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. Fly Through a Degenerated Corridor

In this section, we conduct a simulation experiment in which five UAVs equipped with Livox Mid360 LiDARs need to fly through a degenerated corridor (Fig. 1). In this case, the measurements of a single LiDAR can not provide sufficient constraints for pose determination, but Swarm-LIO2 can perform robust and stable state estimation thanks to the mutual observation measurements from teammates.

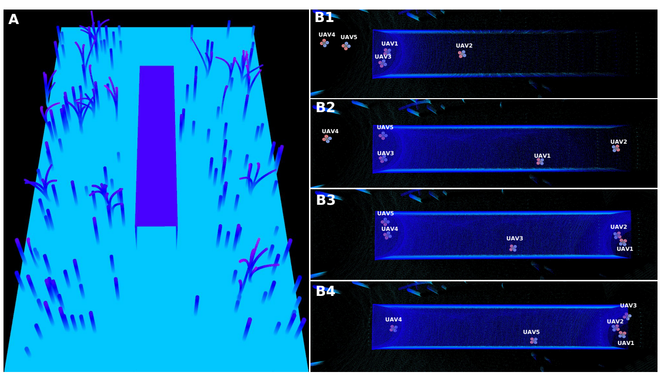

Fig. 1. (A) The simulation environment of the degenerated corridor. (B1-B4) The UAVs fly through the corridor sequentially, so that the mutual observation measurements can be leveraged for localization of UAVs in the corridor.

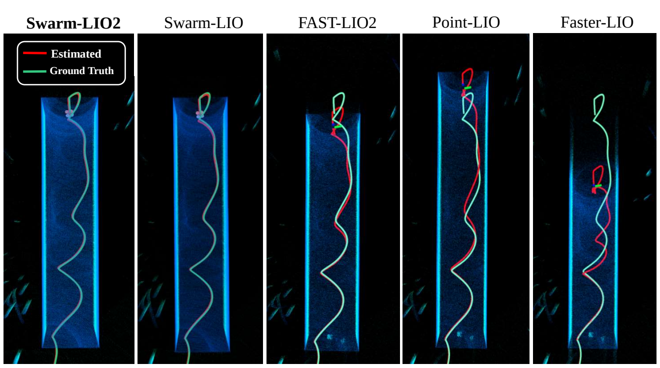

Fig. 2. Bird eye view of the constructed point-cloud map and the trajectory of UAV2 estimated by Swarm-LIO2, Swarm-LIO, FAST-LIO2, Point-LIO, and Faster-LIO.

In the simulation, the UAVs fly cooperatively through the corridor one by one. When the first UAV, here is UAV2, flies into the corridor, other UAVs hover at the entrance (where sufficient structural features exist for their pose estimation) and provide mutual observation measurements for UAV2. As

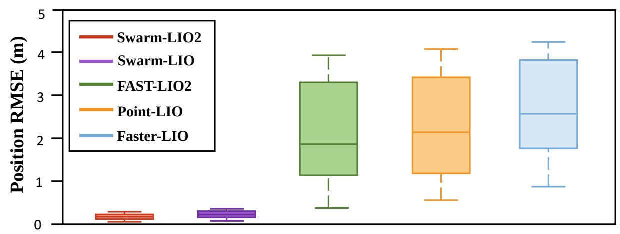

Fig. 3. The localization accuracy comparison in a degenerated corridor scene among Swarm-LIO2, Swarm-LIO, FAST-LIO2, Point-LIO, and Faster-LIO.

shown in Fig. 1(B1), when UAV2 detects LiDAR degeneration, it leverages mutual observation measurements from the rest UAVs to achieve robust state estimation. Then UAV2 flies through the corridor and hovers at the end of the corridor, offering mutual observation measurements for the rest UAVs to pass through the corridor (Fig. 1(B2-B4)).

As far as we know, apart from our previous work Swarm-LIO [1], there is no other open-sourced 3D LiDAR-based state estimation method for UAV swarm, thus we compare the localization accuracy of our method to Swarm-LIO and some state-of-the-art LiDAR-inertial odometry for a single UAV system, including FAST-LIO2 [2], Point-LIO [3], and Faster-LIO [4], in which the ground-truth of the ego-state is provided by the simulator. Take UAV2 as an example, the point-cloud map, the self-estimated position trajectory, and the ground-true trajectory are illustrated in Fig. 2 with quantitative results supplied in Fig. 3. It can be observed that in degenerated scenes, by fusing mutual observation measurements, the localization errors of Swarm-LIO2 and Swarm-LIO are much smaller than those of other single-agent LiDAR-inertial odometry methods. Moreover, in such a degenerated scenario, Swarm-LIO2 can achieve slightly better self-localization robustness and accuracy than Swarm-LIO, which is mainly attributed to the careful measurement modeling (Section V-C1) and temporal compensation (Section V-C2) in the paper.

II. 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. 4(d). We instructed UAV2 to

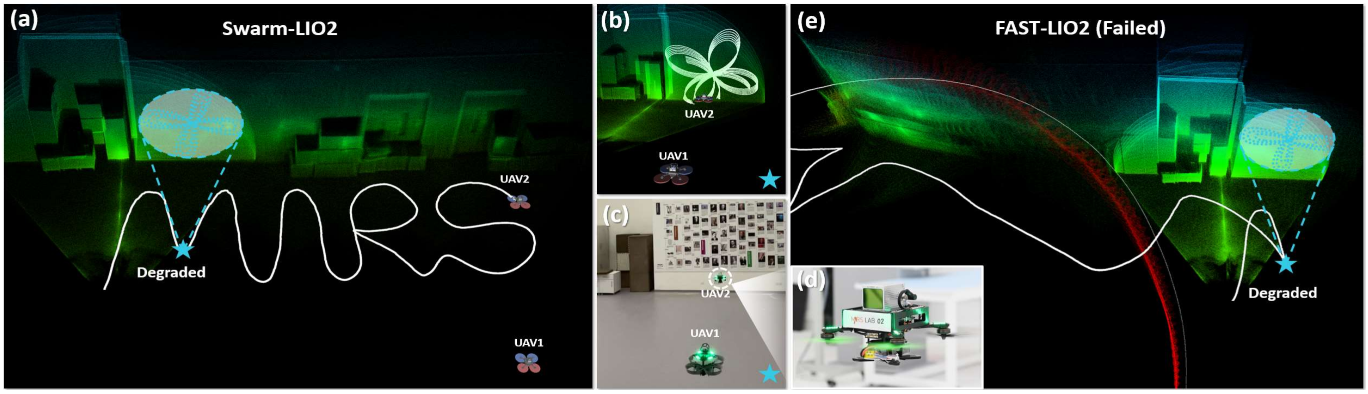

Fig. 4. Degenerated experiment of facing a smooth plane. (a) Clear and consistent point-cloud map constructed and state estimated by Swarm-LIO2 fusing passive observation measurements ${}^{b_1}\mathbf{p}_{b_2}$. The blue star represents the degenerated pose of UAV2 where the LiDAR is facing a smooth 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.

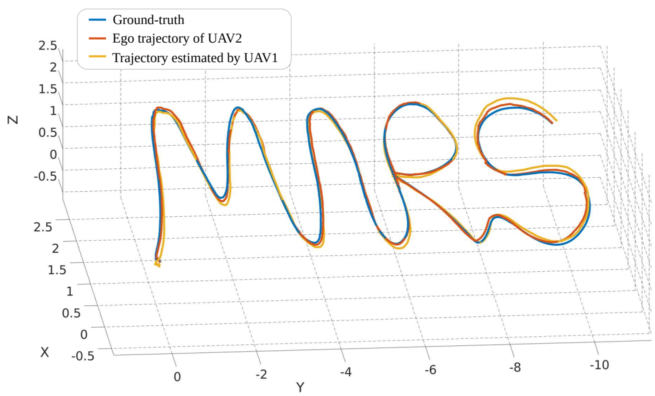

Fig. 5. Trajectory of UAV2 estimated by itself, UAV1, and the motion capture system (*i.e.*, the ground-truth).

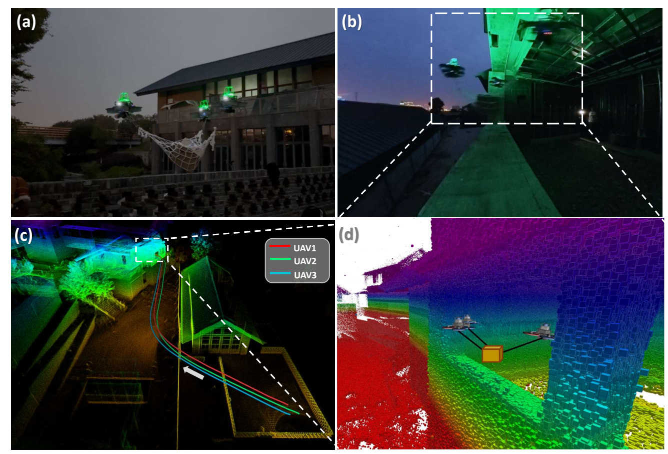

Fig. 6. Cooperative Load Transportation in Outdoor Scenario. (a) Picture of the payload suspended swarm flying in the outdoor scenes. (b) Picture of the swarm flying through the window.(c) The constructed point-cloud map, the planned path of UAV1, the take-off, and the target area. (d) The poses of the three UAVs and the point-cloud of the environment at the moment when fly through the window.

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 [2], as shown in Fig. 4. 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. 5. The average position error estimated by UAV2 itself is **0.043m** and that estimated by UAV1 is **0.059m**, both in the centimeter level.

III. 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. 6. 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 [5].

After loading the payload, the three UAVs fly in a low-light, outdoor scenario shown in Fig. 6(a), and ultimately enter a building through a window, shown in Fig. 6(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.6(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.6(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.

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