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Autonomous navigation of a multirotor robot in GNSS-denied environments for search and rescue

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Dear editor,

In search and rescue missions, robust real-time autonomous navigation in obstacle-strewn, complex, and potentially global navigation satellite system (GNSS)-denied environments is a challenging task for multirotor aerial robots' autonomous navigation system owing to the robots' limited computational and sensing resources, thus remaining an open research topic.

The inertial measurement unit (IMU)-assisted odometry [1] is widely adopted for robot self-localization, which suffers from accumulated errors caused by sensor bias over large-scale and long-term navigation. The loop closure mechanism of mapping algorithms can eliminate accumulated drifts, which could be incorporated into the odometry to obtain non-drift high-accuracy position estimates. Online real-time path planning is another crucial technique for achieving safe navigation for a multirotor robot. Local planners, such as the vector field histogram (VFH) [2], are capable to perform online real-time path planning without global map information.

We present a novel autonomous navigation framework for a multirotor robot to perform search and rescue missions in GNSS-denied complex environments. A multi-sensor fusion self-localization algorithm is proposed that enables cascaded fusion or independent state estimation to achieve high accuracy and robust localization. A 3D path planner improved from 3DVHF+ and A* [3] is proposed to maintain the real-time property while achieving locally optimal path planning.

Self-localization. We propose a multi-sensor fusion self-localization framework to derive high-accuracy and robust pose estimates in real time. The proposed framework incorporates visual, inertial and laser scan information in a cascade to facilitate the visual-inertial odometry (VIO) [1] and laser-inertial odometry (LIO) for state estimates. A vision-based loop closure detection [4–6] is adopted and iSAM2 in the GTSAM library [7] is invoked to minimize errors in the global pose graph, so as to decrease the accumulated drift of fusion odometry to achieve a high-accuracy estimation. A laser-based standby loop closure detection [8] is implemented in case of the vision-based loop closure detection failure owing to the camera's limited field of view (FOV). Moreover, the independent pose estimation and loop closure using either VIO or LIO can also enhance the system's robustness to single sensor failure. In order to achieve long-term online navigation in large-scale environments, RTAB-Map's memory management approach [9] is embedded to limit the number of detected keyframes in the database. The self-localization framework is illustrated in Figure 1, and more details can be found in Appendix A.

Path planning. The proposed path planner benefits from 3DVFH+ and A* to find the locally optimal path while satisfying real-time planning requirement of aerial robots. The planner first calculates the local navigation histogram and evaluates all unoccupied grid nodes p_{can} based on the cost function:

$$C = w_g c_{p_{\mathrm{can}}}^{p_g} + w_s c_{p_{\mathrm{can}}}^{p_{\mathrm{sel}}}, \tag{1}$$

where $c_{p_{\mathrm{can}}}^{p_g}$ denotes the distance cost between p_{can} and the goal position p_g, $c_{p_{\mathrm{can}}}^{p_{\mathrm{sel}}}$ is motion smoothness cost between p_{can} and the previously selected node p_{sel}, and w_g and w_s are weight factors, respectively. Then a heuristic A* algorithm is invoked to search the local grid map using the objective function:

$$F(n) = C(p_{\mathrm{cur}}, n) + H(n, p_g), \tag{2}$$

where p_{cur} is the current node, n is the node being evaluated, and $H(n, p_g)$ is the Euclidean distance between n and p_g. A locally optimal path can thus be obtained. By iterating the above path planning process, a feasible, globally sub-optimal path could be generated in real time. More details of the proposed path planner are illustrated in Appendix B.

Experiment. Softwere-in-the-loop (SITL) experiments were first carried out in a complex 3D virtual environment to investigate the impact of different heuristic and memory parameter settings. The results demonstrate that long-distance heuristic and large memory offer great improvement of system performance, however, at the cost of requiring more computational resources. A combination of short-distance and long-term memory seems the most balanced parameter setting for the proposed system.

Experiments on a robotic platform were first conducted in an indoor area covered by the Opti-track system. The state estimates from the proposed self-localization approach

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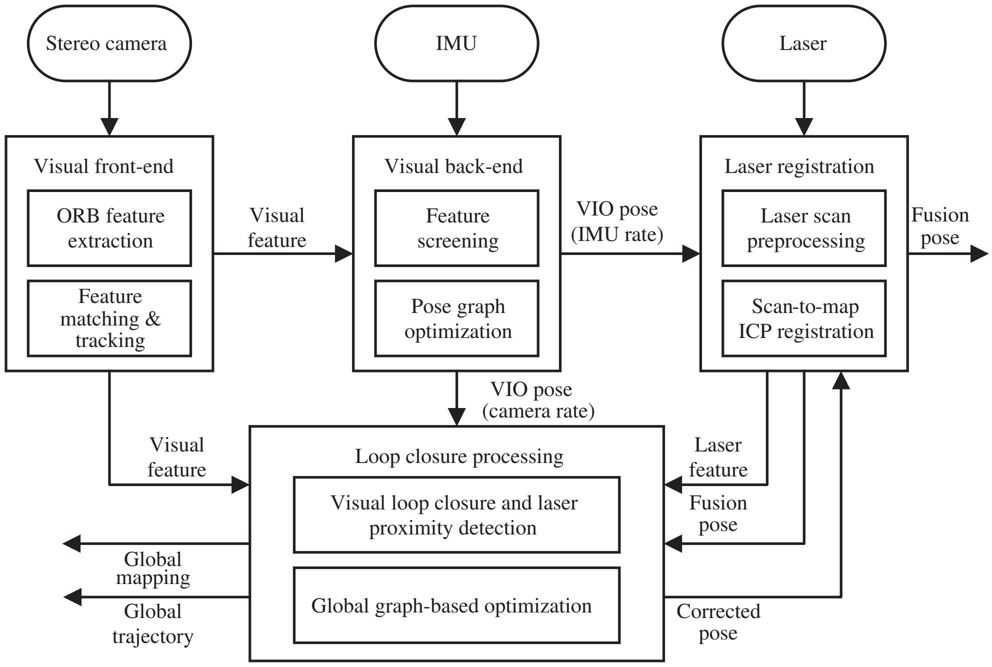

Figure 1 The proposed self-localization framework.

are compared with the ground truth from Opti-track, and the results verify the effectiveness of the proposed algorithm. A series of experiments in indoor and outdoor GNSS-denied environments were carried out, and the outcomes reveal that there are no unstable position estimation or collisions during the flights, which once again confirms the effectiveness and good performance of the autonomous navigation system.

Details of experimental setup, scenarios, results and analysis can be found in Appendix C.

Conclusion. We present a novel autonomous navigation framework for a multirotor aerial robot deployed in complex and GNSS-denied environments for search and rescue missions. An improved self-localization system using vision, IMU, and the laser scanner is proposed to achieve high-accuracy and robust localization, while a path planner based on VFH+ and A* is adopted to search for the locally optimal path in real time. Comprehensive experiments demonstrate the effectiveness and good performance of the proposed framework in assisting a multirotor UAV to quickly and safely navigate in GNSS-denied complex environments in advanced missions.

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Supporting information Appendixes A–C. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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