	1	1	0	1	1	3380	3381	31.7266	0.0	0.0	24.9994	250	25997.5	
4	4	1	1	0	1	1	2912	2913	32.5	0.0	0.0	26.6361	267	29869.0	
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6	6	1	1	0	1	1	3802	3803	34.0469	0.0	0.0	26.1314	262	29102.3	
7	7	1	1	0	1	1	2527	2528	35.0781	0.0	0.0	25.2687	253	29115.4	
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9	9	1	1	0	1	1	2476	2477	36.8828	0.0	0.0	17.0454	171	17560.3	
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11	11	1	2	0	1	1	7441	7442	38.6836	0.0	0.0	29.6971	14	13.4658	
12	12	1	2	0	1	1	11815	11816	41.0039	0.0	0.0	22.5842	11	15.7426	

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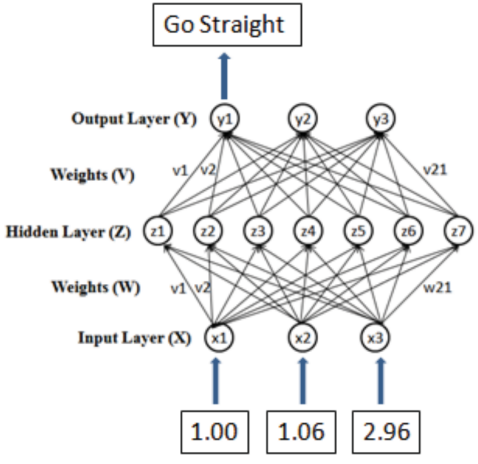
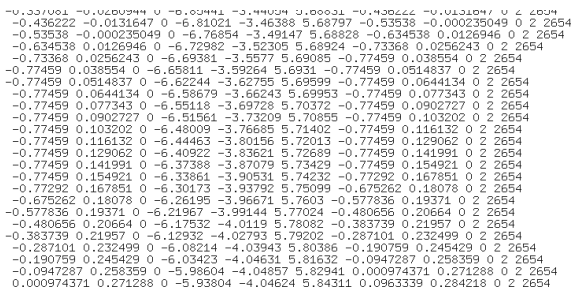


T. Zhao and Y. Wang, "A neural-network based autonomous navigation system using mobile robots", International Conference on Control Automation Robotics & Vision, 2012

Example of models of environments II

Processed data

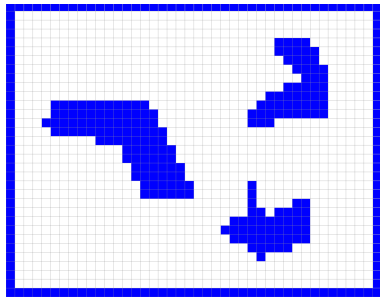
- Interpreted sensor data (e.g. obstacles, walls, ground, free-space, . . .)
- Good generalization
- Can be easily interpreted by humans

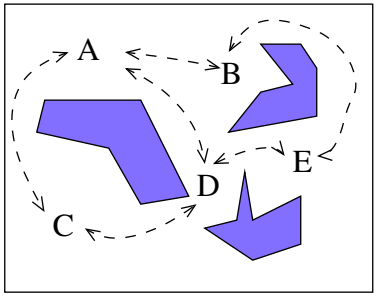


- These models are simply known as **maps**

Maps in robotics

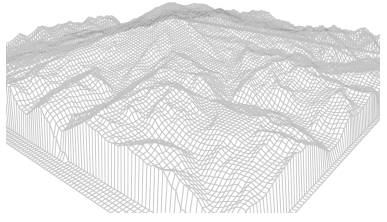
- Map is the model of the world/environment
- Many types (2D/3D, grid, polygonal, . . .)
- Usually contain geometric features (e.g. walls, ground, obstacles)
- Necessary for decision making (e.g. planning, navigation, inspections, . . .)

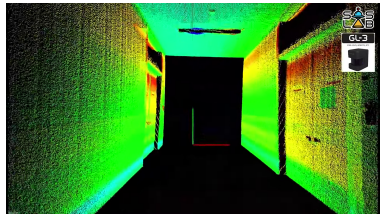




Properties

- Supported operations (e.g. merging maps, adding new information, deleting obstacles, . . .)
- Computational complexity of these procedures
- Memory requirements
- Precision
- Robustness (with respect to numerical errors)
- There is no ‘universal’ map
- One should always choose a map suitable for the given application





Grid maps

- 2D or 3D array (grid) of cells
- Binary maps: 0/1 (obstacle, free spaces)
- Probability: 0–1 (0=free space, 1=obstacle)
  - occupancy grid
  - often used for integration of sensor data, SLAM

✓ Metric information (distance/angle/area . . .)

✓ Easy implementation

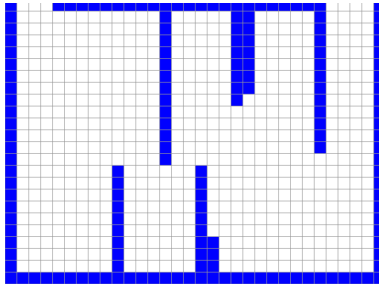
✓ Efficient search for obstacle cells, nearest obstacle cell, . . .

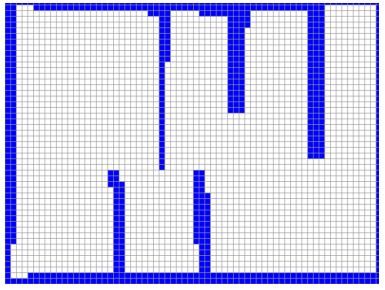
✓ Straightforward update of cells & map merging

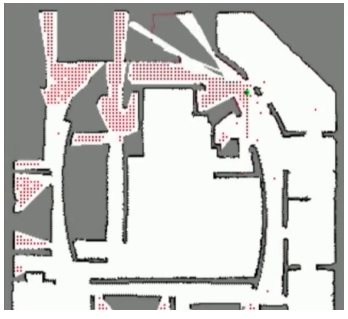
✓ Integration of data from different sensors

✗ High memory requirements

  - depends on environment size & map resolution
  - practical limit to 2D and 3D environments







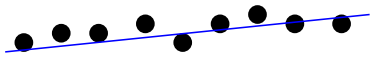
5VdzKHreB_s

Grid maps

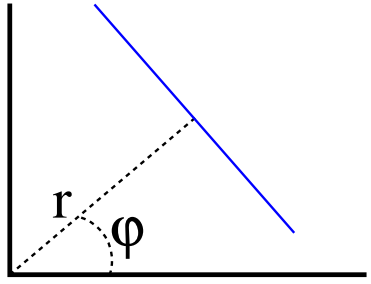
Source: Robotic Dataset repository (Radish): fr097

Line maps

- 2D worlds, suitable for structured indoor scenes
- Obstacles are represented by lines
- Compact way to store range-sensor measurements (x_i, y_i)



$$\tan 2\varphi = \frac{-2\sum_i (\bar{x} - x_i)(\bar{y} - y_i)}{\sum_i \left((\bar{y} - y_i)^2 - (\bar{x} - x_i)^2 \right)}$$



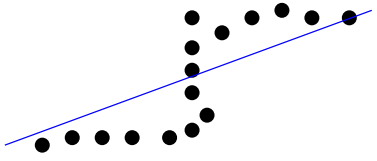
$$r = \bar{x}\cos\varphi + \bar{y}\sin\varphi$$

- Can be extended for 3D planes

✓ Memory efficient, easy to process, metric information

✓ Fast tests for collisions, point location

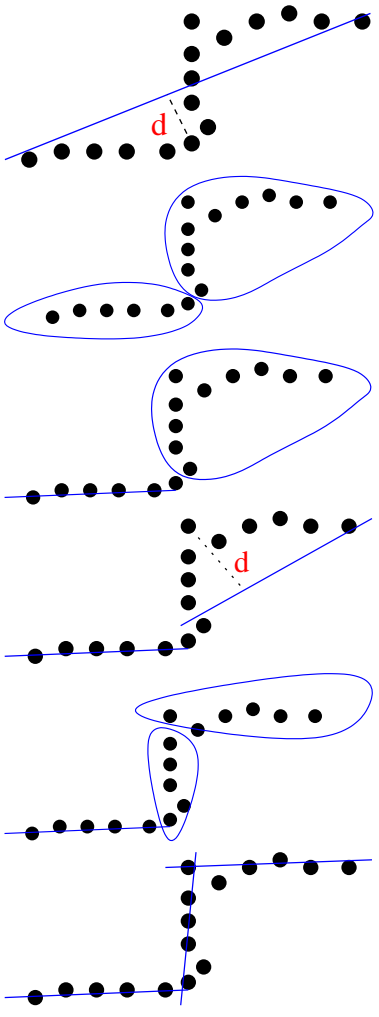
✗ What if data points are generated by multiple linear structures?



  - How many lines are needed?
  - How to assign points to individual lines?

Split and merge recursive approach

1. Compute line for a given set of points $(x_1, y_1) \ldots (x_n, y_n)$
2. Find the most distant point i from the line, its distance is d
3. If d is smaller than a threshold, return line
4. Otherwise, split points to two groups $(x_1, y_1), \ldots (x_i, y_i)$ and $(x_{i+1}, y_{i+1}), \ldots (x_n, y_n)$ and proceed recursively on each group



- Easy to implement, fast
- The result is not optimal (does not minimize square distances of points from lines)

☛ D.H. Douglas, T.K. Peucker: Algorithms for the reduction of the number of points required to represent a line or its caricature, Cdn. Cartogr. 10(2), 1973

Polygonal maps

- 2D worlds
- Obstacle is represented by polygon

$$(x_1, y_1), (x_2, y_2), \ldots, (x_n, y_n)$$

- (x_i, y_i) are vertices
- The map is the collection of obstacles
- Simple polygon: does not intersect itself, no holes
- Polygons with holes: contour + one or more holes

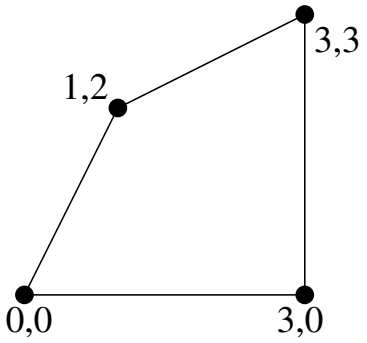
✓ Memory efficient, easy to process, metric information

✓ Fast tests for collisions, point location

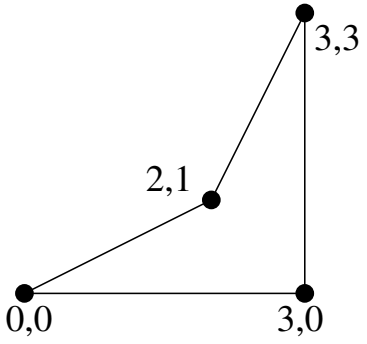
✗ Numerical stability of (some) algorithms

✗ Number of vertices can dramatically grow if map is built from (unfiltered) sensor data

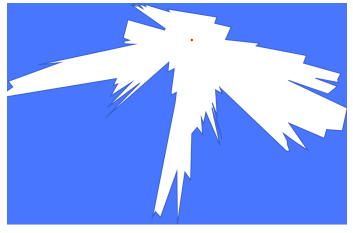
Map $\sim 100 \times 5$ m, $\sim$1k vertices



Convex



Non-convex



Polygon from Lidar

What kind of maps are using humans?

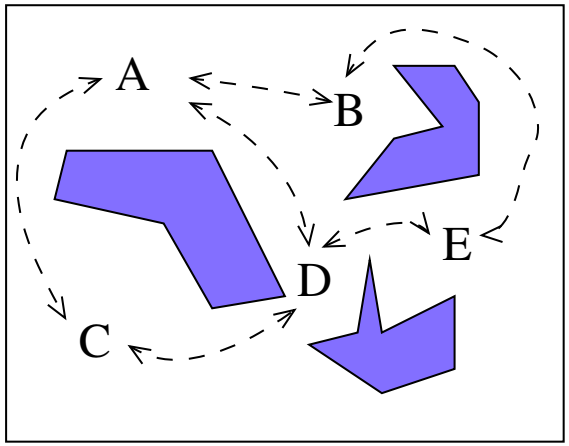
- grid, occupancy grid, polygonal, line-map . . . ?

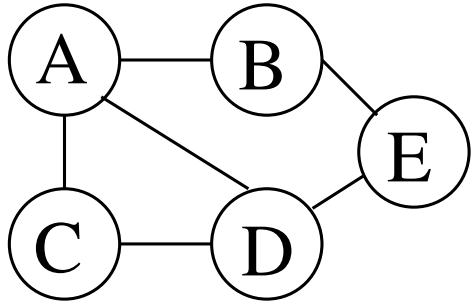
What kind of maps are using humans?

- grid, occupancy grid, polygonal, line-map . . . ?

Topological maps

- Abstract map, lack of geometric and metric features
- Represented by a graph
  - Vertices are (distinguishable) places
  - Edges connecting places between the robot can navigate
- Scalable, used for high-level planning





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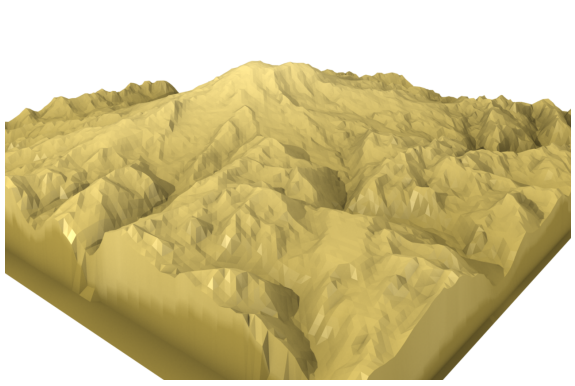
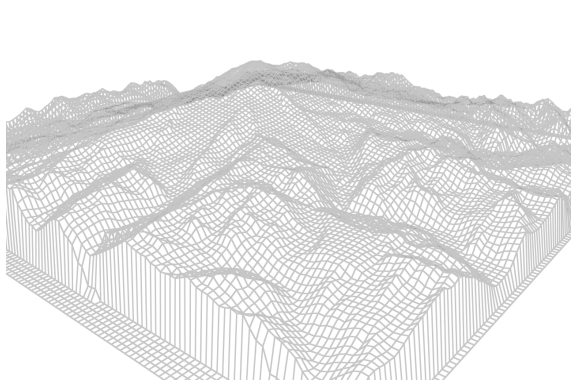
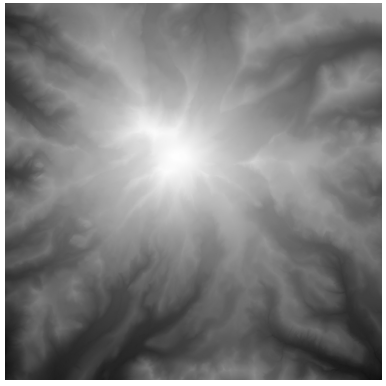
Maps for 3D worlds

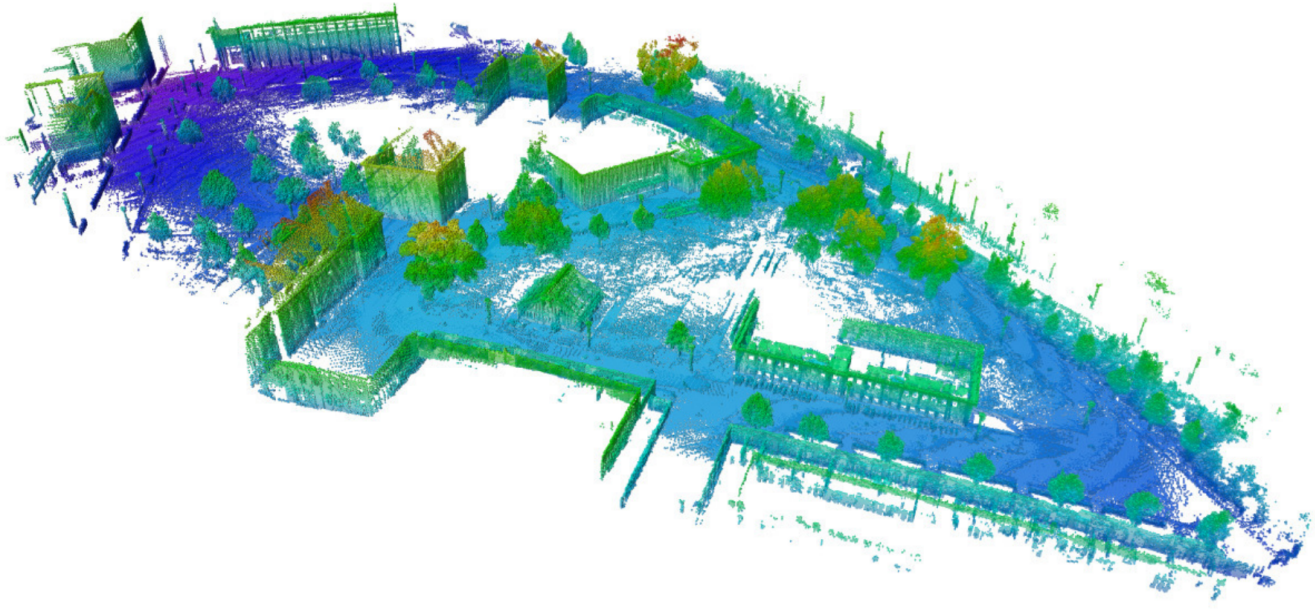
- Elevation (2.5D grid map): each cell describes altitude





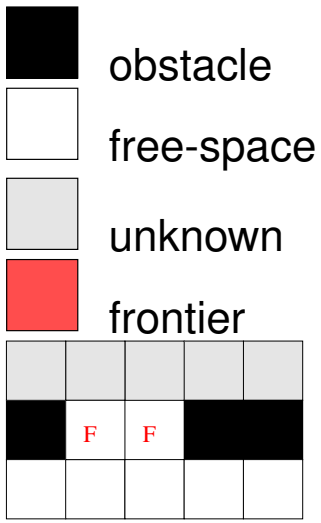


- Pointclouds, octomap



Occupancy grid

- A variant of grid map
  - Known cell: value of $c_i \geq 0$ (contains prob. of being occupied)
  - Unknown cell: value of $c_i = -1$
- Interpretation of known cells:
  - Free-space (no obstacle): $p(occupied) < T$
  - Obstacle: $p(occupied) > T$
  - where T is a threshold, e.g. 0.8
- Frontier: the border between known and unknown regions
- Frontier cell
  - is a free-space cell that is incident with an unknown cell
  - it may not be reachable



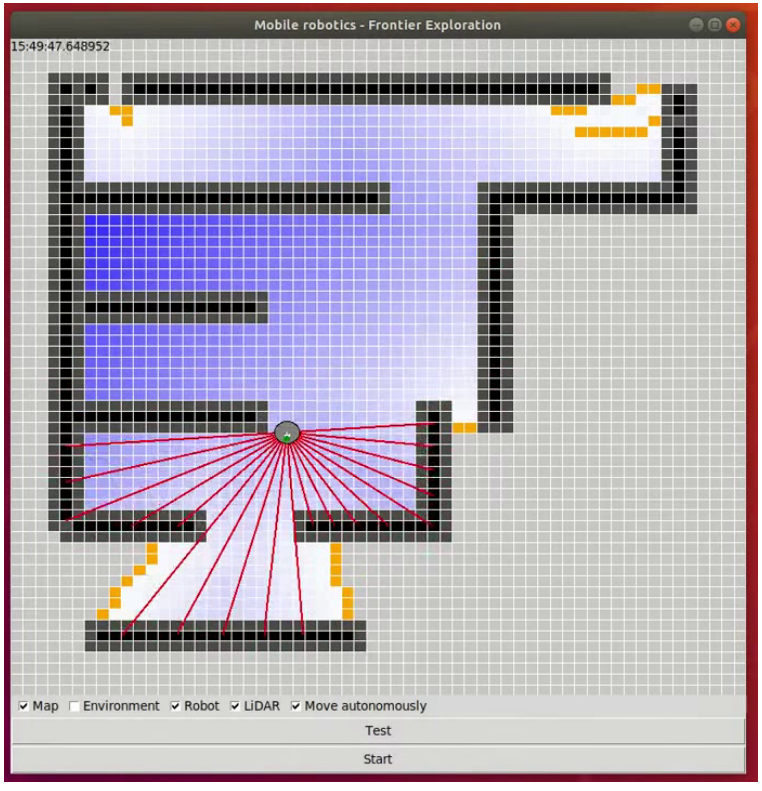
☛ YAMAUCHI, B., et al. Frontier-based exploration using multiple robots. Agents. 1998; 47-53.

Robotic exploration

- Robot is gathering (desired) information in an environment
- Search & rescue, searching for Barbie, precious metals, etc.
- We used model of the environment (map) to do it efficiently
- Often used solution: SLAM (Simultaneous localization and mapping)

Challenges

- How to represent the map
- How to update it
- How to localize
- How to determine where to go
- How to get there



https://www.youtube.com/watch?v=B-dSyKx4Fsc

Frontier-based exploration

Principle: use a frontier as a temporary goal

1. Identify frontiers in the map
2. Filter out unreachable frontiers (if any)
3. Select a frontier and go there
4. Goto 1 until no frontier exists

Notes

- Unreachable frontiers detected using path planning
- Consider navigating to the closest frontier
- Consider detecting frontiers during movement of the robot
- Detection of frontiers should be fast

☛ YAMAUCHI, B., et al. Frontier-based exploration using multiple robots. Agents. 1998; 47-53.

☛ KEIDAR, Matan; KAMINKA, Gal A. Ecient frontier detection for robot exploration. The International Journal of Robotics Research, 2014, 33.2: 215-236.

Frontiers detection

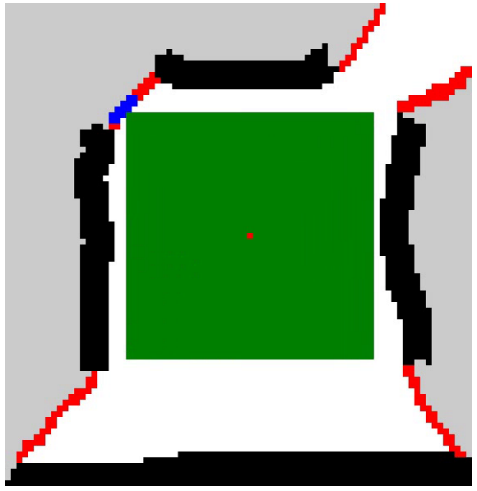
- Image-based
  - Convert occupancy grid to binary image, run edge detection
- Wavefront Frontier Detector (WFD) (☛ Keidar)
  - Graph-search method to detect frontiers
  - Run BFS from actual position of the robot
  - This BFS explores only free cells (i.e., also frontier cells)
  - Run another BFS if frontier cell is visited
  - The second BFS explores only frontier cells
  - The goal of second BFS is to extract all cells belonging to the actually detected frontier
- Both BFS share open/close list

☛ YAMAUCHI, B., et al. Frontier-based exploration using multiple robots. Agents. 1998; 47-53.

☛ KEIDAR, Matan; KAMINKA, Gal A. Ecient frontier detection for robot exploration. The International Journal of Robotics Research, 2014, 33.2: 215-236.

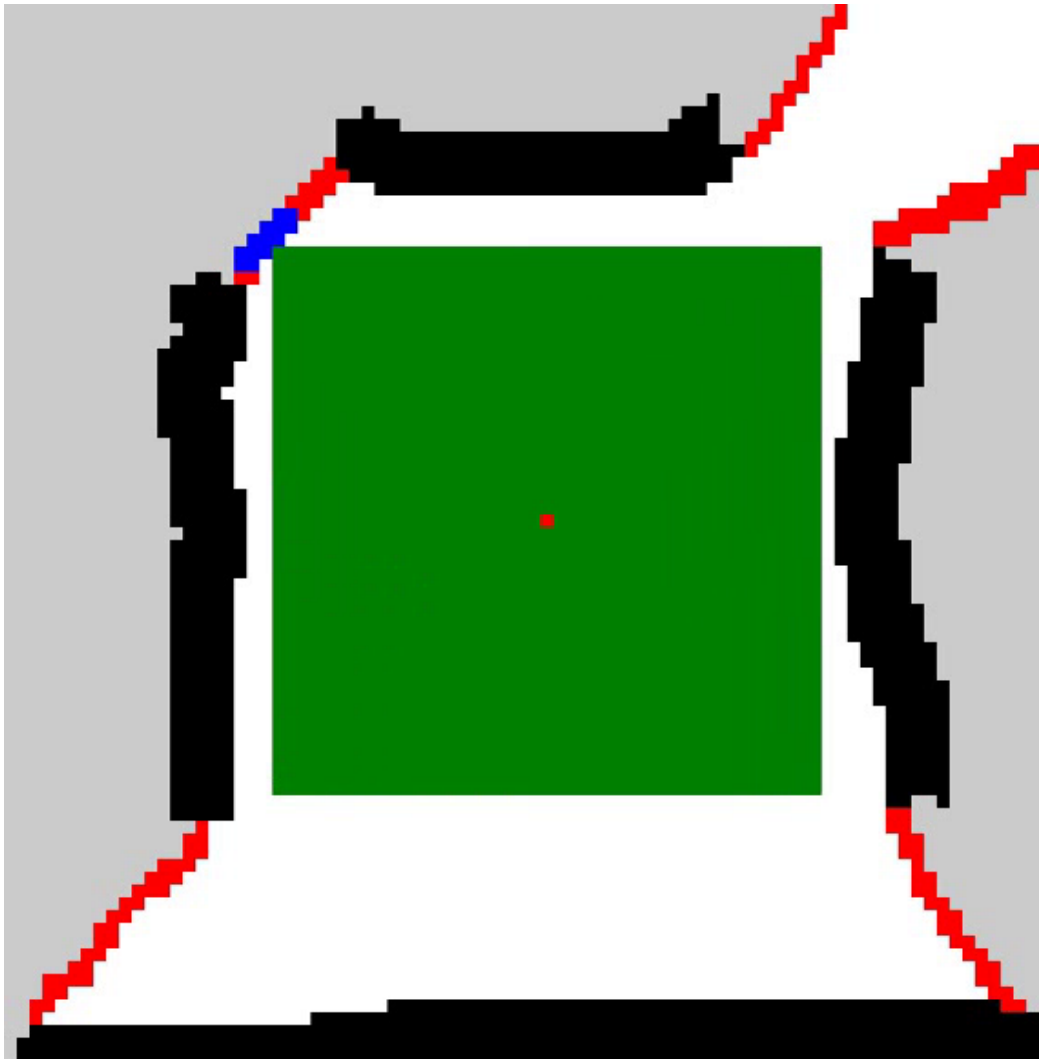
Frontier-based exploration


```
1  O = { robot position }
2  while |O| ≥ 0 do
3      pos = O.pop()          // open list for main BFS
4      mark pos as known
5      for c in neighbors(pos) do
6          if c is explored or c is obstacle then
7              continue
8          if c is frontier cell then
9              O_f = {c}   // open list for second BFS
10             while |O_f| ≥ 0 do
11                 pos_f = O.pop()
12                 mark pos_f as known
13                 for c_f in neighbors(pos_f) do
14                     if c_f is not frontier cell or c_f is known
                           then
15                         continue
16                     O_f.push(c_f)
17         else
18             O.push(c)
```



Explanation of variables

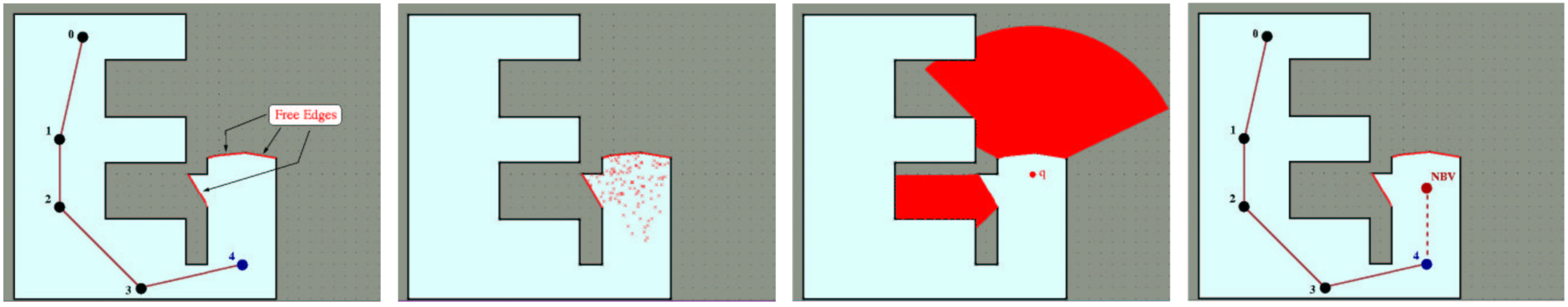
- pos, pos_f = coordinates of a cell in grid, e.g. (x, y)
- robot position = actual position of the robot in the grid
- O: open list for main BFS search — free cells
- O_f: open list for exploration of individual frontiers — frontier cells



Improved Frontier-based exploration

Several ideas to get better (faster) exploration

- Consider cost of path to the frontier for frontier selection
- Consider how much are is ‘behind’ the frontier (aka ’view’), visit the most promising frontiers first $\rightarrow$ next best view approach
- Combination of above



☛ Gonzalez-Banos, H. H.,Latombe, J. C. (2002). Navigation strategies for exploring indoor environments. The International Journal of Robotics Research, 21(10-11), 829-848.

Frontier-based exploration: resources

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