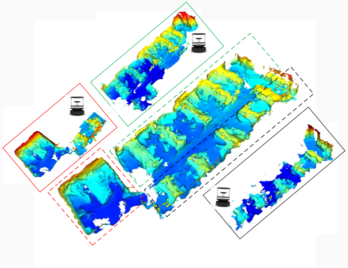

Coxgraph: Multi-Robot Collaborative, Globally Consistent, Online Dense Reconstruction System

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September 11, 2021

Why Multi Robot Reconstruction?

Rapid Exploration, Higher Redundancy, etc. compared to single robot systems

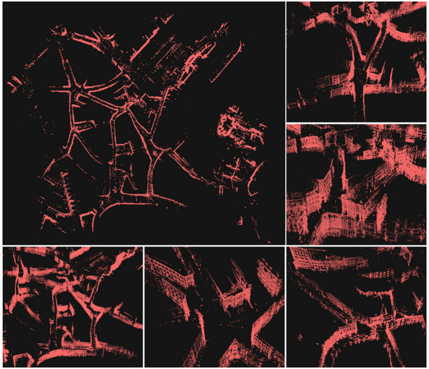


Figure 1: City-scale reconstruction

Figure 2: Search and rescue

Challenges

- maintenance of global consistency across all robots of both localization and dense maps, and
- the high bandwidth requirement for dense map data distribution limits its application in real world.

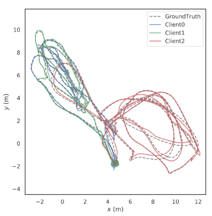


Figure 3: Multi-Robot Trajectory Alignment

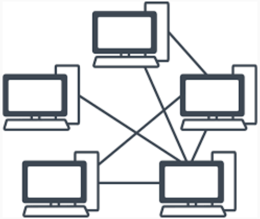


Figure 4: Multi-Robot Network Design

Related Work

- Multi Robot SLAM:

  1. CVI-SLAM 2. CCM-SLAM 3. CORB-SLAM 4. VINS-CLIENT-SERVER
- Multi Robot Reconstruction
  - Not considering global consistency
  - Only optimize local maps without frequent data exchange

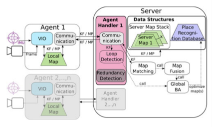


Figure 5: CVI_SLAM

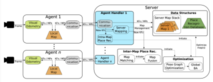


Figure 6: CCM_SLAM

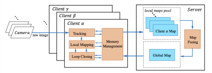


Figure 7: CORB_SLAM

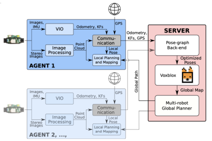


Figure 8: VINS_Client_Server

Contribution

1. We propose an efficient system named *Coxgraph* for centralized multi-robot collaborative dense reconstruction in real-time.
2. We present a compact transmission representation which enables transmitting local 3D submaps with minimal bandwidth requirement.
3. Our system achieves global consistency across robots, by extending online map fusion optimization and loop closure correction methods.

Framework

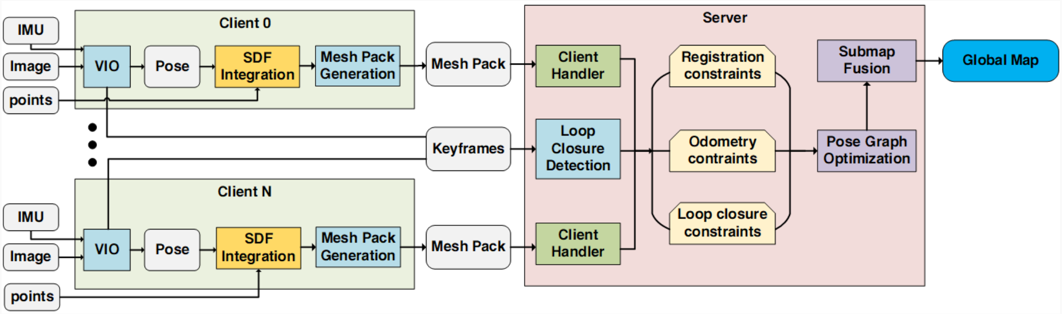


Figure 9: System Framework of Coxgraph

Submap Transmission

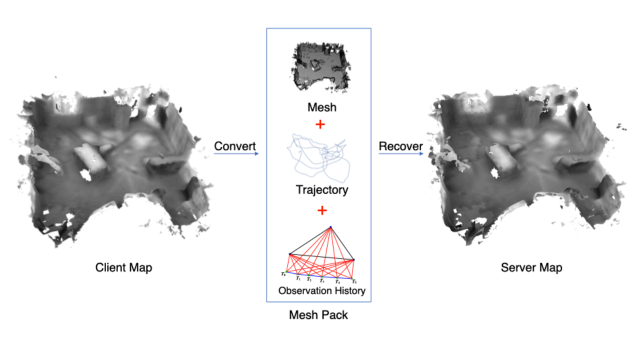


Figure 10: Components of *mesh packs*

Compressing TSDF submaps into *mesh packs*

1. mesh data of submaps $Mesh_i$, containing triangles.
2. frame indices i_{obs} of each mesh triangles when the corresponded voxels are observed, noted as observation history vectors hv.
3. trajectory in each submap.

Submap Transmission

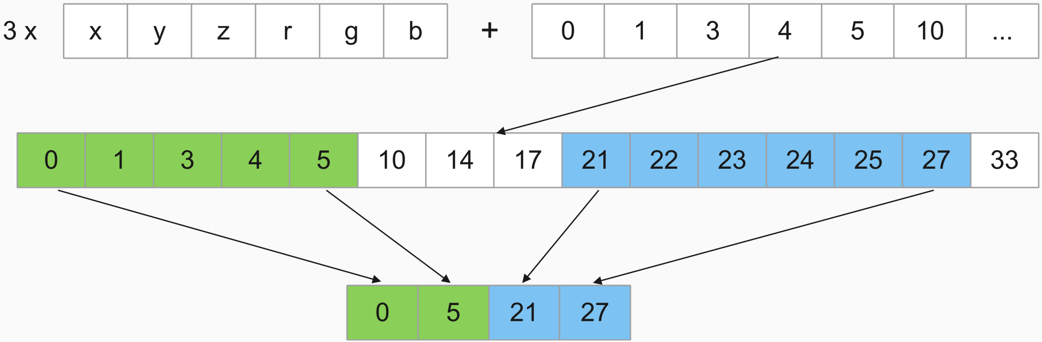
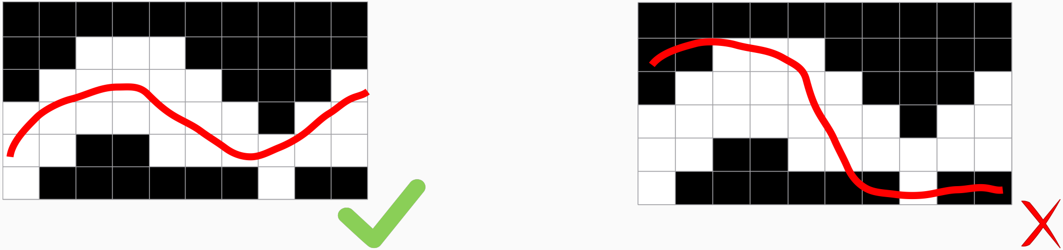


Figure 11: Frame indices trimming

Dense-Map-Based Outlier Rejection

1. Trajectory Collision Check: For every pair of loop closure candidates, the trajectory of one submap, if transformed to the other submap, it should still fall in free space in the second submap.



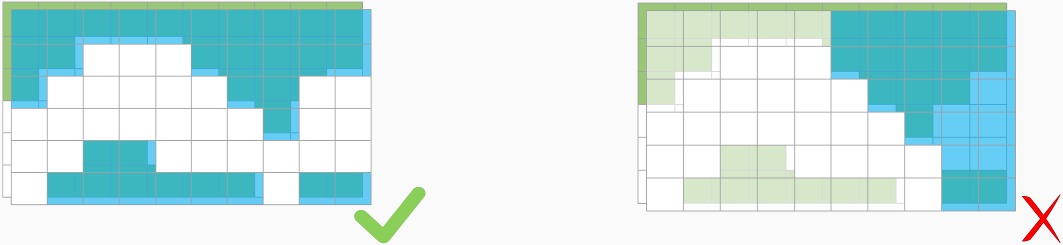
(a) Collision check correct

(b) Collision check wrong

Figure 12: Trajectory collision check examples

Dense-Map-Based Outlier Rejection

2. Fitness Check: Given a correct loop closure transformation, iso-surface points of one submap, if transformed to the second submap, should still fall in the iso-surface, within acceptable error.



(a) Fitness check correct **(b)** Fitness check wrong

Figure 13: Fitness check examples

Optimization

Three types of constraints are considered:

Loop Closure: Given a loop closure transformation T_{ab} between two frames, submap poses should be aligned accordingly.

$$T_{S_iS_j} = (T_{C_\alpha S_i} T_{S_i t_a})^{-1} T_{ab} (T_{C_\beta S_b} T_{S_b t_j}) \tag{1}$$

Therefore the loop closure constraint is given as:

$$e_{loop}^{i,j}(T_{WS_i}, T_{WS_j}) = \log(T_{WS_i} T_{S_iS_j} T_{WS_j}^{-1}) \tag{2}$$

Optimization

Odometry: Odometry-estimated relative poses $T_{S_k S_l}$ of submaps from the same client, between submap S_k and S_l, are added as constraints as following,

$$e_{pose}^{k,l}(T_{WS_k}, T_{WS_l}) = \log(T_{WS_k} T_{S_k S_l} T_{WS_l}^{-1}) \tag{3}$$

Optimzation

Registration:

The correspondence-free registration constraint proposed in *Voxgraph* is included in optimization. In conclusion, the principle is, the iso-surface point of the first submap, if transformed to a second submap, should also fall in iso-surface ideally, but if not, the distance values in voxels are able to represent the constraint residuals.

$$e_{reg}^{m,n}(T_{WS_m}, T_{WS_n}) = \sum_{i=0}^{N_{S_m}} r_{S_m S_n}(\boldsymbol{p}_{S_m}^{i}, T_{S_m S_n})^2 \qquad (4)$$

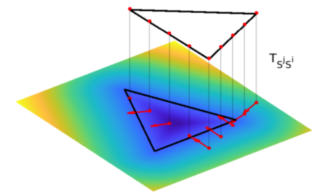


Figure 14: Correspondence-free alignment for a simplified example. (Figure from the paper of *Voxgraph*.)

Optimization

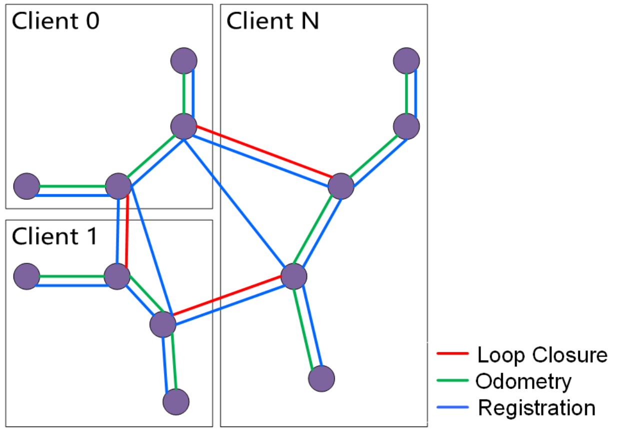


Figure 15: The pose graph.

Experiment

Submap Compression & Recovery: The proposed submap compression and recovery method is evaluated on both Machine Hall and Vicon Room 1 scene of EuRoC Dataset.

Scene	V1_01	MH_01	MH_02	MH_03
RMSE(m)	0.059	0.065	0.069	0.029

Table 1: Reconstruction error of the proposed SDF recovery method compared to original SDF map.

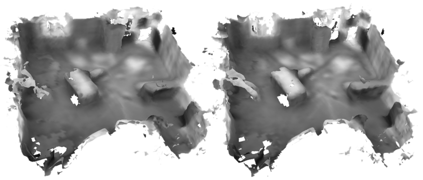


Figure 16: Comparison between meshes generated from original(left) and recovered(right) SDF maps of Vicon Room 1.

Experiment

Multi Robot Reconstruction: We reconstruct Machine Hall with flights MH_01, MH_02 and MH_03 of the EuRoC Dataset using depth maps generated from stereo cameras, evaluating the results on metrics of Absolute Trajectory Error (ATE), reconstruction error and average data size transmitted for submaps.

Method	MH_01	MH_02	MH_03	merged	merged mesh
direct	0.238	0.267	0.264	0.116	-
compression	0.247	0.269	0.262	0.129	0.111

Table 2: Surface reconstruction comparison between meshes generated from SDF transferred directly, transferred as mesh packs, and by combining mesh according to optimized submap poses. RMSE (m) values are reported.

Experiment

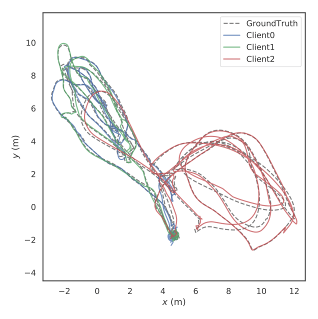


Figure 17: Trajectory comparison of 3 sequences.

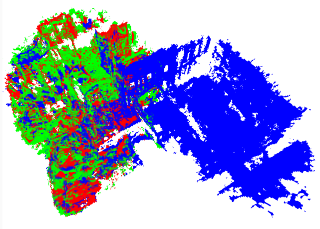


Figure 18: Merged map colored by sequence index.

Experiment

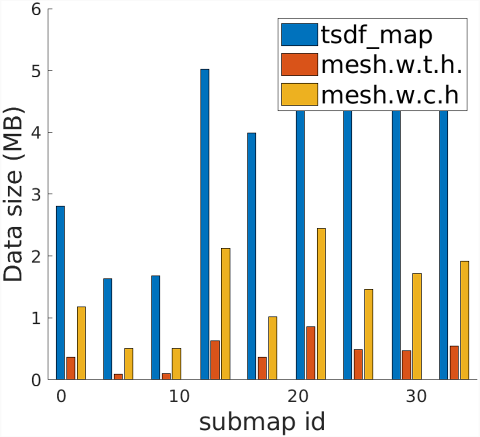


Figure 19

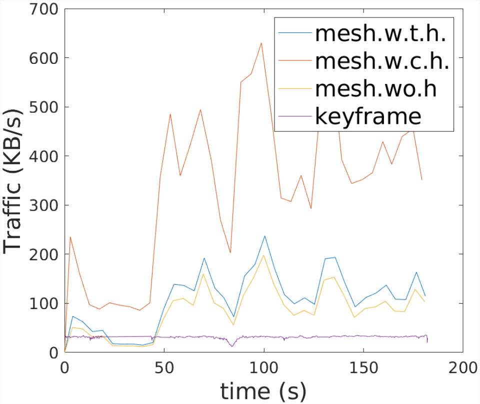


Figure 20

Experiment

Platform Experiment We reconstruct our lab, using three clients, using Realsense D435i depth cameras.

Message Type	Mean Bandwidth	Std Deviation
Keyframes	20.25 KB/s	6.58 KB/s
Mesh Packs	25.24 KB/s	11.70 KB/s

Table 3: Network traffic load of messages from clients to server during reconstruction of CVG lab.

Experiment

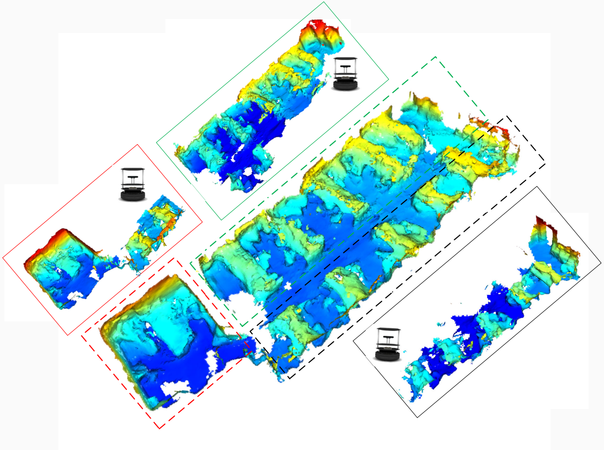
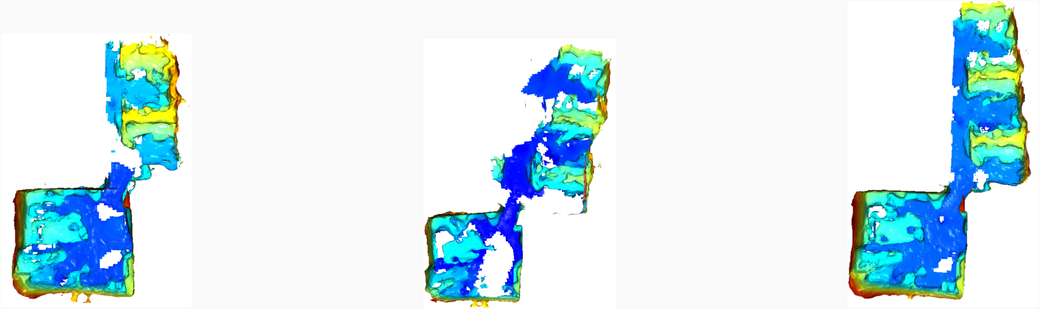


Figure 21: A multi-robot reconstruction result of CVG lab. The center picture shows the global mesh generated online by server, and the surroundings show meshes from three clients corresponding to different regions.

Experiment



(a) Client 0 **(b)** Client 1 **(c)** Global map

Figure 22: Global consistency maintaining ability of our system.

Using CORB-SLAM with RGBD odometry

Thank you!