Efficient / Real-Time Volumetric Mapping

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M.Sc. Robotics, Cognition, Intelligence

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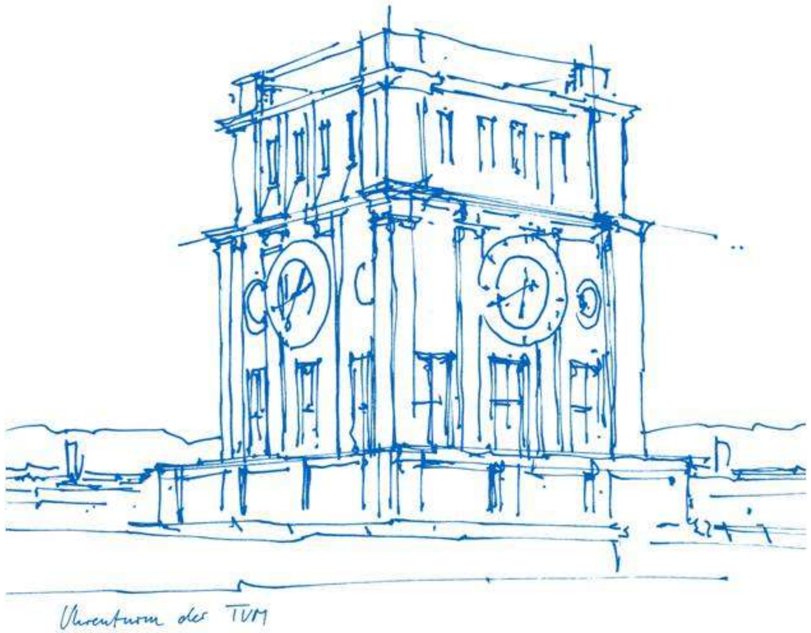
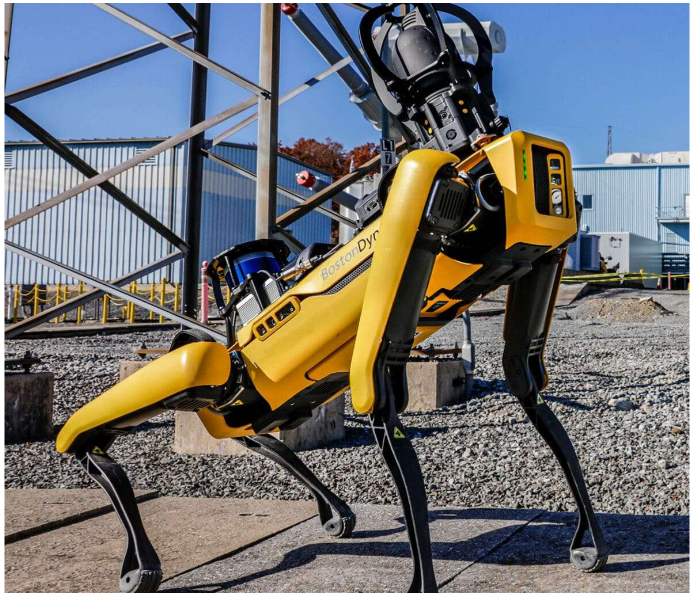
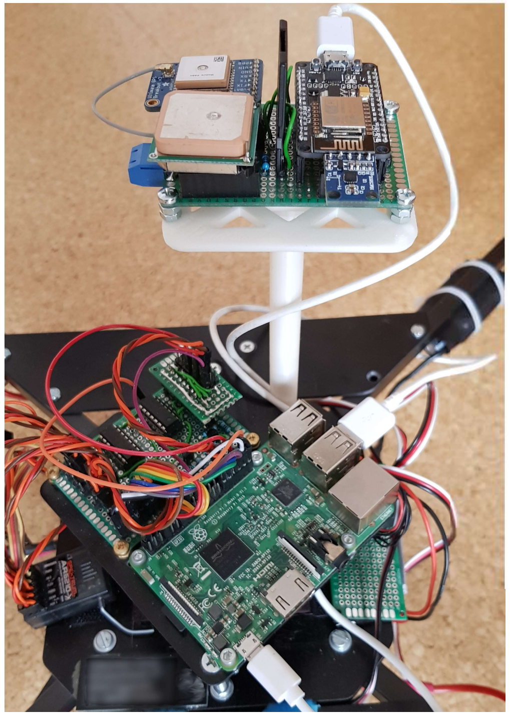


Motivation

https://bostondynamics.com/products/spot/



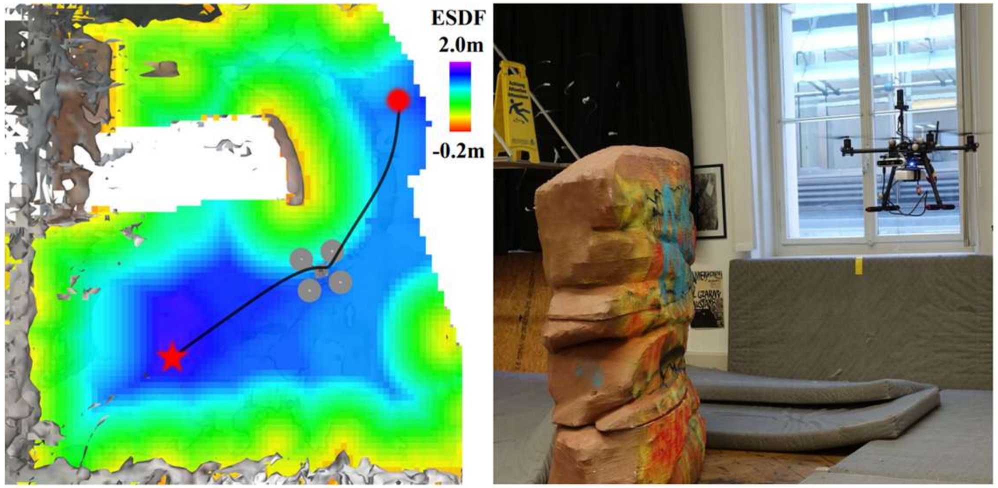


https://ouster.com/

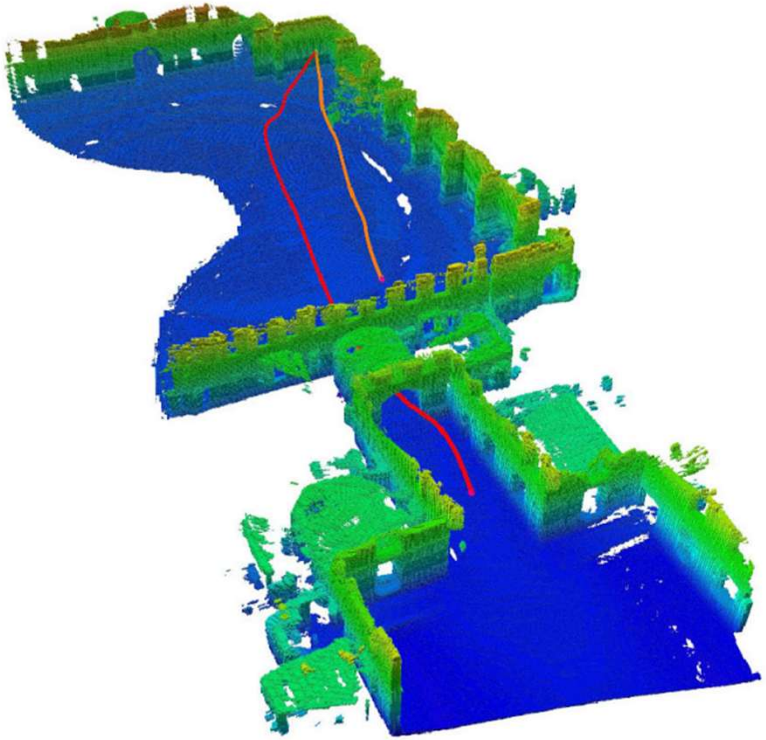
https://www.intelrealsense.com/depth-camera-d435i/

Motivation

Pan et al. 2022

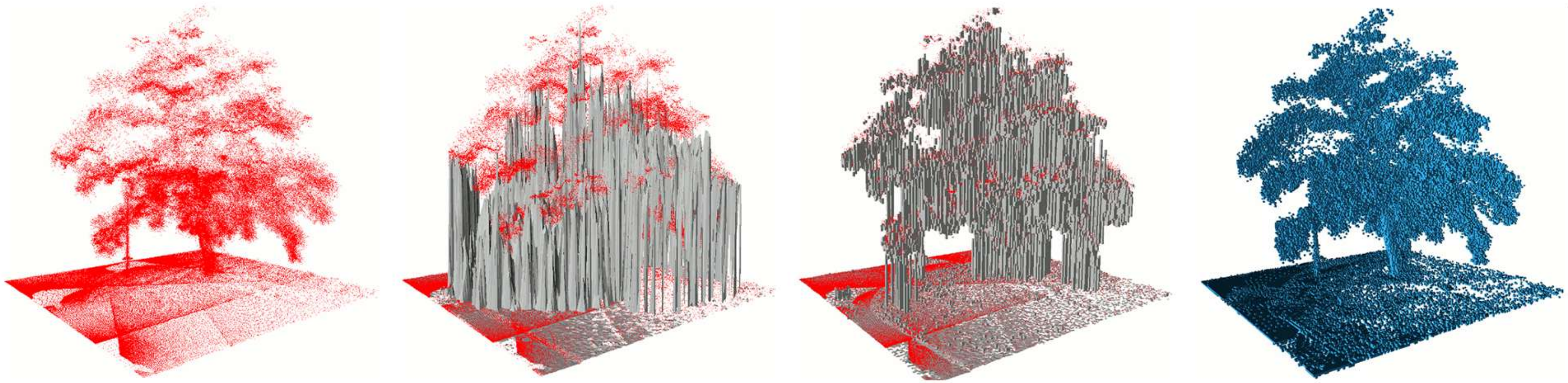


Funk et al. 2021



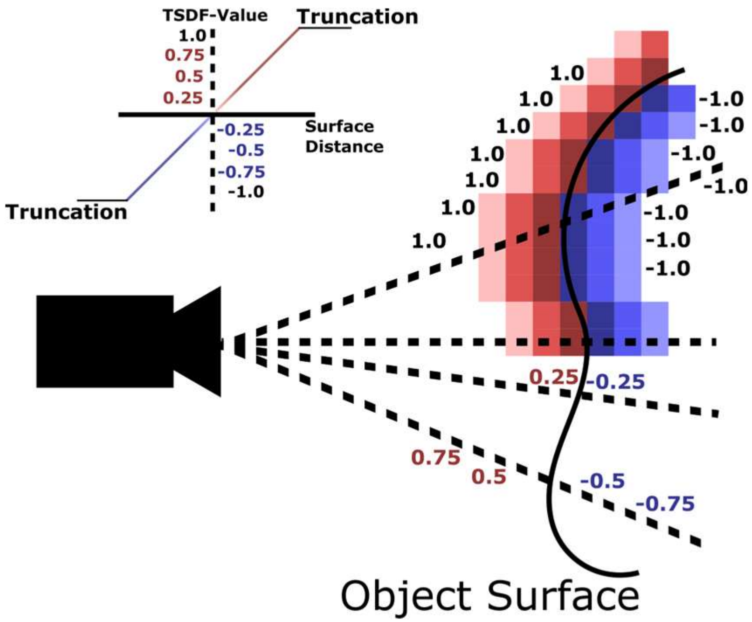
3D Scene Representations

Hornung et al. 2013



Point Cloud　Elevation Map　Multi-Level Surface Map　Occupancy Grid

Volumetric Representations



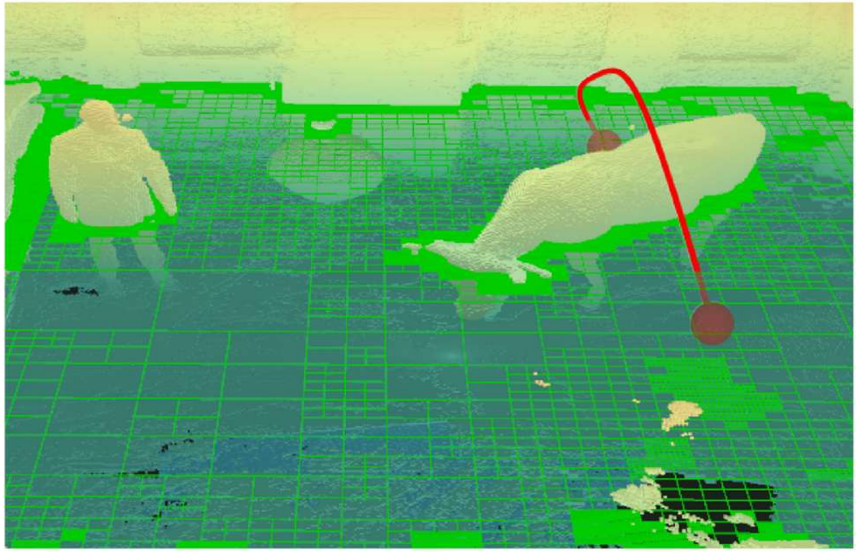
$$L(n|z_{1:t}) = L(n|z_{1:t-1}) + \log\left[\frac{P(n|z_t)}{1-P(n|z_t)}\right]$$

Challenges:

- Speed:
  - Frame integration
  - Collision detection/sampling
  - Simultaneous exploration & mapping
- State representation:
  - Free space
  - Occupied space
  - Unknown space

Volumetric Representations

Funk et al. 2021



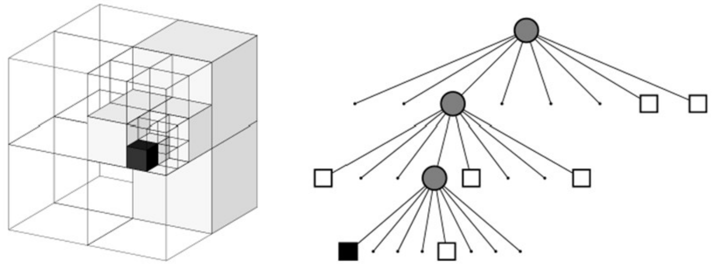
Challenges:

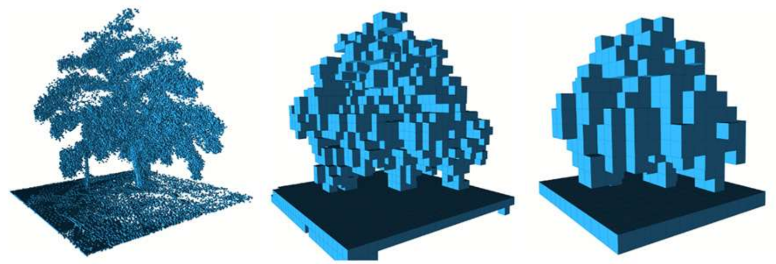
- Accuracy:
  - Robustness to sensor noise
  - Large-Scene representations
  - Detail preservation
- Memory-Efficiency: Voxel-Size?
  - $O(n^3)$ scaling for naive implementation

OctoMap(-RT)

- Probabilistic occupancy map
- Unknown Space: Implicit representation
- Slow pointcloud insertion
- No simultaneous mapping & exploration

- Rapidly improved by recent (-RT) paper
  - ➢ GPU accelerated ray tracing
  - ➢ Claims up to 40x faster integration



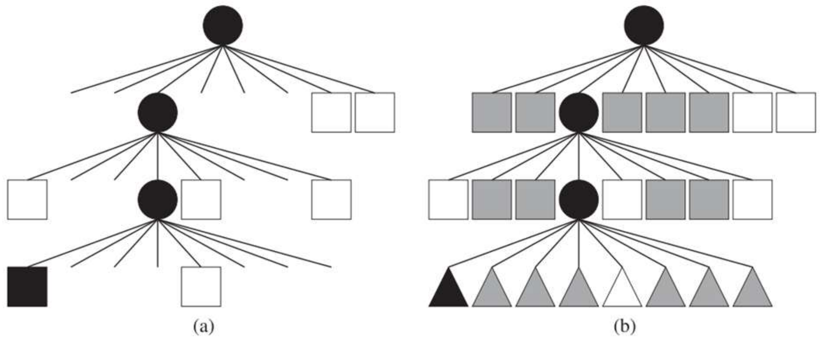


Hornung et al. (2013): OctoMap: An Efficient Probabilistic 3D Mapping Framework Based on Octrees. Autonomous Robots, pp. 189–206.

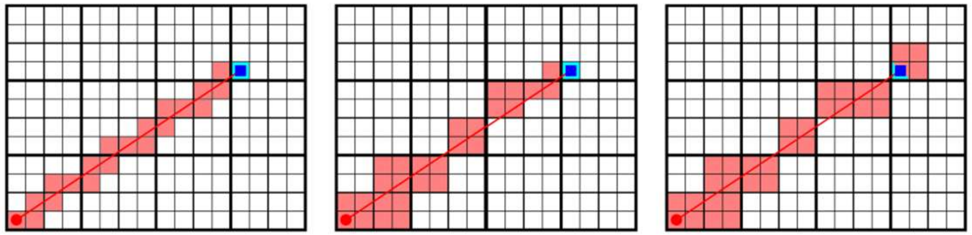
Min et al. (2023): OctoMap-RT: Fast Probabilistic Volumetric Mapping Using Ray-Tracing GPUs. Robotics and Automation Letters, pp. 5696–5703

UFOMap

- Octree representation
- Unknown space: explicit representation
- Ray tracing: Coarser strategies
- More efficient memory usage
- Faster insertion & accessing

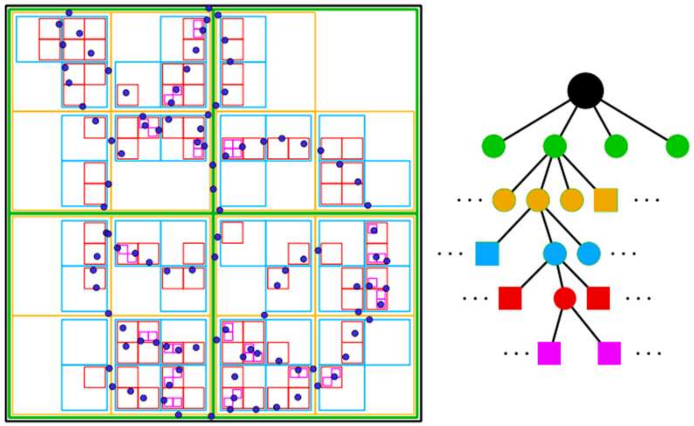


OctoMap UFOMap

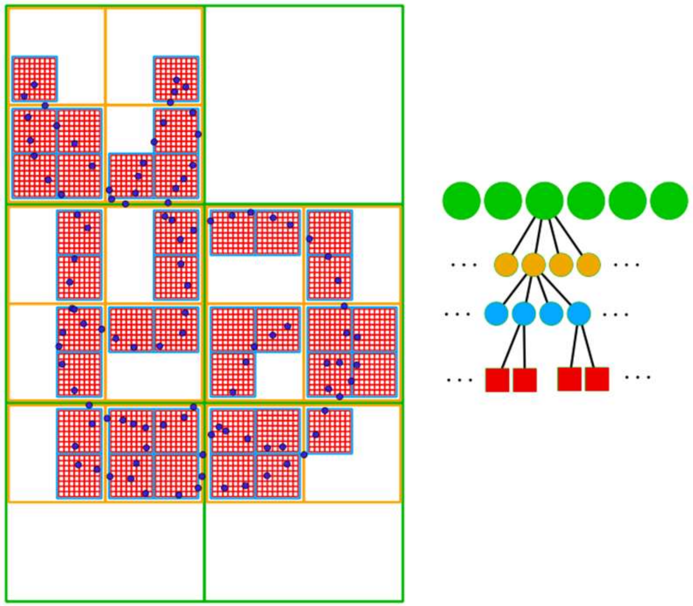


Duberg et al. (2020): UFOMap: An Efficient Probabilistic 3D Mapping Framework That Embraces the Unknown.
Robotics and Automation Letters, pp. 6411–6418.

VDB Mapping/Fusion



Octree



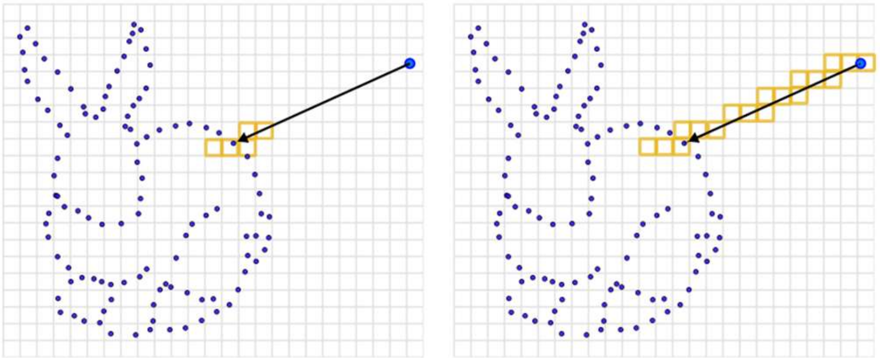
VDB tree structure

Besselmann et al. (2021): VDB-Mapping: A High Resolution and Real-Time Capable 3D Mapping Framework for Versatile Mobile Robots International Conference on Automation Science and Engineering, pp. 448–454.

Vizzo et al. (2022): VDBFusion: Flexible and Efficient TSDF Integration of Range Sensor Data. *Sensors*.

VDB Mapping/Fusion

- OpenVDB tree-datastructure
  - Direct access via bitmasks
  - Efficient insertion
  - Fixed tree height
  - Similar to memory footprint of OctoMap
- VDBFusion: TSDF integration
  - ➢ Non-Probabilisitic
- VDB-Mapping: Occupancy grid



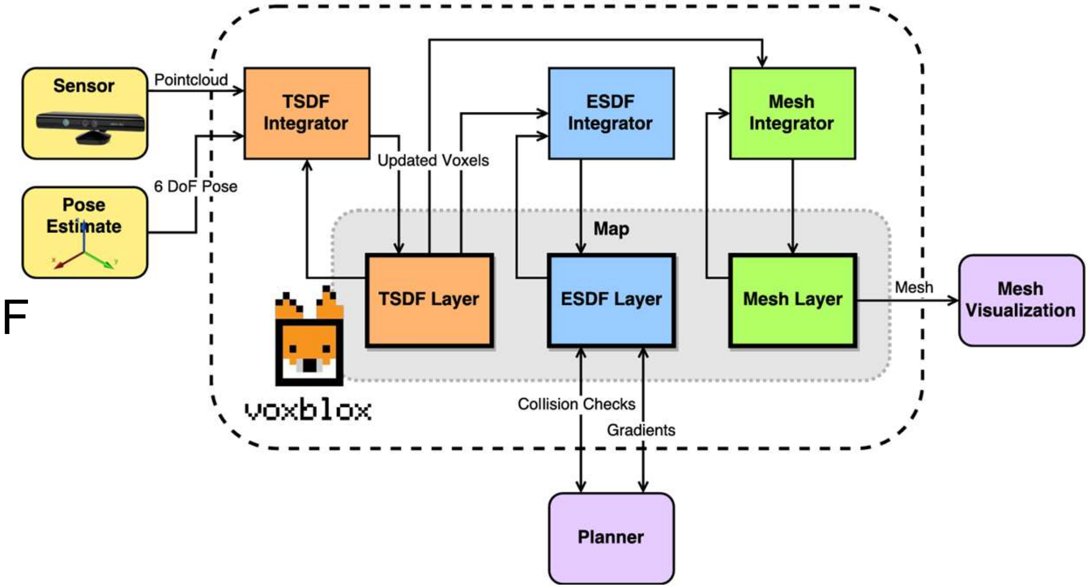
VDBFusion: Space carving is optional (but expensive)

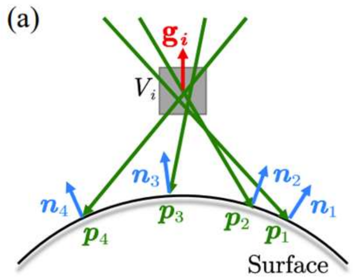
Besselmann et al. (2021): VDB-Mapping: A High Resolution and Real-Time Capable 3D Mapping Framework for Versatile Mobile Robots International Conference on Automation Science and Engineering, pp. 448–454.

Vizzo et al. (2022): VDBFusion: Flexible and Efficient TSDF Integration of Range Sensor Data. *Sensors*.

Voxblox/Voxfield

- TSDF + ESDF
- Voxel-hashing backbone
- „Grouped Raycasting“
- Weighted TSDF integration
- Voxfield: Non-Projective ESDF

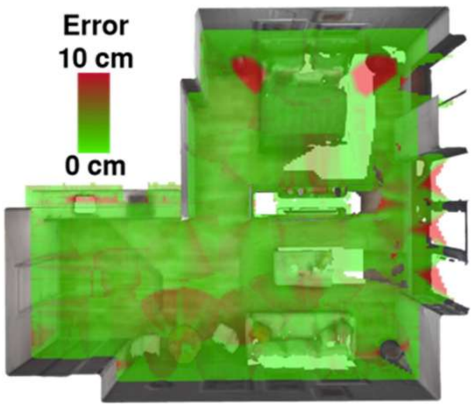




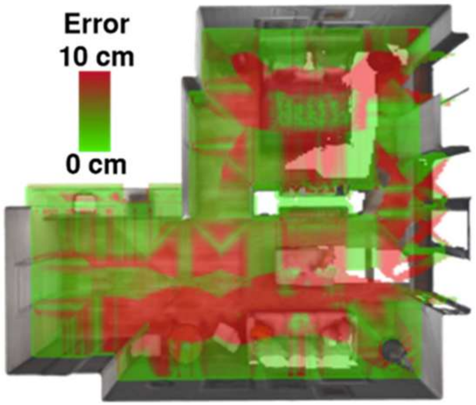
Pan et al. (2022): Voxfield: Non-Projective Signed Distance Fields for Online Planning and 3D Reconstruction. International Conference on Intelligent Robots and Systems, pp. 5331–5338.

Oleynikova et al. (2017): Voxblox: Incremental 3D Euclidean Signed Distance Fields for On-Board MAV Planning. International Conference on Intelligent Robots and Systems, pp. 1366-1373.

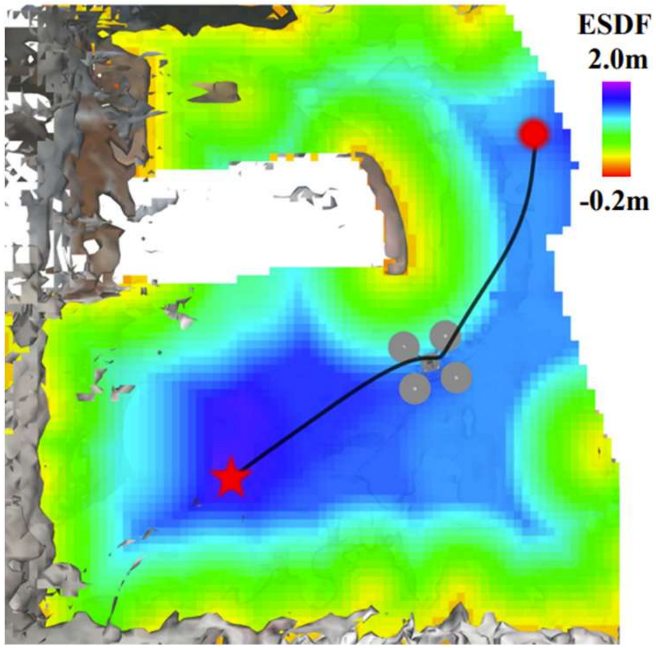
Voxblox/Voxfield



Voxfield



Voxblox



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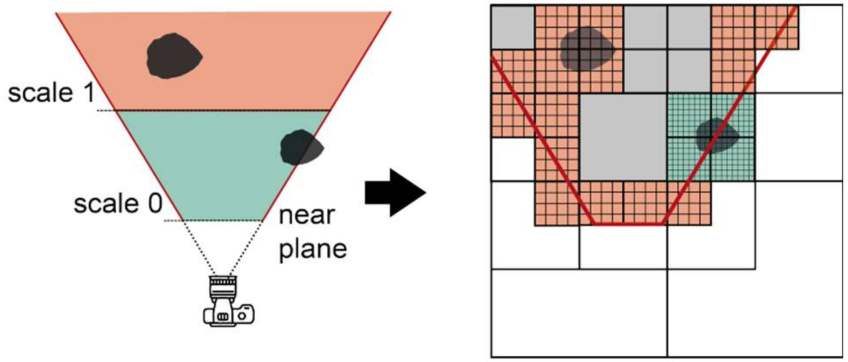
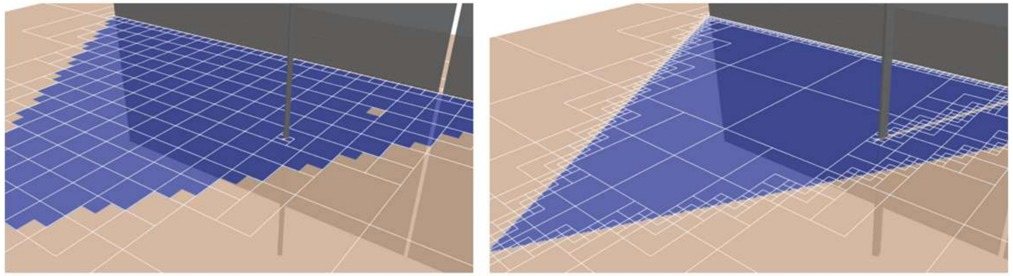
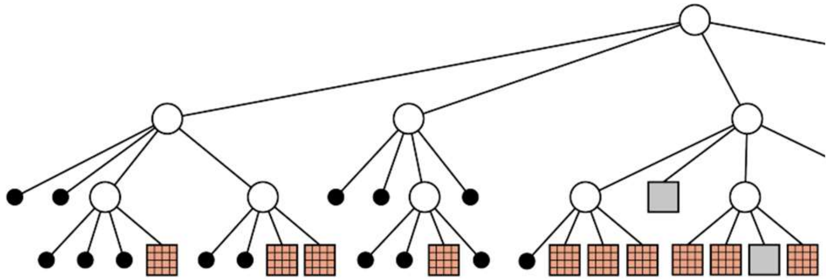
Supereight 2

- Aimed at higher resolutions than Voxblox/OctoMap
- Weighted probabilistic occupancy map
  - ➢ No costly ESDF for planning required





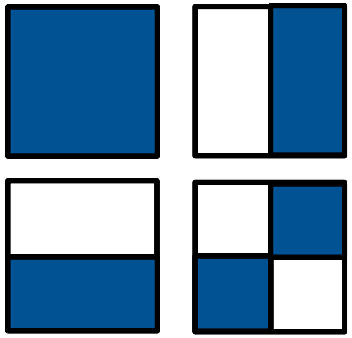


Heuristic (e.g., UFOMap) vs. Adaptive-Resolution Volume Allocation

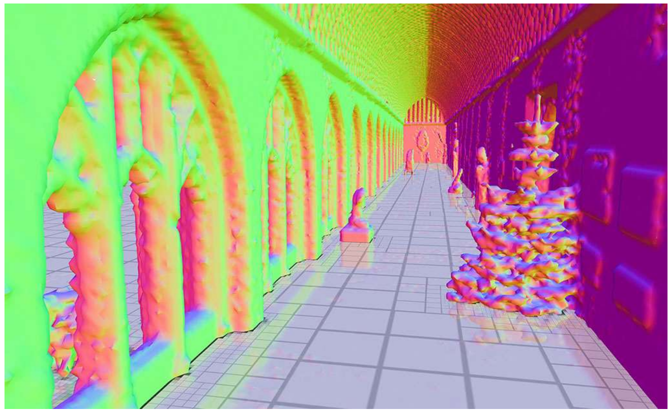
Funk et al. (2021): Multi-Resolution 3D Mapping With Explicit Free Space Representation for Fast and Accurate Mobile Robot Motion Planning. Robotics and Automation Letters, pp. 3553–3560.

Wavemap

2D Haar Wavelet:

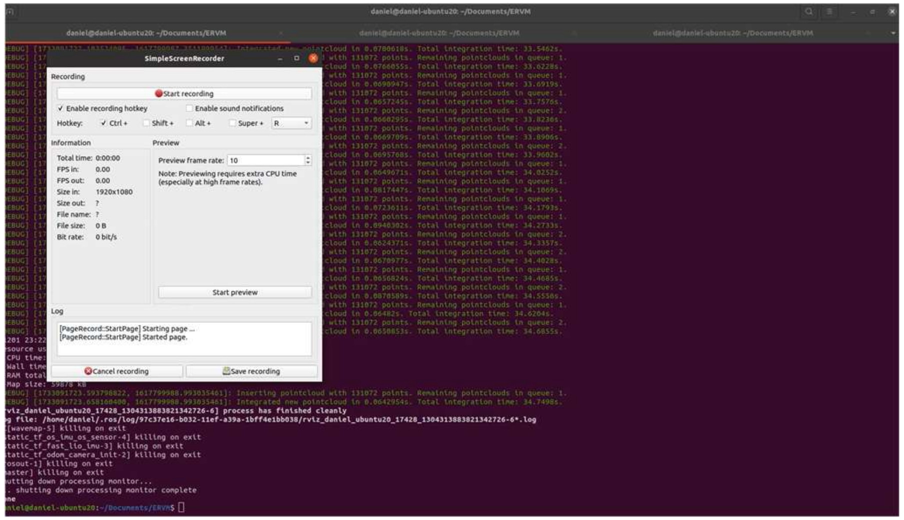


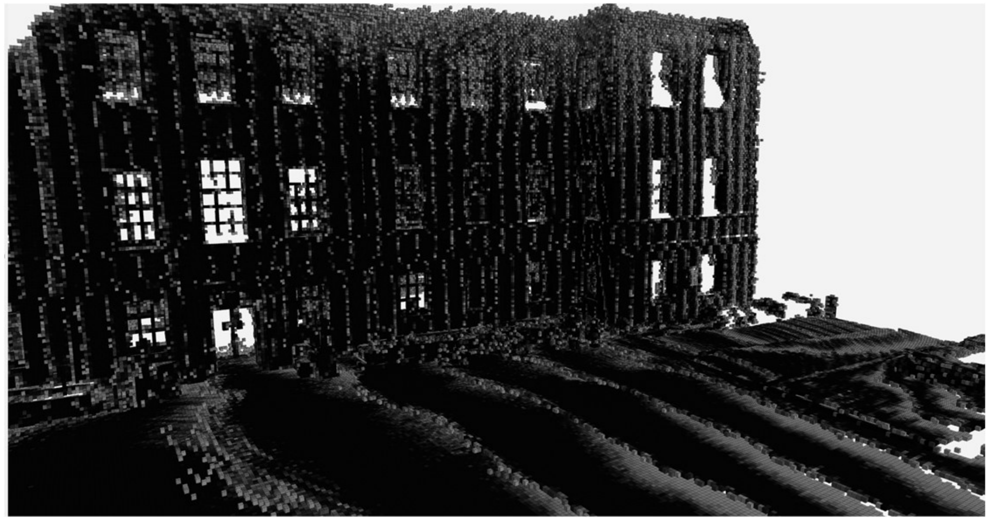
- Probabilistic occupancy map
- Only stores differences between resolution levels
- Coherent representation by construction
- Wavelet coefficients stored in Octree



Reijgwart et al. (2023): Efficient volumetric mapping of multi-scale environments using wavelet-based compression.
Robotics: Science and Systems.

Wavemap: Experiment





Evaluation: Efficiency

Reijgwart et al. 2023

Res	Framework	Memory (MB) RAM	Memory (MB) Map only	Time (s) CPU time	Time (s) Wall time
20cm	octomap	203.25	20.78	688.71	709.99
	supereight2	249.03	107.79	411.67	67.14
	voxblox	261.02	66.32	228.12	**48.07**
	ours (rays)	180.86	**6.94**	**87.39**	88.78
	ours (beams)	**138.92**	8.82	107.67	113.26
5cm	octomap	14404.76	981.02	36252.70	35790.60
	supereight2	2926.42	2333.93	2853.12	404.19
	voxblox	3718.85	2362.58	1788.90	**162.36**
	ours (rays)	1192.95	**241.84**	**1656.26**	1671.58
	ours (beams)	**1065.21**	402.18	2085.05	2083.61

Duberg et al. 2020

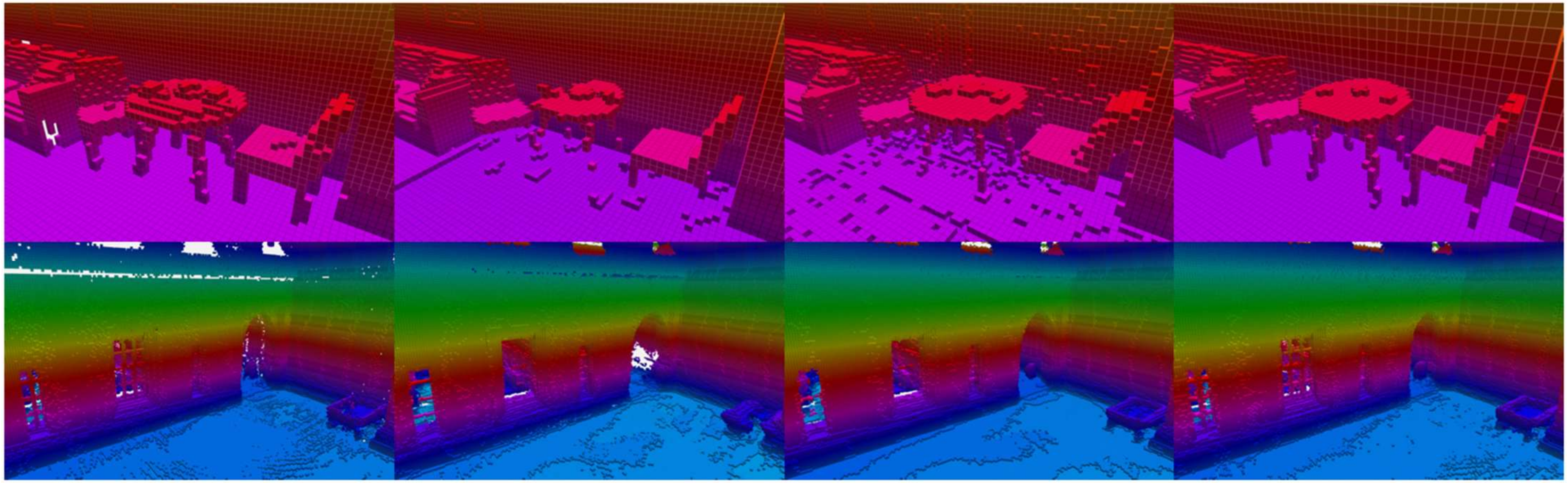
Method	Voxel size (cm)	Total (ms)	Ray casting (ms)	Insertion (ms)
UFOMap	4	60.9 ± 44.7	46.8 ± 32.7	14.1 ± 12.2
OctoMap		104.6 ± 82.2	71.8 ± 53.0	32.9 ± 30.1
UFOMap*		21.1 ± 12.0	14.3 ± 6.7	6.8 ± 5.4
UFOMap†		10.9 ± 4.7	9.3 ± 3.5	1.6 ± 1.3
UFOMap	2	371 ± 254	264 ± 176	107 ± 79
OctoMap		745 ± 548	521 ± 369	224 ± 188
UFOMap*		74 ± 44	42 ± 22	32 ± 22
UFOMap†		28 ± 15	20 ± 9	9 ± 7

Vizzo et al. 2022

Dataset	w/o Space Carving Voxblox	w/o Space Carving VDBFusion	w/ Space Carving Octomap	w/ Space Carving Voxblox	w/ Space Carving VDBFusion	Point cloud	Dense Voxel Grid	Octomap	Voxblox	VDBFusion
KITTI 07	10.11 fps	**19.57** fps	0.42 fps	0.60 fps	**1.37** fps	2.95 GB	30.6 GB	1.12 GB	n/a	**847.0 MB**
Cow and Lady	4.76 fps	**14.14** fps	**1.05** fps	0.42 fps	0.84 fps	8.57 GB	363.5 MB	124.5 MB	n/a	**122.9 MB**

Evaluation: Accuracy

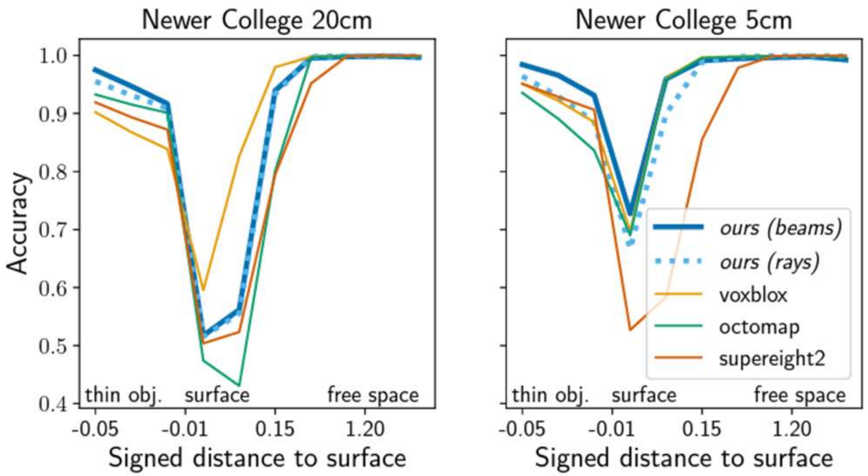
Reijgwart et al. 2023



octomap supereight2 voxblox ours (beams)

Evaluation: Accuracy

Reijgwart et al. 2023



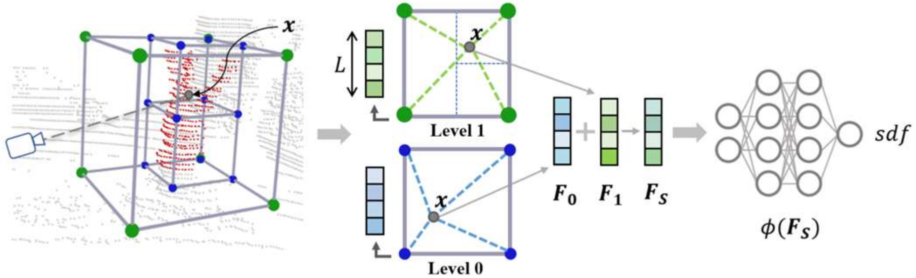
Vizzo et al. (2022)

Dataset	**w/o Space Carving**		**w/ Space Carving**		
	Voxblox	**VDBFusion**	**Octomap**	**Voxblox**	**VDBFusion**
KITTI 07	failed	**0.031** $\pm$ **0.102** m	0.033 $\pm$ 0.035 m	0.497 $\pm$ 1.991 m	**0.023** $\pm$ **0.022** m
Cow	0.236 $\pm$ 0.298 m	**0.049** $\pm$ **0.065** m	0.195 $\pm$ 0.262 m	0.319 $\pm$ 0.398 m	**0.045** $\pm$ **0.062** m

it.

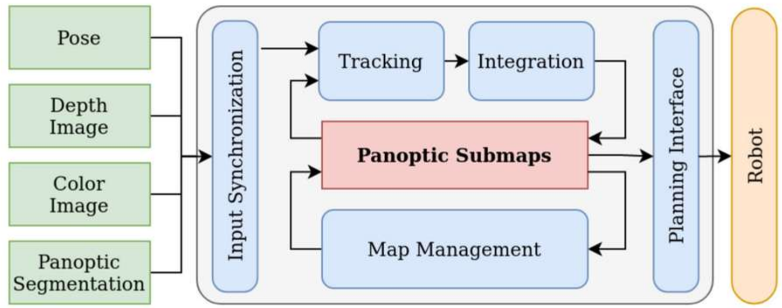
Additional/Future Work

SHINE-Mapping:



Zhong et al. (2023): SHINE-Mapping: Large-Scale 3D Mapping Using Sparse Hierarchical Implicit Neural Representations. International Conference on Robotics and Automation, pp. 8371–8377.

Panoptic Multi-TSDFs:



Schmid et al. (2022): Panoptic Multi-TSDFs: a Flexible Representation for Online Multi-resolution Volumetric Mapping and Long-term Dynamic Scene Consistency. International Conference on Robotics and Automation, pp. 8018–8024.

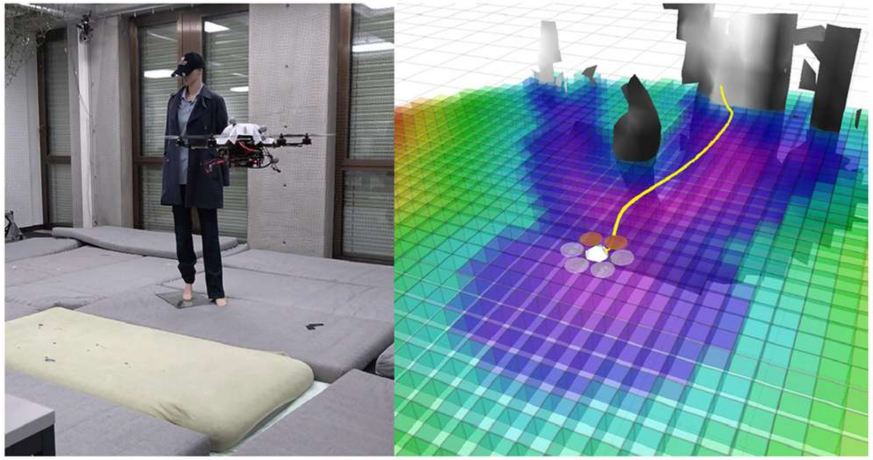
Conclusion

- Many methods available
- Up- / down sides: Use-case specific
- Example for good usability: VDB-Fusion

Best performing:

- Wavemap
- Supereight 2

Oleynikova et al. (2017)



Questions?
Go ahead!