Design and Simulation of an Emergency Navigation System for Indoor Swarm Drones

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Abstract. In this study, we designed an emergency navigation system for swarm drones operating without Global Navigation Satellite System (GNSS) support. The system is intended to facilitate emergency landings using Visual-Inertial Odometry (VIO) based on mission cameras when LiDAR-based Simultaneous Localization and Mapping (SLAM) is deemed unreliable. To reduce computational load on the mission computer, LiDAR is utilized for position estimation during regular mission operations, while the mission camera is employed for position estimation only in emergency situations. For application in swarm drones, emergency landing zones are further subdivided to prevent collisions among drones. To validate the emergency navigation system, various scenarios were created and simulated using the Gazebo simulator. The results confirmed that, during indoor swarm drone operations, the proposed emergency navigation system allows safe and collision-free landings in emergency situations.

Keywords. Emergency Landing, Swarm drones, SLAM(Simultaneous Localization and Mapping), VIO(Visual Inertial Odometry)

1 Introduction

Recent advancements in drone technology have expanded their application in sectors such as agriculture, surveillance, logistics, and disaster management [1-3]. Small drones, especially in indoor environments, are now widely used for delivery, inspection, and surveillance tasks. However, indoor drone operation remains challenging due to weak or disrupted GNSS signals. To overcome this limitation, drones often rely on LiDAR or camera-based systems for autonomous position estimation [4-6]. While LiDAR provides highly accurate 3D spatial data, its performance can be affected by environmental conditions, and camera systems may struggle in low-visibility or visually homogeneous environments.

To enhance position estimation accuracy, researchers are focusing on sensor fusion—integrating multiple sensors to improve reliability and redundancy [7-8]. However, for small indoor drones, size and weight constraints limit the use of multiple high-performance sensors. Thus, a navigation system that can operate efficiently with minimal equipment, even during sensor failures, is essential. This study proposes a system in which a drone primarily uses LiDAR for position estimation but can switch to the mission camera as a backup in emergency scenarios.

For missions requiring extended flight times, deploying a swarm of drones can reduce overall mission duration. However, in emergency situations, it is crucial to ensure that designated emergency landing sites are spatially distributed to avoid potential collisions. This study extends a previously developed emergency navigation system for individual drones to a swarm configuration, allowing multiple drones to select appropriate landing sites based on the mission environment.

Verification simulations involving up to four drones in a swarm confirmed the system's effectiveness, enabling safe landings without collisions. This navigation system design has applications beyond the missions investigated in this study, providing a robust framework for safe and efficient drone operations across diverse environments.

2 Emergency Navigation System

In this paper, we present an emergency navigation system designed for GNSS-denied environments. The primary position estimation module is based on LiDAR SLAM and operates under normal conditions when GNSS is unavailable. LiDAR SLAM creates a real-time map and estimates the drone's position by continuously processing 3D point cloud data captured by the LiDAR sensor, making it highly effective in environments where GNSS is inaccessible. The SLAM process identifies and matches points across successive LiDAR scans, which are then used to construct an environmental map and track the drone's position relative to this map. This enables robust localization even in dynamically changing surroundings.

In the event of an emergency, or if LiDAR SLAM becomes unreliable, a secondary position estimation module, based on VIO, takes over. VIO estimates the drone's position by combining feature points from camera images with inertial data from an onboard IMU (Inertial Measurement Unit). This integration allows VIO to track the drone's movement by analyzing visual changes between frames and compensating for rapid motion through IMU measurements. VIO is particularly useful in situations where LiDAR SLAM may fail, such as environments with insufficient geometric features for LiDAR-based mapping.

The proposed system is composed of four main modules: the primary LiDAR SLAM-based module, the secondary VIO-based module, the Pose Publisher module, and the Command module. The Pose Publisher relays position estimation results and monitors the status of LiDAR SLAM. When LiDAR SLAM functions normally, its estimated position is sent to the Flight Controller (FC); otherwise, VIO's estimation is used as a backup. The Command module generates mission or emergency landing commands based on information from the FC and Pose Publisher, and manages landing site information to prevent overlap among drones.

If LiDAR SLAM is found to be in an abnormal state during a mission, the last known position and attitude from LiDAR SLAM are used to correct VIO, thereby improving VIO's accuracy under emergency conditions. The drone then lands at the nearest designated emergency site using the corrected VIO data. If the intended landing site is occupied, the drone proceeds to an alternative nearby site.

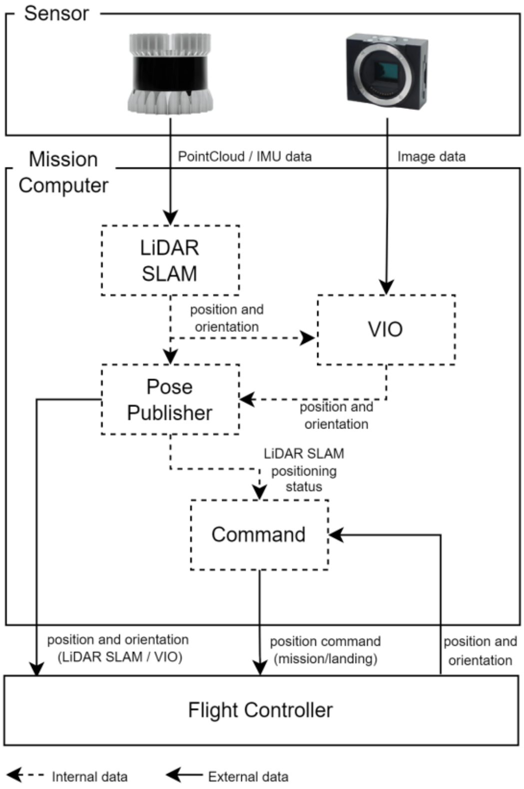

Fig. 1. Architecture of the emergency navigation system, utilizing LiDAR SLAM as the primary and VIO as the backup position estimation module.

2.1 LiDAR SLAM Positioning Status Assessment

The assessment of the LiDAR SLAM positioning status is performed by the Pose Publisher module. Depending on the LiDAR SLAM positioning status, the Pose Publisher module outputs the position estimation results from either LiDAR SLAM or VIO to the FC. The flowchart of the Pose Publisher module is shown in Figure 2. In this study, the inability of LiDAR SLAM to perform positioning is categorized into two cases: abnormal SLAM position estimation results and SLAM malfunction due to LiDAR failure.

An abnormal SLAM position estimation result is identified when the difference between the current position and the previous position exceeds a predefined threshold. SLAM malfunction due to LiDAR failure is determined when SLAM cannot operate because the LiDAR measurements are invalid or not received by the mission computer, and the Pose Publisher module fails to receive SLAM's position and attitude estimation results for more than a specified number of times.

Fig. 2. Flowchart of the Pose Publisher module's LiDAR SLAM positioning status, selecting between SLAM and VIO for position estimation.

2.2 Emergency Landing Site Determination

To prevent collisions due to overlapping emergency landing sites during mission execution by a swarm of drones, the emergency landing sites are divided into external and internal sites, as shown in Figure 3. In the event of an emergency, the system first searches for the nearest external emergency landing site and then additionally searches for the closest internal landing site within the selected external emergency landing site. During this process, any internal emergency landing sites that have already been occupied by other drones are excluded from the search to avoid collisions. The determination of emergency landing sites is performed by the Command module each time it receives the drone's position information. To prevent collisions due to overlapping landing sites, information about the emergency landing sites of all drones performing the mission is transmitted and received. If the LiDAR SLAM positioning status is determined to be abnormal, the Command module stops further landing site determination and transmits the determined information to the FC to guide the emergency landing

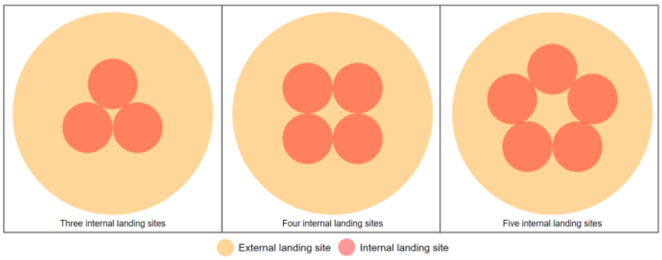

Fig. 3. Example configurations of external and internal emergency landing sites to prevent collisions in drone swarms.

2.3 Emergency Landing Site Selection

Prior preparation is required to determine the size and number of emergency landing sites necessary for applying the emergency navigation system according to the mission environment. The selection of emergency landing sites depends on the mission environment and the accuracy of the position estimation algorithm, and follows the procedure shown in Figure 4.

To validate the emergency navigation system proposed in this paper, we assumed a scenario where a drone flies along the exterior of an aircraft to detect defects. To select emergency landing sites, a rectangular flight path encompassing the fuselage of the target aircraft was generated, as shown in Figure 6. Since there is a low probability of collision with the aircraft along this flight path and it is necessary to cover the entire flight path, a total of six temporary emergency landing sites were positioned at the front and rear of the aircraft, as well as at the front and rear of both wings.

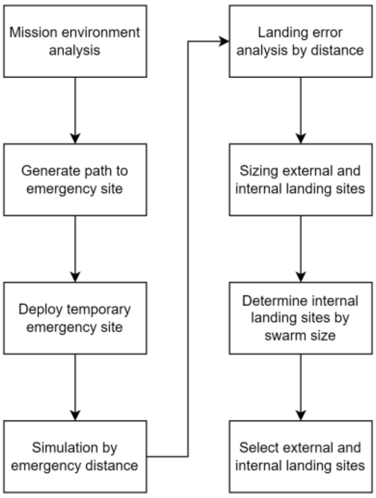

Fig. 4. Process for selecting and simulating emergency landing sites for the proposed emergency navigation system.

To determine the size of the emergency landing sites, the distance from the temporary emergency landing sites to the location where an emergency might occur was set. The potential locations of emergency situations were defined as occurring either before or after reaching the temporary emergency landing sites, categorizing them into cases where the drone is approaching or moving away from the temporary emergency landing site.

Based on the simulation results, the distance at which the average error margin is satisfied was set as the radius of the external emergency landing sites. The radius of the internal emergency landing sites was determined by considering the maximum distance error and the size of the drone. Additionally, to ensure that the entire flight path is covered within the radius of the external emergency landing sites, the minimum number and placement of emergency landing sites were determined. The number of internal emergency landing sites was set to match the number of swarm drones.

2.4 Emergency Landing Site Selection Results

The simulation environment for emergency landing site selection was set up using Ubuntu 20.04, ROS Noetic, and Gazebo 11. For the simulation, a quadcopter with a 550mm wheelbase, a LiDAR with a maximum detection range of 100m and a vertical field of view of ±45º, and an HD quality camera were used. The aircraft and hangar models used in the mission environment are shown in Figure 5.

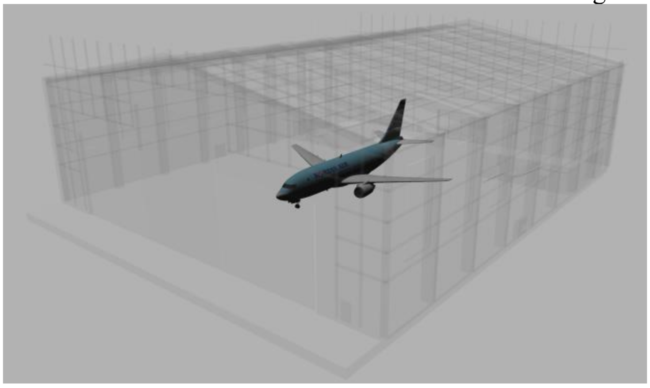

Fig. 5. Aircraft and hangar models used in the simulation environment for emergency landing site selection.

The drone's navigation information was derived from the position and attitude data obtained through LiDAR SLAM and VIO. The distance error was calculated by comparing the GNSS information of the drone's landing position with the GNSS information of the designated emergency landing site.

The results of the emergency landing site selection simulation are presented in Table 1. In this simulation, a total of 60 landing attempts were conducted: five attempts were made at distances of 1, 5, 10, and 20 meters before and after each of the six emergency landing sites. These distances were selected with consideration of the mission range (30–40 meters) to assess the system's adaptability across different proximity levels—from very close (1 meter) to moderate (5–10 meters) and longer distances (20 meters)—representing various emergency scenarios. Results indicate that as the distance to the emergency landing site decreases, both the average and maximum distance errors also decrease.

Table 1. Simulation results of Emergency landing zone decision

Distance from landing site	Max landing error [m]	Mean landing Eror [m]	1σ landing Error [m]
1m	1.10	0.54	0.28
5m	1.11	0.55	0.26
10m	1.76	0.69	0.38
20m	1.79	0.91	0.39

Even under the condition where the emergency occurrence distance was 20 meters, it was confirmed that the drone landed within an average of 1 meter and a maximum of 2 meters. Therefore, the emergency landing sites were configured with external landing sites having a radius of 20 meters and internal landing sites with a radius of 2.5 meters. As shown in Figure 6, four external emergency landing sites were positioned to encompass both the single and swarm operation verification paths and the swarm mission paths. The internal emergency landing sites were set to four, considering the operation of four swarm drones.

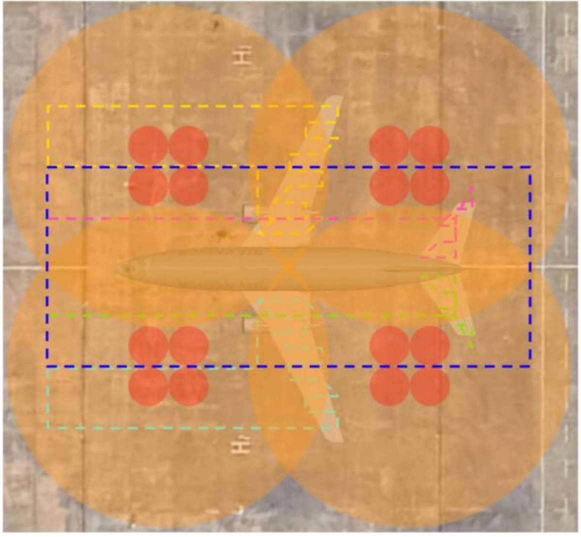

Fig. 6. Configuration of external (20m radius) and internal (2.5m radius) emergency landing sites, designed for single and swarm operations around the mission path.

3. Emergency navigation system simulation

The simulation to verify the feasibility of the emergency navigation system involves landing on pre-selected emergency landing sites based on the results of an emergency landing site selection simulation. This process confirms the usability of the designated emergency landing sites. Additionally, further drones are deployed to evaluate the landing outcomes when multiple drones from the swarm attempt to land on the same emergency landing site.

3.1 Swarm Operation Scenario

In the scenario of operating a drone swarm, the first drone to encounter an emergency is assumed to be the one taking off from the front left side relative to the aircraft. The first scenario involves all drones halting their mission and switching to the emergency navigation system when an emergency occurs. The second scenario involves only the drone experiencing the emergency halting its mission and switching to the emergency navigation system, with nearby drones also encountering emergencies. The third scenario assumes that only the drone experiencing the emergency halts its mission and switches to the emergency navigation system, while other drones encounter emergencies in different areas. Finally, the fourth scenario assumes an abnormal operating environment where all drones halt their mission and switch to the emergency navigation system.

The scenario for operating a swarm of four drones involves each drone following a rectangular flight path, as depicted in Figure 7.

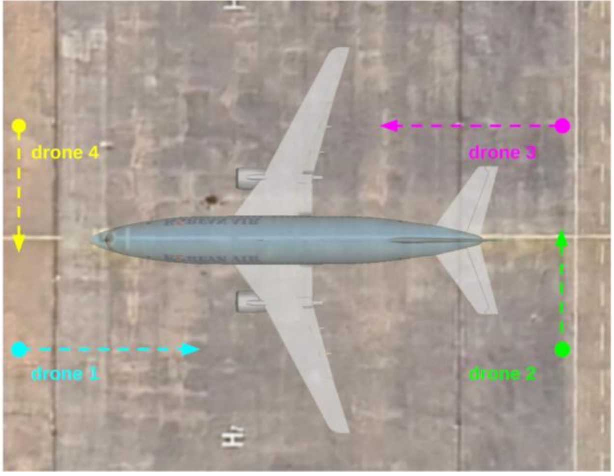

Fig. 7. Flight paths for a swarm of four drones, each following a designated rectangular path around the aircraft.

3.2 Swarm Operation Simulation Results

The results of the emergency navigation simulation for the swarm operation are shown in Table 2. A total of 80 emergency landings were attempted, with 5 attempts at each external emergency landing site. The standard deviation (1-sigma) of the distance error was recorded at 0.24 meters, and the maximum distance error was 1.38 meters. It was confirmed that even during swarm operation, the maximum distance error remained within the radius of the internal emergency landing sites. Additionally, it was verified that in scenarios where external emergency landing sites overlapped, each drone selected a different internal emergency landing site, successfully landing without collisions.

Table 2. Distance Error in the Swarm Drone Emergency Navigation Simulation.

Drone Start Position (x, y)	Max landing error [m]	Mean landing Eror [m]	1σ landing Error [m]
#1 (0, 0)	1.36	0.43	0.28
#2 (0, 60)	1.38	0.34	0.27
#3 (-25, 60)	0.72	0.21	0.14
#4 (-25, 0)	0.84	0.23	0.16
Total	1.38	0.30	0.24

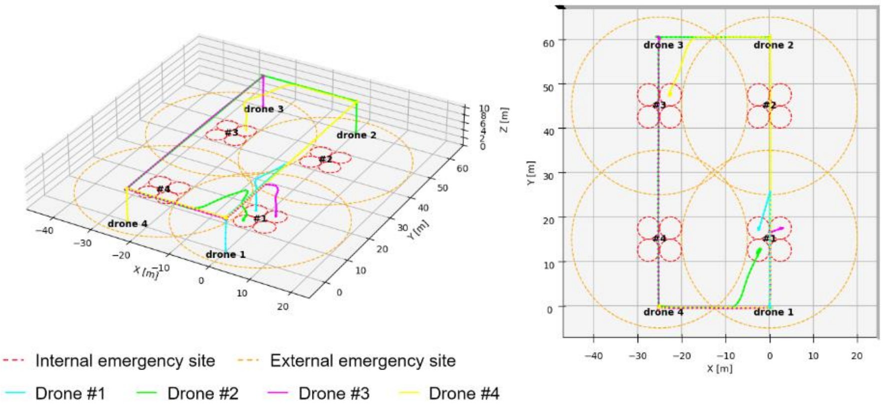

Fig. 8. Emergency landing paths and site allocations for swarm operation, showing each drone's designated path and selected emergency landing sites to avoid collisions.

4. Conclusion

In this paper, we propose an emergency navigation system designed to handle unexpected situations during the operation of a drone swarm in indoor environments. During the mission, the drone's position is estimated using LiDAR SLAM, and if the LiDAR SLAM positioning is abnormal, the system switches to VIO using the mission camera to perform an emergency landing. To prevent collisions between drones during emergency landings, dual emergency landing sites were configured, and scenarios for operating the emergency navigation system in a swarm of drones were developed and simulated.

Through the temporary emergency landing site simulation, we established external landing sites with a 20-meter radius and internal emergency landing sites with a 2.5-meter radius. The simulation results for the swarm drone scenario showed that the 1-sigma distance error was 0.24 meters, with a maximum distance error of 1.38 meters. Additionally, even when three drones attempted to land on the same emergency landing site due to overlapping emergency situations, all three successfully landed without collision, with a minimum distance of 4.33 meters between them. This demonstrates the feasibility of applying an emergency navigation system that uses VIO-based navigation with the mission camera, even when LiDAR SLAM is unreliable, to ensure safe emergency landings in indoor swarm drone operations.

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