Robust Autonomous Ship Deck Landing for Rotorcraft

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Benjamin Grocholsky	Patrick DeFranco	Hugh Cover	Ayman Singh	Sanjiv Singh
ben@nearearth.aero	patrick@nearearth.aero	hugh@nearearth.aero	ayman@nearearth.aero	ssingh@nearearth.aero
Senior Scientist	Robotics Engineer	Robotics Engineer	Software Engineer	President
Near Earth Autonomy	Near Earth Autonomy	Near Earth Autonomy	Near Earth Autonomy	Near Earth Autonomy
Pittsburgh, PA, USA	Pittsburgh, PA, USA	Pittsburgh, PA, USA	Pittsburgh, PA, USA	Pittsburgh, PA, USA

ABSTRACT

Landing rotorcraft on a ship deck is a difficult and dangerous task. The US Navy is interested in expanding landing capabilities in degraded visual environments, with impaired or no GPS signal, and in autonomous operations, while at the same time reducing the cost of guidance infrastructure on the ship deck. This paper describes how a suite of multi-modal sensors can provide relative pose estimate from an aircraft to a ship deck in a wide range of conditions. The sensor suite enables robust performance while requiring minimal deck side infrastructure. We describe a three-phase trajectory planner that allow for safe, autonomous landing on a ship deck based on the relative pose estimate from the sensor suite and knowledge of the aircraft dynamics. At the aircraft approaches the ship, the trajectory planner uses a ship deck motion model to time the landing for minimal touchdown impact.

INTRODUCTION

The US Navy is investing significantly in enabling autonomous aircraft to operate out of ships at sea. In particular, there is a need for autonomous rotorcraft to operate on destroyers and even smaller ships. The aircraft will be expected to operate in situations where GPS signals are degraded or unavailable and in degraded visual environments (DVE). This work seeks to provide robust, autonomous ship landing capability for rotorcraft without the aid of GPS and in DVE. This work specifically addresses detection, estimation, and guidance algorithms for ship deck operations.

The current process of landing rotorcraft on a destroyer at sea is tedious and accident-prone. A navigation system capable of "perching" the aircraft over the deck for fast, accurate touchdown is essential for unmanned rotary-wing aircraft operations on ships. This paper describes a navigation solution that guides a rotorcraft to the touchdown position while simultaneously aligning it with the ship's state, which constantly changes with wave movement. While the focus here is on autonomous operations, this technology could benefit both manned and unmanned aircraft.

The navigation solution comprises three components: detection, estimation, and guidance. A careful selection of airborne sensors and ship deck markings can provide robust platform detection. With accurate detections, an estimator can determine the relative pose of the aircraft with respect to the ship deck and even predict the motion of the deck in the near future. Accurate state estimates allow a guidance system to predict a safe and direct landing trajectory.

Our method separates the aircraft approach to a ship deck into three phases based on range to the deck. At distances of several thousands to 500 meters, the sensors on the aircraft detect the ship and align its trajectory along the correct deck approach heading, compensating for sailing direction, sailing speed, wind, and other factors. As the aircraft draws in to distances of 500 to 50 meters, it starts to estimate the motion model of the deck. In the final 50 meters, the trajectory planner refines the motion model of the deck and then uses this model to execute the final landing maneuver.

Research in autonomous ship landing is surveyed in Ref. 1. Landing a quadrotor on a small moving platform is demonstrated in Ref. 2. The approach presented in Ref. 3 studies guidance with wave motion estimation in the presence of GPS. The work proposed here builds on the results of these prior publications by exploring new sensor options, particularly LWIR cameras. In addition, our method does not rely on tethered systems, as is presented in Ref. 4.

Our previous work (Ref. 5) presents the use of lidar and a combination of forward- and downward-facing cameras for different flight stages. This paper extends that work with added sensors and perception methods. Near Earth Autonomy has also conducted sensor analysis for precision ship-relative navigation in degraded visual environments as part of Office of Naval Research-funded research. This work combines results from sensor analysis (Ref. 6) with new perception and guidance methods.

Our end goal is to demonstrate helicopter landing on a platform with full ship deck motion without relying heavily on significant deck infrastructure. While it is premature to expect a system to operate with no deck side infrastructure—especially in DVE conditions—this research does seek to minimize the amount required for autonomous operations.

RESULTS

In the navigation chain, each step depends on the output of the previous one. Thus, the overall strength of the system depends heavily on the ability of each component, whether detection, estimation, or guidance.

The first step in the relative navigation system is to detect the ship. One promising sensor for long-range ship detection is a long-wave infrared camera. Long-wave infrared radiation, which propagates with wavelengths between 8 and 12 μm, has a unique ability to penetrate obscurants in DVE conditions, such as fog or smoke, better than light in the visual spectrum. In LWIR images, a ship on the sea appears as a hot, bright object against a cool, dark background.

An example of visible and LWIR imagery is shown in Figure 1. These are pictures of tug pulling a small barge with a ¼ scale (4.9 m by 4.9 m, 16 ft. by 16 ft.) mock ship deck mounted on it, imaged from 1.2 nautical miles by sensors mounted on a manned helicopter. These images suggest that LWIR can be an effective tool for detecting ships at a very long range.

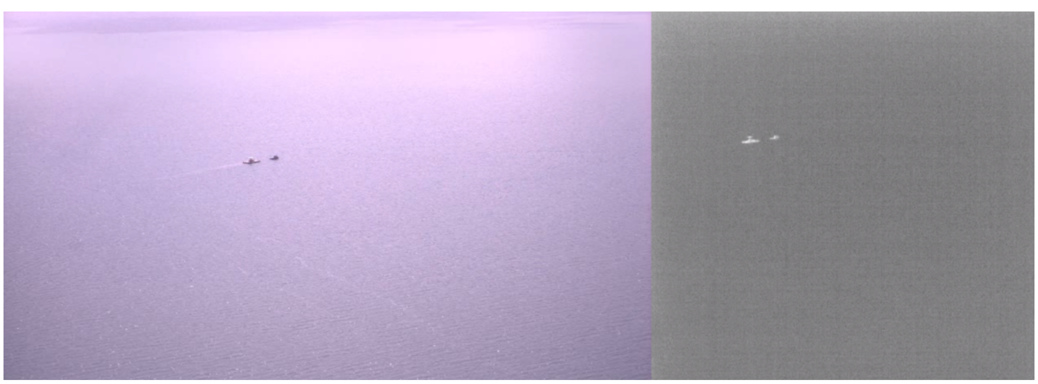

Figure 1 Comparison of visible light (left) and LWIR (right) camera images of a small barge on Lake Erie seen from 1.2 nautical miles away; the cameras are mounted on a manned helicopter flying toward the barge.

In situations where radio communication between the ship and the rotorcraft is possible, the ship can transmit information such as its position and heading; the aircraft can then use this information to narrow the search for the ship in the LWIR spectrum and align with it. If radio communication is not possible, then it may still be feasible to determine the ship's heading by examining the shape of the ship's outline in the infrared image.

As the rotorcraft approaches a ship, detection shifts from the ship itself to the landing deck on the ship. Deck detection can be done with cameras by either detecting active beacons on the deck or by tracking a painted pattern on the deck. LWIR cameras are generally much lower resolution than currently available visible light cameras, so they will not be able to provide very accurate pose estimation in the mid-range distances. When usable, visual cameras can provide much more accurate pose estimation at the cost of higher processing and reduced DVE capabilities.

Figure 2 Pose estimation from deck pattern detection. The pose estimate is used to overlay a green rendering of the white pattern painted on the the ¼ scale deck. The patterns align almost exactly.

Figure 2 demonstrates the ability to detect a pattern painted on a ¼ scale deck from a camera mounted on a helicopter at a range of 195 meters; we have obtained similar results for ranges of 30 to 500 meters. Once the pattern is detected, the method can use knowledge of the size of the pattern to determine relative pose of the aircraft to the deck. It is expected that the reliability and accuracy of the method will increase with the addition of active beacons—in both visible and IR wavelengths—to the deck; this will also allow night operation for the visible light camera with minimal deck infrastructure.

At close range, (below 50 meters), the ship deck will fall out of the narrow field-of-view of the cameras used to detect the landing platform at long distances. Other sensors, though, will come into range at about 200 meters from the deck and remain effective until touchdown. Lidar will be able to provide wide field of view range and bearing measurements to reflective deck markers with centimeter-level accuracy. A sample lidar output is shown in Figure 3. Most lidars operate in the near-IR band, which allows them better performance then visible light sensors in DVE conditions.

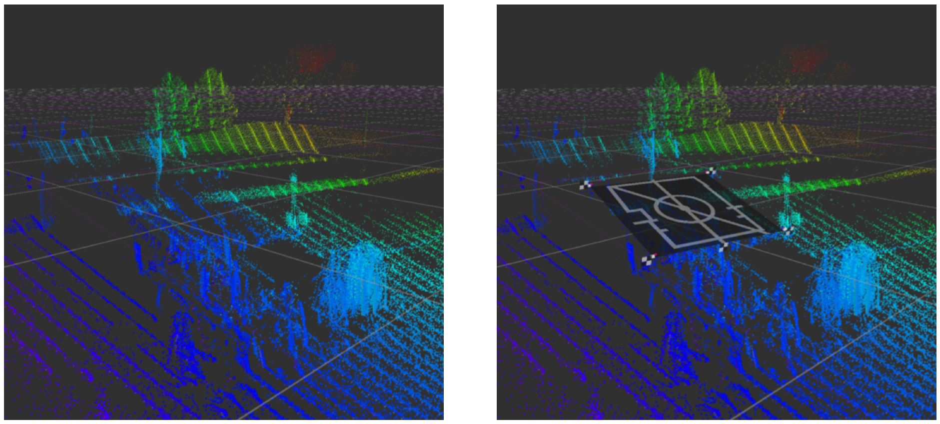

Figure 3 Example of scanning lidar data. The right image shows the data overlaid with the ship deck ground truth model.

Ranging radios can provide centimeter-level accuracy from a few hundred meters until final touchdown, regardless of visibility conditions. By mounting reflective markers for lidar and ranging radio transceivers on the deck, a pose solution for the rotorcraft to the deck is available for the entire flight. These sensors also require minimum deck-side infrastructure, with the ranging radio transceivers only needing power.

Additional sensors for terminal guidance may include wide-field-of-view, downward-facing cameras, which can take over the functionality of the forward-facing cameras when they cannot see the deck, as was investigated in Ref. 5.

In addition to estimating current relative pose, it is important to predict the motion of the ship and use the prediction to plan a trajectory that minimizes touchdown impact. The challenges associated with trajectory planning are significant. First, ship attitude (especially surge and sway) can change rapidly depending on sea state; for example, in sea state 4, waves can reach up to 3 m in height, leading to large ship pitch angles that result in variations in deck height of up to ±10 m (33 ft.). Hence, safe landing will require estimation of the ship deck state beyond what the Precision Ship-Relative Navigation (PS-RN) can provide.

Since there is no guarantee that the ship motion is periodic, ship deck prediction must be sophisticated without requiring a long observation period. Also, since the helicopter has limited maneuverability—especially in the final moments of landing—the trajectory planning must use knowledge of aircraft dynamics to create trajectories that maximize aircraft capability, respect aircraft dynamic limits, and ensure trajectory feasibility all the way to touchdown.

We model the motion of the ship as a superposition of sinusoidal functions of time, of unknown frequency, amplitude, and phase. This model is continuously updated and used by a control law that, despite the uncertainties about the parameters that characterize the motion of the aircraft and the deck, brings the aircraft to a smooth landing in high-fidelity simulation.

If an IMU is available on the ship, its data can be broadcast to the aircraft. The aircraft estimator can then use this information to improve the fidelity of the ship motion model. If this information is not available, the aircraft can still solve for its attitude and subtract its own motion to determine the motion of the deck.

The guidance system uses output from the deck motion estimation to plan a trajectory to the deck. Like the detection and estimation steps, the guidance step splits behavior into phases based on distance to the deck. In Phase 1 the aircraft uses position of the ship to calculate an approach vector, based only on the ship heading and sailing direction. In Phase 2 (approximately 500 meters from deck) a predictive model (iteratively refined as the approach proceeds) is used to refine trajectories based on the deck location. At 50 meters a deck motion model is built and used to calculate a final trajectory that is followed to landing. The use of the ship deck motion model in trajectory planning allows for touchdown with minimal impact.

At the core of the trajectory planning is a cost function parameterized by time to arrival on deck to simulate forward trajectories that land on the deck while meeting the constraints of vehicle dynamics, as illustrated in Figure 4. A key advantage of this method is that it requires a quick forward simulation of the rotorcraft dynamics instead of a complex inverse problem that requires a large amount of computation. Frames captured from a simulation of this method are shown in Figure 5.

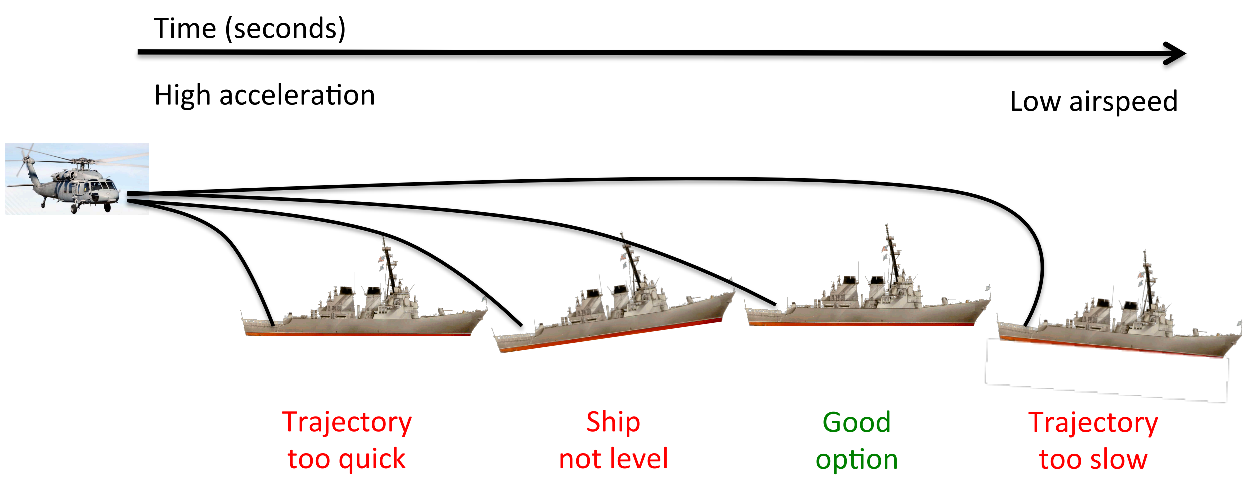

Figure 4 Our method continuously evaluates a large number of landing trajectories (~1000/s) because the terminal condition itself can be varied. This approach accounts for helicopter dynamics as well as significant deck motion.

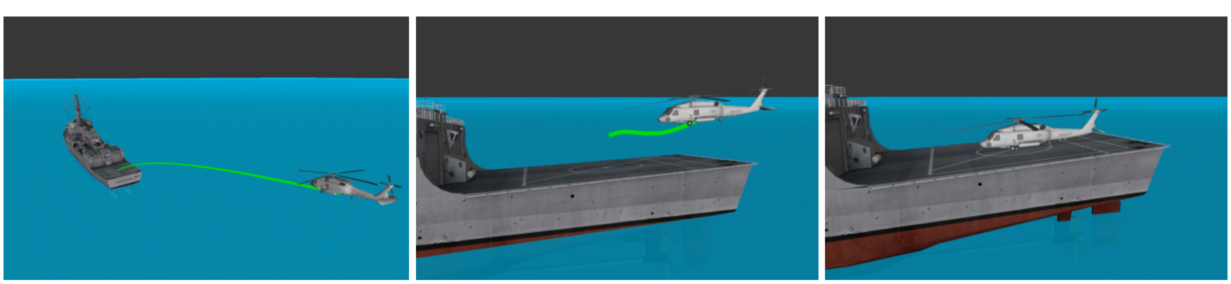

Figure 5. Three frames from a simulation of a MH-60 performing rapid landing on a destroyer deck using the proposed method.

ACKNOWLEDGMENTS

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