

Multi-goal Planning

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Lecture 05

Robotic Exploration and Data Collection Planning



Overview of the Lecture

- Part 1 – Multi-goal Planning
 - Inspection Planning
 - Multi-goal Planning
- Part 2 – Unsupervised Learning for Multi-goal Planning
 - Unsupervised Learning for Multi-goal Planning
 - TSPN in Multi-goal Planning with Localization Uncertainty



Part I

Part 1 – Multi-goal Planning



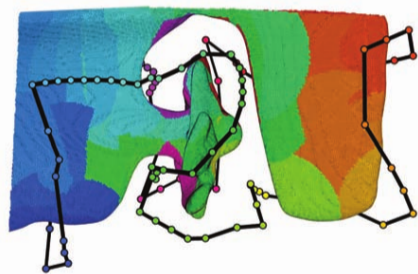
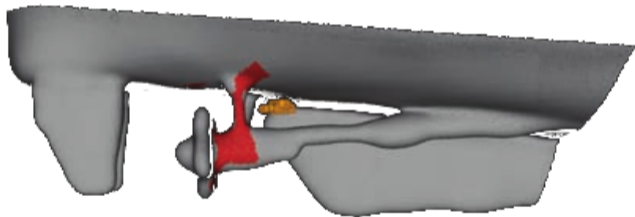
Outline

- Inspection Planning
- Multi-goal Planning



Robotic Information Gathering in Inspection of Vessel's Propeller

- The planning problem is to determine a shortest inspection path for an Autonomous Underwater Vehicle (AUV) to inspect the vessel's propeller.



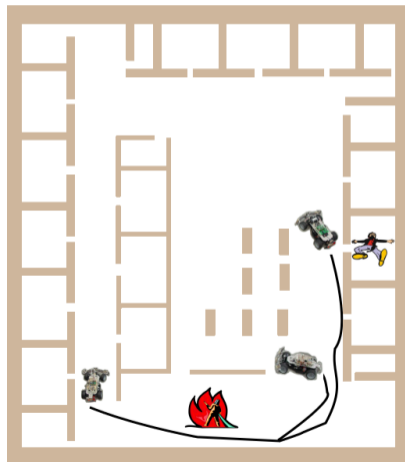
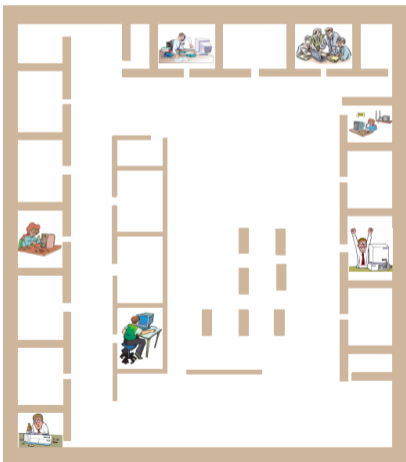
https://www.youtube.com/watch?v=8azP_9VnMtM

Englot, B., Hover, F.S.: *Three-dimensional coverage planning for an underwater inspection robot*, International Journal of Robotics Research, 32(9–10):1048–1073, 2013.



Example of Inspection Planning in Search Scenario

- Periodically visit particular locations of the environment and return to the starting locations.
- Use [available floor plans](#) to guide the search, e.g., finding victims in search-and-rescue scenario.

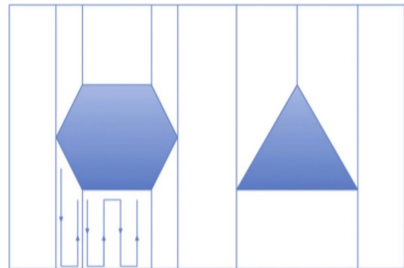
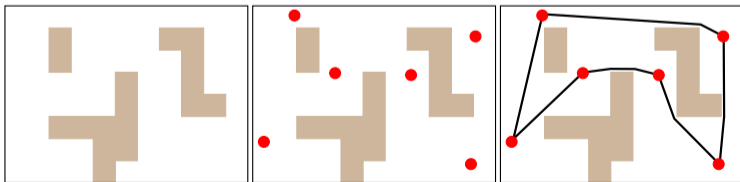


Inspection Planning

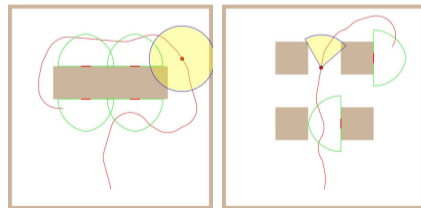
- **Inspection/coverage planning** stands to determine a plan (path) to inspect/cover the given areas or point of interest.
- We can directly find inspection/coverage plan using
 - predefined covering patterns such as *ox-plow* motion;
 - a “general” path satisfying coverage constraints.

Galceran, E., Carreras, M.: *A survey on coverage path planning for robotics*, *Robotics and Autonomous Systems*, 61(12):1258–1276, 2013.

- **Decoupled** approach – Locations to be visited are determined before path planning as the **sensor placement** problem.



Trapezoidal decomposition method

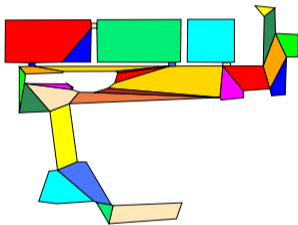


Kafka, Faigl, Vána: ICRA 2016

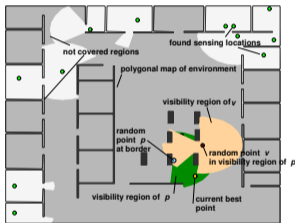
Inspection Planning – Decoupled Approach

1. Determine sensing locations such that the whole environment would be inspected (seen) by visiting them. It is **Sampling design problem**.

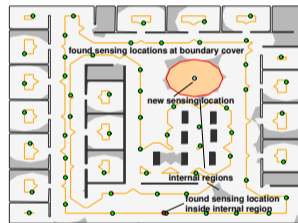
*In the geometrical-based approach, a solution of the **Art Gallery Problem**.*



Convex Partitioning
(Kazazakis and Argyros, 2002)



Randomized Dual Sampling
(González-Baños et al., 1998)



Boundary Placement
(Faigl et al., 2006)

*The problem is related to the **sensor placement** and **sampling design**.*

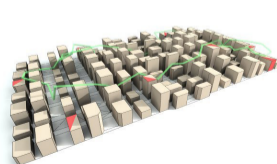
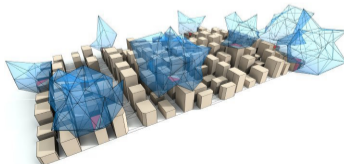
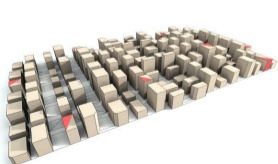
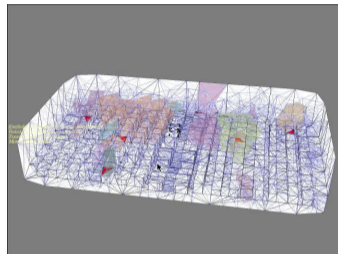
2. Create a roadmap connecting the sensing location.
3. Find the inspection path visiting all the sensing locations as a solution of the multi-goal path planning (a solution of the robotic TSP).

Such as visibility graph or randomized sampling-based method.



Planning to Capture Areas of Interest using UAV

- Determine a cost-efficient path from which a given set of target regions is covered.
- For each target region a subspace $S \subset \mathbb{R}^3$ from which the target can be covered is determined. *S represents the neighborhood.*
- **We search for the best sequence of visits to the regions.**
Combinatorial optimization
- The PRM is utilized to construct the planning roadmap (a graph).
PRM – Probabilistic Roadmap Method – sampling-based motion planner, see lecture 8.
- The problem can be formulated as **the Traveling Salesman Problem with Neighborhoods**, as it is not necessary to visit exactly a single location to capture the area of interest.



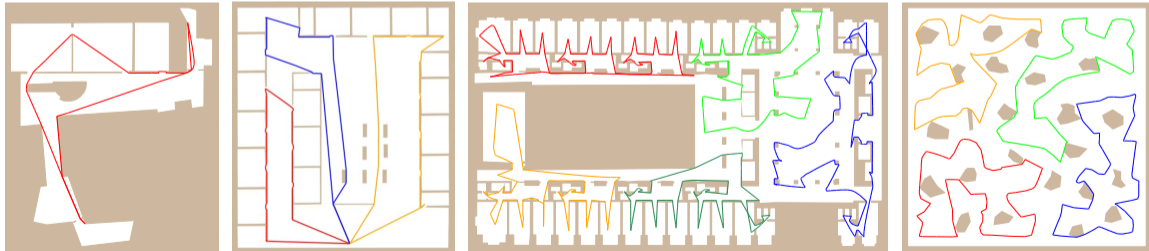
Janoušek and Faigl, ICRA 2013



Inspection Planning – “Continuous Sensing”

- If we do not prescribe a discrete set of sensing locations, we can formulate the problem as the **Watchman route problem**.

Given a map of the environment \mathcal{W} determine the shortest, closed, and collision-free path, from which the whole environment is covered by an omnidirectional sensor with the radius ρ .



Faigl, J.: *Approximate Solution of the Multiple Watchman Routes Problem with Restricted Visibility Range*, IEEE Transactions on Neural Networks, 21(10):1668-1679, 2010.



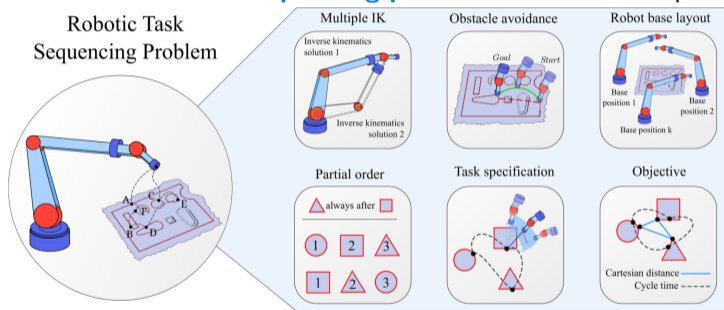
Outline

- Inspection Planning
- Multi-goal Planning



Multi-Goal Planning

- Having a **set of locations** to be visited, determine the cost-efficient path to visit them.
 - Locations where a robotic arm or mobile robot performs some task. *The operation can be repeated—closed path.*
- The problem is called **robotic task sequencing problem** for robotic manipulators.



Alatartsev, S., Stellmacher, S., Ortmeier, F. (2015): **Robotic Task Sequencing Problem: A Survey**. Journal of Intelligent & Robotic Systems.

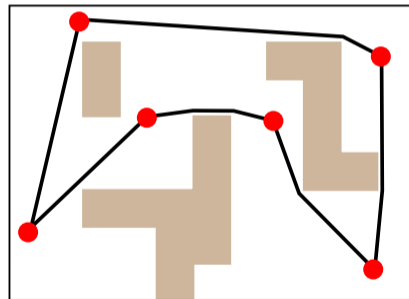
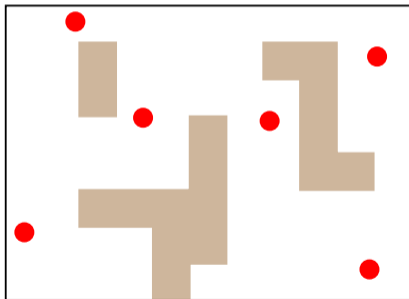
- The problem is also called **Multi-goal Path Planning** (MTP) problem or **Multi-goal Planning** (**MGP**).

Also studied in its Multi-goal Motion Planning (MGMP) variant.



Multi-Goal Path Planning (MTP)

- Multi-goal planning problem is a problem how to visit the given set of locations.
- It consists of **point-to-point path planning** on how to reach one location from another.
- The *challenge* is to determine the optimal sequence of the visits to the locations w.r.t. cost-efficient path to visit all the given locations.



- Determination the sequence of visits is a **combinatorial optimization problem** that can be formulated as the **Traveling Salesman Problem (TSP)**.



Traveling Salesman Problem (TSP)

Given a set of cities and the distances between each pair of cities, what is the shortest possible route that visits each city exactly once and returns to the origin city.

- The TSP can be formulated for a graph $\mathbf{G}(V, E)$, where V denotes a set of locations (cities) and E represents edges connecting two cities with the associated travel cost c (distance), i.e., for each $v_i, v_j \in V$ there is an edge $e_{ij} \in E$, $e_{ij} = (v_i, v_j)$ with the cost c_{ij} .
- If the associated cost of the edge (v_i, v_j) is the Euclidean distance $c_{ij} = |(v_i, v_j)|$, the problem is called the **Euclidean TSP** (ETSP).
- It is known, the TSP is NP-hard (its decision variant) and several algorithms can be found in literature.

William J. Cook (2012) – In Pursuit of the Traveling Salesman: Mathematics at the Limits of Computation.



Traveling Salesman Problem (TSP)

- Let S be a set of n sensor locations $S = \{\mathbf{s}_1, \dots, \mathbf{s}_n\}$, $\mathbf{s}_i \in \mathbb{R}^2$ and $c(\mathbf{s}_i, \mathbf{s}_j)$ is a cost of travel from \mathbf{s}_i to \mathbf{s}_j
- Traveling Salesman Problem (TSP)** is a problem to determine a closed tour visiting each $\mathbf{s} \in S$ such that the total tour length is minimal.
 - We are searching for the optimal **sequence of visits** $\Sigma = (\sigma_1, \dots, \sigma_n)$ such that

$$\begin{aligned} \text{minimize } \Sigma \quad & L = \left(\sum_{i=1}^{n-1} c(\mathbf{s}_{\sigma_i}, \mathbf{s}_{\sigma_{i+1}}) \right) + c(\mathbf{s}_{\sigma_n}, \mathbf{s}_{\sigma_1}) \\ \text{subject to} \quad & \Sigma = (\sigma_1, \dots, \sigma_n), 1 \leq \sigma_i \leq n, \sigma_i \neq \sigma_j \text{ for } i \neq j. \end{aligned} \quad (1)$$

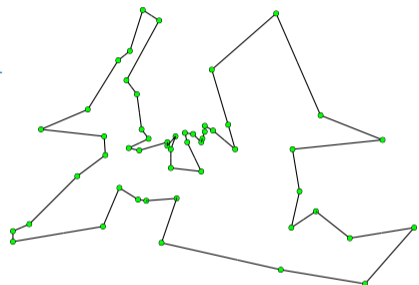
- The TSP can be considered on a graph $G(V, E)$ where the set of vertices V represents sensor locations S and E are edges connecting the nodes with the cost $c(\mathbf{s}_i, \mathbf{s}_j)$.
- For simplicity we can consider $c(\mathbf{s}_i, \mathbf{s}_j)$ to be Euclidean distance; otherwise, we also need to address the path/motion planning problem. **Euclidean TSP**
- If $c(\mathbf{s}_i, \mathbf{s}_j) \neq c(\mathbf{s}_j, \mathbf{s}_i)$ it is the **Asymmetric TSP**.
- The TSP is known to be NP-hard unless P=NP.

Traveling vs Travelling – <http://www.math.uwaterloo.ca/tsp/history/travelling.html>



Existing Approaches to the TSP

- Exact solutions
 - Branch&Bound, Branch&Cut, and Integer Linear Programming (ILP).
 Concorde-<http://www.math.uwaterloo.ca/tsp/concorde.html>
- Approximation algorithms
 - Minimum Spanning Tree (MST) heuristic with $L \leq 2L_{opt}$.
 - Christofides's algorithm with $L \leq \frac{3/2}{L_{opt}}$.
- Heuristic algorithms
 - Constructive heuristic – Nearest Neighborhood (NN) algorithm;
 - 2-Opt – local search algorithm proposed by Croes 1958;
 - LKH – K. Helsgaun efficient implementation of the Lin-Kernighan heuristic (1998). <http://www.akira.ruc.dk/~keld/research/LKH/>
- Combinatorial meta-heuristics
 - Variable Neighborhood Search (VNS);
 - Greedy Randomized Adaptive Search Procedure (GRASP).
- Soft-computing techniques, evolutionary methods, and unsupervised learning.

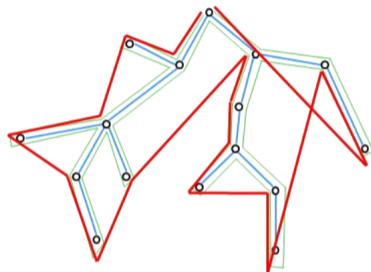


Problem Berlin52 from the TSPLIB



MST-based Approximation Algorithm to the TSP

- Minimum Spanning Tree heuristic
 1. Compute the MST (denoted T) of the input graph G .
 2. Construct a graph H by doubling every edge of T .
 3. Shortcut repeated occurrences of a vertex in the tour.



- For the triangle inequality, the length of such a tour L is

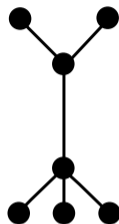
$$L \leq 2L_{optimal},$$

where $L_{optimal}$ is the cost of the optimal solution of the TSP.

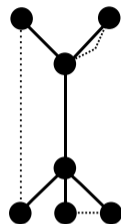


Christofides's Algorithm to the TSP

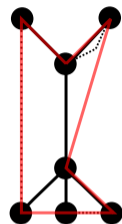
- Christofides's algorithm
 1. Compute the MST of the input graph G .
 2. Compute the minimal matching on the odd-degree vertices.
 3. Shortcut a traversal of the resulting Eulerian graph.



MST



Matching



Final tour

- For the triangle inequality, the length of such a tour L is

$$L \leq \frac{3}{2} L_{\text{optimal}},$$

where L_{optimal} is the cost of the optimal solution of the TSP.

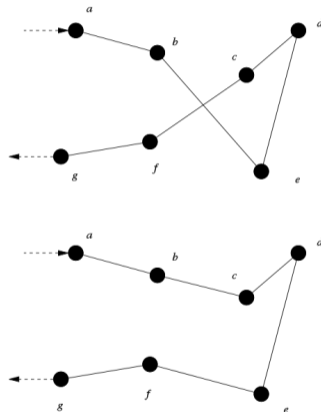
Length of the MST is $\leq L_{\text{optimal}}$

Sum of lengths of the edges in the matching $\leq \frac{1}{2} L_{\text{optimal}}$



2-Opt Heuristic

1. Use a construction heuristic to create an initial route
 - NN algorithm, cheapest insertion, farther insertion
2. Repeat until no improvement is made
 - 2.1 Determine swapping that can shorten the tour (i, j) for $1 \leq i \leq n$ and $i + 1 \leq j \leq n$
 - route[0] to route[i-1];
 - route[i] to route[j] in reverse order;
 - route[j] to route[end];
 - Determine length of the route;
 - Update the current route if the length is shorter than the existing solution.



Croes, G.A.: *A method for solving traveling salesman problems*, Operations Research 6:791–812, 1958.



Overview of the Variable Neighborhood Search (VNS) for the TSP

- **Variable Neighborhood Search (VNS)** is a metaheuristic for solving combinatorial optimization and global optimization problems by searching distant neighborhoods of the current **incumbent solution** using **shake** and **local search**.

Mladenović and Hansen, 1997

1. **Shake** procedure explores the neighborhood of the current solution to escape from a local minima using operators:

- **Insert** – moves one element;
- **Exchange** – exchanges two elements.

2. **Local search** procedure improves the solution by

- **Path insert** – moves a subsequence;
- **Path exchange** – exchanges two subsequences.

Algorithm 1: VNS-based Solver to the TSP

Input: S – Set of the target locations to be visited.

Output: Σ – Found sequence of visits to locations S .

```

 $\Sigma^* \leftarrow$  Initial sequence found by cheapest insertion
while terminal condition is not met do
   $\Sigma' \leftarrow$  shake( $\Sigma^*$ )
  for  $n^2$ -times do
     $\Sigma'' \leftarrow$  localSearch( $\Sigma'$ )
    if  $\Sigma''$  is "better" than  $\Sigma'$  then
       $\Sigma' \leftarrow \Sigma''$  // Select  $\Sigma''$  instead of  $\Sigma'$ 
    if  $\Sigma'$  is "better" than  $\Sigma^*$  then
       $\Sigma^* \leftarrow \Sigma'$  // Replace the incumbent sequence.
return  $\Sigma^*$ 
  
```

Insert



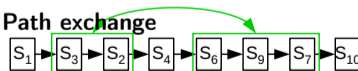
Exchange



Path insert



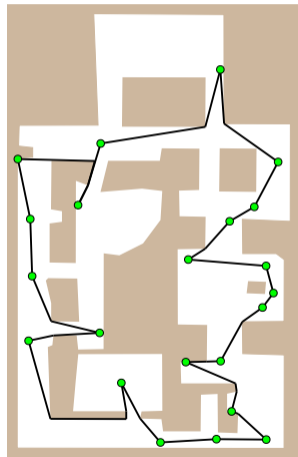
Path exchange



Multi-Goal Path Planning (MTP) Problem

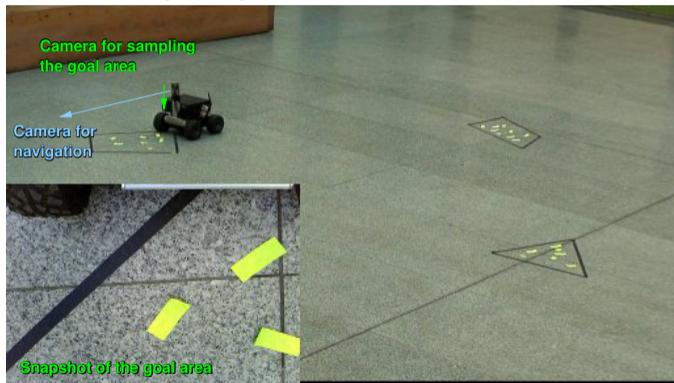
- **MTP problem** is a **robotic variant of the TSP** with the edge costs as the length of the *shortest* path connecting the locations.
- Variants of the **robotic TSP** includes additional constraints arising from limitations of real robotic systems such as
 - obstacles, curvature-constraints, sensing range, location precision.
- For n locations, we need to compute up to n^2 shortest paths.
- Having a **roadmap** (graph) representing \mathcal{C}_{free} , the paths can be found in the graph (roadmap), from which the $G(V, E)$ for the TSP can be constructed.
Visibility graph as a roadmap for a point robot provides a straightforward solution, but such a shortest path may not be necessarily feasible for more complex robots.
- We can determine the roadmap using randomized sampling-based motion planning techniques.

See optional lecture 8.



Multi-goal Path Planning with Goal Regions

- It may be sufficient to visit a goal region instead of the particular point location.



Not only a **sequence** of goals visit has to be determined, but also an **appropriate location** at each region has to be found.

The problem with goal regions can be considered as a variant of the **Traveling Salesman Problem with Neighborhoods (TSPN)**.



Traveling Salesman Problem with Neighborhoods

Given a set of n regions (neighbourhoods), what is the shortest closed path that visits each region.

- The problem is NP-hard and APX-hard, it cannot be approximated to within factor $2 - \epsilon$, where $\epsilon > 0$.
Safra and Schwartz (2006) – Computational Complexity
- Approximate algorithms exist for particular problem variants such as disjoint unit disk neighborhoods.
- **TSPN provides a suitable problem formulation for planning various inspection and data collection missions.**
- It enables to exploit non-zero sensing range, and thus find shortest (more cost-efficient) **data collection plans.**

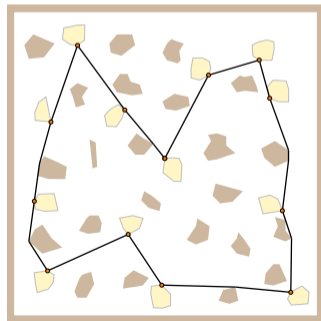


Traveling Salesman Problem with Neighborhoods (TSPN)

- Instead visiting a particular location $\mathbf{s} \in S$, $\mathbf{s} \in \mathbb{R}^2$ as in the TSP, we request to visit a set of regions $R = \{r_1, \dots, r_n\}$, $r_i \subset \mathbb{R}^2$ to save travel cost.
- The TSP becomes the **TSP with Neighborhoods (TSPN)** where, in addition to the determination of the **sequence** Σ , we determine a suitable locations of visits $P = \{\mathbf{p}_1, \dots, \mathbf{p}_n\}$, $\mathbf{p}_i \in r_i$.
- The problem is a combination of combinatorial optimization to determine Σ with **continuous optimization** to determine P .

$$\text{minimize}_{\Sigma, P} \quad L = \left(\sum_{i=1}^{n-1} c(\mathbf{p}_{\sigma_i}, \mathbf{p}_{\sigma_{i+1}}) \right) + c(\mathbf{p}_{\sigma_n}, \mathbf{p}_{\sigma_1})$$

$$\text{subject to} \quad \begin{aligned} R &= \{r_1, \dots, r_n\}, r_i \subset \mathbb{R}^2 \\ P &= \{\mathbf{p}_1, \dots, \mathbf{p}_n\}, \mathbf{p}_i \in r_i \\ \Sigma &= (\sigma_1, \dots, \sigma_n), 1 \leq \sigma_i \leq n, \\ &\sigma_i \neq \sigma_j \text{ for } i \neq j \\ &\text{Foreach } r_i \in R \text{ there is } \mathbf{p}_i \in r_i. \end{aligned}$$



Approaches to the TSPN

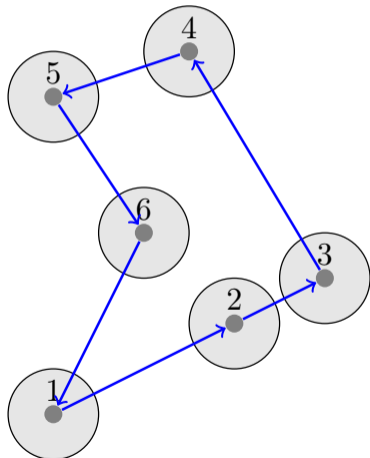
- A direct solution of the TSPN – approximation algorithms and heuristics
 - E.g., using evolutionary techniques or [unsupervised learning](#)
- Euclidean TSPN with, disk-shaped δ neighborhoods is called **Closed Enough TSP (CETSP)**.
 - Simplified variant with regions as disks with radius δ – remote sensing with the δ communication range.
- **Decoupled approach**
 1. Determine sequence of visits Σ independently on the locations P , e.g., as a solution of the TSP using centroids of the (convex) regions R .
 2. For the sequence Σ determine the locations P to minimize the total tour length using
 - Touring polygon problem (TPP);
 - Sampling possible locations and use a forward search for finding the best locations;
 - Continuous optimization such as hill-climbing.

E.g., [Local Iterative Optimization](#) (LIO), Váňa & Faigl (IROS 2015)
- **Sampling-based** approaches
 - For each region, sample possible locations of visits into a discrete set of locations for each region.
 - The problem can be then formulated as the **Generalized Traveling Salesman Problem (GTSP)**.

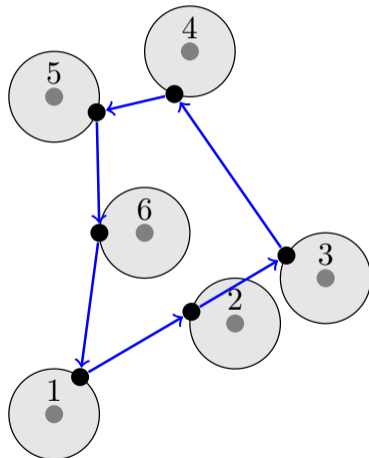


Close Enough Traveling Salesman Problem (CETSP)

- **Close Enough TSP (CETSP)** is a variant of the TSPN with disk shaped δ -neighborhoods.



A solution of the TSP for the centers of the disks



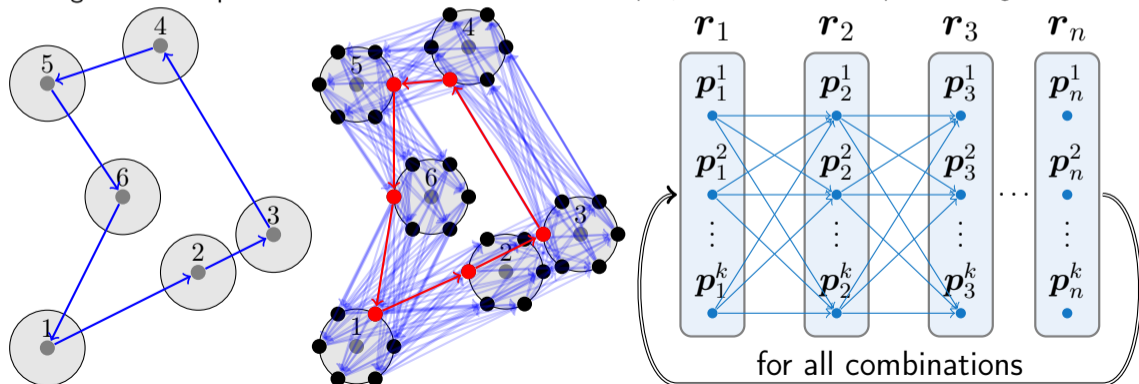
A solution of the CETSP



Decoupled Sampling-based Solution of the TSPN / CETSP

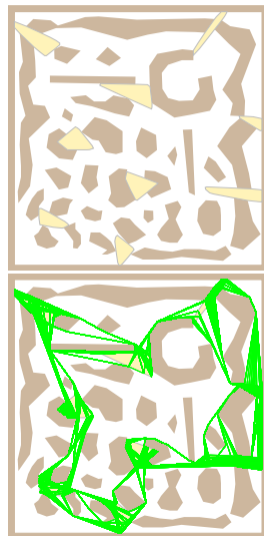
- **Decoupled** – Determine sequence of visits as a solution of the Euclidean TSP for the representatives of the regions R , e.g., using centroids.
- Sample each region (neighborhood) with k samples, e.g., $k = 6$.
- Construct graph and find the shortest tour in by graph search in $\mathcal{O}(nk^3)$ for n regions and nk^2 edges in the sequence.

For the closed path, we need to examine all k possible starting locations.



Iterative Refinement in the Multi-goal Planning Problem with Regions

- Let the sequence of n polygon regions be $R = (r_1, \dots, r_n)$.
 - Li, F., Klette, R.: Approximate algorithms for touring a sequence of polygons. 2008
- 1. Sampling regions into a discrete set of points and determine all shortest paths between each sampled points in the sequence of visits to the regions.
 - E.g., using visibility graph*
- 2. *Initialization:* Construct an initial touring polygons path using a sampled point of each region. Let the path be defined by $P = (\mathbf{p}_1, \mathbf{p}_2, \dots, \mathbf{p}_n)$, where $\mathbf{p}_i \in r_i$ and $L(P)$ be the length of the shortest path induced by P .
- 3. *Refinement:* **For** $i = 1, 2, \dots, n$:
 - Find $\mathbf{p}_i^* \in r_i$ minimizing the length of the path $d(\mathbf{p}_{i-1}, \mathbf{p}_i^*) + d(\mathbf{p}_i^*, \mathbf{p}_{i+1})$, where $d(\mathbf{p}_k, \mathbf{p}_l)$ is the path length from \mathbf{p}_k to \mathbf{p}_l , $\mathbf{p}_0 = \mathbf{p}_n$, and $\mathbf{p}_{n+1} = \mathbf{p}_1$.
 - If the total length of the current path over point \mathbf{p}_i^* is shorter than over \mathbf{p}_i , replace the point \mathbf{p}_i by \mathbf{p}_i^* .
- 4. Compute the path length L_{new} using the refined points.
- 5. *Termination condition:* If $L_{new} - L < \epsilon$ Stop the refinement. Otherwise $L \leftarrow L_{new}$ and go to Step 3.
- 6. *Final path construction:* Use the last points and construct the path using the shortest paths among obstacles between two consecutive points.
 - On-line sampling during the iterations – [Local Iterative Optimization \(LIO\)](#), Vána & Faigl (IROS 2015).



Part II

Part 2 – Unsupervised Learning for Multi-goal Planning



Outline

- Unsupervised Learning for Multi-goal Planning
- TSPN in Multi-goal Planning with Localization Uncertainty



Unsupervised Learning based Solution of the TSP

- Iterative learning procedure where neurons (nodes) adapt to the target locations.

- Based on self-organizing map by T. Kohonen.

Somhom, S., Modares, A., Enkawa, T. (1999)

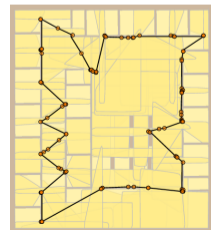
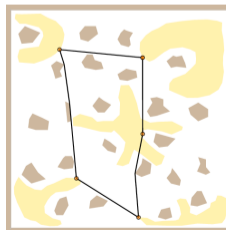
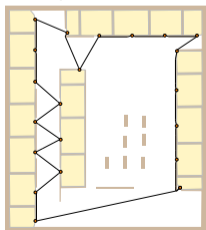
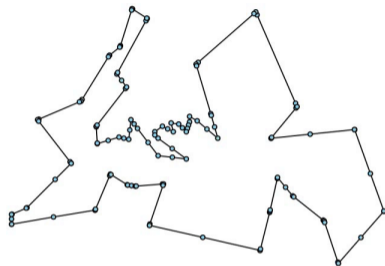
- Deployed in robotic problems such as inspection and search-and-rescue planning.

Faigl, J. et al. (2011)

- Generalized to polygonal domain with (overlapping) regions.

- Evolved to **Growing Self-Organizing Array (GSOA)**.

A general heuristic for various routing problems with neighborhoods; including routing problems with profit aka the orienteering problem.



Unsupervised Learning based Solution of the TSP

Kohonen's type of **unsupervised** two-layered neural network (**Self-Organizing Map**)

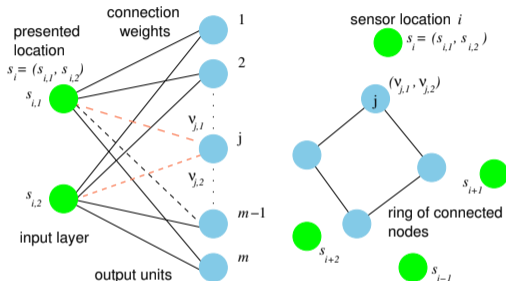
- Neurons' **weights** represent **nodes** $\mathcal{N} = \{\nu_1, \dots, \nu_m\}$ in a **plane** (input space \mathbb{R}^2).
- Nodes are organized into a **ring** that evolved in the output space \mathbb{R}^2).
- Target locations $\mathbf{S} = \{s_1, \dots, s_n\}$ are presented to the network in a **random** order.
- Nodes **compete** to be winner according to their distance to the presented goal \mathbf{s}

$$\nu^* = \operatorname{argmin}_{\nu \in \mathcal{N}} |\mathcal{D}(\{\nu, \mathbf{s}\})|.$$

- The **winner** and its **neighbouring** nodes are adapted (**moved**) towards the target according to the neighbouring function $\nu' \leftarrow \mu f(\sigma, d)(\nu - \mathbf{s})$

$$f(\sigma, d) = \begin{cases} e^{-\frac{d^2}{\sigma^2}} & \text{for } d < m/n_f, \\ 0 & \text{otherwise,} \end{cases}$$

- Best matching unit ν to the presented prototype \mathbf{s} is determined according to the distance function $|\mathcal{D}(\nu, \mathbf{s})|$.



- For the Euclidean TSP, \mathcal{D} is the Euclidean distance
- However, for problems with obstacles, the multi-goal path planning, \mathcal{D} should correspond to the length of the shortest, collision-free path.

Fort, J.C. (1988), Angéniol, B. et al. (1988), Somhom, S. et al. (1997), and further improvements.



Unsupervised Learning based Solution of the TSP - Detail

- Target (sensor) locations $S = \{\mathbf{s}_1, \dots, \mathbf{s}_n\}$, $\mathbf{s}_i \in \mathbb{R}^2$; Neurons $\mathcal{N} = (\nu_1, \dots, \nu_m)$, $\nu_i \in \mathbb{R}^2$, $m = 2.5n$.
- Learning gain σ ; epoch counter i ; gain decreasing rate $\alpha = 0.1$; learning rate $\mu = 0.6$.

- $\mathcal{N} \leftarrow$ init ring of neurons as a small ring around some $\mathbf{s}_i \in S$, e.g., a circle with radius 0.5.
- $i \leftarrow 0$; $\sigma \leftarrow 12.41n + 0.06$;
- $I \leftarrow \emptyset$ // clear inhibited neurons

- foreach** $\mathbf{s} \in \Pi(S)$ (a permutation of S)

- $\nu^* \leftarrow \operatorname{argmin}_{\nu \in \mathcal{N} \setminus I} \|\nu, \mathbf{s}\|$

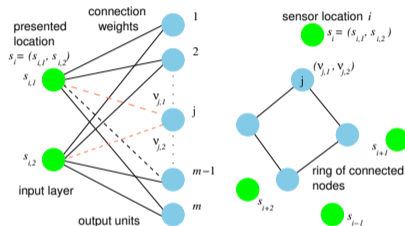
- foreach** ν in d neighborhood of ν^*

$$\nu \leftarrow \nu + \mu f(\sigma, d)(\mathbf{s} - \nu)$$

$$f(\sigma, d) = \begin{cases} e^{-\frac{d^2}{\sigma^2}} & \text{for } d < 0.2m, \\ 0 & \text{otherwise,} \end{cases}$$

- $I \leftarrow I \cup \{\nu^*\}$ // inhibit the winner

- $\sigma \leftarrow (1 - \alpha)\sigma$; $i \leftarrow i + 1$;
- If (**termination condition** is not satisfied) Goto Step 3; Otherwise retrieve solution.



Termination condition can be

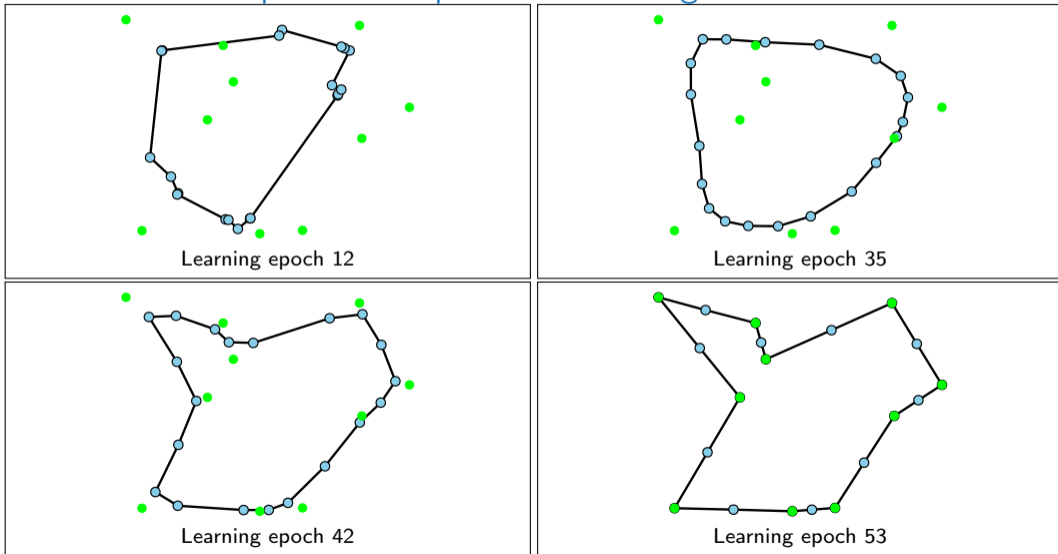
- Maximal number of learning epochs $i \leq i_{max}$, e.g., $i_{max} = 120$.
- Winner neurons are negligibly close to sensor locations, e.g., less than 0.001.

Somhom, S., Modares, A., Enkawa, T. (1999): [Competition-based neural network for the multiple travelling salesman problem with minmax objective](#). Computers & Operations Research.

Faigl, J. et al. (2011): [An application of the self-organizing map in the non-Euclidean Traveling Salesman Problem](#). Neurocomputing.



Example of Unsupervised Learning for the TSP



Unsupervised Learning for the Multi-Goal Path Planning

- Unsupervised learning procedure for the Multi-goal Path Planning (**MTP**) problem a robotic variant of the Traveling Salesman Problem (TSP).

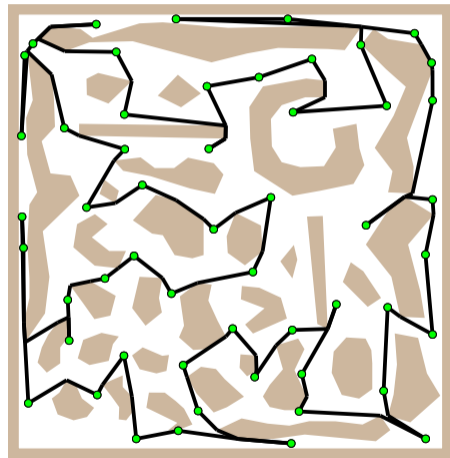
Algorithm 2: SOM-based MTP solver

```

 $\mathcal{N} \leftarrow \text{initialization}(\nu_1, \dots, \nu_m);$ 
repeat
   $error \leftarrow 0;$ 
  foreach  $g \in \Pi(\mathcal{S})$  do
     $\nu^* \leftarrow$ 
      selectWinner  $\text{argmin}_{\nu \in \mathcal{N}} |S(g, \nu)|;$ 
      adapt  $(S(g, \nu), \mu f(\sigma, l) |S(g, \nu)|);$ 
       $error \leftarrow \max\{error, |S(g, \nu^*)|\};$ 
   $\sigma \leftarrow (1 - \alpha)\sigma;$ 
until  $error \leq \delta;$ 

```

- For multi-goal path planning – the **selectWinner** and **adapt** procedures are based on the solution of the **path planning problem**.

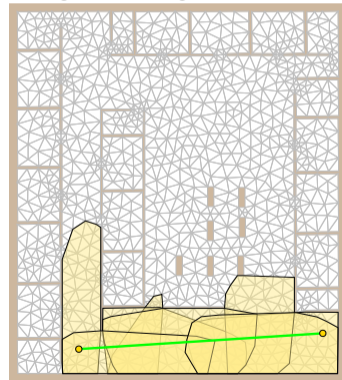
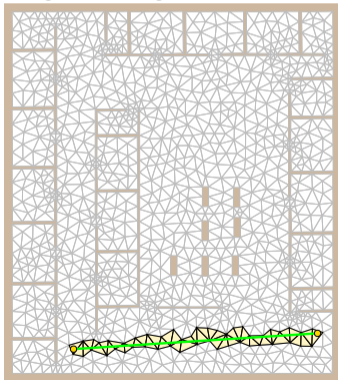
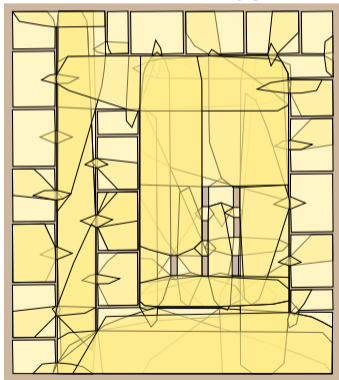


Faigl, J., Kulich, M., Vonásek, V., Přečil, L.: *An Application of Self-Organizing Map in the non-Euclidean Traveling Salesman Problem*, *Neurocomputing*, 74(5):671-679, 2011.

SOM for the TSP in the Watchman Route Problem – *Inspection Planning*

During the unsupervised learning, we can compute *coverage* of \mathcal{W} from the current *ring* (solution represented by the neurons) and *adapt* the network *towards uncovered parts* of \mathcal{W} .

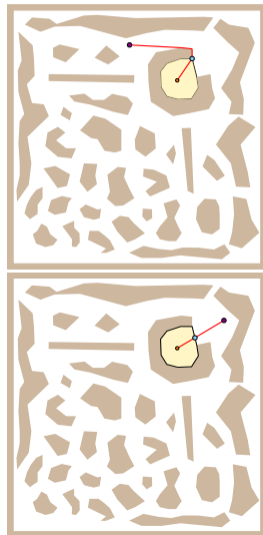
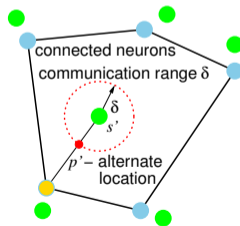
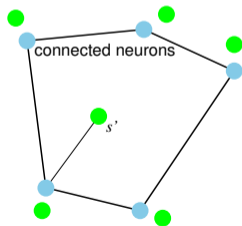
- Convex cover set of \mathcal{W} created on top of a triangular mesh.
- Incident convex polygons with a straight line segment are found by walking in a triangular mesh.



Faigl, J.: *Approximate solution of the multiple watchman routes problem with restricted visibility range*, IEEE Transactions on Neural Networks, 21(10):1668-1679, 2010.

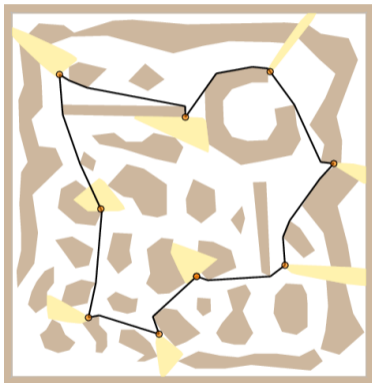
Unsupervised Learning for the TSPN

- A suitable location of the region can be sampled during the winner selection.
- We can use the centroid of the region for the shortest path computation from ν to the region r presented to the network.
- Then, an intersection point of the path with the region can be used as an alternate location.
 - Faigl, J. et al. (2013): [Visiting convex regions in a polygonal map](#). Robotics and Autonomous Systems.
- For the Euclidean TSPN with disk-shaped δ neighborhoods, we can compute the alternate location directly from the Euclidean distance.

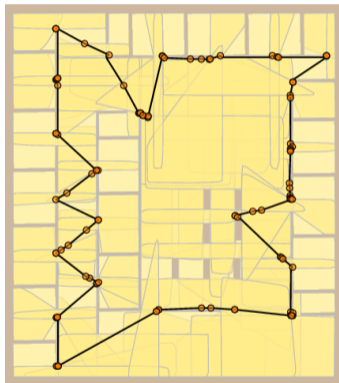


SOM for the Traveling Salesman Problem with Neighborhoods (TSPN)

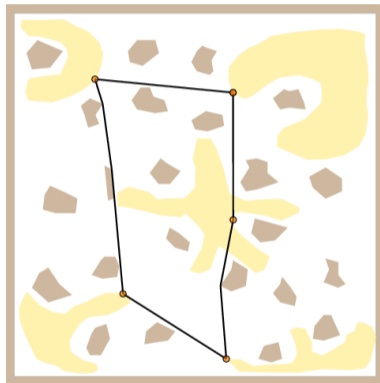
- Unsupervised learning of the SOM for the TSP allows to generalize the adaptation procedure to the TSPN.
- It also provides solutions for non-convex regions, overlapping regions, and coverage problems.



Polygonal Goals
 $n=9$, $T=0.32$ s



Convex Cover Set
 $n=106$, $T=5.1$ s



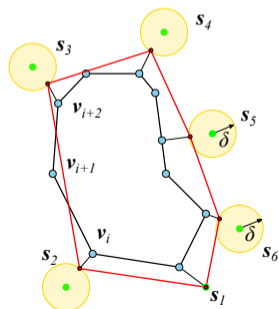
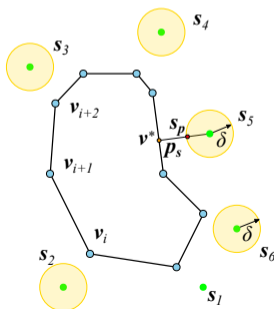
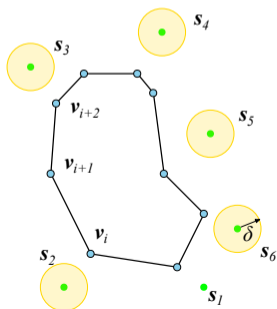
Non-Convex Goals
 $n=5$, $T=0.1$ s

Faigl, J., Vonásek, V., Přeučil, L.: *Visiting Convex Regions in a Polygonal Map*, Robotics and Autonomous Systems, 61(10):1070–1083, 2013.



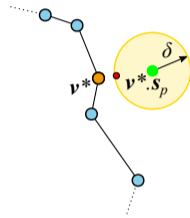
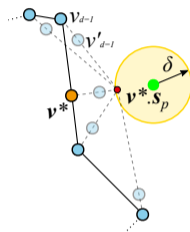
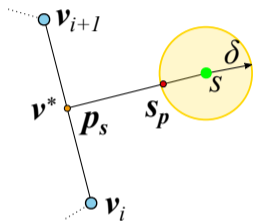
Growing Self-Organizing Array (GSOA)

- **Growing Self-Organizing Array (GSOA)** is generalization of the unsupervised learning to routing problems motivated by data collection planning, i.e., routing with neighborhoods such as the **Close Enough TSP**.
- The GSOA is an array of nodes $\mathcal{N} = \{\nu_1, \dots, \nu_M\}$ that evolves in the problem space using unsupervised learning.
- The array adapts to each $s \in S$ (in a random order) and for each s a **new winner node** ν^* is determined together with the corresponding s_p , such that $\|(s_p, s)\| \leq \delta(s)$.
It **adaptively adjusts** the number of nodes.
- The winner and its neighborhoods are adapted (moved) towards s_p .
- After the adaptation to all $s \in S$, each s has its ν and s_p , and the array defines the sequence Σ and the requested waypoints P .



GSOA – Winner Selection and Its Adaptation

- Selecting winner node ν^* for s and its waypoint s_p
- Winner adaptation

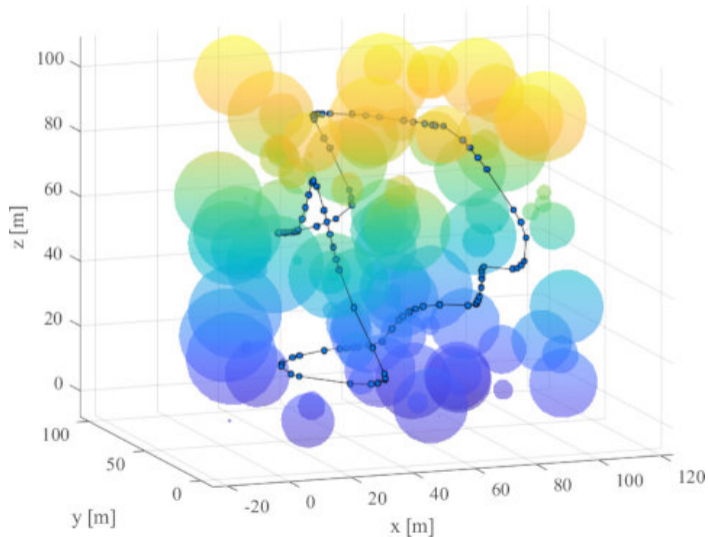


- For each $s \in S$, we create new node ν^* , and therefore, all not winning nodes are removed after processing all locations in S (one learning epoch) to balance the number of nodes in the GSOA.
- After **each learning epoch**, the **GSOA encodes a feasible solution of the CETSP**.
- The power of adaptation is decreasing using a cooling schedule after each learning epoch.
- The GSOA converges to a stable solution in tens of epochs. Number of epochs can be set.

Faigl, J. (2018): **GSOA: Growing Self-Organizing Array - Unsupervised learning for the Close-Enough Traveling Salesman Problem and other routing problems**. Neurocomputing 312: 120-134 (2018).



GSOA Evolution in solving the 3D CETSP



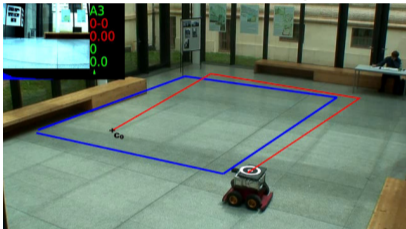
Outline

- Unsupervised Learning for Multi-goal Planning
- TSPN in Multi-goal Planning with Localization Uncertainty



Example – TSPN for Planning with Localization Uncertainty

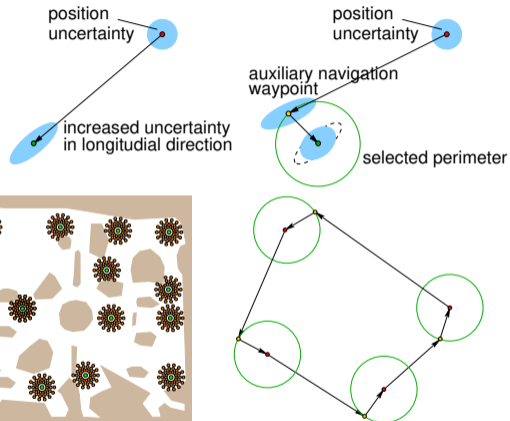
- Teach-and-repeat autonomous navigation using vision-based bearing corrections that are more precise than estimation of the traveled distance based on odometry measurements.



Krajník, T., Faigl, J., Vonásek, V., Košnar, K., Kulich, M., and Přeučil, L.: *Simple yet stable bearing-only navigation*, *Journal of Field Robotics*, 27(5):511-533, 2010.

- The localization uncertainty can be decreased by visiting auxiliary navigation waypoints prior the target locations.
- It can be formulated as a variant of the TSPN with auxiliary navigation waypoints.

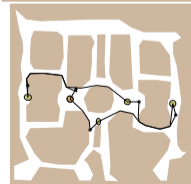
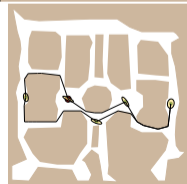
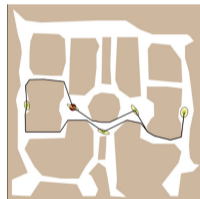
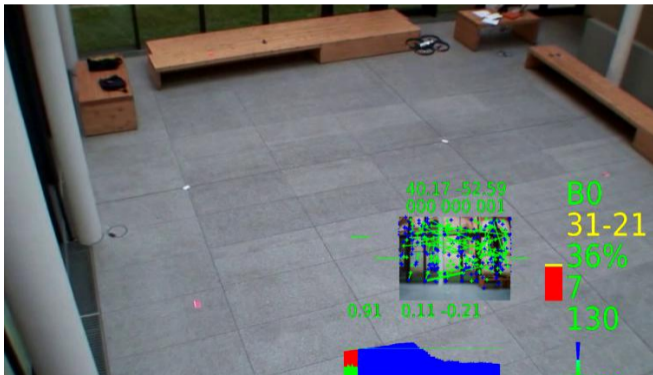
Faigl, J., Krajník, T., Vonásek, V., and Přeučil, L.: *On localization uncertainty in an autonomous inspection*, *IEEE International Conference on Robotics and Automation (ICRA)*, 2012, pp. 1119-1124.



- The adaptation procedure is modified to select the auxiliary navigation waypoint to decrease the expected localization error at the target locations.

Example – Results on the TSPN for Planning with Localization Uncertainty

- Deployment in indoor and outdoor environment with ground mobile robots and aerial vehicle in indoor environment.
- For the MMP5 robot, the error decreased from 16.6 cm \rightarrow 12.8 cm in indoor.
- For the P3AT robot, the real overall error at the goals decreased from 0.89 m \rightarrow 0.58 m (about 35%) in outdoor.
- For a small aerial vehicle, the Parrot AR.Drone, the success of the locations' visits improved from 83% to 95%.



TSP: $L=184$ m, $E_{avg}=0.57$ m TSPN: $L=202$ m, $E_{avg}=0.35$ m

Summary of the Lecture



Topics Discussed

- Robotic information gathering in inspection missions
- Inspection planning and multi-goal path planning - coverage planning
- **Multi-goal path planning (MTP)**
 - Robotic Traveling Salesman Problem (TSP)
 - Traveling Salesman Problem with Neighborhoods (TSPN) and Close Enough Traveling Salesman Problem (CETSP)
 - **Decoupled** and **Sampling-based** approaches
 - TSP can be solved by efficient heuristics such as **LKH**
 - Optimal, approximation, and heuristics solutions
 - **Generalized TSP (GTSP)**
- **Next: Data collection planning**

