Vision-based Autonomous Landing in Catastrophe-Struck Environments

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Control Problems in Robotics: Modeling and control of multi-rotor UAVs
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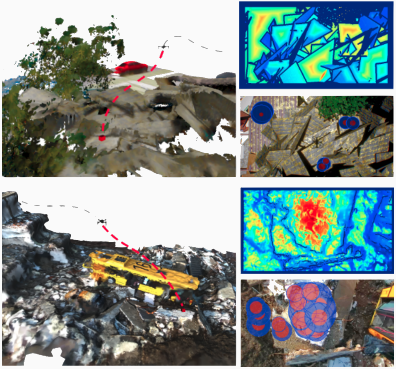
Introduction

Equipping UAVs with **bioradars**:

- estimate a set of candidate **safe landing sites**
- optimize over the global area via **clustering**
- project landing sites onto **volumetric reconstruction**
- compute a **minimum-jerk trajectory** to land on debris piles
- validate on simulated and real-world environments

Technical Approach

- State Estimation
- Landing Site Detection
- 3D Volumetric Mapping
- Landing Trajectory Estimation



Technical Approach: State Estimation

- downward-facing stereo camera
- ORB-SLAM2 (oriented FAST and rotated BRIEF)
- multi-sensor fusion (EKF) using IMU, barometer and GPS
- sensor precalibrated with Kalibr toolbox

Technical Approach: Landing Site Detection

Confidence in Depth Information J_{DE}:

$$J_{DE}(p) = 1 - \frac{D(p)^2 - min\{D^2\}}{max\{D^2\}}$$

with D depthmap obtained from the stereo camera and $p = (x, y)$ pixel in the depthmap.

Technical Approach: Landing Site Detection

Flatness Information J_{FL}:

$$di(B, p) = min\left\{ \|p - q\| \middle| B(q) = 1 \right\}$$

$$J_{FL}(p) = di(Canny(D), p)$$

with B binary image and p, q pixels in the image plane. *Canny* applies the Canny edge detector over the depthmap D.

Technical Approach: Landing Site Detection

Steepness Information J_N:

- point cloud from the depthmap in global frame
- average 3D gradients algorithm to estimate normals map N
- evaluate deviation of the normalized surface normal $\hat{n}$ wrt z-axis $\hat{z}$ in the world frame: $\theta = cos^{-1}(\hat{n}^T \hat{z})$
- compute $n(p)$ steepness score for each pixel p given $\theta_{th} = \pi/12$ maximum tolerable slope

$$n(p) = exp\left\{-\frac{\theta^2}{2\theta_{th}^2}\right\}$$

Technical Approach: Landing Site Detection

Energy Consumption Information J_{EC}:

$$J_{EC}(p) = \int_{t_0}^{t_f} P(t)dt$$

with t_0 and t_f time of flight to reach p and $P(t)$ instantaneous battery power. Approximate the integral with Euclidean distance between the UAV and p.

Technical Approach: Landing Site Detection

Scale the costmaps to the same range through min-max normalization and compute the final decision map J taking a weighted sum:

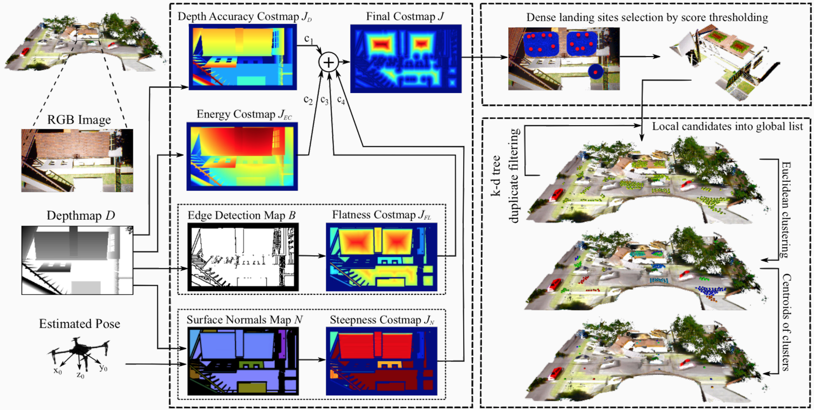
$$J = c_1 J_{DE} + c_2 J_{FL} + c_3 J_N + c_4 J_{EC}$$

$$c_i \in [0, 1] \quad \sum_i c_i = 1$$

- keep the sites checking whether the UAV could actually land
- k-d tree to efficiently store new landing sites
- hierarchical clustering algorithm to agglomerate sites

Technical Approach: Landing Site Detection

Figure 1: Overview of the landing site detection algorithm. In the costmaps, red indicates high score while blue indicates a lower score. Detected landing sites are projected onto a 3D reconstruction of the environment.



Technical Approach: 3D Volumetric Mapping

Probabilistic volumetric map:

- navigation and planning
- low-resolution map (0.5m) using OctoMaps
- faster trajectory planning

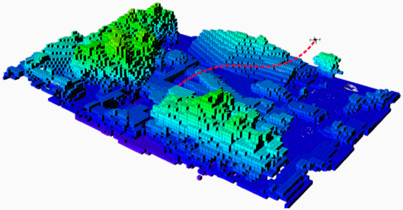
3D textured mesh:

- dynamic map growing using Voxblox
- high-resolution mesh transmitted to the rescue team

Technical Approach: Landing Trajectory Estimation

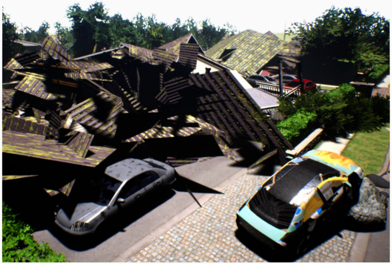
Minimum-jerk trajectory generator with non-linear optimization:

- **RRT*** for collision free path
- line-of-sight for waypoints
- minimum-snap polynomial trajectories using differential flat model
- high speed arcs in obstacles free regions
- low velocities in tight places



Experimental Evaluation

Hyperrealistic Simulation



- AirSim + Unreal Engine + ROS
- RGBD 640x480 20Hz
- Octomap 0.5m
- Voxblox 0.1m

$c_1 = 0.05, c_2 = 0.4, c_3 = 0.4, c_4 = 0.15$

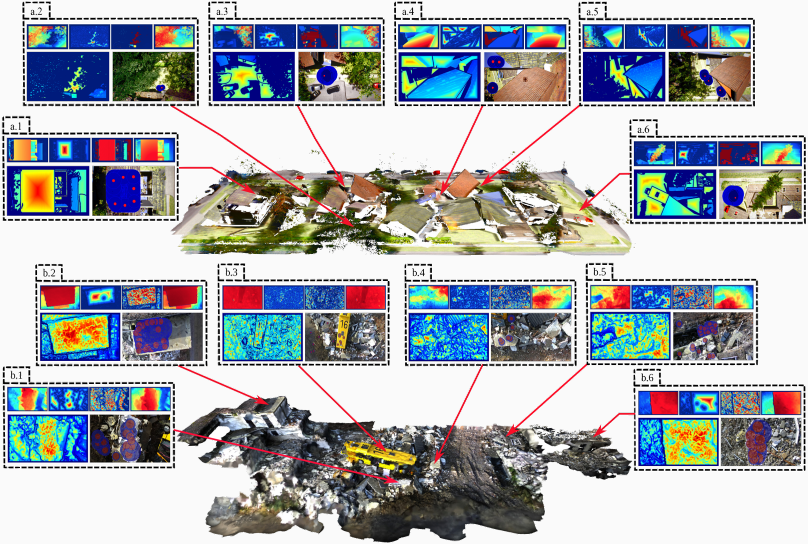
Training Center for Rescue

- DJI M100 + NVIDIA TX2
- ZED stereo camera 640x480 20Hz
- Octomap 0.5m
- Voxblox 0.1m

$c_1 = 0.15, c_2 = 0.35, c_3 = 0.4, c_4 = 0.1$

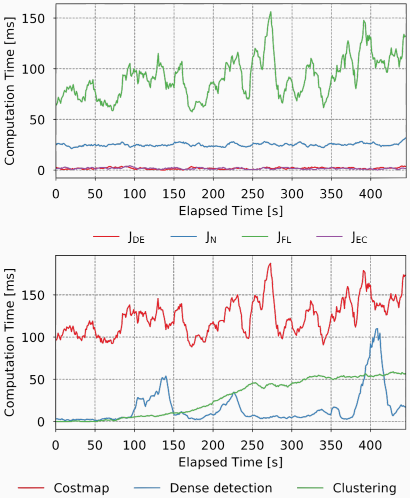
Experimental Evaluation

Figure 2: Costmap evaluation and dense landing sites detection steps in both simulated and real-world scenarios.



Computation Costs

- landing site detection algorithm runs in 167.5ms using 193.8MB
- J_{DE}, J_N, J_{EC} are linear
- J_{FL} depends on distance transformation operation: $O(dk)$, $d = 2$
- clustering time and memory complexity: $O(n^2)$ and $O(n)$



Conclusion

- **vision-based autonomous landing system** for UAVs
- bioradars, search and rescue operations
- hazardous terrain factors
- nearest neighbor filtering and clustering
- both low and high resolution map

Q&A

References

M. Mittal, A. Valada, and W. Burgard, "Vision-based autonomous landing in catastrophe-struck environments," *CoRR*, vol. abs/1809.05700, 2018.