Supplementary Materials for Swarm-LIO2: Decentralized, Efficient LiDAR-inertial Odometry for UAV Swarms

Fangcheng Zhu, Yunfan Ren, Longji Yin, Fanze Kong, Qingbo Liu,
Ruize Xue, Wenyi Liu, Yixi Cai, Guozheng Lu, Haotian Li, Fu Zhang

I. Flight In Degenerated Scenario

To validate the robustness of Swarm-LIO2 in LiDAR degenerated environments, we conduct a flight experiment for a swarm consisting of two UAVs. UAV1 carries a Livox Mid360 LiDAR, while UAV2 carries a Livox Avia LiDAR with a smaller FoV (especially in the horizontal direction) which is only $70.4^\circ \times 77.2^\circ$, shown in Fig. 1(d). We instructed UAV2 to follow a pre-planned trajectory, shaped like "*MARS*" which is the name of our laboratory. At certain poses, the Avia LiDAR mounted on UAV2 would directly face a smooth plane, leading to LiDAR degeneration. During the entire flight, UAV1 is flying behind UAV2 as an observer to provide UAV2 passive mutual observation measurements.

We compare the self-localization result of our method with a representative single-agent LIO system, FAST-LIO2 [1], as shown in Fig. 1. Since the LiDAR measurements can not provide sufficient constraints for pose determination, the state estimation of FAST-LIO2 diverges soon, the odometry largely drifts, and the point-cloud map gets messy. For Swarm-LIO2, the passive observation measurements offered by UAV1 provide the necessary information for robust localization and a consistent map. For the degenerated UAV2. The ground-truth provided by the motion capture system, the self-estimated trajectory of UAV2, and the trajectory of UAV2 estimated by UAV1 are depicted in Fig. 2. The average position error estimated by UAV2 itself is **0.043m** and that estimated by UAV1 is **0.059m**, both in the centimeter level.

II. Cooperative Payload Transportation

In this section, we implemented an interesting application in which a swarm composed of three UAVs completes the payload transportation from an outdoor location to an indoor area, see Fig. 3. The focus of this application is to demonstrate the capability of estimating the temporal offset and the global extrinsic transformations of Swarm-LIO2, rather than trajectory planning for the swarm. Therefore, in this experiment, the trajectory for UAV1 is priorly planned to ensure collision-free flight. The trajectories of the other two UAVs are obtained by transforming online the pre-planned trajectory into their respective global frames with appropriate offsets, using the precise temporal offset and global extrinsic transformations provided online by Swarm-LIO2. The three trajectories are then tracked independently with controller [2].

After loading the payload, the three UAVs fly in a low-light, outdoor scenario shown in Fig. 3(a), and ultimately enter a building through a window, shown in Fig. 3(b). Throughout the entire flight, the three UAVs maintain the formation of a triangle, ensuring that each UAV contributes nearly equal pulling forces. It is accurate state estimation, temporal offset, and global extrinsic calibration that empowers the UAVs to maintain the correct formation at any given moment, and successfully complete the payload transportation mission without collisions. The point-cloud map of the whole experiment site, which is constructed in real-time, and the transformed paths of the three UAVs are illustrated in Fig.3(c). The poses of the three UAVs and the point-cloud of the environment at the moment when UAVs were flying through the window are illustrated in Fig.3(d). It is worth noting that the entire swarm successfully flies through the narrow window without any collisions between the UAVs, payload, and the surrounding environment.

References

[1] W. Xu, Y. Cai, D. He, J. Lin, and F. Zhang, "Fast-lio2: Fast direct lidar-inertial odometry," *IEEE Transactions on Robotics*, 2022.

[2] G. Lu, W. Xu, and F. Zhang, "On-manifold model predictive control for trajectory tracking on robotic systems," *IEEE Transactions on Industrial Electronics*, 2022.

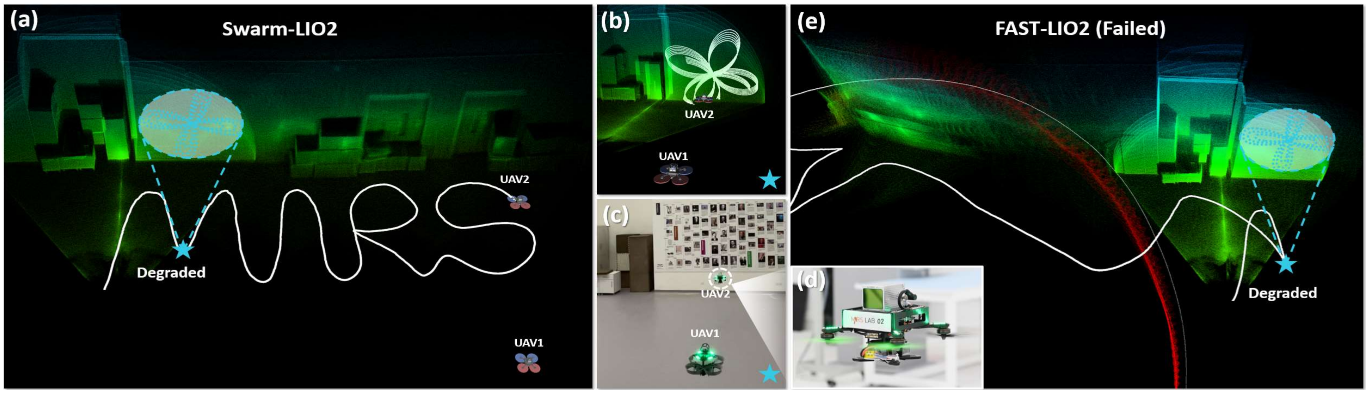

Fig. 1. Degenerated experiment of facing a smooth plane. (a) Clear and consistent point-cloud map constructed and state estimated by Swarm-LIO2 fusing passive observation measurements ${}^{b_1}\mathbf{p}_{b_2}$. The blue star represents the degenerated pose of UAV2 where the LiDAR is facing a smooth wall. UAV1 is flying behind UAV2 to provide mutual observation measurements. (b) Detail of the degenerated pose, the white points represent the current LiDAR scan. (c) Third personal view of the degenerated pose. (d) Detailed depiction of UAV2, a quadrotor equipped with Livox Avia LiDAR. (e) Point-cloud map constructed and state estimated by FAST-LIO2, severe drift occurs due to scarce structural constraints, resulting in a messy map.

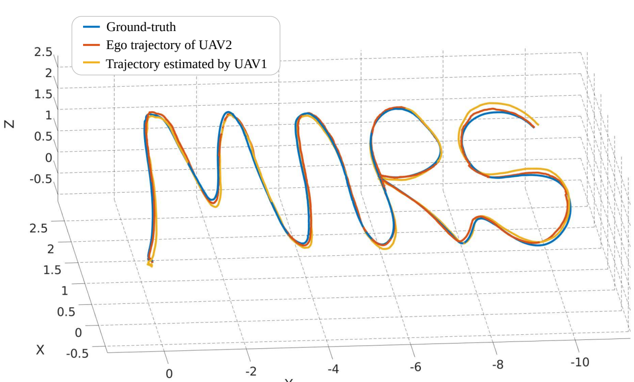

Fig. 2. Trajectory of UAV2 estimated by itself, UAV1 and the motion capture system (i.e., the ground-truth).

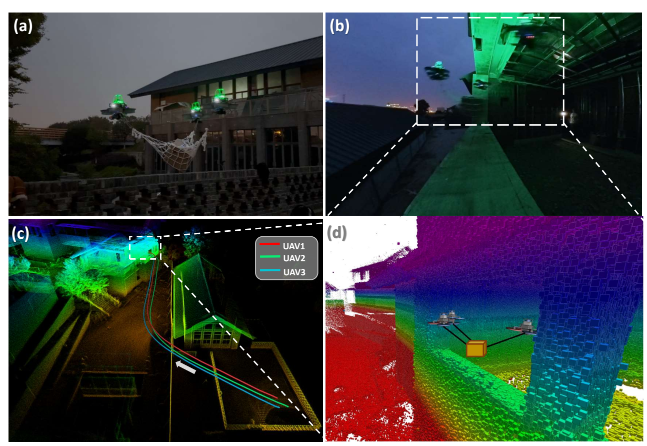

Fig. 3. Cooperative Load Transportation in Outdoor Scenario. (a) Picture of the payload suspended swarm flying in the outdoor scenes. (b) Picture of the swarm flying through the window.(c) The constructed point-cloud map, the planned path of UAV1, the take-off, and the target area. (d) The poses of the three UAVs and the point-cloud of the environment at the moment when fly through the window.