1 Study of using pose with higher frequency

In this study, we are investigating the effect that pose estimation uncertainty brings to tracking performance. In SLAM pose-based control, the pose estimation errors immediately cause worse tracking performance. The design of trajectory servoing intends to improve the performance by less frequently requesting robot poses and shifting to the image domain. We already have the comparison of SLAM and TS in the paper. To further show the effect of pose estimation uncertainty, we conduct ablation studies about tracking performance when trajectory servoing more frequently using SLAM poses.

1.1 Feature replenishment threshold τ_{fr}

From §III.A in the paper, the feature replenishment threshold τ_{fr} controls the frequency of feature trajectory regeneration and robot pose requesting with long distance trajectories. In the simulation, we conduct an ablation study about the influence of varying τ_{fr}. The same two trajectory tracking performance metrics are used: average lateral error (ALE) and terminal error (TE). The number of feature trajectory regeneration per length is also recorded. Outcomes of averages over all trajectory templates are included in Table 1 and Fig. 1

With smaller τ_{fr}, trajectory servoing uses less number of tracked features, and works similar to pure IBVS. The computed control could be unstable and have oscillations, which reduces the tracking performance. In contrast, if τ_{fr} is significantly large, trajectory servoing will more frequently trigger feature replenishment. The performance will be more related to pose estimation accuracy, and be close to SLAM pose-based control. More pose estimation errors cause worse performance.

Table 1: Raw data from ablation study of feature replenishment τ_{fr}

τ_{fr}	4	6	**10**	16	22	36	50
ALE	7.01	5.11	4.52	**4.03**	4.67	4.67	4.57
TE	14.08	9.97	**8.23**	8.53	9.73	9.53	10.47
# of Reg/m	**1.4**	1.5	1.6	1.7	1.8	2.0	2.7

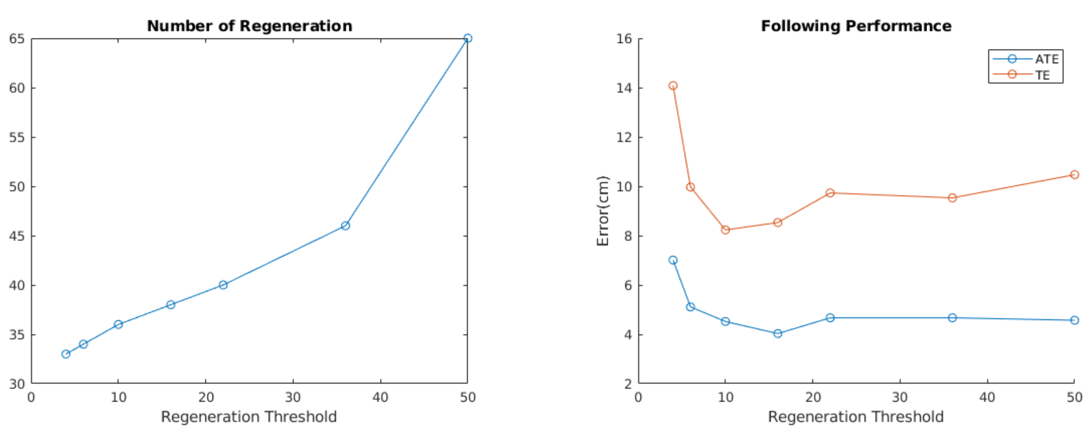

Figure 1: Ablation study plots of feature replenishment τ_{fr}

1.2 Incremental Trajectory Servoing

In order to further investigate the effect that pose estimation uncertainty brings to tracking performance. The trajectory servoing system is modified to use robot pose information in every control loop and recomputes the desired feature set for the next pose on the given trajectory. The feature trajectory will not be precomputed at the beginning. This version is called *Incremental Trajectory Servoing* (I-TS). Unlike the regular feature replenishment in §III.A that is triggered by τ_{fr}, desired feature regeneration is triggered by time. By doing this modification, trajectory servoing works similar to SLAM pose-based control, but shifting feedback to the image domain.

We applied the same simulation benchmark and metrics (i.e. ALE and TE) to compare tracking performance. The benchmark is only tested with long distance trajectories, because SLAM pose estimation uncertainty is not explicit with short distance trajectories. Tables 2(a,b) gives outcomes for the two metrics. I-TS has worse ALE and TE than TS and is similar to SLAM. It shows that frequently using SLAM pose information will introduce more uncertainty that potentially do harm to the tracking.

Table 2: Incremental Trajectory Servoing Outcomes.

(a) Sim ALE (cm)

Seq.	PO	SLAM	TS	I-TS
LRU	0.53	3.88	4.00	3.56
LLU	0.86	8.21	5.18	7.68
LST	1.13	5.03	3.00	4.19
LZZ	1.06	7.54	5.90	9.72
Avg.	0.90	6.17	**4.52**	6.29

(b) Sim TE (cm)

Seq.	PO	SLAM	TS	I-TS
LRU	8.57	10.66	6.42	8.82
LLU	5.54	29.48	15.75	24.3
LST	6.01	7.60	1.76	10.45
LZZ	7.83	9.28	9.00	9.91
Avg.	6.99	14.26	**8.23**	13.37

1.3 Conclusion

The above two studies shows the effect of pose estimation uncertainty when using SLAM poses with higher frequency. In addition, the results of TS+PO in the paper also indicate the improved performance with more accurate pose information. Overall, pose estimation uncertainty can lead to worse trajectory tracking performance. Our trajectory servoing design can reduce the effect of this uncertainty and have better tracking results.