Vision-Based UAV Autonomous Landing on USV with Altitude-Dependent AprilTag Selection

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Abstract

Autonomous landing of Unmanned Aerial Vehicles (UAVs) on Unmanned Surface Vehicles (USVs) is a challenging problem due to continuous vessel motion induced by sea waves and limited visual perception at varying altitudes. While recent studies address this problem using complex state estimation or model predictive control, such approaches often require accurate USV motion prediction and high computational cost. This paper presents a simplified vision based autonomous landing framework for UAV landing on USV, comparing different AprilTag markers and using a smart tag selection strategy. The proposed method relies on a landing procedure and altitude dependent marker switching to improve detection robustness during descent. The system is evaluated in a Gazebo PX4 simulation environment under wave affected conditions. Results show that the use of dual markers improves landing success rates by 7–10% compared to single marker configurations, demonstrating a practical and lightweight alternative for cooperative UAV and USV operations.

Keywords: UAV, USV, Auto Landing, AprilTag

I. Introduction

The cooperation between UAV and USV has gained increasing attention in maritime applications such as inspection, surveillance, search and rescue, and offshore monitoring. In such scenarios, USV often serves as mobile landing and recharging platforms for UAV. However, autonomous landing on a USV remains challenging. Recent research has addressed this problem using USV state estimation and prediction [1] or Model Predictive Control (MPC) for agile landing [2]. While these methods achieve high precision, they require complex modeling, multiple sensors, and significant onboard computation. For small UAV, simpler and more robust solutions are desirable. In contrast, vision-based landing using fiducial markers [3], such as AprilTag, offers a lightweight and widely adopted. However, a single marker often suffers from limited field of view (FOV) and detection loss when the UAV is too far or too close to the landing platform.

This paper proposes a simple and robust vision-based landing approach in which different UAV platforms are evaluated independently while landing on the same USV, each guided by different AprilTag markers. The focus of this work is comparative evaluation of landing between UAV platforms under identical USV and wave conditions as preliminary development.

II. Method

The proposed system is implemented in a Gazebo simulation environment using ROS2, PX4 Autopilot, and QGroundControl. UAV control is executed in offboard mode via bridging, while AprilTag detection and pose estimation are implemented based on onboard camera data. Each UAV performs the landing procedure independently, and only one UAV is active in the simulation at a time. Two different quadrotor UAV models are evaluated, PX4 X500 and Custom 5inch quadrotor. Both UAVs are equipped with onboard computers (Nvidia Jetson or intel NUC), battery, IMU, GNSS, and depth cameras. The USV model is a Wave Adaptive Modular Vessel (WAM-V), equipped with thrusters, buoyancy, and hydrodynamic plugins to simulate sea wave interaction. The physical unmanned vehicles [Fig.1a] models were built from scratch or modified and simplified from the available repository [Fig.1b].

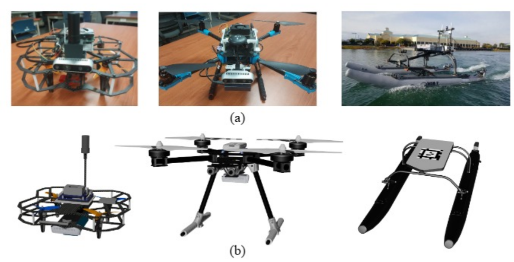

Fig. 1. Unmanned vehicles: custom drone-X500-wamV (a) 3D visualization and .sdf model (b)

Two different AprilTag markers are deployed on the landing platform to evaluate their detection performance. The first marker is an AprilTag from the tagStandard41h12 family with ID 7 [Fig. 2a]. The second marker is a custom AprilTag consisting of an outer layer from the tagCustom48h12 family with ID 9 and an inner layer from the tagStandard41h12 family with ID 7 [Fig. 2b]. The use of two marker designs enables a comparative analysis of detection during the UAV descent towards the USV.

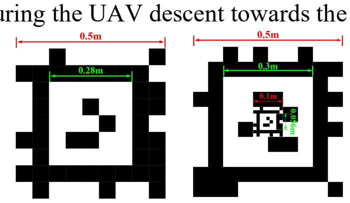

Fig. 2. AprilTag standard layout (a), custom layout (b)

The autonomous navigation landing procedure is implemented as a process consisting of four sequential states: Search, Approach, Descend, and Flare [Fig.3]. At the search state, the UAV maintains a constant altitude while executing a predefined search pattern to detect the AprilTag marker on the USV using a downward facing depth camera. After marker detected, the UAV approaches horizontally toward the marker while maintaining altitude. The UAV aligns its camera center with the marker center and adjusts its yaw to match the USV heading. Once aligned, the UAV descends toward the USV at a constant velocity selected based on the nominal landing velocity in QGroundControl. A proportional controller is used to minimize alignment error during descent. When the UAV reaches an altitude threshold above the landing platform, it enters the flare state. In this state, the vertical descent velocity is reduced to ensure a smooth touchdown. Simultaneously, a smart tag selection strategy is activated, allowing the UAV to dynamically switch between the large and small AprilTag markers as it approaches the landing platform.

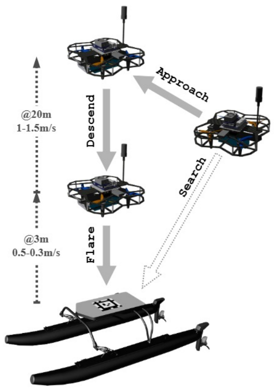

Fig. 3. UAV-USV autonomous landing states

A smart tag selection logic is used to improve visual robustness during landing. Both large and small AprilTag families are detected simultaneously and are identified by family name and ID while recording their detection quality (decision margin). If both tags are detected, the larger tag is selected at higher altitudes for better angular precision, whereas the smaller tag is preferred at lower altitudes to avoid FOV limitations. If only one tag is visible, it is selected automatically. When multiple detections occur, the detection with the highest decision margin is chosen. Rough estimation of the UAV altitude is used only to select the appropriate tag.

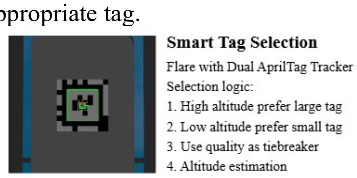

Fig. 4. Smart Tag Selection Logic

The smart tag selection logic follows altitude dependent strategy [Table 1] to ensure marker detection throughout the landing process. At high altitudes, the larger AprilTag is preferred due to its better detectability, while at low altitudes smaller tag is selected to avoid FOV limitations.

Altitude	Detectable Tag	Selection Logic
> 5m	Large only	Use large (0.5m AprilTag)
3-5m	Both tags	Prefer large tag
1-3m	Both tags	Prefer small tag
< 1m	Small only	Use small (0.1m AprilTag)

Table. 1. Selection logic example based on UAV altitude

A simplified wave environment is modeled based on VRX framework with a Pierson–Moskowitz wave spectrum, applying identical wave parameters across all simulations. In each experiment, the UAV initially hovers at an altitude of 20m above the USV (the maximum height for UAV to detect the given size of Apriltag markers) before starting the landing procedure.

Drone Type	AprilTag	AprilTagCustom
X500	77	84
Custom Drone 5in	81	92

Table. 2. Simulation result (in % of success) with each 100 landing attempts

Simulation results [Table 2] indicate that the custom AprilTag configuration improves landing success rates across different UAV platforms. The performance gain is most pronounced during the final descent phase, where single marker configurations frequently experience detection loss due to limited camera field of view and relative motion between UAV and tUSV. The unsuccessful landing attempts reveal three primary failure modes. First, marker detection is occasionally lost when the UAV is very close to the landing platform. Second, vertical heave motion of the USV can induce residual relative velocity exceeding 0.1 m/s at touchdown, causing the UAV to drift away from the marker after contact. Third, aggressive vertical oscillations of the USV combined with a fixed descent velocity can result in unstable landings, leading the UAV to miss the target platform.

III. Conclusion

The Flare state is critical for autonomous landing, as it allows the UAV to realign itself and adapt to the USV dynamic motion while reducing descent velocity before touchdown. The smart tag selection strategy improves landing robustness by mitigating FOV onboard camera limitations, particularly at close range where larger markers may become partially visible while smaller markers remain detectable. To further improve landing robustness, the UAV should be aware of the USV motion state and adapt its behavior accordingly. This can be achieved either by predicting the USV motion using onboard sensing or by establishing communication between the UAV and USV to provide real time state information or landing warnings.

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