Safe Landing and Navigation Framework for UAVs

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Abstract

Emergency landing for multicopter UAVs in cluttered, unknown environments demands rapid terrain assessment and trajectory planning under strict time and computational constraints. This paper presents a 3D LiDAR-based system that integrates a searching algorithm to identify safe landing sites, and employs a path planning method for trajectory generation. The planner ranks site–path pairs and selects the best trajectory, which is evaluated via a multi-criteria scoring function that weights computing efficiency, path optimality, safety, and landing quality. Extensive experiments across multiple scenarios achieve the highest emergency score for both path and safety metrics. The framework delivers a robust, real-time solution for autonomous emergency landings, balancing rapid decision-making with reliable safety margins.

Keywords: Uncrewed Aerial Vehicle, safe landing, path planning, autonomous mobility

Ⅰ. Introduction

Uncrewed aerial vehicles (UAVs) are increasingly essential for sectors ranging from urban logistics to disaster management due to their superior mobility compared to ground platforms [1,2]. However, achieving full autonomy in these domains requires the tight integration of safe landing capabilities with obstacle-avoiding navigation—areas that existing research predominately treats as separate problems. Current systems often rely on simplified vertical descent strategies or sensors with limited environmental perception, such as cameras and 2D LiDAR, which struggle to identify safe landing zones in complex 3D environments or under low-light conditions [3,4].

To address these limitations, this paper proposes a unified framework designed for safe landing and navigation in emergency situations. By utilizing real-time 3D environmental mapping, the proposed system simultaneously identifies flat, stable landing sites and generates collision-free, energy-efficient trajectories to reach them, moving beyond the constraints of simple vertical descent. This integration ensures that UAVs can dynamically navigate around obstacles—such as overhanging structures—while securing a safe touchdown point, significantly enhancing mission reliability and safety in unpredictable real-world environments.

Ⅱ. Proposed System

The framework establishes a standardized pipeline for UAV emergency landing, comprising four phases: point cloud down sampling and ROI extraction, algorithm-agnostic landing site detection as presented in algorithm 1, 3D occupancy map construction, and path planning with multi-criteria evaluation. As outlined in the integrated framework algorithm, the system identifies candidate sites satisfying geometric constraints and subsequently generates trajectories using two complementary planners—RRT* for exploratory sampling and A* for refining dynamically feasible paths. This dual-planner approach evaluates reachability under fixed compute budgets, recording metrics such as runtime and obstacle clearance to expose trade-offs between exploration and local optimality.

Algorithm 1 Integrated Safe Landing Site Detection and Path Planning Scoring

Input:
  $\mathcal{P}$: Input 3D point cloud of the environment
  $\mathbf{p}_{\text{start}}$: UAV's initial pose (x, y, z)
  $\mathcal{C}$: Configuration parameters
Output:
  $\mathcal{L}$: Ranked list of landing sites with metrics
  $\mathcal{T}$: Set of feasible trajectories to top-k sites
IntegratedPlanningFramework$\mathcal{P}, \mathbf{p}_{\text{start}}, \mathcal{C}$
$\mathcal{P}_{\text{resampled}} \leftarrow$ VoxelDownsample$(\mathcal{P}, \mathcal{C}.voxel_size)$
$\mathcal{P}_{\text{ROI}} \leftarrow$ ExtractROI$(\mathcal{P}_{\text{resampled}}, \mathbf{p}_{\text{start}}, \mathcal{C}.search_radius)$
// Phase 1: Landing Site Detection
$\mathcal{S}_{\text{candidates}} \leftarrow \emptyset$ {Set of candidate landing sites}
$\mathcal{S}_{\text{candidates}} \leftarrow$ LandingSiteDetection$(\mathcal{P}_{\text{ROI}}, \mathcal{C}_{\text{site}})$
assert $\mathcal{S}_{\text{candidates}} \neq \emptyset$ {Terminate if no sites found}
// Phase 2: Occupancy Map Construction
$\mathcal{M}_{\text{3D}} \leftarrow$ BuildOccupancyMap$(\mathcal{P}_{\text{resampled}}, \mathcal{C}.resolution)$
// Phase 3: Path Planning and Evaluation
$\mathcal{L} \leftarrow \emptyset$ {List for evaluated sites}
for $\mathbf{s}_i \in \mathcal{S}_{\text{candidates}}$ **do**
  $\tau_i \leftarrow$ PathPlanner$(\mathcal{M}_{\text{3D}}, \mathbf{p}_{\text{start}}, \mathbf{s}_i.\text{center}, \mathcal{C}_{\text{path}})$
  $\mathbf{m}_i \leftarrow$ EvaluateMetrics$(\mathbf{s}_i, \tau_i, \mathcal{C})$
  $\mathcal{L}$.insert$((\mathbf{s}_i, \tau_i, \mathbf{m}_i))$
end for
// Phase 4: Multi-Criteria Decision Making (MCDM)
$\mathcal{L}_{\text{ranked}} \leftarrow$ RankSites$(\mathcal{L}, \mathcal{C}.weights)$
$\mathcal{T} \leftarrow \{\tau_i \mid (\mathbf{s}_i, \tau_i, \mathbf{m}_i) \in \mathcal{L}_{\text{ranked}}[1:k]\}$
return $(\mathcal{L}_{\text{ranked}}, \mathcal{T})$ =0

The procedure begins by preprocessing the input point cloud through down sampling and extracting a Region of Interest (ROI) centered on the UAV's initial pose. In the first phase, the system detects candidate landing sites within this ROI using a specified detection algorithm, terminating immediately if no suitable sites are identified. Subsequently, a 3D occupancy map is constructed from the down sampled data to serve as the environmental model. During the planning phase, the system iterates through each candidate site to compute a trajectory from the start pose to the site center, evaluating specific metrics such as runtime and clearance for every site-path pair and storing them in a list. Finally, the sites are ranked using a weighted scoring system, and the framework returns the ranked list along with the feasible trajectories for the top candidates as presented in Fig.1.

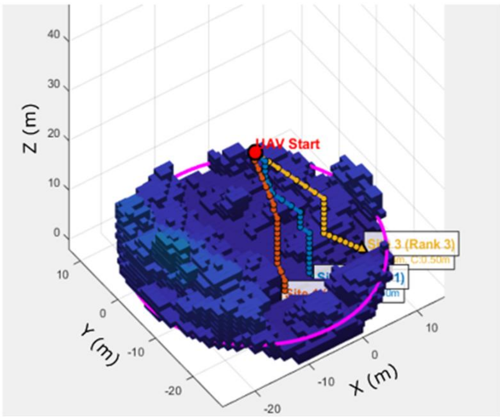

Fig. 1. Safe landing candidate and path

Ⅲ. Conclusion and Future Work

The framework's standardized approach for algorithm evaluation provides a valuable contribution to the field, enabling systematic comparison of detection-planning pairs under emergency constraints. The demonstrated balance between speed, safety, and computational efficiency establishes a planner as a robust foundation for next-generation autonomous emergency landing systems in multicopter drone operations. Future work should focus on expanding the framework to handle dynamic obstacles, integrating machine learning-based terrain classification, and validating performance across diverse environmental conditions.

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