Robotics Short Seminars

Introduction to Inspection Path Planning

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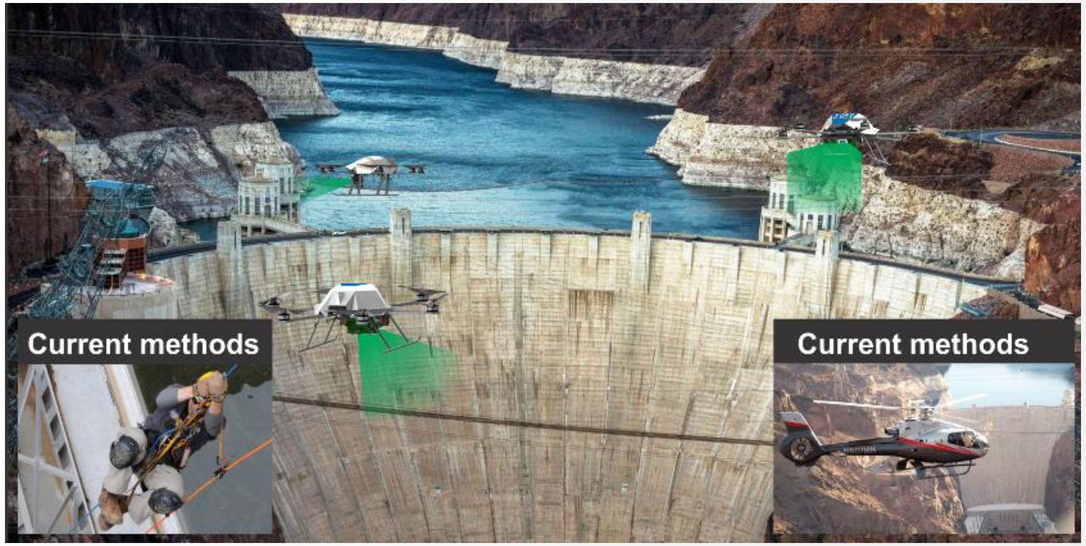
Motivation

- Autonomous Exploration and Inspection of even unknown or partially known environments.
- Autonomous complete coverage 3D **structural path planning**
- Enable real-time dense reconstruction of infrastructure
- Consistent mapping and re-mapping of infrastructure to derive models and detect change
- Long-endurance mission by exploiting the ground robot battery capacity
- Aerial robots that autonomously inspect our infrastructure or fields, detect changes and risks.

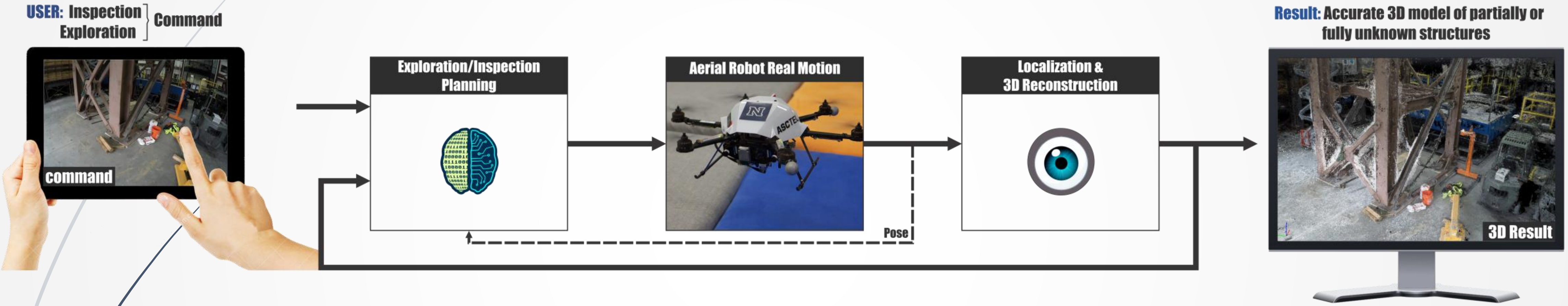


Motivation

Known Model to Compute Global Inspection Path

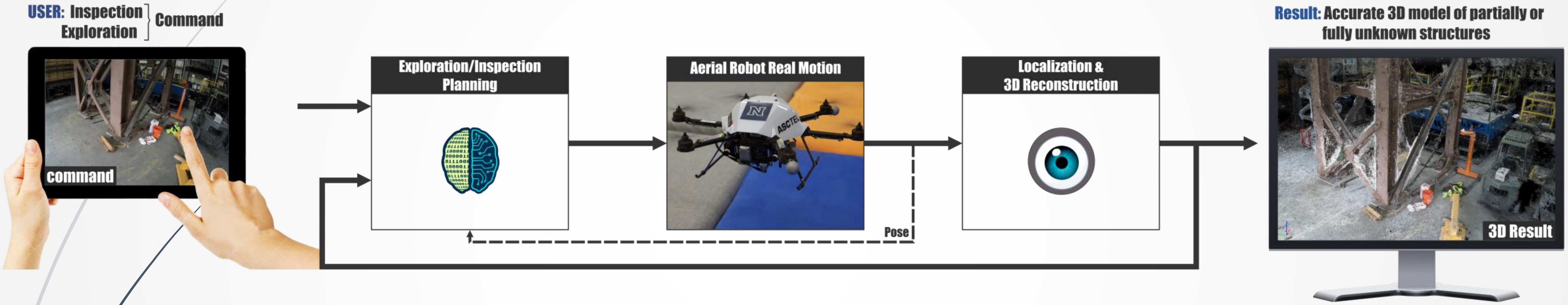
Unknown Model – execute Autonomous Exploration

The Basic Robot Loop



- The environment and the structures to be inspected may be fully known geometrically:
  - Perform **optimized inspection path planning** mission: find an optimized coverage route.
- The environment and the structured to be inspected may be unknown or only partially known:
  - Perform an efficient **autonomous exploration** mission.

The Basic Robot Loop



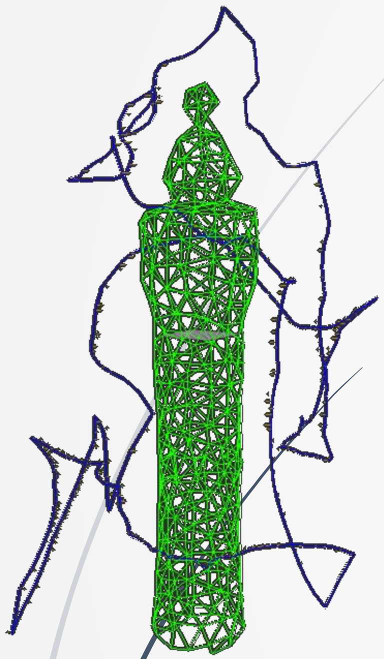
- Methods to be presented:
  - **Optimized Inspection:**
    - Structural Inspection Planner via Iterative Viewpoint Alternation and Tour Optimization
    - Rapidly exploring Random Tree-of-Trees
    - Uniform Coverage Inspection Path Planning
  - **Autonomous Exploration**
    - Receding Horizon "Next-Best-View" Planning

Basic Concepts of the Inspection Planner

- **Main classes of existing 3D methods:**
  - Separated Approach (AGP + TSP or Control)
    - Prone to be suboptimal
    - In specific cases lead to infeasible paths (nonholonomic vehicles)
  - First attempts for optimal solutions via a unified cycle
    - In specific cases can lead to the optimal solution
    - Very high CPU and Memory Requirements & Time

- **Structural Inspection Planner (SIP):**
  - Driven by the idea that *with a continuously sensing sensor, the number of viewpoints is not necessarily important but **mostly their configuration in space***.
  - Not a minimal set of viewpoints but a set of full coverage viewpoints positioned such that the overall path gets minimized.
  - 2-step paradigm with viewpoint alternation
  - Guaranteed feasible paths for both holonomic and nonholonomic vehicles

Structural Inspection Planner (SIP)



First solution

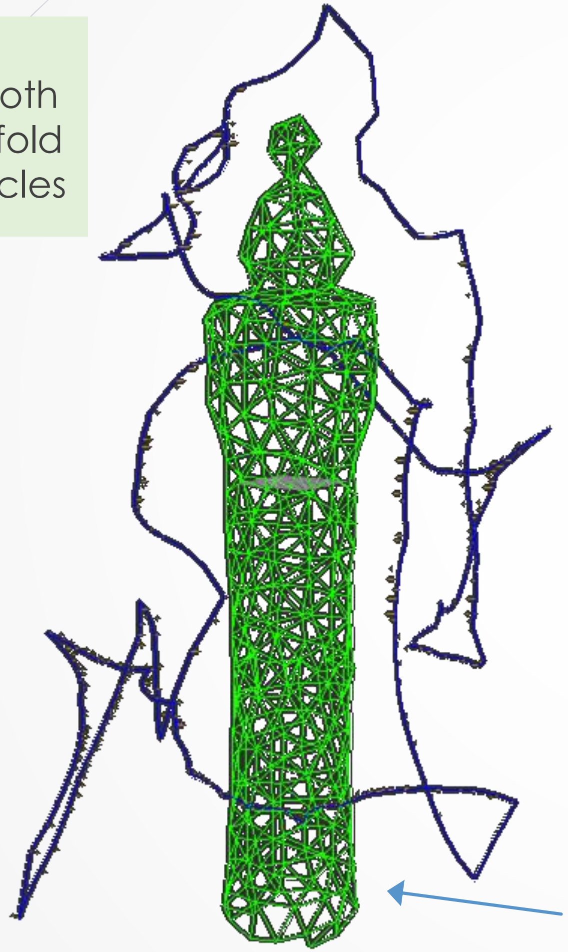
- Load the mesh model
- k = 0
- Sample Initial Viewpoint Configurations (Viewpoint Sampler)
- Find a Collision-free path for all possible viewpoint combinations (BVS, RRT*)
- Populate the Cost Matrix and Solve the Traveling Salesman Problem (LKH)
- **while** running
  - Re-sample Viewpoint Configurations (Viewpoint Sampler)
  - Re-compute the Collision-free paths (BVS, RRT*)
  - Re-populate the Cost Matrix and solve the new Traveling Salesman Problem to update the current best inspection tour (LKH)
  - k = k + 1
- **end while**
- **Return *BestTour, CostBestTour***

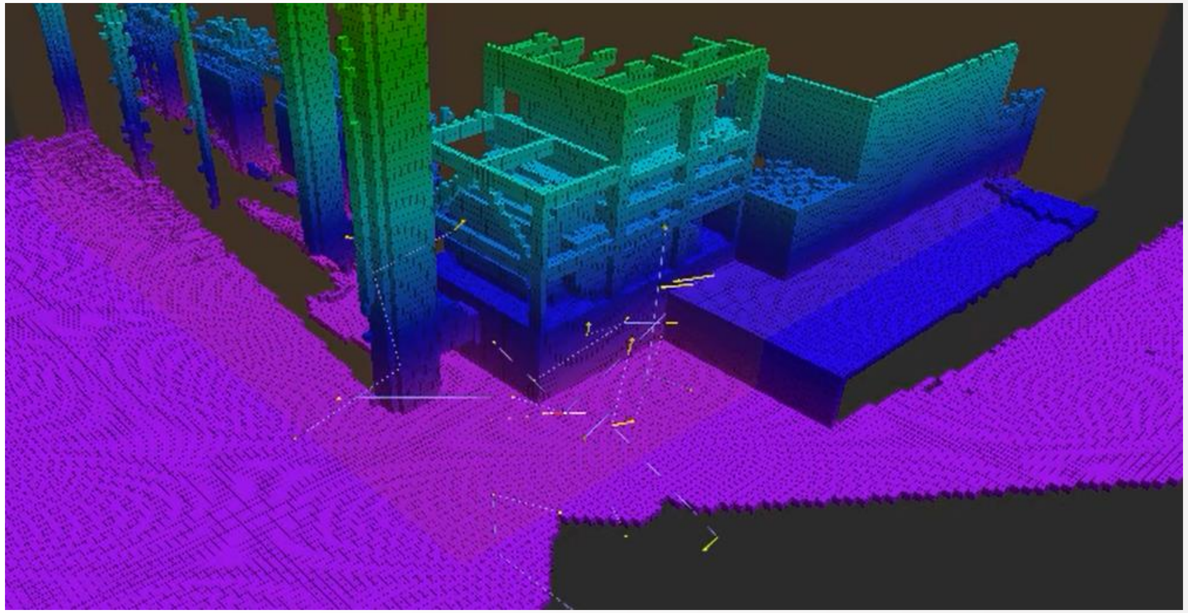
Available Time

Optimized solutions

SIP: Supported World Representations

Same type of representation for both the inspection manifold as well as any obstacles





Octomap [possibly enlarged voxels]

Not currently open-sourced

Meshes [possibly downsampled]

Supported in the open-sourced SIP

Sampling-based and Collision-checking implemented

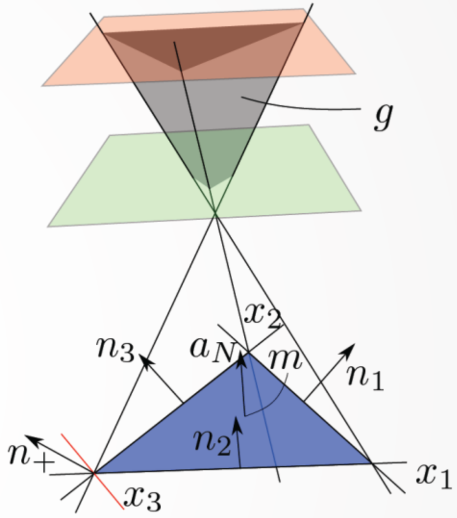
SIP: Viewpoint Sampler

- **Optimize Viewpoint Configurations**
  - Admissible viewpoints are optimized for distance to the neighboring viewpoints
  - To guarantee admissible viewpoints, the position solution $g = [x,y,z]$ is constrained to allow finding an orientation for which the triangular face is visible:

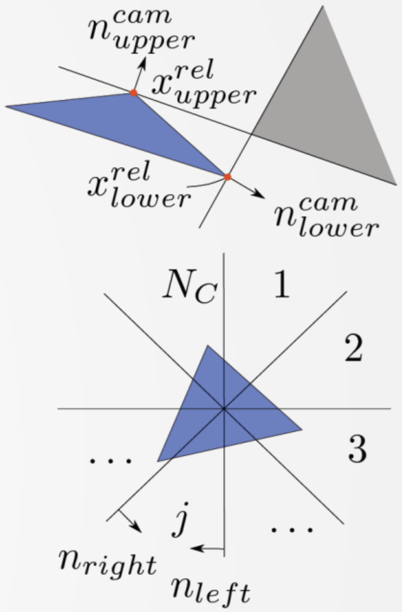
$$\begin{bmatrix} (g-x_i)^T n_i \\ (g-x_1)^T a_N \\ -(g-x_1)^T a_N \end{bmatrix} \succeq \begin{bmatrix} 0 \\ d_{min} \\ -d_{max} \end{bmatrix}, \, i = \{1,2,3\}$$

  - Account for limited **F**ield **o**f **V**iew by imposing a revoluted 2D-cone constraint. This is a nonconvex problem which is then convexified by dividing the problem into N_c equal convex pieces.

$$\begin{bmatrix} (g-x_{lower}^{rel})^T n_{lower}^{cam} \\ (g-x_{upper}^{rel})^T n_{upper}^{cam} \\ (g-m)^T n_{right} \\ (g-m)^T n_{left} \end{bmatrix} \succeq \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$



Incidence angle constraints on a triangular surface



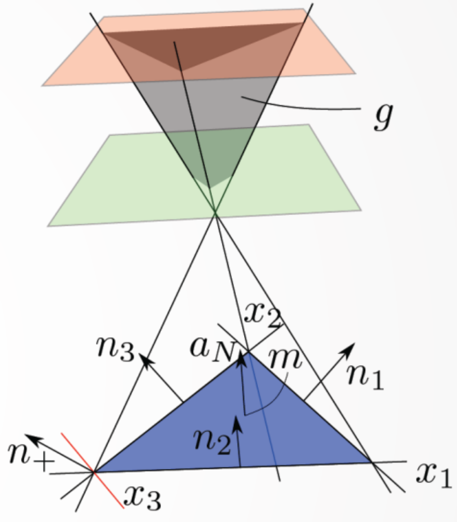
Camera constraints and convexification

SIP: Viewpoint Sampler

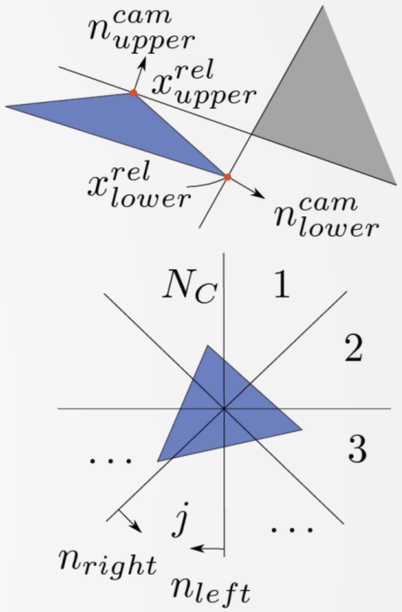
- **Sample 1 Viewpoint/Triangular face**
  - Minimize the sum of squared distances to the preceding viewpoint $\boldsymbol{g_p^{k-1}}$, the subsequent viewpoint $\boldsymbol{g_s^{k-1}}$ and the current viewpoint in the old tour $\boldsymbol{g^{k-1}}$.

$$
\begin{aligned}
\min_{g^k} \quad & (g^k - g_p^{k-1})^T(g^k - g_p^{k-1}) + \\
& +(g^k - g_s^{k-1})^T(g^k - g_s^{k-1}) + (g^k - g^{k-1})^T(g^k - g^{k-1}) \\
\text{s.t.} \quad & \begin{bmatrix} n_1^T \\ n_2^T \\ n_3^T \\ a_N^T \\ -a_N^T \\ n_{lower}^{cam\ T} \\ n_{upper}^{cam\ T} \\ n_{right}^T \\ n_{left}^T \end{bmatrix} g^k \succeq \begin{bmatrix} n_1^T x_1 \\ n_2^T x_2 \\ n_3^T x_3 \\ a_N^T x_1 + d_{min} \\ -a_N^T x_1 - d_{max} \\ n_{lower}^{cam\ T} x_{lower}^{rel} \\ n_{upper}^{cam\ T} x_{upper}^{rel} \\ n_{right}^T m \\ n_{left}^T m \end{bmatrix}
\end{aligned}
$$

QP + Linear Constraints



Incidence angle constraints on a triangular surface



Camera constraints and convexification

  - The heading is determined according to:

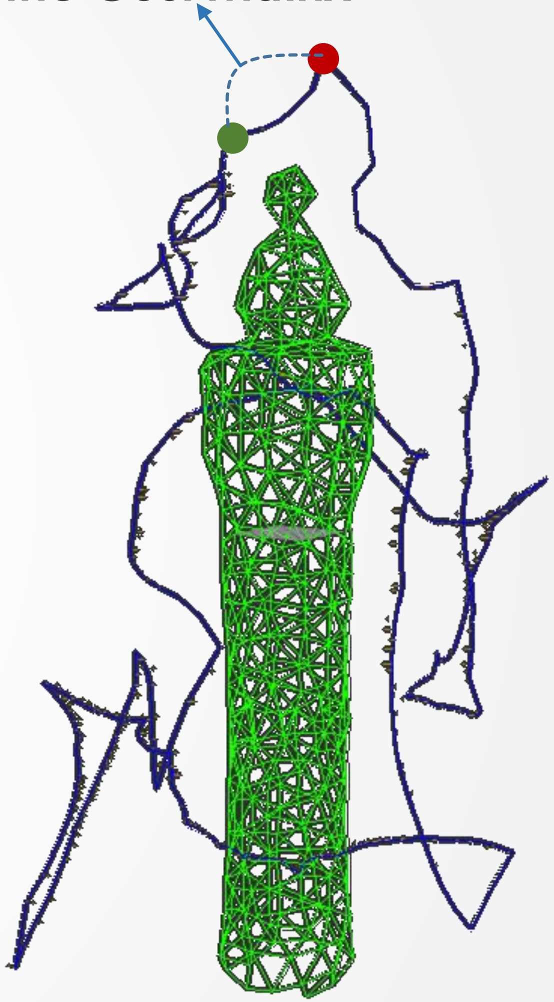
$$
\min_{\psi^k} \ = \ \left(\psi_p^{k-1} - \psi^k\right)^2 / d_p + \left(\psi_s^{k-1} - \psi^k\right)^2 / d_s, \qquad \text{s.t.} \qquad \mathbf{Visible}(g^k, \psi^k)
$$

While ensuring visibility, try to align the vehicle heading over a path

SIP: Point-to-Point Paths

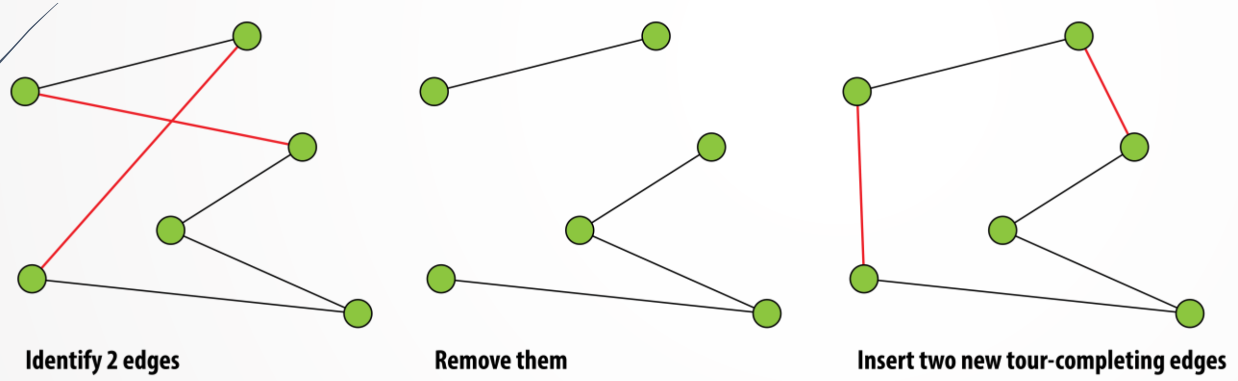
- State-Space Sampling – *extension to Control-Space sampling possible*
- Employ **B**oundary **V**alue **S**olvers for
  - Holonomic (with Yaw-rate constraints) or
  - Nonholonomic Aerial Robots *(fixed-wing UAVs – 2.5D approx., Dubins Airplane approx.)*
- Derive Collision-free paths that connect all viewpoint configurations by invoking ***RRT****
- Assemble the Traveling Salesman Problem Cost Matrix using the path execution times t_{ex}

- **Compute RRT* Path**
- **Extract the t_{ex} of the RRT* Path**
- **Populate the Cost Matrix**

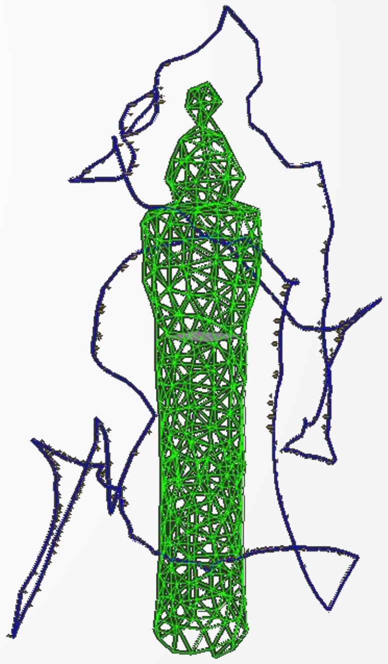


SIP: TSP Solution

- Solve the (possibly asymmetric) TSP problem using the Lin-Kernighan-Helsgaun heuristic
- ***Extract the Optimized Inspection Tour***

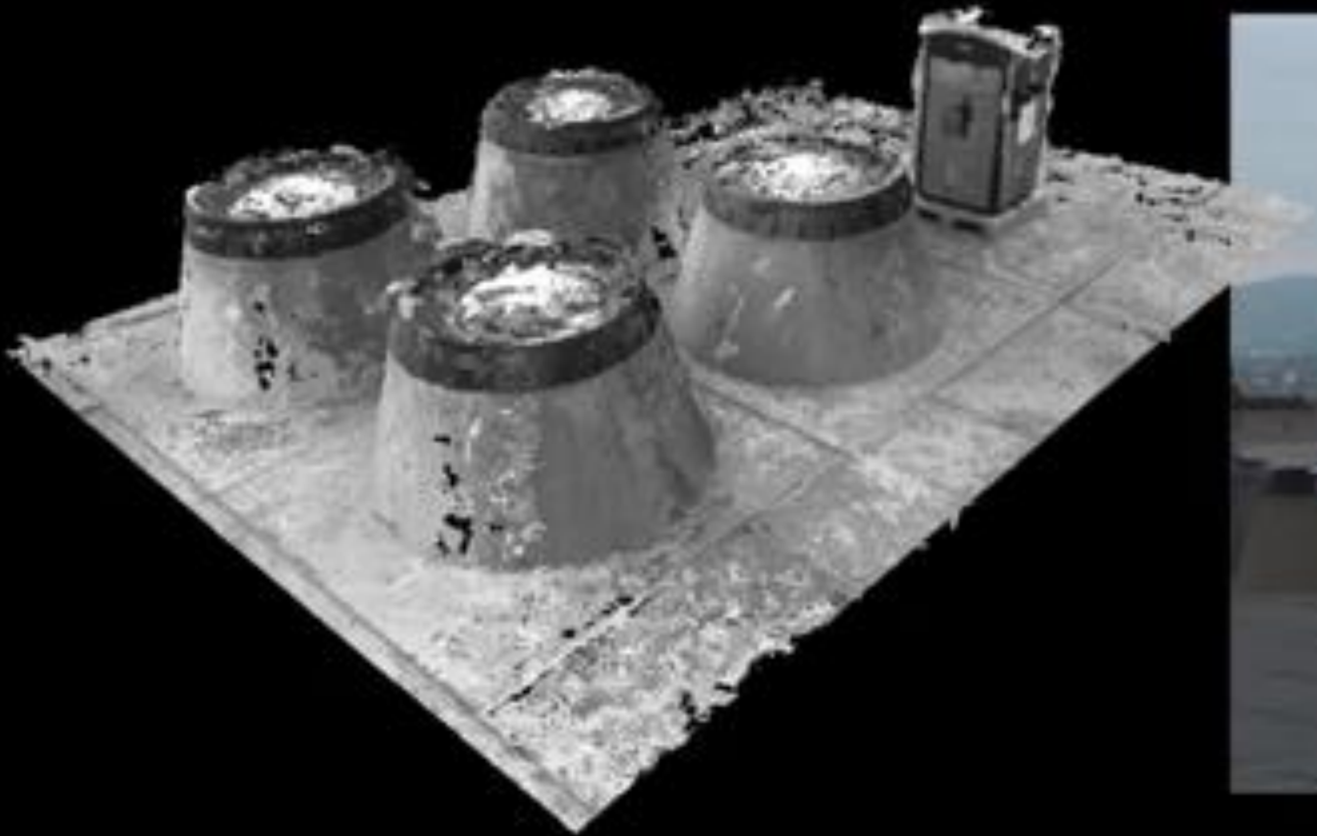


$O(N^{2.2})$, N the number of viewpoints



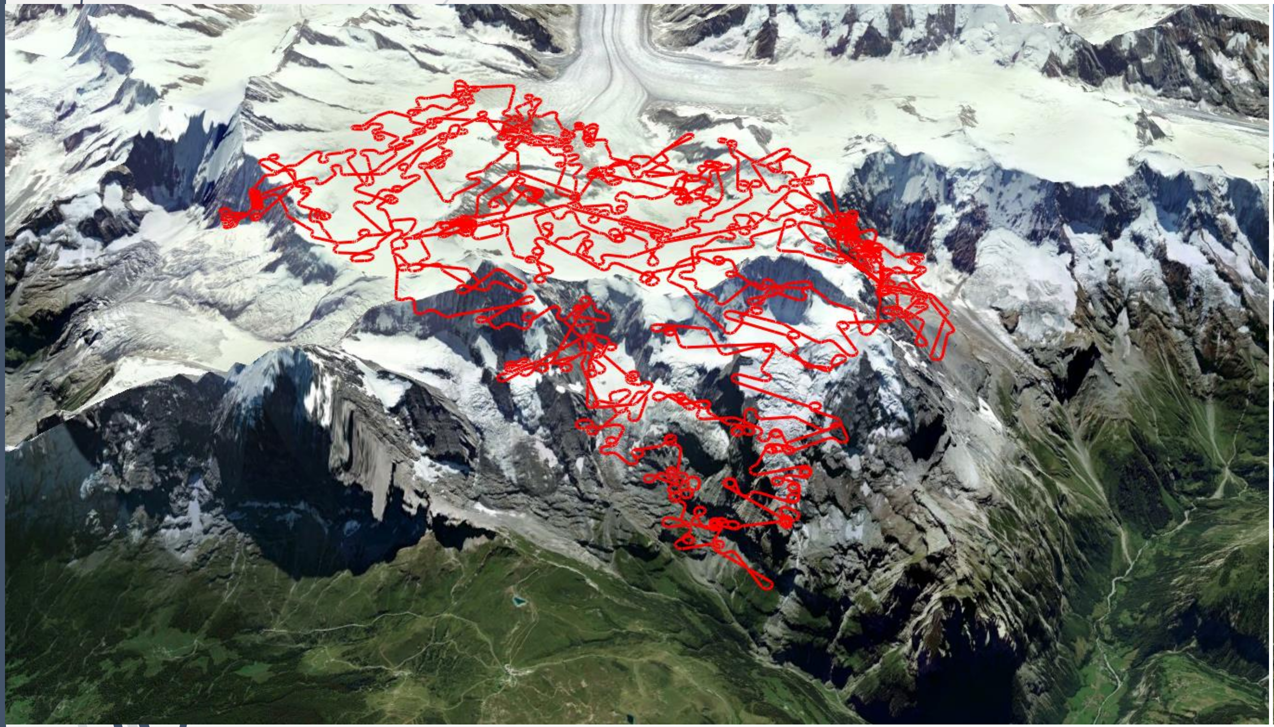
Three-dimensional Coverage Path Planning via Viewpoint Resampling and Tour Optimization using Aerial Robots

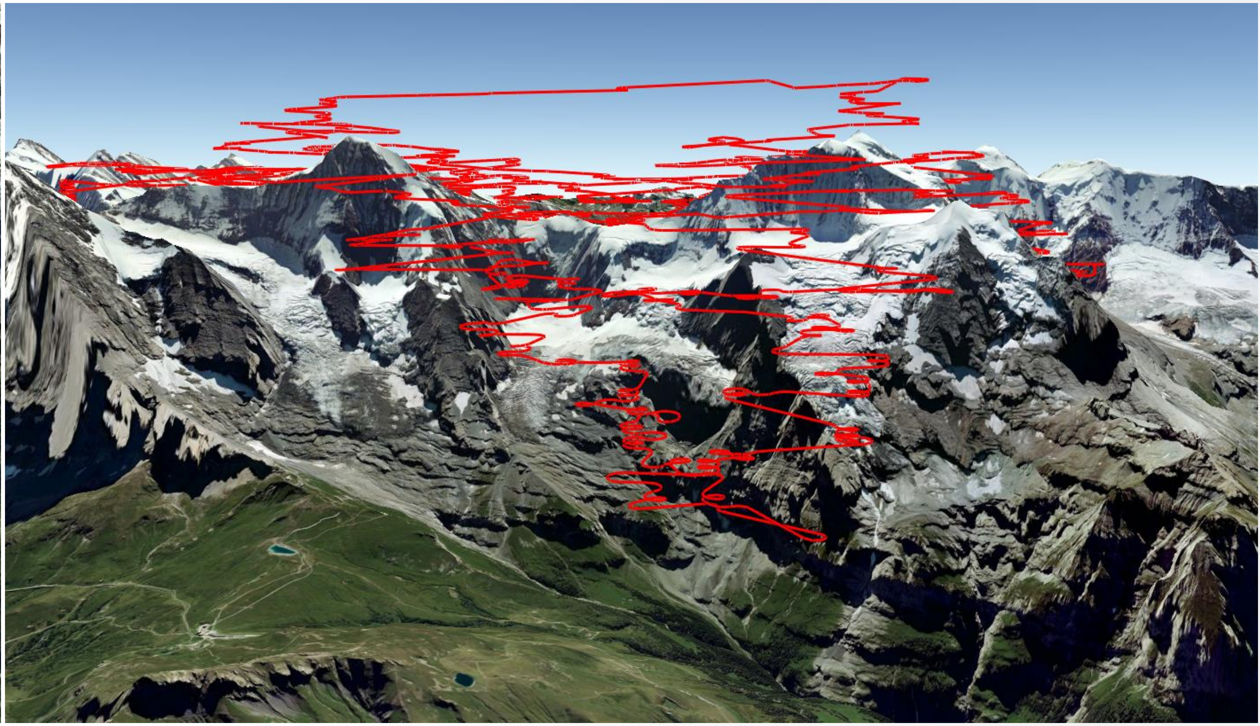
A. Bircher, K. Alexis, M. Kamel, M. Burri, P. Oettershagen, S. Omari, T. Mantel, R. Siegwart




Structural Inspection Path Planning via Iterative Viewpoint Resampling
with Application to Aerial Robotics
Andreas Bircher, Kostas Alexis, Michael Burri, Phlipp Oettershagen, Sammy Omari, Thomas Mantel and Roland Siegwart
ETH

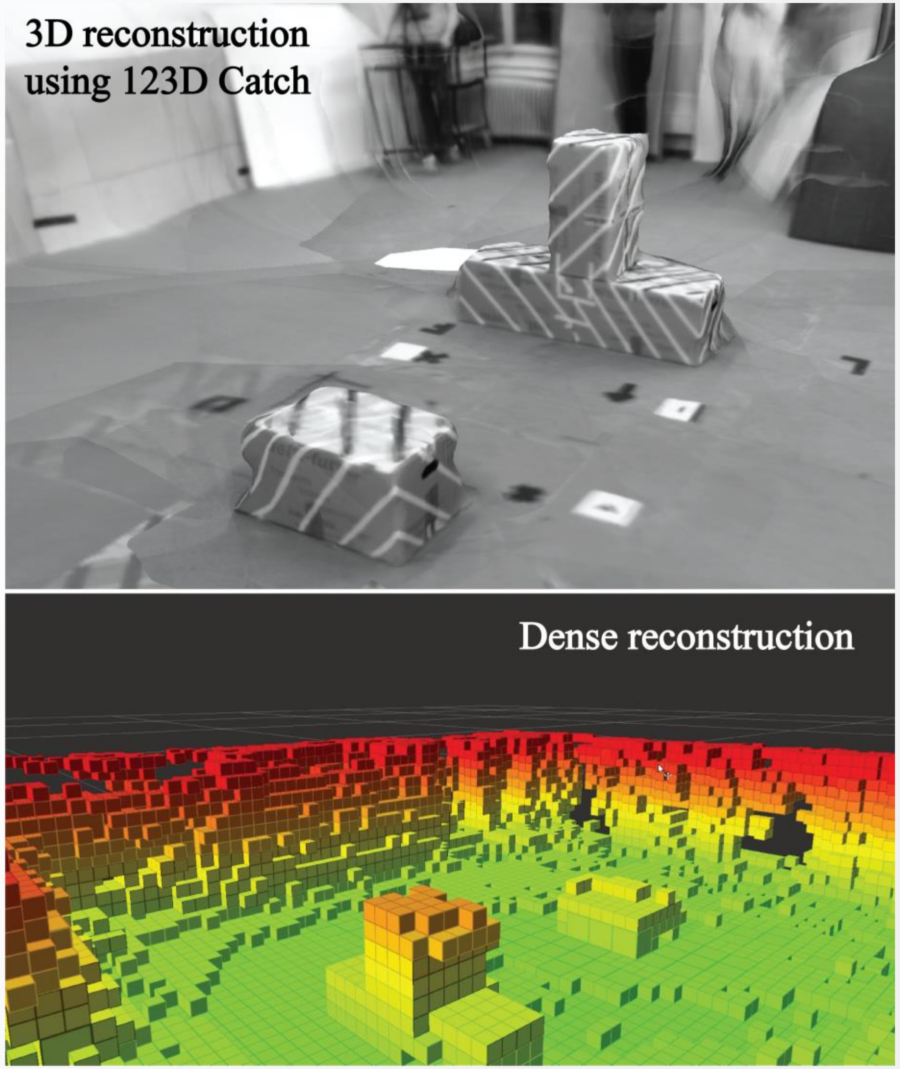
Large Scale Planning: Inspection of the JungFrau mountain (Simulation)





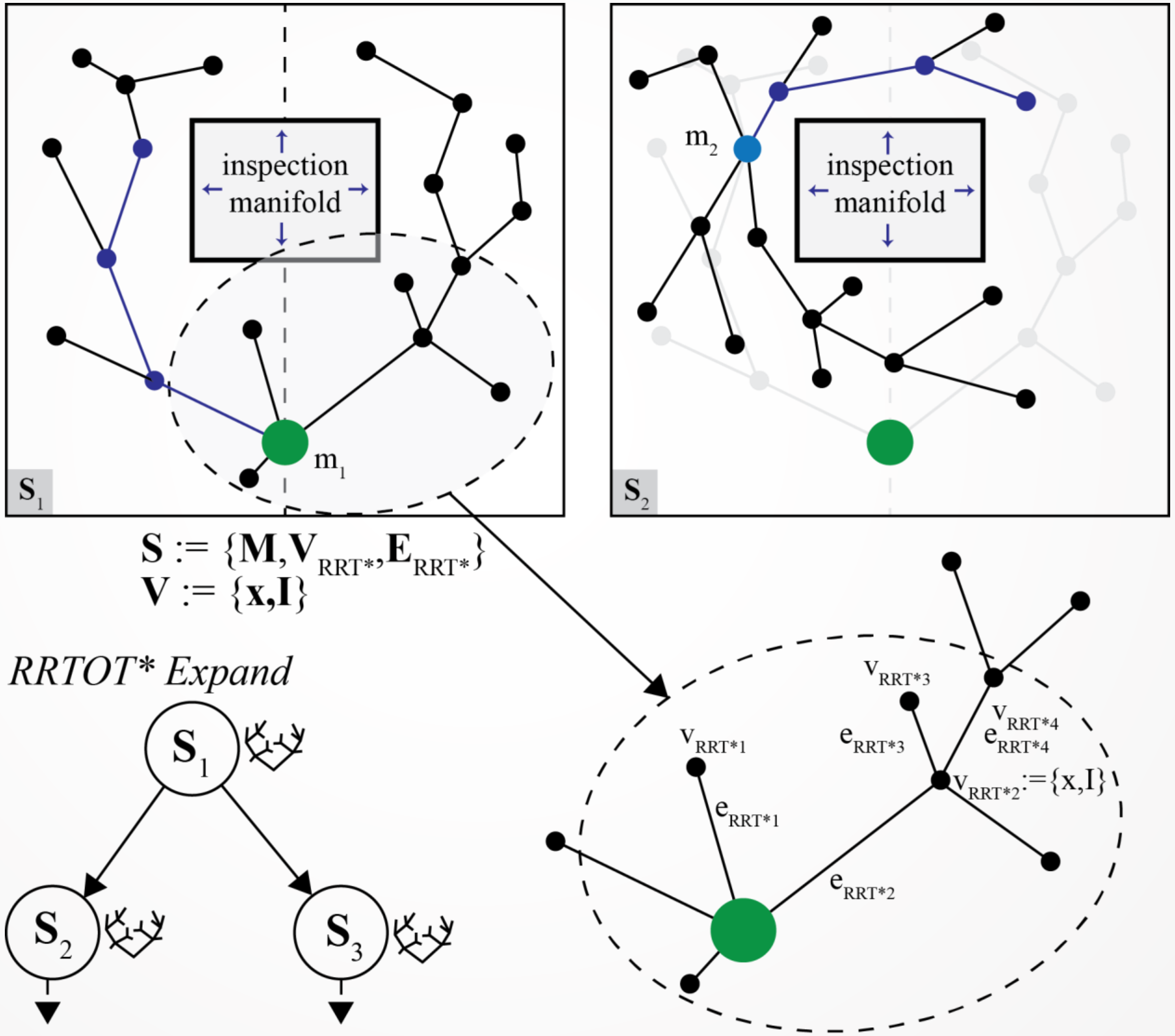
Rapidly-exploring Random Tree-Of-Trees (RRTOT)

- **Problem:** given a representation of the structure find the optimal coverage path.
- **Challenges:** can we find the optimal path? Can we converge asymptotically to that solution?
- **Goal:** Provide an algorithm that can incrementally derive the optimal solution and be able to provide admissible paths "anytime".



RRTOT: Functional Principle

Overcome the limitations of motion planners designed for navigation problems.

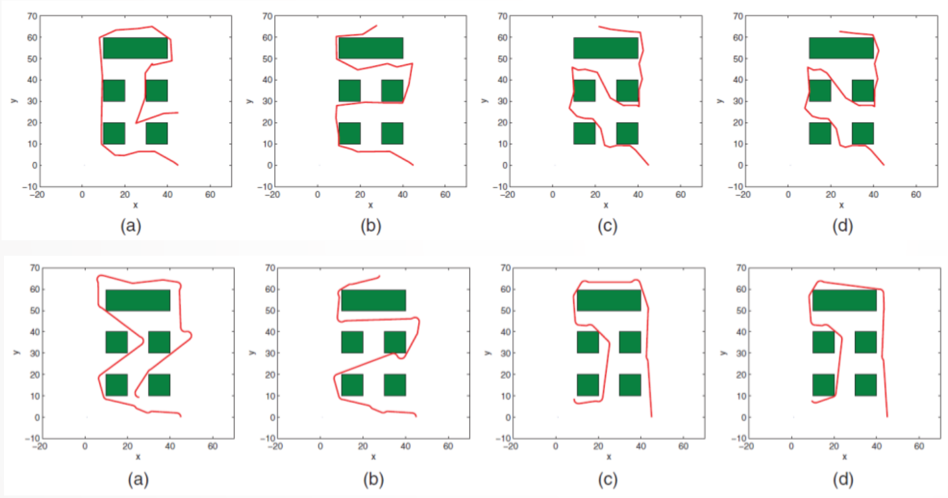


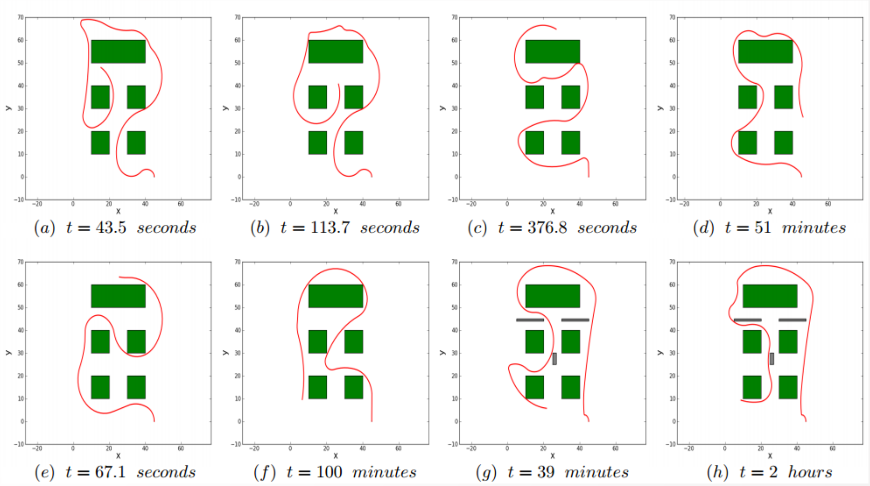
Vary the solution topology – be able to find the optimal solution. X`

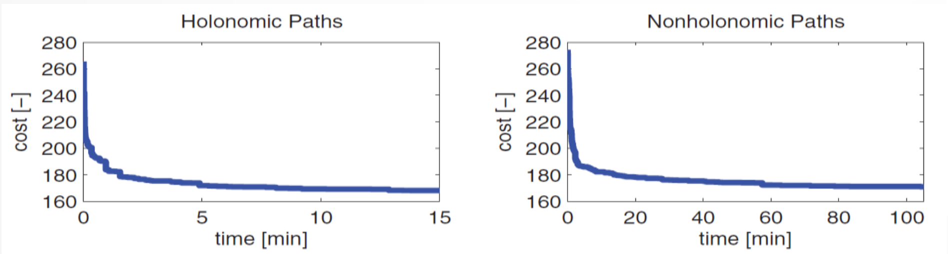
Overcome the limitations of SIP but in a computationally very expensive way.

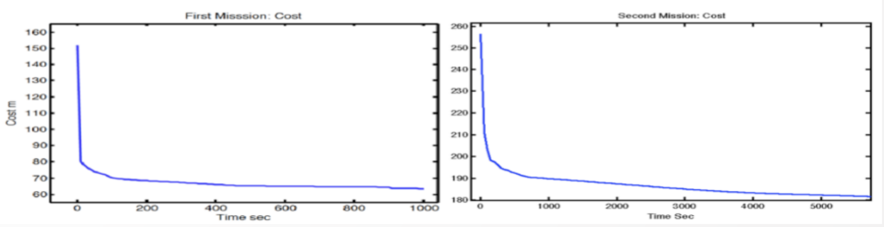
RRTOT: Functional Principle

- **Comparison with the state-of-the-art:** RRTOT seems to be able to provide solutions faster.





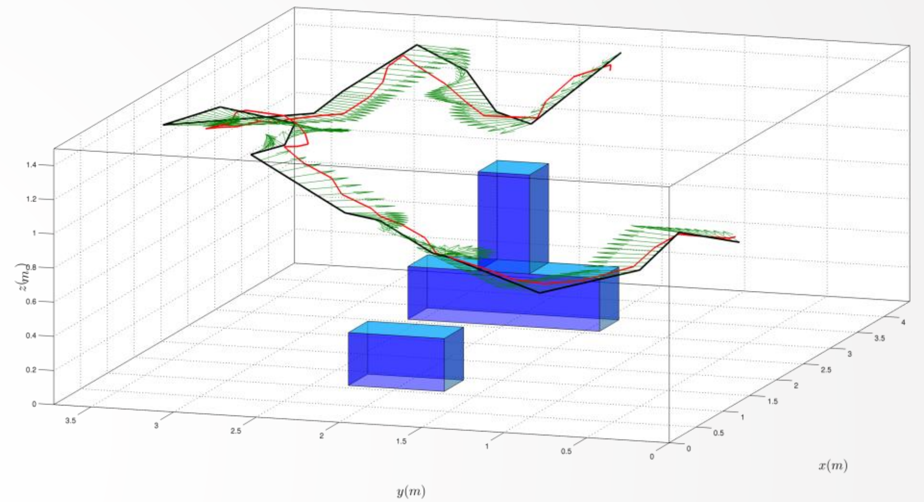




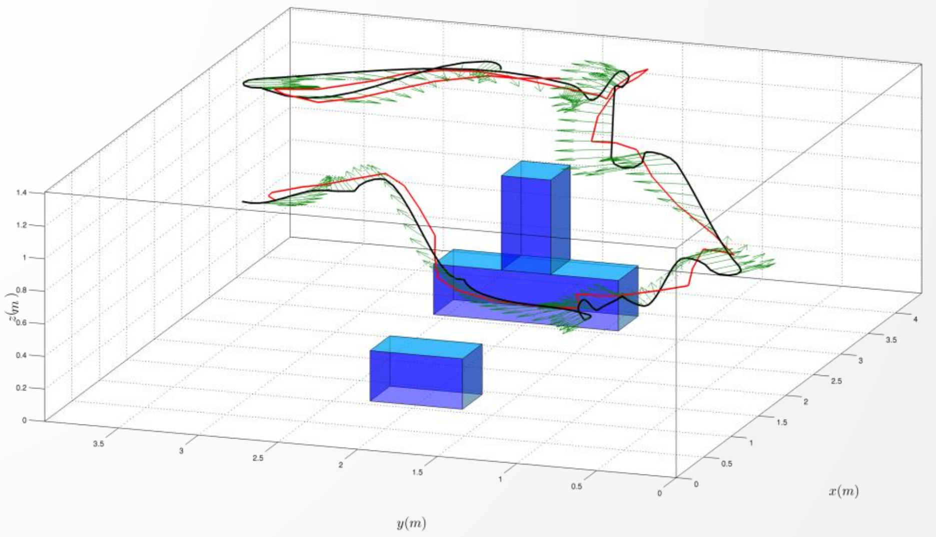
- **Comparison against:** G Papadopoulos, H Kurniawati, N Patrikalakis, "Asymptotically optimal path planning and surface reconstruction for inspection", IEEE International Conference on Robotics and Automation (ICRA) 2013.

RRTOT: Indicative Solutions

- **Holonomic**

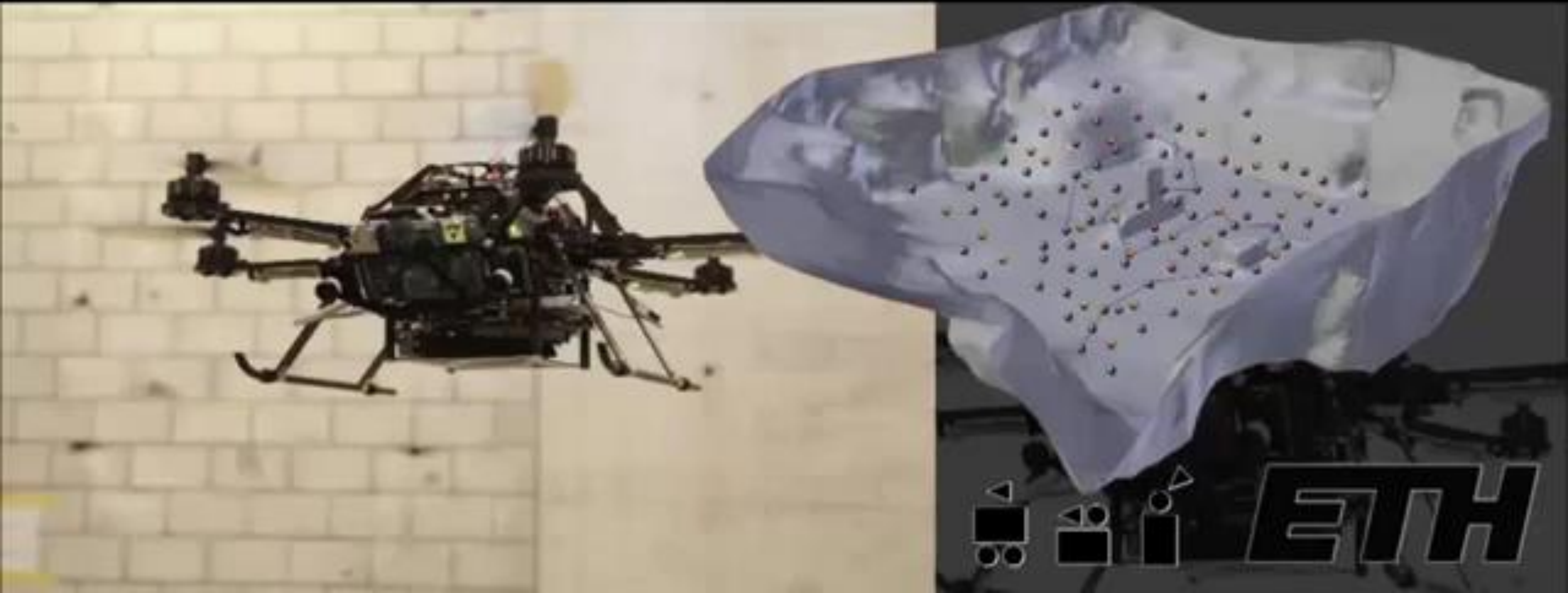


- **Nonholonomic**



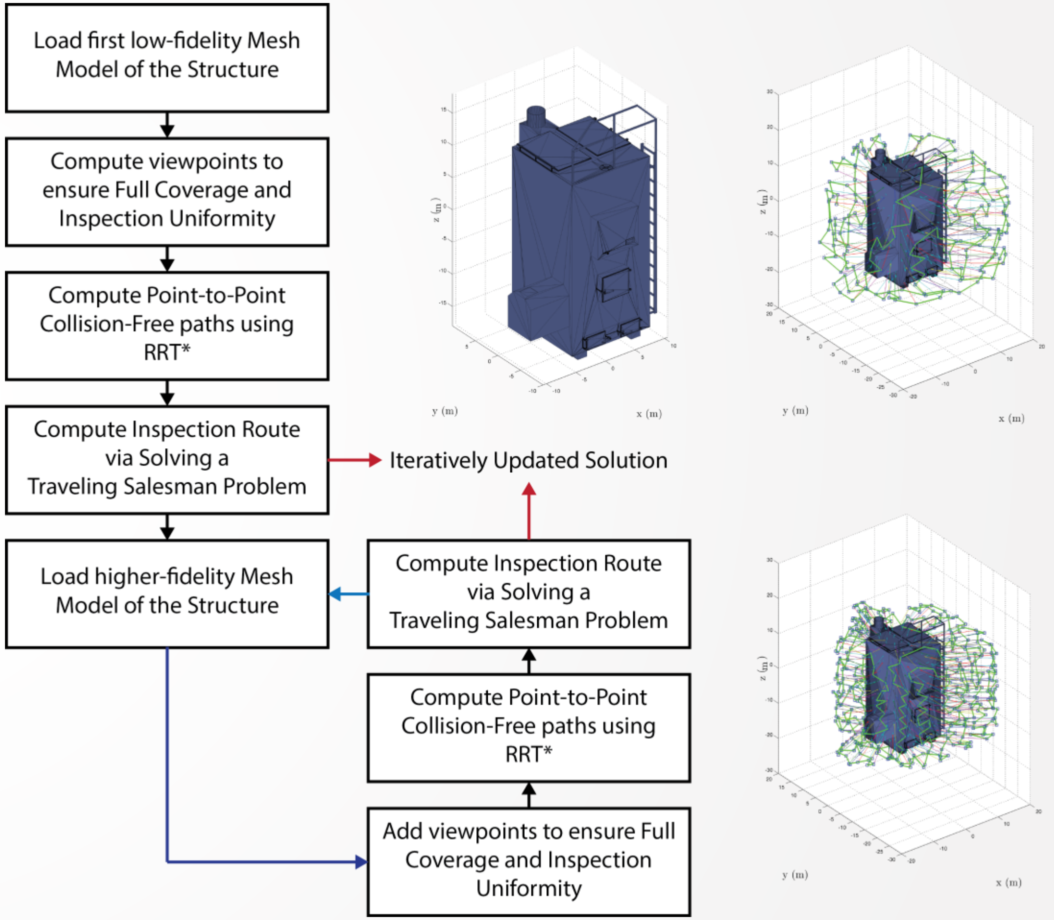
An Incremental Sampling-based approach to Inspection Planning: the Rapidly-exploring Random Tree Of Trees

Andreas Bircher, Kostas Alexis, Ulrich Schwesinger, Sammy Omari, Michael Burri and Roland Siegwart

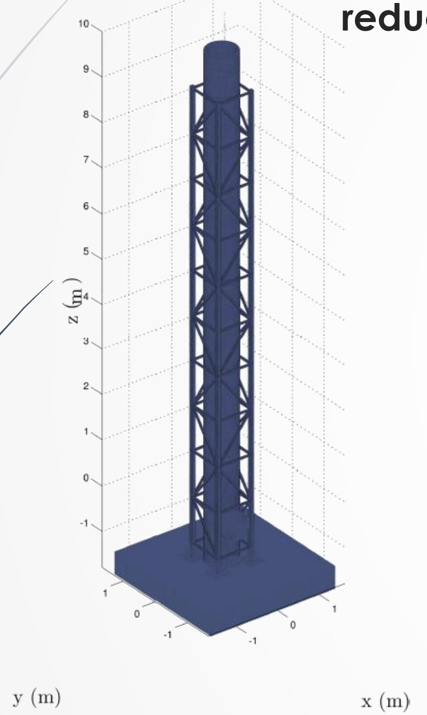


Uniform Coverage Inspection Path-Planning (UC3D)

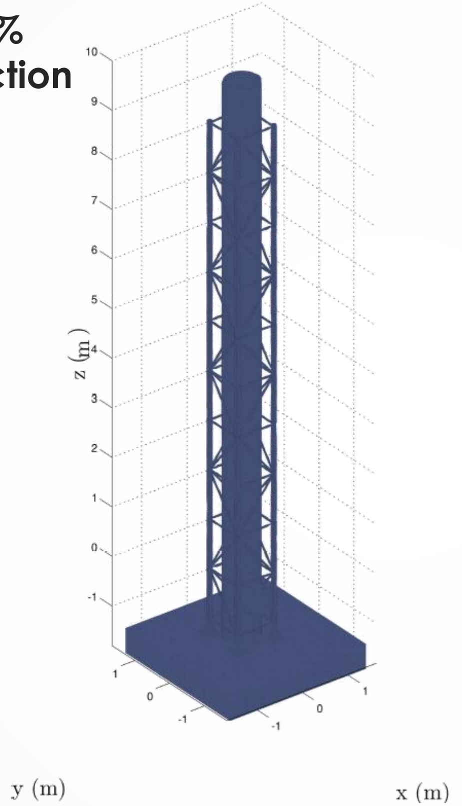
- **Problem:** given a representation of the structure, compute a full coverage path that provides uniform focus on the details.
- **Challenge:** provide a good solution at “anytime”.
- **Goal:** an efficient “anytime” inspection path planning algorithm with uniformity guarantees.
- Key for the solution: Voronoi-based remeshing techniques and a combination of viewpoint computation algorithms, collision-free planners and efficient TSP solvers.

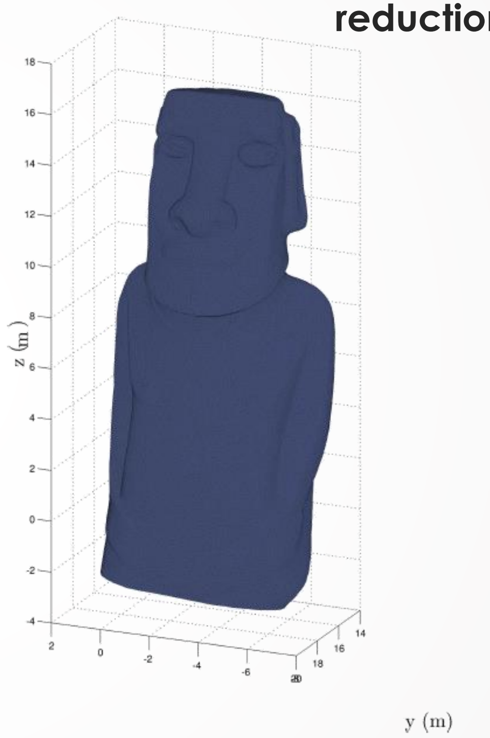


UC3D: Remeshing techniques play a key role

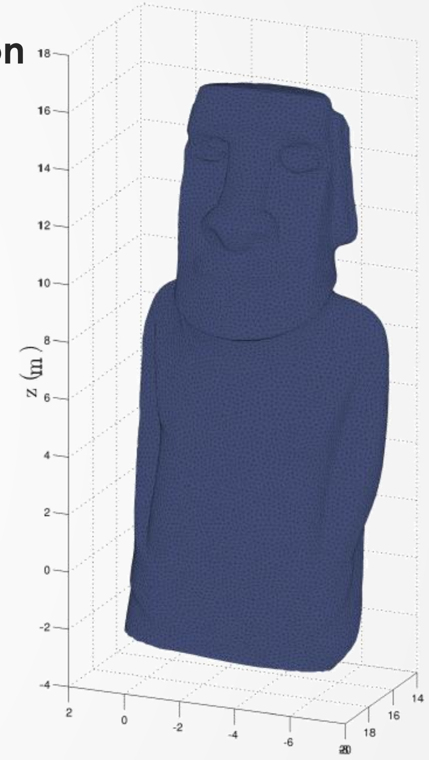


25% reduction





25% reduction



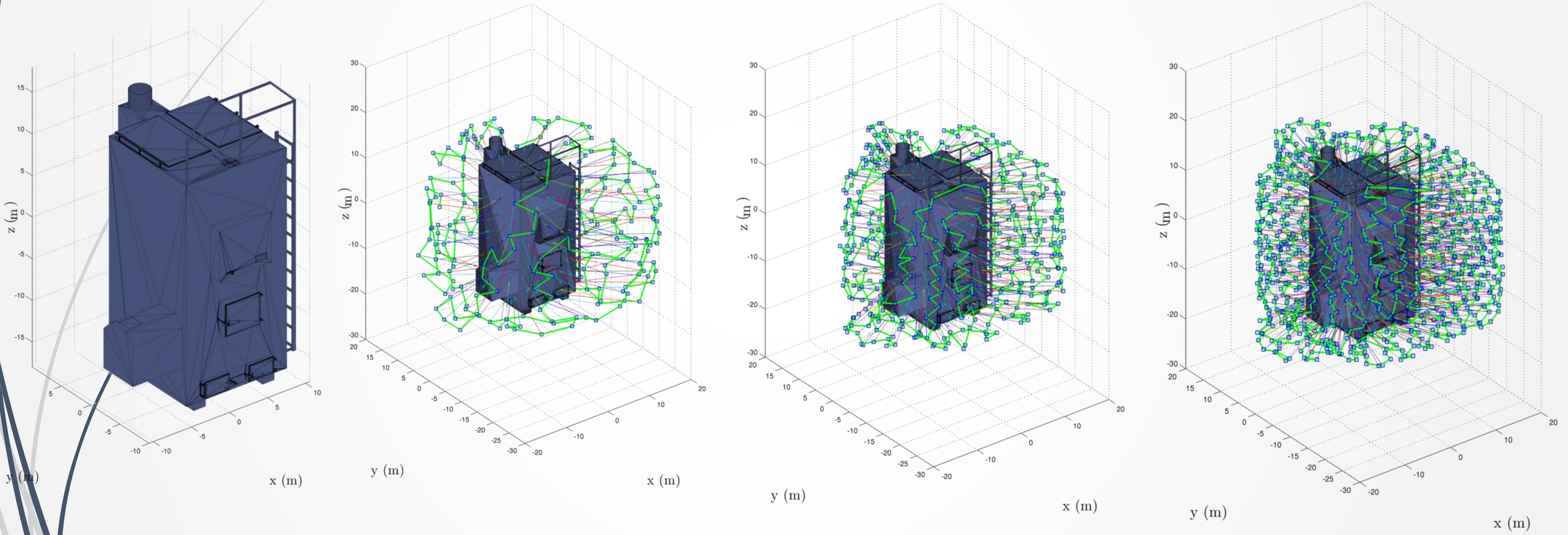
- **Voronoi-based remeshing techniques allow for uniform downsampling of the mesh with minimal structural loss**

UC3D: Iterative UC3D-IPP

$\mathcal{V}^{i-1} \leftarrow \mathcal{V}^{basic}$
$\mathcal{V}^{i} \leftarrow \mathcal{V}^{i-1}$
$\mathcal{P}_i \leftarrow \text{ExtractPolygons}(\mathcal{G}_i, \mathcal{F}_i)$
for all $\mathbf{p}_{k,i} \in \mathcal{P}_i$ **do**
  if $\text{IsCoveredUniformly}(\mathbf{p}_{k,i}, \mathcal{V}^{i-1}) == \textbf{FALSE}$ **then**
    $\mathbf{v}_{k,i} \leftarrow \text{ComputeViewpoint}(\mathbf{p}_{k,i})$
    $\mathcal{V}^{i} \leftarrow \mathcal{V}^{i} \cup \mathbf{v}_{k,i}$
for all $\mathbf{v}_n \in \mathcal{V}^i$ **do**
  for all $\mathbf{v}_m \in \mathcal{V}^i$ **do**
    $\mathbf{C}(n,m) \leftarrow \text{ConnectionDistance}(\mathbf{v}_n, \mathbf{v}_m)$
$\mathbf{r}_i \leftarrow \text{ComputeViewpointsRoute}(\mathbf{C}(n,m))$
return $\mathbf{r}_i$

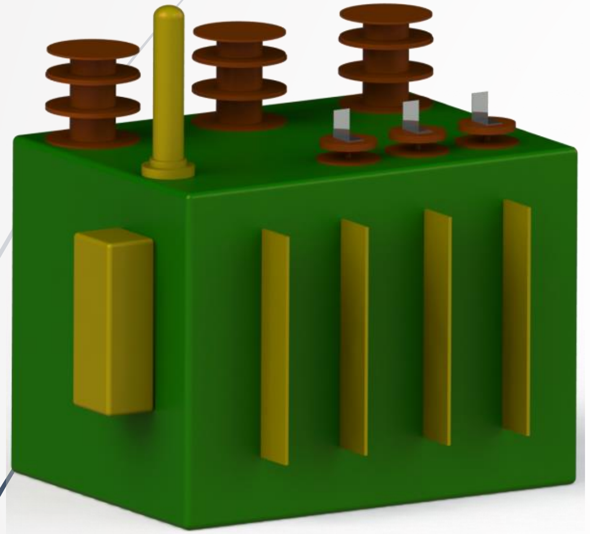
- **Difference of Iterative version:**
  - For each higher quality mesh, instead of computing a whole new set of viewpoints, only some additional are added to re-ensure uniform coverage.

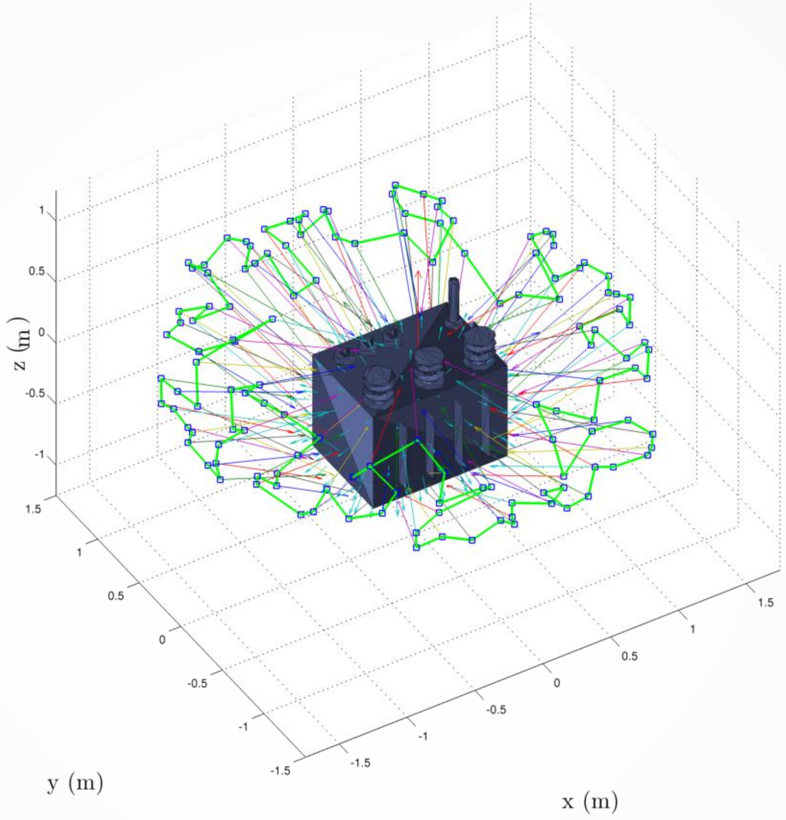
UC3D: Basic UC3D-IPP Result

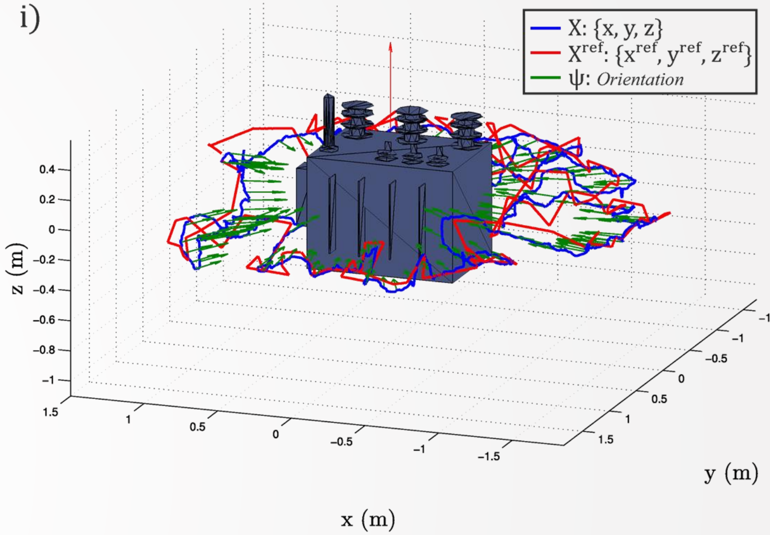


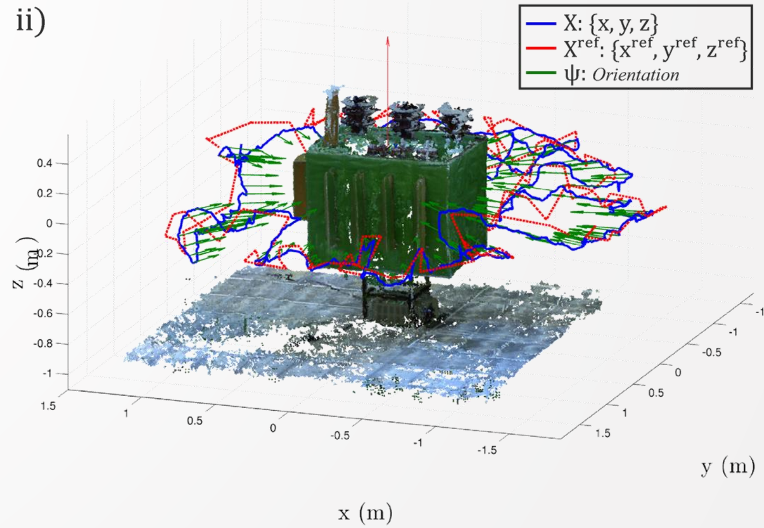
Sequential execution of the basic UC3D-IPP algorithm

UC3D: Experimental study on a Power Transforer MockUp



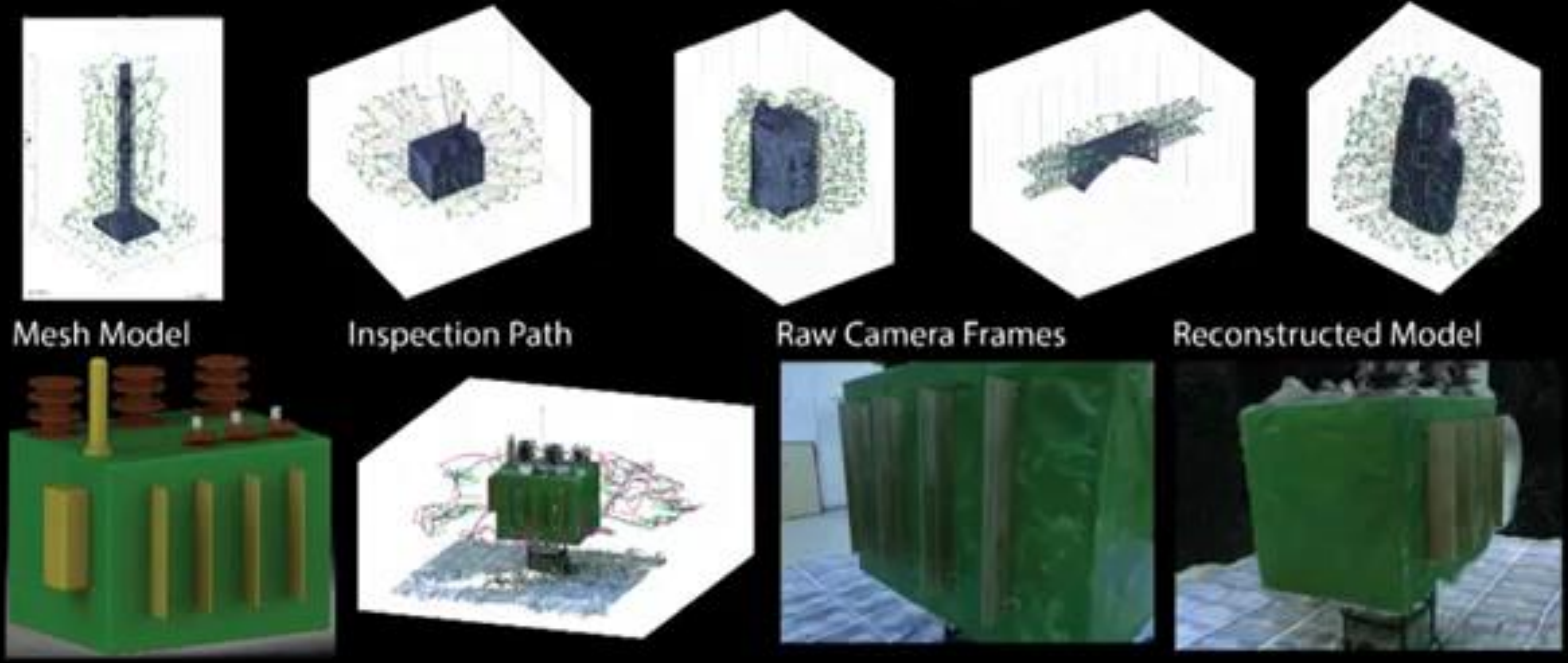






Uniform Coverage Structural Inspection Path-Planning for Micro Aerial Vehicles

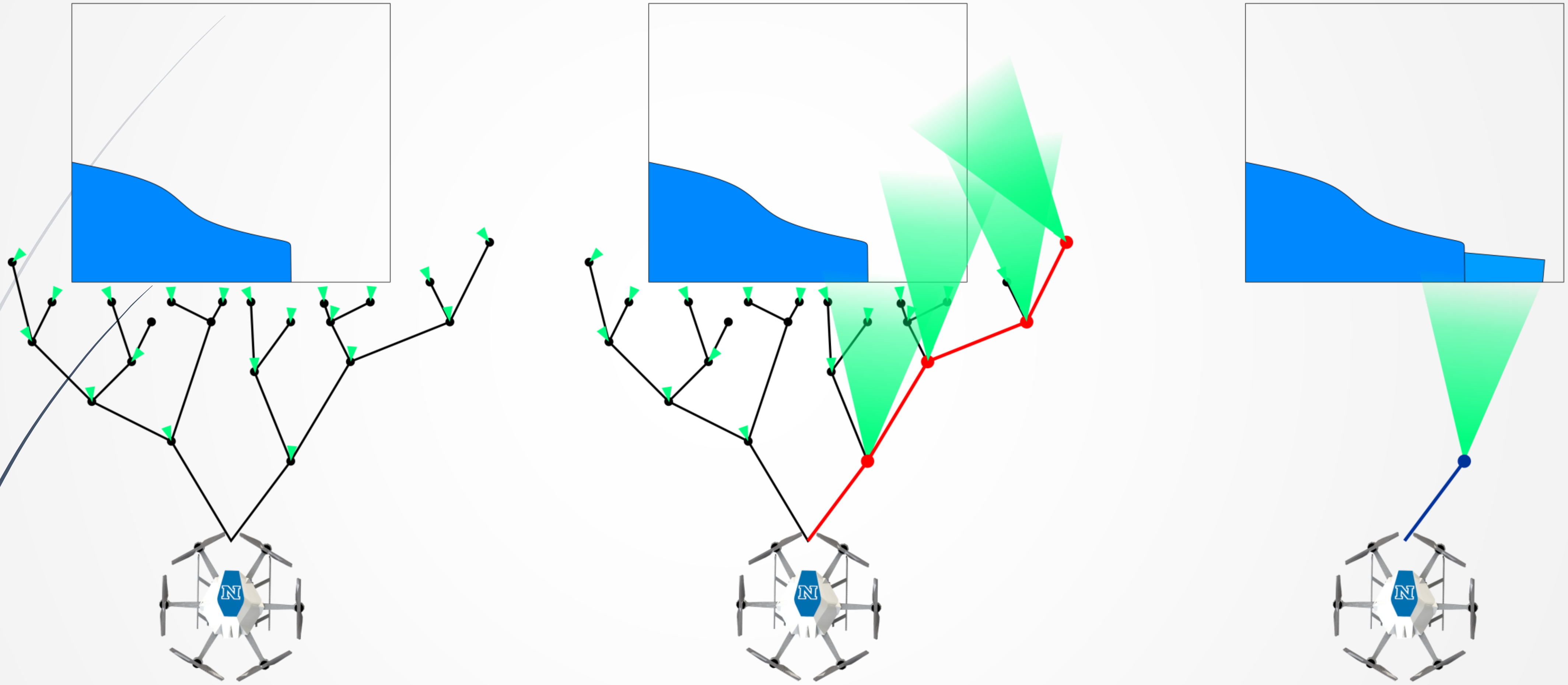
K. Alexis, C. Papachristos, R. Siegwart, A. Tzes



Receding Horizon Next-Best-View (NBVP)

- 3D models of the structure to be inspected are typically not available.
- Real infrastructure is typically very complex in terms of geometry.
- Most of the times we care for some sort of local exploration and not coverage of everything in our environment.
- What does it take for a robot to be able to conduct such as mission autonomously?

(NBVP): Functional Principle



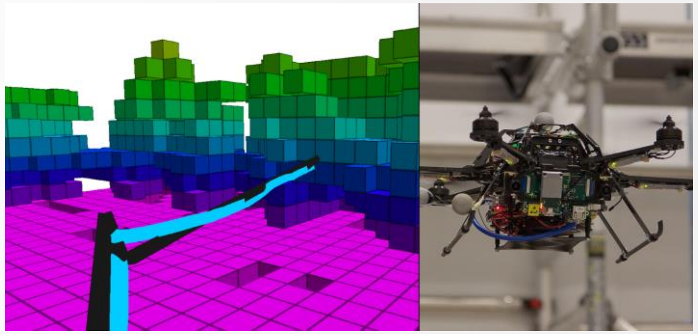
$$\mathbf{Gain}(n_k) = \mathbf{Gain}(n_{k-1}) + \mathbf{Visible}(\mathcal{M}, \xi_k) e^{-\lambda c(\sigma_{k-1}^k)}$$

Receding Horizon Next-Best-View

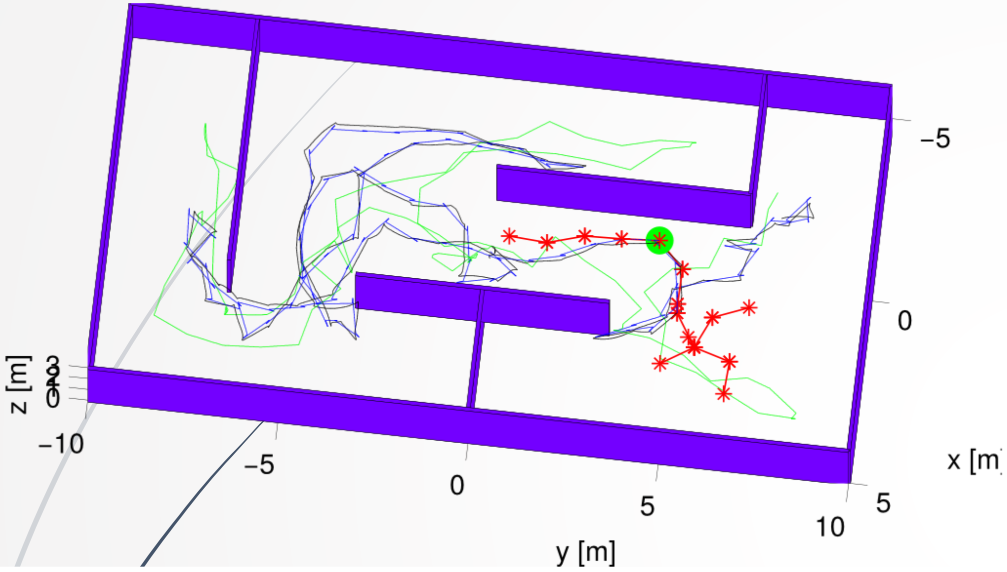
- **Versatility:** The algorithm can be formulated both based on the amount of volume to be explored as well as based on the area of the surface to be covered.
  - Perform autonomous exploration and derive volumetric map.
  - Use a surface-based receding horizon next-best-view-planner to perform a coverage/inspection mission or call an instance of the structural inspection planner.
- **Comparison against previous state-of-the-art:** frontier-based methods.
  - Receding Horizon Next-Best-View presents significantly improved rate of exploration and constantly manages to find full-exploration routes whereas frontier-based stuck.

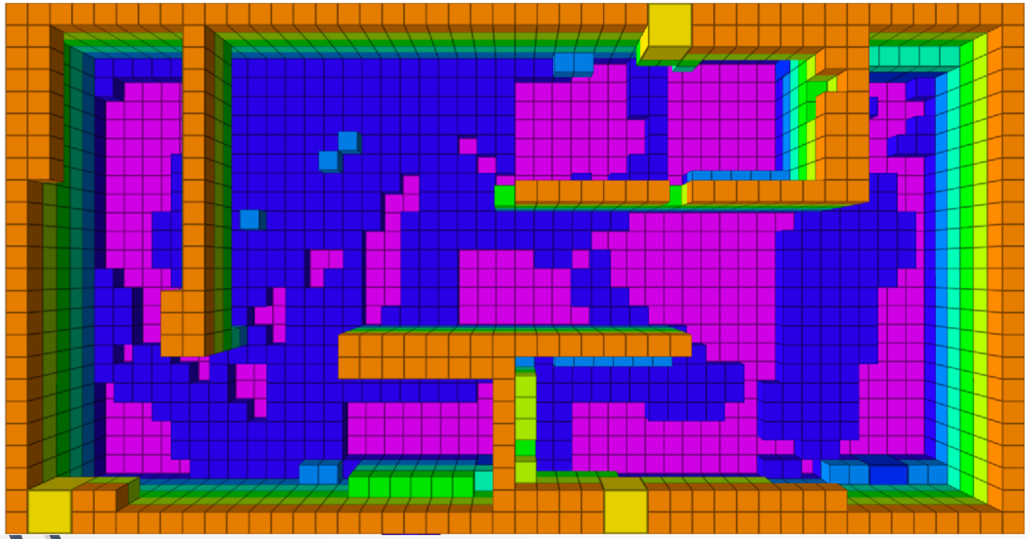
Exploration is conceptually a volumetric-mapping mission

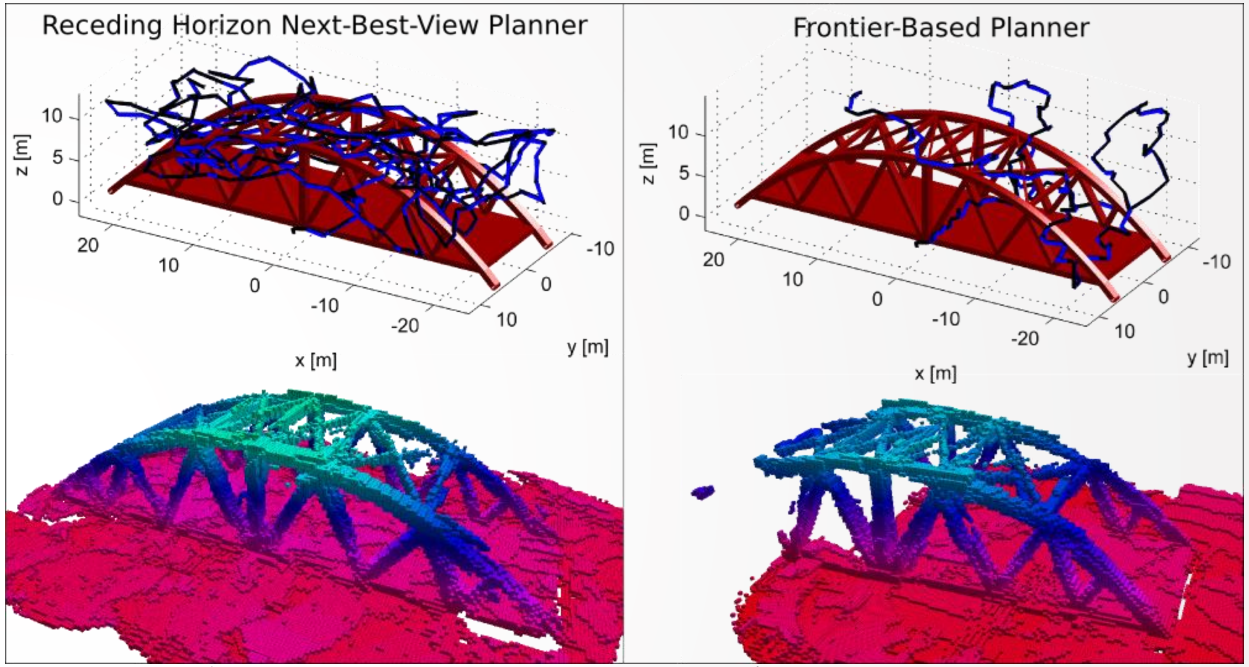
Inspection/coverage is conceptually a surface-mapping mission

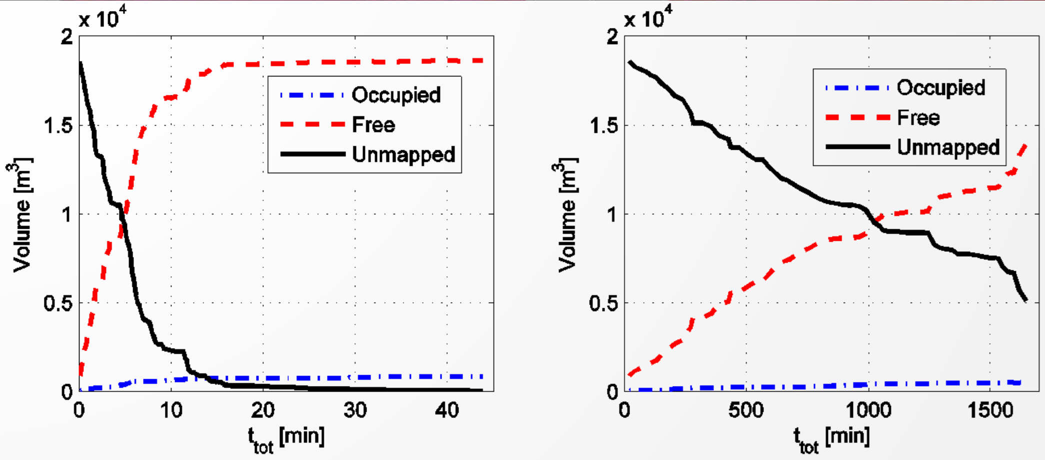


Receding Horizon Next-Best-View

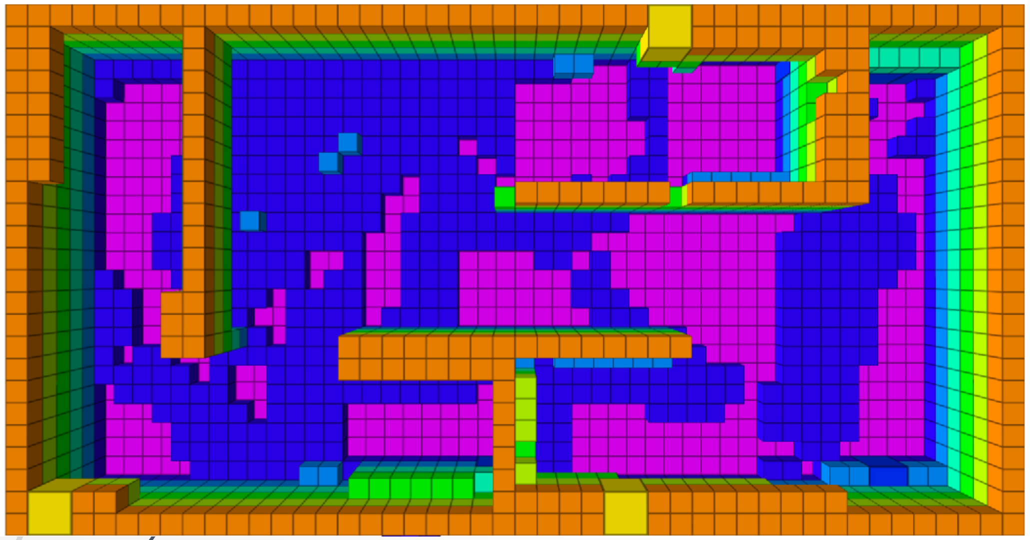


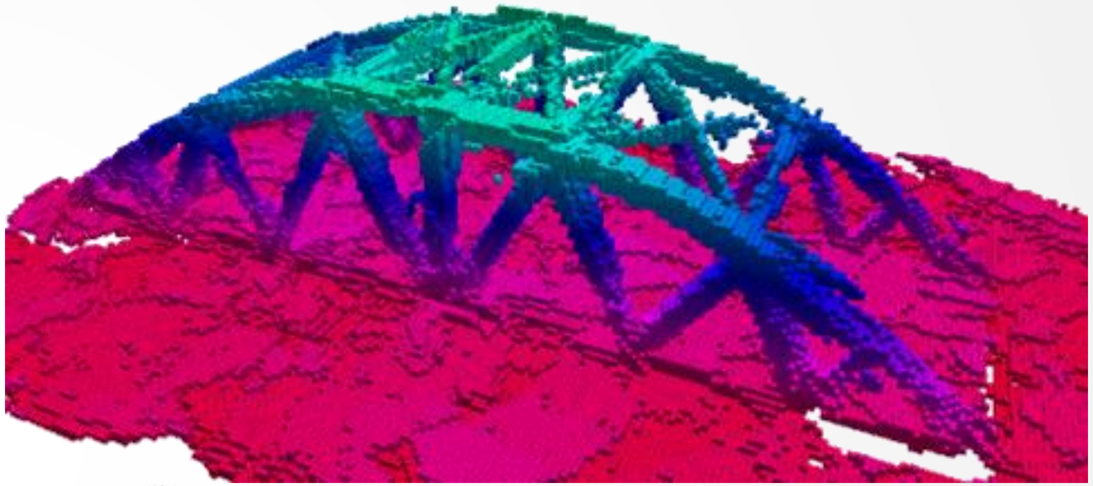


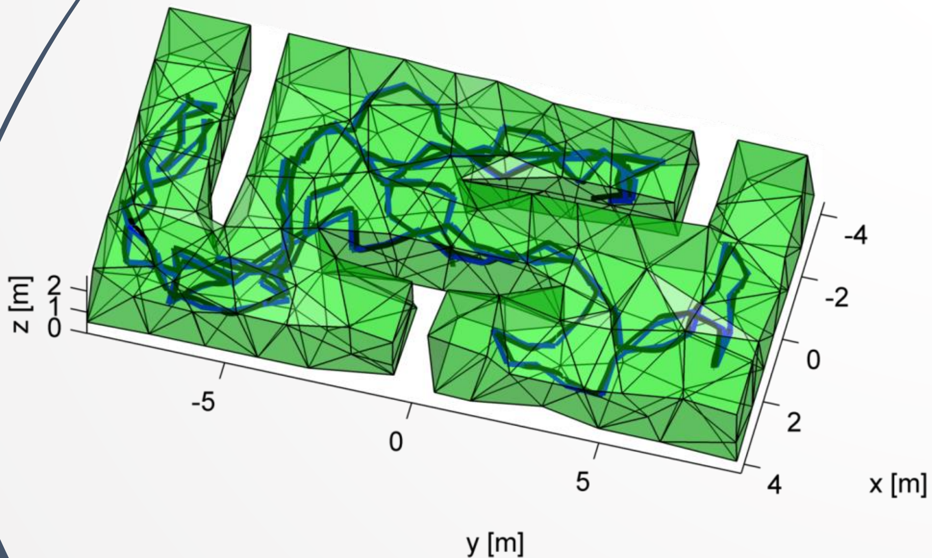


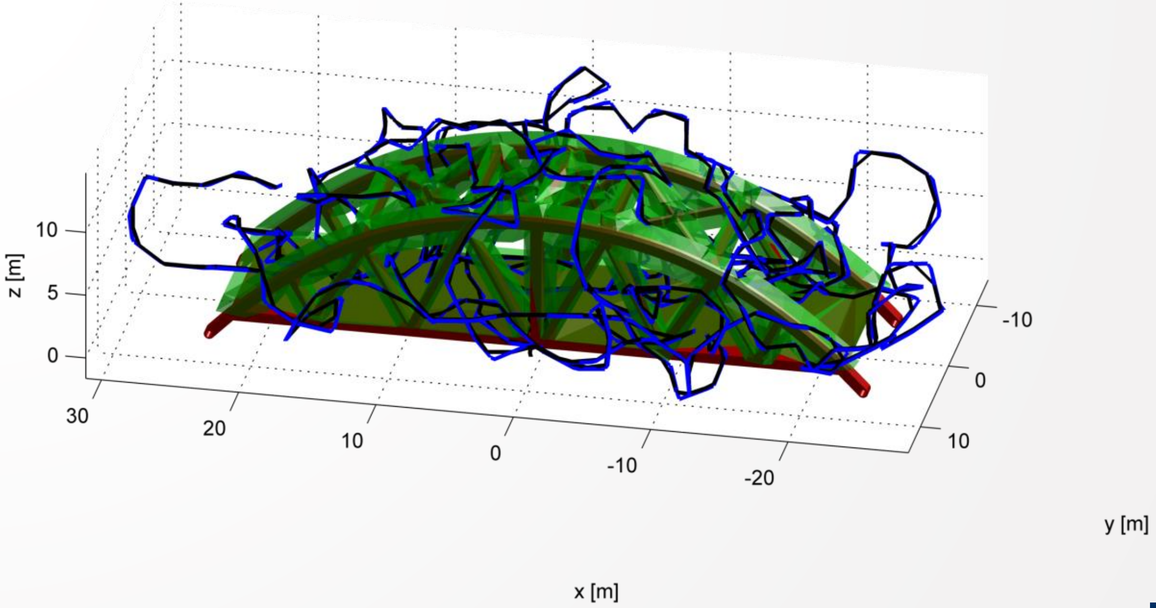


Receding Horizon Next-Best-View

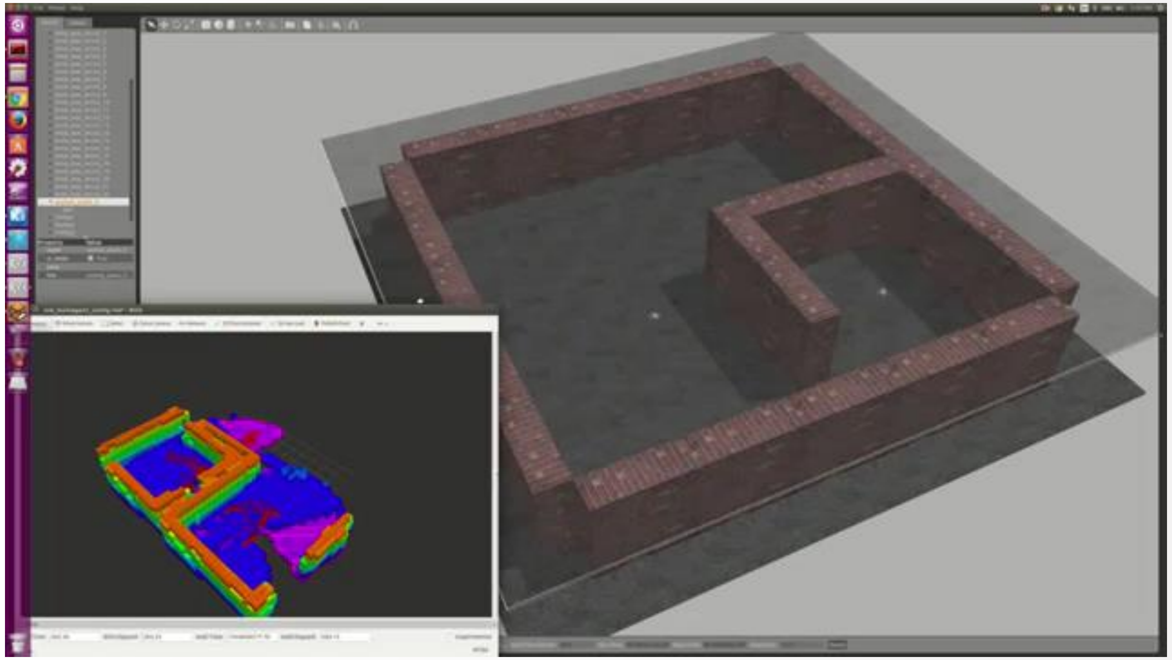








Receding Horizon Next-Best-View



Open Source Code

- **Open Source Code:**
  - Structural Inspection Planner:
    - https://github.com/ethz-asl/StructuralInspectionPlanner
  - Next-Best-View Planner:
    - https://github.com/ethz-asl/nbvplanner

- **Associated Datasets:**
  - Structural Inspection Planner:
    - https://github.com/ethz-asl/StructuralInspectionPlanner/wiki/Example-Results
  - Next-Best-View Planner:
    - https://github.com/ethz-asl/nbvplanner/wiki/Example-Results
  - Solar-powered UAV Sensing & Mapping:
    - http://projects.asl.ethz.ch/datasets/doku.php?id=fsr2015

What do I need to know? How do I start?

- **Motion Planning algorithms**
  - Deep understanding of motion planning algorithms.
- **Robot Dynamics**
  - Capability to model the robot dynamics and solve state-space sampling problems (require boundary value solvers) or control-space sampling.
- **Robot Localization & Mapping**
  - At the very minimum, understand Simultaneous Localization & Mapping as well as sensor modeling.

- **How do I start?**
  - Use the Open-Sourced code!
  - Use RotorS: https://github.com/ethz-asl/rotors_simulator
  - Learn ROS and one of the C++/Python
  - Contact us

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- Kostas Alexis, Christos Papachristos, Roland Siegwart, Anthony Tzes, "Uniform Coverage Structural Inspection Path-Planning for Micro Aerial Vehicles", Multiconference on Systems and Control (MSC), 2015, Novotel Sydney Manly Pacific, Sydney Australia. 21-23 September, 2015
- K. Alexis, G. Darivianakis, M. Burri, and R. Siegwart, "Aerial robotic contact-based inspection: planning and control", Autonomous Robots, Springer US, DOI: 10.1007/s10514-015-9485-5, ISSN: 0929-5593, http://dx.doi.org/10.1007/s10514-015-9485-5
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Thank you!

Please ask your question!