Night-Time UAV Precision Landing with a Multi-Spectral Helipad: IR Visual Alignment and Range Sensor-Based Descent Control

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abstract

This paper presents a night-time UAV precision-landing framework integrating (i) a multi-spectral helipad marker, (ii) IR vision-based horizontal alignment, and (iii) range sensor-based descent safety control. The proposed helipad is designed to be observable across RGB, near-infrared (NIR), and long-wave infrared (LWIR) imaging, enabling a unified perception–control workflow even when the camera modality changes. Landing is organized into Search–Align–Descent phases. In Align, the UAV minimizes the normalized image-space center error of the detected marker, with an adaptive dead-zone that shrinks as ground distance decreases. In Descent, the vertical speed is limited using a 1D range sensor and is allowed only while alignment is maintained. Experiments in day/night real-world trials show stable real-time operation (~30 FPS) and improved landing performance versus a GPS-only baseline (10 trials each), achieving 100% success and 12±5 cm offset at night.

Keywords: UAV, Precision Landing, Multi-spectral Helipad, Infrared Marker, UTM

Ⅰ. Introduction

Reliable landing is a key enabler for UAV services such as logistics, inspection, and surveillance. In UAV traffic management (UTM) scenarios, landing performance directly affects safety and throughput: large offsets can cause collisions/tip-over, while delayed or aborted landings increase pad occupancy and disrupt scheduling. These issues are amplified at night due to low illumination, exposure fluctuations, and reduced visual cues, which can destabilize perception and induce control oscillations near touchdown.

Marker-based vision landing and perception–control integration have been widely studied, including gimbal-assisted target acquisition. However, practical deployments may require different sensing modalities (RGB/NIR/LWIR) depending on mission constraints. If the target or perception pipeline must be redesigned whenever the modality changes, reusability and standardization across fleets are reduced. In addition, final descent is vulnerable to temporary detection instability; thus, a safety mechanism is necessary for predictable touchdown.

Contributions:

(1) Multi-spectral helipad marker observable across RGB/NIR/LWIR for sensor-agnostic landing.

(2) Search–Align–Descent pipeline combining IR visual alignment with range-based descent safety control.

(3) Real-world night-time evaluation demonstrating higher success rate and smaller landing offset than a GPS-only baseline.

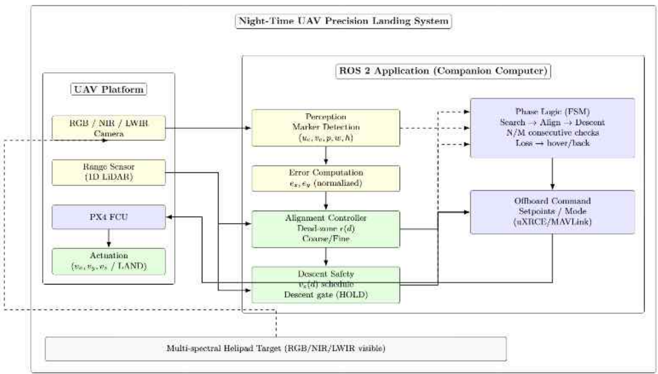

Figure 1 Overall architecture of the proposed system

Ⅱ. Method

2.1 Image-space error and validity

Let the image size be W x H with marker center (u_c, v_c) and image center (u_0, v_0), the normalized error is

$$e_x = \frac{u_c - u_0}{W/2}, e_y = \frac{v_c - v_0}{H/2} \quad (1)$$

A detection is valid if $p \geq p_{\min}$, Alignment (HOLD) is satisfied as:

$$|e_x| < \epsilon(d), |e_y| < \epsilon(d) \quad (2)$$

where d is the range-to-ground.

2.2 Align control with adaptive dead-zone

Horizontal commands drive $(e_x, e_y) \rightarrow (0, 0)$. To avoid oscillations, we use a range-adaptive dead-zone $\epsilon(d)$ that decreases near the ground (coarse-to-fine alignment). Coarse/Fine gains are switched by the error magnitude $E = |e_x| + |e_y|$. If confidence drops $(p < p_{min})$ or detections are lost, commands are paused and the UAV hovers.

2.3 Range-based descent safety

During Descent, the vertical speed is limited using a 1D range sensor. A simple speed schedule (fast -> slow) is applied as the UAV approaches touchdown. Descent is permitted only while HOLD is maintained; otherwise, descent stops and the system returns to Align. Landing terminates when $d \leq d_{td}$ (and/or landing-detected).

2.4 Phase transitions (Search -> Align -> Descent)

Search acquires the marker. Align runs until HOLD is satisfied for consecutive frames. Descent applies the range-limited v_z while maintaining HOLD; loss of detection triggers fallback (Align/Search).

Ⅲ. Result

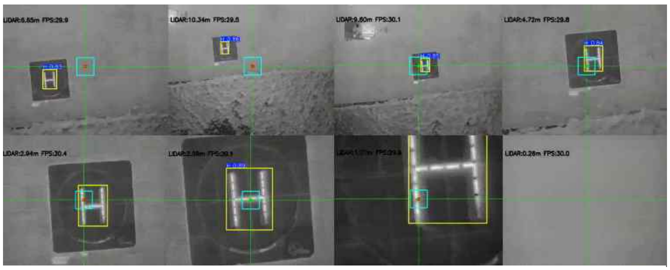

Figure 2 IR marker detection during approach with distance and runtime overlays

In night-time trials, the marker was detected from d=20.4 m down to d=0.5 m with near real-time throughput (~29.5–30.4 FPS) and stable confidence (0.84–0.93). Near touchdown, partial visibility can occur due to FOV/framing limits; therefore, landing is safely terminated using range-based touchdown detection (d <= d_td) and a LAND command.

3.1 Multi-spectral marker visibility

The proposed helipad provides consistent observability in RGB, NIR (with IR LEDs), and LWIR imagery. In LWIR, LED operation can generate local thermal contrast around the marker region, supporting stable detectability across modalities in night-time environments.

3.2 Real-time detection and alignment performance

The marker was detected from d = 20.4 m down to d = 0.5 m while maintaining near real-time performance (~29.5 - 30.4 FPS) and stable confidence (~0.84 - 0.93). Near touchdown, partial visibility can occur due to camera FOV/framing limits; therefore, landing is safely terminated using range-based touchdown detection and a LAND command.

3.3 Quantitative comparison vs. GPS-only landing (night-time, 10 trials each)

Method	GPS-only baseline	Proposed system
Trials	10 trials per method	
Success criterion	Offset ≤ 30cm	
Success (count)	1	10
Success rate (%)	10 %	100 %
Landing offset (cm, mean ± std)	163± 50 cm	12± 5 cm
Max offset (cm)	213 cm	28 cm
Time-to-land	11 s	24 s

Ⅳ. Conclusion

We presented a night-time UAV precision-landing framework using a multi-spectral helipad (RGB/NIR/LWIR), IR vision-based alignment, and range-based descent safety control. The Search - Align - Descent pipeline ensures stable touchdown by minimizing (e_x, e_y) with an adaptive dead-zone epsilon(d) and limiting descent speed using a 1D range sensor. Night-time experiments confirm improved success rate and landing accuracy compared with a GPS-only baseline. Future work will address IR saturation/reflections and wind disturbances.

ACKNOWLEDGMENT

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIT) (RS-2025-00553810, 50%)

This research was supported by the MSIT(Ministry of Science and ICT), Korea, under the ITRC(Information Technology Research Center) support program(IITP-2025-RS-2024-00437190, 50%) supervised by the IITP(Institute for Information & Communications Technology Planning & Evaluation)

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