Object-based Loop Closure with Directional Histogram Descriptor

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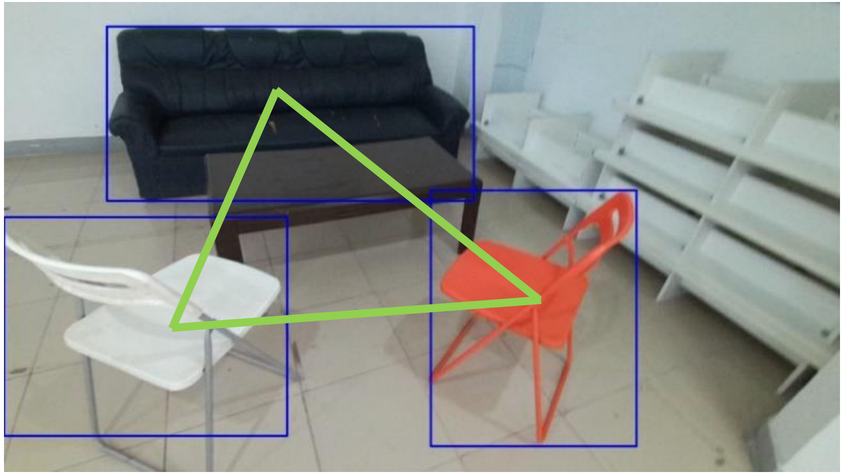
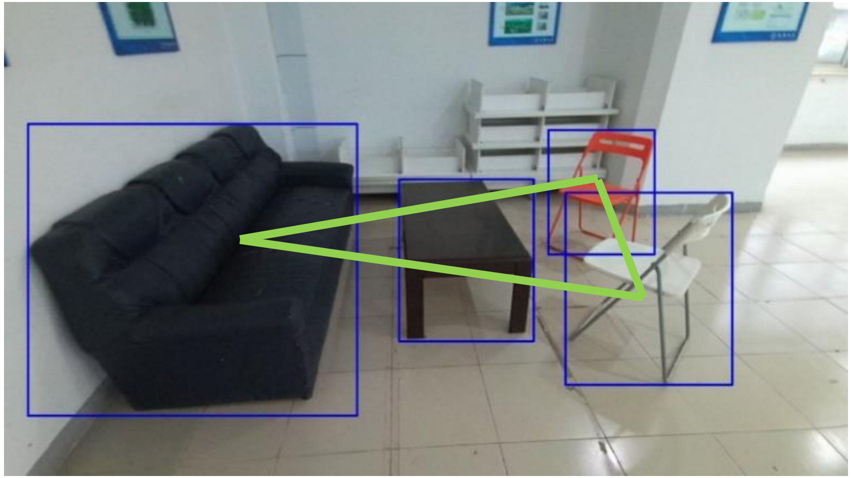
Background

- Mobile robots will produce inevitable accumulated errors because of sensor noise
- Traditional feature-based loop closure methods are sensitive to environment changes and failed to detect loop under large viewpoint difference.

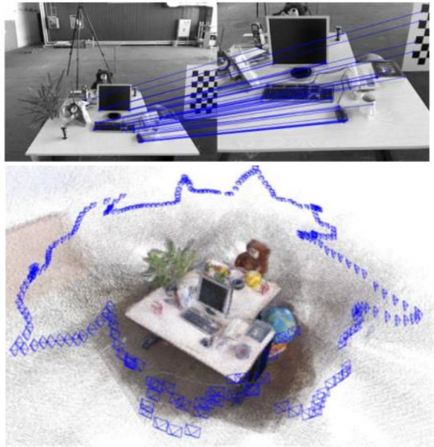
- Research problem: How to effectively detect the loop under large viewpoint difference?



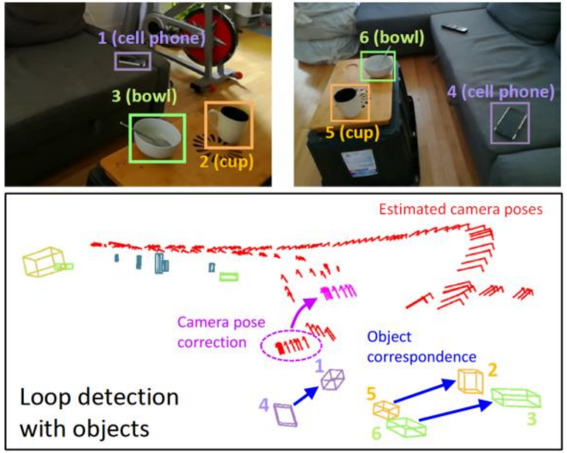


Related work

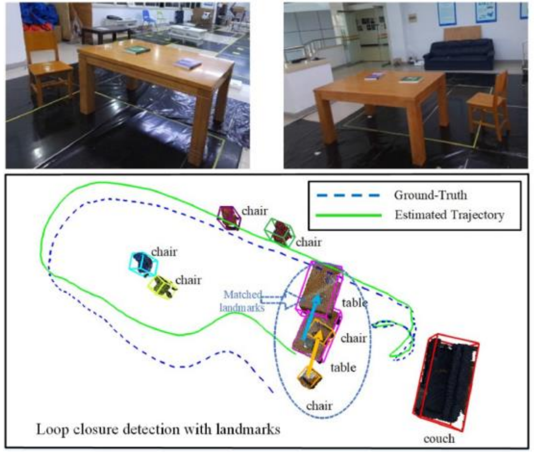
- Research problem: How to effectively detect the loop under large viewpoint difference?
  - ➢ feature-based loop closure: accurate, but sensitive to environment changes
  - ➢ object-based loop closure: robust to viewpoint changes but not accurate
  - ➢ our idea: feature-based + object-based loop closure



ORB SLAM 2: Loop detection with ORB features (Mur-Artal at al. 2017)



Loop detection with objects (Li, et al, 2020)



Loop detection with objects (Lin, at al, 2021)

Method: overall framework

Assumptions:
1) Use only RGB images.
2) Objects are static and, on the ground.
3) Objects can be viewed in different viewpoint.

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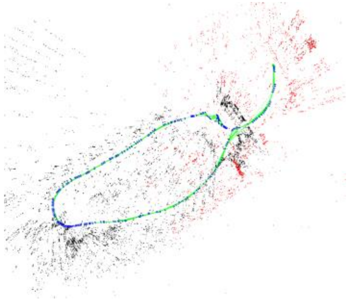
Feature based Loop Closure

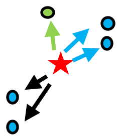
RGB Sequence → Camera Pose Tracking with ORB SLAM 2 → Object Mapping → Graph Construction and Descriptor Extraction → Object Loop Detection → Object Loop Correction

Object-based Loop Closure



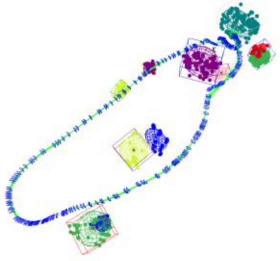
Sparse Point Map

Sparse Object Map



Direction Range	Chair	Sofa	Table	Book …
[-180°, -135°]	1	0	0	0
[-135°, -90°]	1	0	0	0
…	…	…	…	…
[0°, 45°]	2	0	0	0
[45°, 90°]	0	0	0	0
[90°, 135°]	0	1	0	0
[135°, 180°]	0	0	0	0

Graph Example with Directional Histogram Descriptor

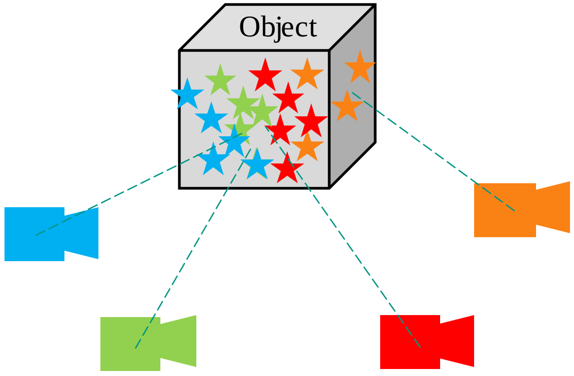


Corrected the drift

IFL

Method: object mapping

- How to detect objects in the environment?
- Object Representation: 3D bounding box with
  class, translation, rotation, dimension, feature points
- Object Detection: YOLOv5, collect the feature points that belongs to the object.
- Object Association: In every frame, check detected objects has a large 2D IoU (>0.5) with mapped objects, if so, merge them, if not, add a new object to the map.

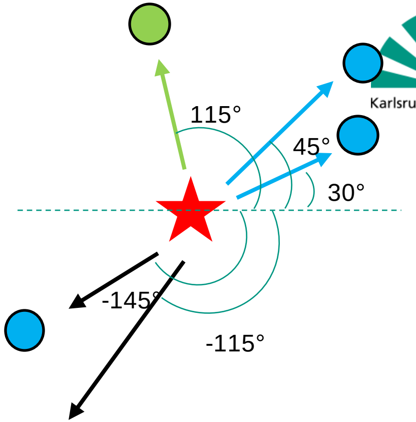


Object detection example

Method: graph construction

- How to represent the environment (not only the objects but also their relationship)?
- Graph (G) = {N, E},
  - Node (N): = {ID, Class, Centroid, Descriptor, Others},
  - Edge (E): = {distance_ij , yaw_ij}

Algorithm 2: directional histogram descriptor
Input: O: Object landmarks;
Output: V: directional histogram descriptor for O;
1. **for** o in objects **do**
2. neighbor ← find the closest 8 objects;
3. **for** n in neighbor of o **do**
4. direction: a ← calculate the direction(n,o);
5. label: ln ← record the object label;
6. histogram ← the histogram cell Vo(a,ln) +1;
7. **end for**
8. add Vo to into V;
9. **end for**



Graph Example

Yaw Angle Range	Chair	Sofa	Table	Book
[-180°, -135°]	1	0	0	0
[-135°, -90°]	1	0	0	0
…	…	…	…	…
[0°, 45°]	2	0	0	0
[45°, 90°]	0	0	0	0
[90°, 135°]	0	1	0	0
[135°, 180°]	0	0	0	0

Directional Histogram Descriptor

Method: loop detection

- How to detect loop with object information?
- General check: same class and ID difference > 3

$$\eta(a,b) = |ID_a - ID_b| \quad (a \in L_a, b \in L_b)$$

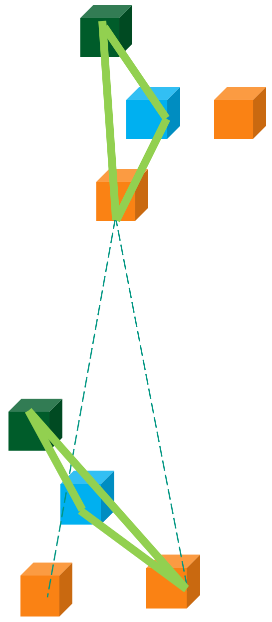
- Graph check: the similarity score of their directional histogram descriptor > 0.8

$$\mathrm{Score}(\mathrm{A},\mathrm{B}) = \frac{\sum_{d=1}^{n_d} A_d \times B_d}{\sqrt{\sum_{d=1}^{n_d} (A_d)^2} \times \sqrt{\sum_{d=1}^{n_d} (B_d)^2}}$$

- Geometry check: at least 3 objects are matched, and their scale factor < 0.01

$$s_{12} = |dis_{a_1,a_2}| \,/\, |dis_{b_1,b_2}| \qquad \delta = \sqrt{(s_{12}-\overline{s})^2 + (s_{23}-\overline{s})^2 + (s_{13}-\overline{s})^2}$$

- Duplicated check:



Geometry verification example

Method: loop correction

- How to correct the drift after the object loop is detected?
- General idea: compute a similarity transformation that satisfy:

$$O_a = sR * O_b + t$$

- However, use only object information may cause errors, because the object detection is not so accurate, instead, we take the associated map points and compute a scaled ICP.
- The scale ratio is computed by:

$$s = \frac{1}{n} \sum \frac{|dis_{a_1,a2}|}{|dis_{b_1,b_2}|} + \cdots + \frac{|dis_{a_n,a1}|}{|dis_{b_n,b_1}|}$$

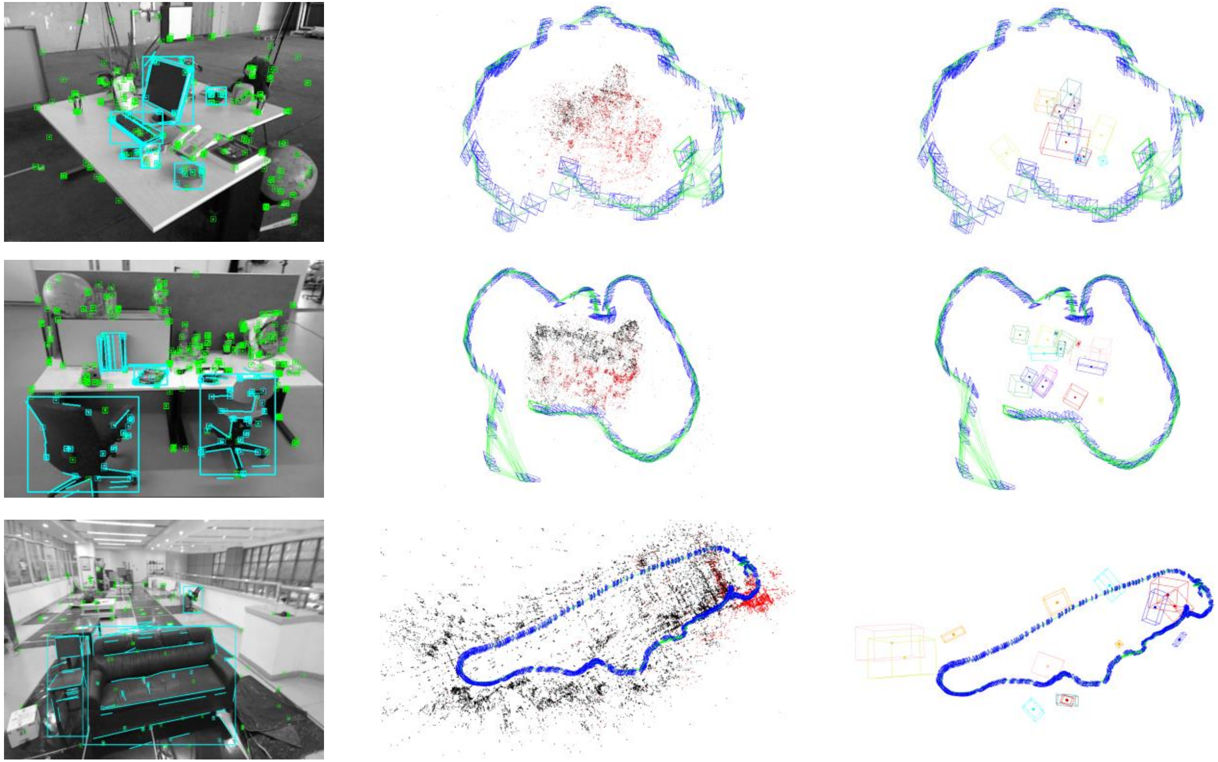
- Then, we scale the associated map points and compute the rigid transform (R, t) by minimizing the sum of squared error

$$(R^*, t^*) = \underset{R,t}{\operatorname{argmin}} \sum_{k=1}^{N_p} \|p_{a,k} - sR * p_{b,k} - t\|^2$$

Experiments

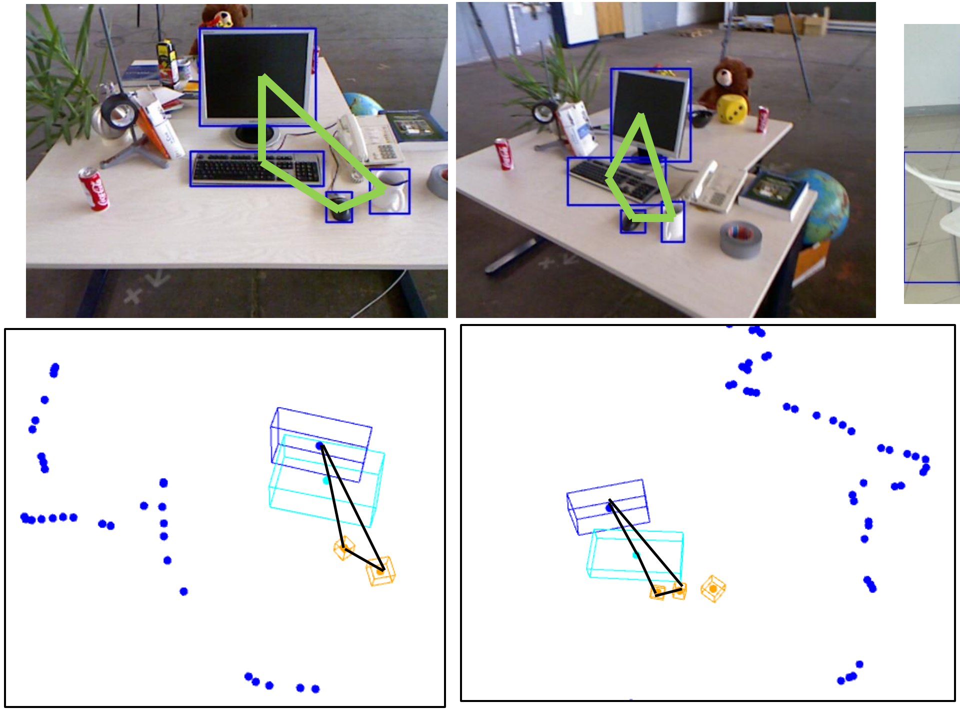
- Datasets:
  - TUM RGB-D Dataset
  - USTC RGB-D Dataset
- Metrics:
  - Object mapping performance
  - Loop detection performance
  - Localization performance

Experiments – object mapping performance

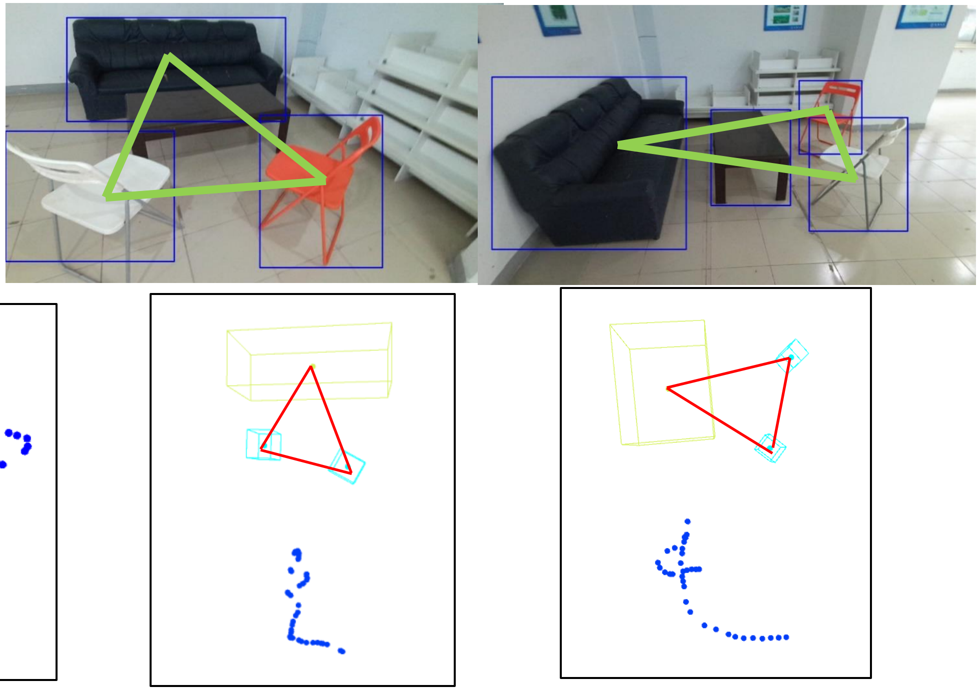


images feature point map object oriented map

Experiments – loop detection performance

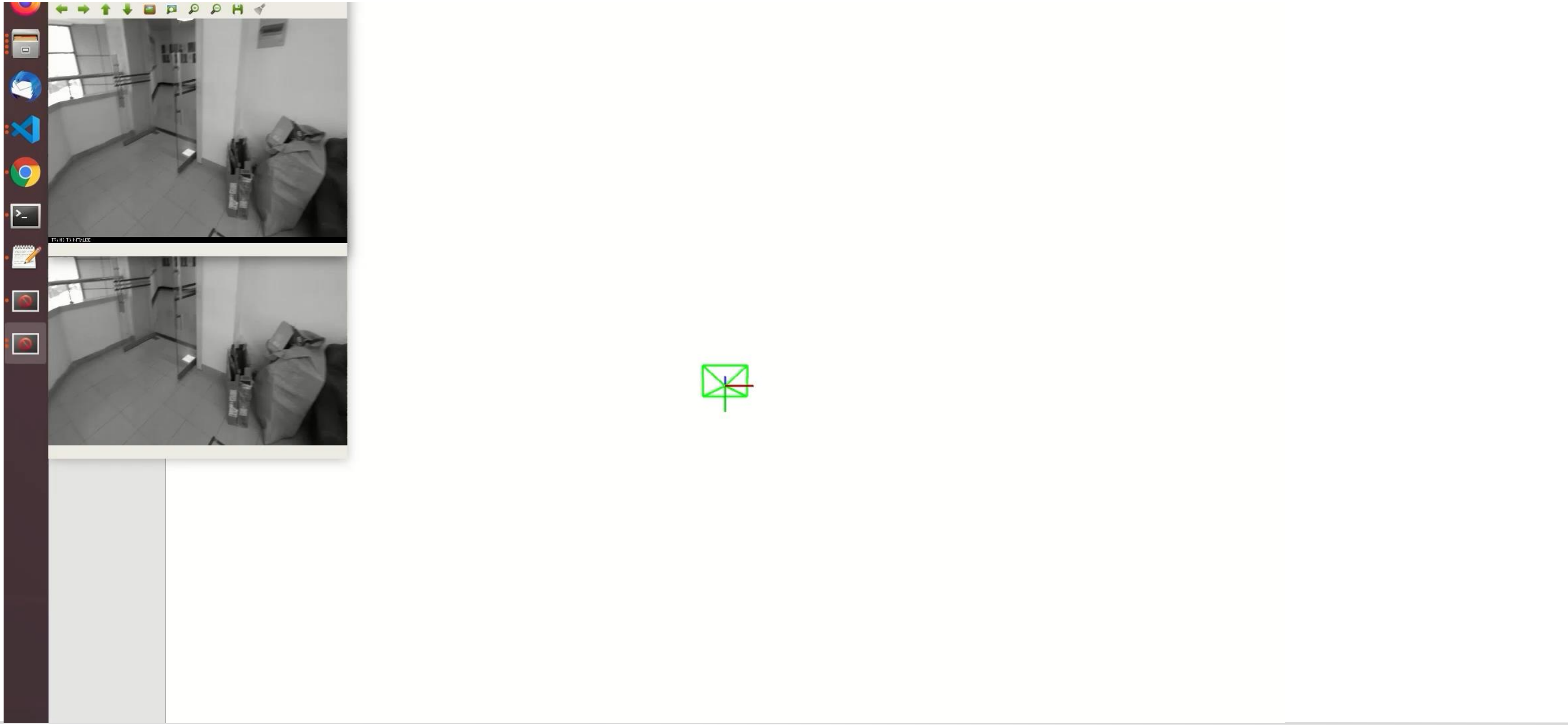


fr2_desk sequences



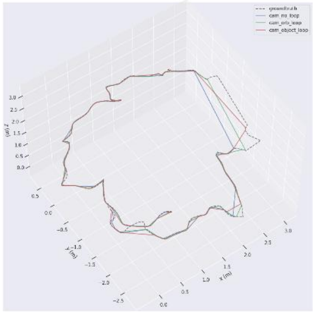
ustc_07 sequence

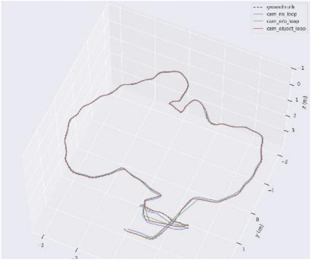
Experiments – offline video

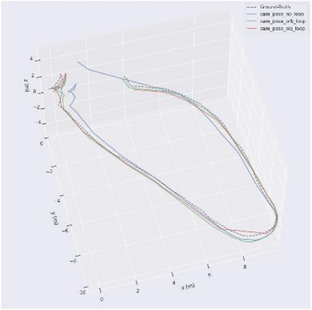


Experiments – localization result

Sequence	ORB SLAM without loop closure (m)	ORB SLAM with feature-based loop closure (m)	Ours (object and feature-based loop)
fr2_desk	0.012499	**0.007723**	0.008851
fr3_long_office	0.034488	**0.012362**	0.013587
ustc_01	1.515137	1.515137	**0.268989**
ustc_02	0.733596	0.733596	**0.191738**
ustc_03	4.399249	4.399249	**0.742086**
ustc_07	0.733087	0.733087	**0.498279**







Conclusion

- We present a monocular SLAM system that can build a semantic map with feature points and object landmarks.
- An object-based loop closure method based on semantic graph matching is proposed, which is robust to the change of viewpoint.
- We propose a loop correction method to align the matched objects, which can effectively correct the drift error.

- Future work
- Object detection method with other sensors
- Field experiments in logistic environment

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