Exploration and path planning

Autonomous Robotics Labs

Labs 04

Outline

- Path planning
- OccupancyGrid
- Exploration
  - Frontier-based exploration
  - WFD
  - Frontier filtering
  - Frontier selection

Path planning – quick refresh

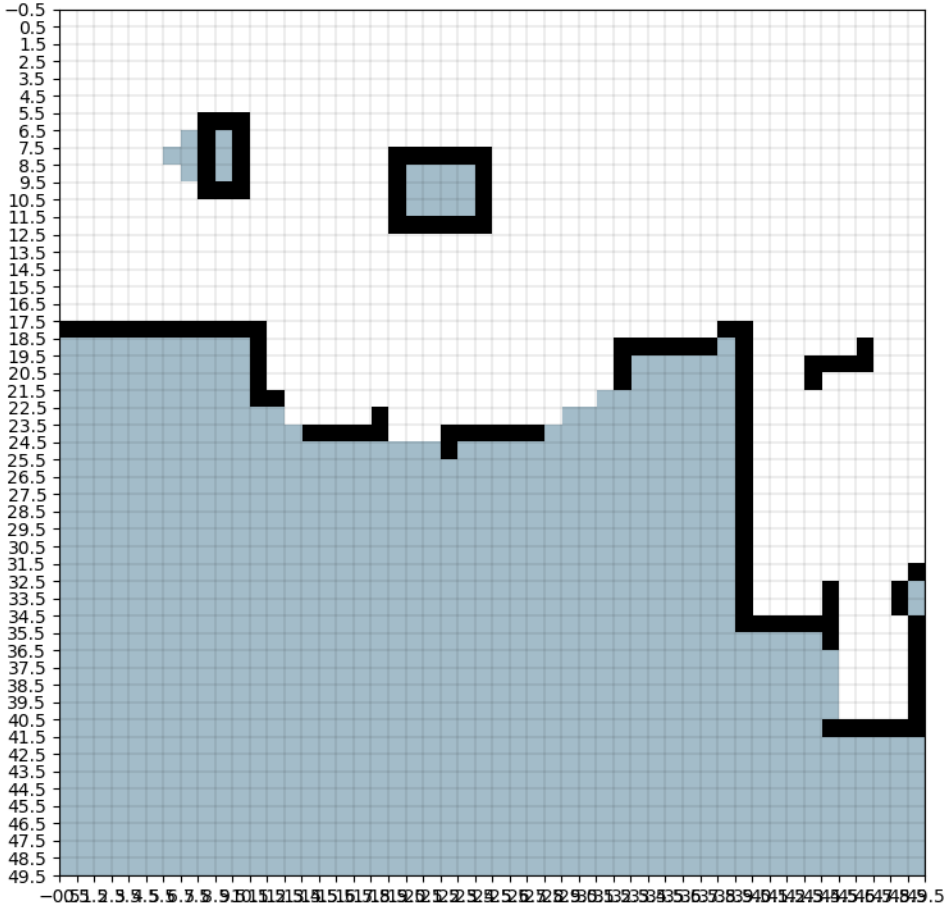
Path an ordered set of points $\sim$ locations in either joint or operational space – that the robot should follow

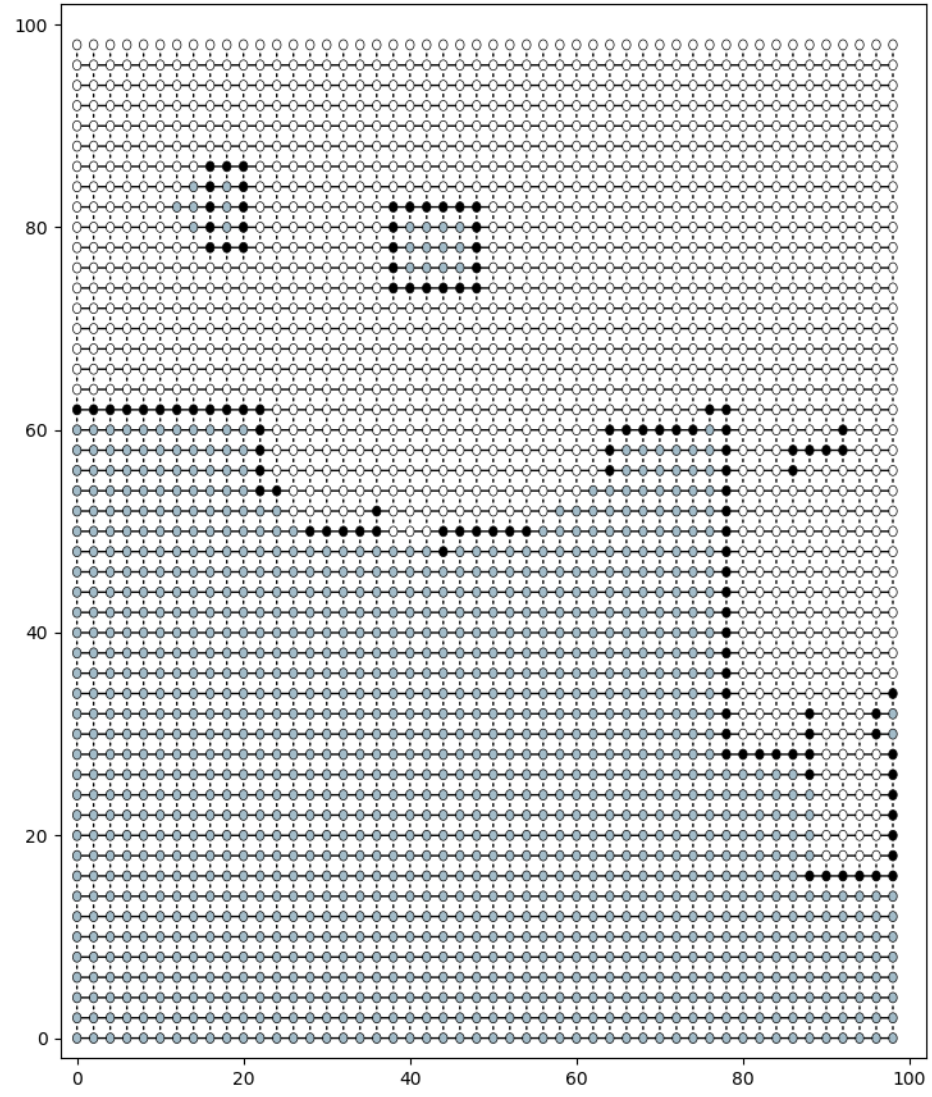
Trajectory is path plus velocities and accelerations at each point

- We will be concerned only with *path*
- Planning on a 2D grid (oocupancy grid – **nav_msgs/OccupancyGrid**)
- Graph based algorithms (other types exist)
  - Breadth-first search (BFS) – "*Grass fire*"
  - Depth-first search (DFS)
- A very simplistic explanations of some well-known algorithms:
  - Dijkstra – explore the node that has the least cost so far
  - A* – explore the node with the lowest expected distance
    - uses a heuristic to estimate the distance to target

    $$\textit{expected cost}(\textit{node}) = \textit{cost so far}\,(\textit{node}) + \textit{heuristic}\,(\textit{node})$$

  - Performance depends on the space (e.g., complexity of obstacles) and the specific task (single vs. multi-target search)
- There are many search algorithms and modifications of the most popular ones (A*, Dijkstra)




0
20
40
60
80
100

Path planning

- Note: *Even the most simplistic approach will (probably) work, the difference is execution time and overall efficiency (...memory)*
- Obstacles:
  - path planning with sufficient "safety" margin
  - easiest approach (only possible with a rigid robot or maybe holonomic):
    - inflate obstacles
    - in case of occupancy grid – morphological dilation can be used, e.g.:

```
from scipy.ndimage import morphology
inflated_grid = morphology.binary_dilation(grid)
OR
inflated_grid = morphology.grey_dilation(grid)
```

Parameters:

```
size=(n, m)   # kernel size
structure=np.ones((n, m))   # the kernel itself
iteration=1   # number of iterations
```

OccupancyGrid

`nav_msgs/OccupancyGrid`

- **data** (int8[]) the occupancy grid itself (flattened)
  - $0 ==$ empty cell
  - $1 \ldots 100 ==$ (probably) occupied cell
  - $-1 ==$ unknown (unseen) cell
- **info** (nav_msgs/MapMetaData) additional information about the grid
  - **resolution** (float23) "size" of cell in meters
  - **width** width of the grid (in cells)
  - **height** height of the grid (in cells)
  - **origin** (geometry_msgs/Pose) the relation of the origin [0, 0] of the grid to the "real world" (e.g. map *tf*)
    - **position** (Point) translation of the origin w.r.t. real world
    - **orientation** (Quaternion) rotation of the XY-axes w.r.t. real world

OccupancyGrid

- Remember:
  - robot position needs to be transformed to fit into the grid coordinates
    - translation and rotation – origin
    - scaling – resolution
  - thresholding and/or recalculation of the values of the grid might be necessary depending on the operation (e.g. dilation, probability threshold, ...)
  - make sure you know where the origin is and which is the X-direction and which is the Y-direction (might be confusing when plotting)
  - It's a good idea to optimize the code – operations on a large grid will be costly

Exploration

- Goal:
  - explore the existing world (e.g., the maze)
  - map currently unknown locations $\rightarrow$ where to focus the search?
    $\sim$ explore the "frontier"

  Frontier a cell that separates known and unknown regions, possibly hiding new parts of the "maze"

- Cells in the grid:

  Open space $p(occupied) < threshold$
  Occupied space $p(occupied) > threshold$
  Known_region $cell\ value \geq 0$
  Unknown region $cell\ value = -1$

- Frontier-based exploration (in as few words as possible):
  1. Find frontiers
  2. Select and go to a frontier
  3. Repeat until there are no more frontiers (or some other goal is reached)

Frontier-based exploration

[1] YAMAUCHI, Brian, et al. Frontier-based exploration using multiple robots. In: Agents. 1998. p. 47-53.

[2] TOPIWALA, Anirudh; INANI, Pranav; KATHPAL, Abhishek. Frontier Based Exploration for Autonomous Robot. arXiv preprint arXiv:1806.03581, 2018.

[3] USLU, Erkan, et al. Implementation of frontier-based exploration algorithm for an autonomous robot. In: 2015 International Symposium on Innovations in Intelligent SysTems and Applications (INISTA). IEEE, 2015. p. 1-7.

Slightly more indepth article & more efficient implementations:

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

Wave-front detection (WFD)

- A BFS algorithm to search for frontiers
  - **outer BFS** search for frontier points connected to the robot position
  - **inner BFS** "frontier assembly" – search for contiguous frontier points
- Definitions:

pose the robot position in the occupancy grid

Map-Open-List list of points enqueued (selected for processing) by the outer BFS

Map-Close-List list of points dequeued (already processed) by the outer BFS

Frontier-Open-List list of points enqueued by the inner BFS

Frontier-Close-list of points dequeued by the inner BFS

queue$_m$ a queue for the map points (points for the outer BFS)

queue$_f$ a queue for the frontier points (points for the inner BFS)

Wave-front detection [4]

```
queue_m ← φ
ENQUEUE(queue_m , pose)
mark pose as "Map-Open-List"

while queue_m is not empty:
        p ← DEQUEUE(queue_m)
        if p is marked as "Map-Close-List":
                continue
        if p is a frontier point:
                queue_f ← φ
                NewFrontier ← φ
                ENQUEUE(queue_f, p)
                mark p as "Frontier-Open-List"

                while queue_f is not empty:
                        q ← DEQUEUE(queue_f)
                        if q is marked as {"Map-Close-List","Frontier-Close-List"}:
                                continue
                        if q is a frontier point:
                                NewFrontier ← q
                                for all w ∈ neighbors(q):
                                        if w not marked as {"Frontier-Open-List",
                                        "Frontier-Close-List","Map-Close-List"}:
                                                ENQUEUE(queue_f, w)
                                                mark w as "Frontier-Open-List"
                        mark q as "Frontier-Close-List"
                save data of NewFrontier
                mark all points of NewFrontier as "Map-Close-List"
        for all v ∈ neighbors(p):
                if v not marked as {"Map-Open-List","Map-Close-List"}
                and v has at least one "Map-Open-Space" neighbor:
                        ENQUEUE(queue_m, v)
                        mark v as "Map-Open-List"
        mark p as "Map-Close-List"
```

Wave-front detection

```
queue_m ← φ
ENQUEUE(queue_m , pose)
mark pose as "Map-Open-List"
```

- The algorithm receives some pose (in our case the robot's pose)
- A queue (FIFO) is initialized for the outer BFS – "map queue" called queue_m
- The input pose is added to the queue and marked as Map-Open-List, i.e. as a point opened by the outer BFS for processing

Wave-front detection – outer BFS

```
while queue_m is not empty:
        p ← DEQUEUE(queue_m)
        if p is marked as "Map-Close-List":
                continue
        if p is a frontier point:
        .
        .
        .
        for all v ∈ neighbors(p):
                if v not marked as {"Map-Open-List","Map-Close-List"}
                and v has at least one "Map-Open-Space" neighbor:
                        ENQUEUE(queue_m, v)
                        mark v as "Map-Open-List"
        mark p as "Map-Close-List"
```

- This while loop implements the outer BFS
- At the beginning of each loop, the outer BFS dequeues a point from the queue_m if there is any
- If the point is marked as closed/processed by the outer BFS, it ignores it
- If the point is a frontier point, that is, if it has value of -1 and has an open space next to it, the inner BFS is started for that point (inside the `if p is a frontier point` condition, explained on the next slide)
- At the end of each loop, neighbors of the current point are added to the queue_m if the are not yet processed or enqueued for processing and have at least one open space neighbor
- Lastly, the current point is marked as processed by the outer BFS

Wave-front detection – inner BFS

```
...
if p is a frontier point:
        queue_f ← φ
        NewFrontier ← φ
        ENQUEUE(queue_f, p)
        mark p as "Frontier-Open-List"
...
```

- Once a point is identified as a frontier point, the inner BFS is initialized
- A secondary queue, called queue_f (frontier queue) is created
- New frontier (e.g. instance of a frontier class or an array) is created
- The current point from the outer BFS is added to the queue_f and marked as opened for processing by the inner BFS

Wave-front detection – inner BFS

```
...
while queue_f is not empty:
        q ← DEQUEUE(queue_f)
        if q is marked as {"Map-Close-List","Frontier-Close-List"}:
                continue
        if q is a frontier point:
                NewFrontier ← q
                for all w ∈ neighbors(q):
                        if w not marked as {"Frontier-Open-List",
                        "Frontier-Close-List","Map-Close-List"}:
                                ENQUEUE(queue_f, w)
                                mark w as "Frontier-Open-List"
        mark q as "Frontier-Close-List"
save data of NewFrontier
mark all points of NewFrontier as "Map-Close-List"
...
```

- This while loop implements the inner BFS
- While there are points in the $queue_f$ they are dequeued and processed
- If the where already processed either by the outer or inner BFS, they are ignored
- If the point is a frontier point, the point is added to the NewFrontier and its neighbors are added to the $queue_f$ if they are not marked as processed or already enqueued in the $queue_f$
- The current point is marked as processed
- At the end of the inner BFS while loop, the NewFrontier is saved and it's points are marked as processed by the outer BFS (so these frontier points are not picked up again by the outer BFS)

Frontier filtering

- Make sure the frontier is reachable
  - test path planning
  - run WFD on grid with inflated obstacles
    - remember connectivity
    - keep occupancy information (-1/0/>0)
- Discard useless frontiers
  - too small
  - possibly does not conceal explorable areas

Frontier selection

- Simple approach:
  Random frontier
- Better approach:
  Closest frontier
  - direct distance (Euclidean, Manhattan)
  - path distance – costly but more accurate & includes reachability test

  Most promising frontier
  - e.g., expected distance to a goal

Thank you for your attention