Maritime Landing of Quadrotor UAS In Challenging Conditions

by

Jesse S. Wynn

A prospectus submitted to the faculty of
Department of Mechanical Engineering
Brigham Young University

January 13, 2017

BYU

Mechanical Engineering

Prospectus Approval

Prospectus submitted by:

_____   _____

Your name   Date

This prospectus has been approved by each member of the Graduate Committee:

_____   _____

Committee Member - Chair   Date

_____   _____

Committee Member   Date

_____   _____

Committee Member   Date

1   Problem Statement

Thanks to the rapid advancement of quadrotor unmanned aircraft systems (UAS) technology, applications in maritime environments and conditions are becoming more viable. A critical capability for nearly all UAS at sea is the ability to autonomously and accurately land on moving platforms, such as a ship deck [1]. A variety of algorithms for shipboard landing have already been developed–many of which incorporate a downward-facing vision sensor to track some kind of marker on deck [2] [3]. A widespread weakness of current landing techniques however, is that they usually require good visibility, and relatively calm sea state to operate reliably [4]. Also, the assumption is often made that the ship is a large vessel and is therefore much less agile than the UAS, and less affected by turbulent seas [5]. Given that favorable visibility and sea state may, at any time not be found on actual seas, and that the resulting challenges are further compounded should the sea vessel be small, the problem of enhancing quadrotor UAS maritime landing capabilities is motivated.

The objective of this proposed research is not to create a new landing algorithm entirely from scratch, but rather to explore how the addition and fusion of additional sensors and measurements can enable current techniques to operate reliably for vessels of all sizes in a broader range of conditions. Of particular interest is the ability to operate in low-light environments, and in conditions where ship deck motion (heave, roll, pitch) is relatively large.
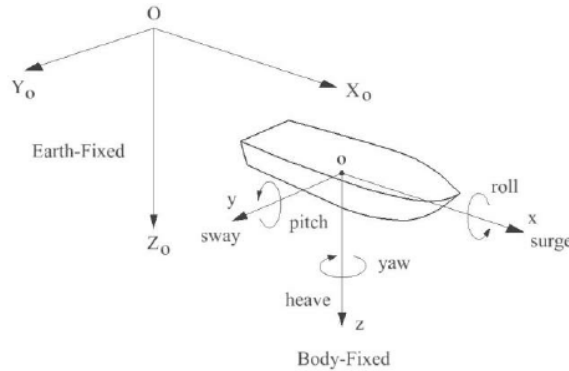

Figure 1: Definitions of reference frames and ship motions (surge, sway, heave, roll, pitch and yaw)

2   Background

Current vision-based approaches to quadrotor UAS shipboard landing typically segment the maneuver into separate stages, guided by a state machine. An outline that briefly describes each of these stages generally, is given below.

1. Global Interception. In this stage, the UAS navigates to within a near vicinity of the ship using its own global positioning capabilities, and known GPS data from the ship. The goal of this stage is to bring the UAS and ship into close enough proximity for the UAS to be able to spot the landing marker on deck using on-board vision sensors.

2. Relative Interception. In this stage, the UAS position controller switches from GPS commands to relative commands based on the position and orientation of the landing marker in the image frame. In this stage the UAS may also begin tracking the heave motion of the ship, attempting to maintain constant height above the ship deck.

3. Initial Descent. The goal of this stage is to slowly reduce the height distance between the UAS and the ship deck while keeping the UAS laterally positioned above the marker.

4. Touchdown. In this stage, the UAS is close to the ship deck and the edges of the marker are leaving the FOV of the vision sensor(s). The goal of this stage is to achieve a gentle touchdown on the ship deck by relying on any relative sensor data that is still available, and/or on-board predictions about the ship deck motion.

In 2009, Garratt et. al. [6] detailed a shipboard landing method for autonomous collective pitch helicopters that used a digital IR camera and a laser range finder pointed at a spinning mirror to supply data for estimating the relative position and motion of the ship deck. Flight test results showed that their system was able to estimate the relative roll and pitch angles, as well as height distance between the helicopter and the simulated ship deck to a high degree of accuracy. Their results however only demonstrated the capabilities of their measurement and estimation system and did not demonstrate the actual ability to execute a successful landing maneuver.

In 2014 Ling et. al. [5] presented a low-cost method for performing autonomous maritime landings with small VTOL aerial vehicles. Their sensing system consisted of a uEye camera on-board the VTOL and an AprilTag fiducial target on the simulated ship deck. Their method demonstrates the ability to accurately track the position of the shipboard landing target, but more work would be needed before a robust estimate of the ship deck attitude could be obtained. Further, their system was constructed around a highly simplified model for the ship dynamics and would likely breakdown if actual ship motion were to be more extreme.

In 2016 Tan et. al. [4] developed a linear controller that uses an invariant ellipsoid method to restrict the ship-motion tracking error to within an optimal bound. Their developed controller was robust to unknown wind disturbances, and ship heave motion. Their simulation results showed impressive performance for a planar quadrotor scenario. The invariant ellipsoid method could be adapted to a full three-dimensional quadrotor and simulation, but was not done in this work. While this paper does present a strong controls strategy that seems worthy of future consideration, the lack of sensor inputs and real-world flight tests gives ample room for further research and testing.

From this brief survey of the current research, it can be seen that although various and significant contributions have been made in the field of autonomous shipboard landing, there is still great opportunity for continued research. The research I would like to propose I believe would help to move some of the current research from the simulation and simplified use case, to real-world application.

3 Research Objectives

To successfully complete this proposed research, the following objectives will be accomplished:

- Build up a simulation environment that models and controls a generic quadrotor UAS, and also includes a model of a ship deck whose motion can be driven based on a given sea state.

- Implement an existing vision-based landing approach in simulation to be used as a baseline for shipboard landing performance.

- Augment the simulation by modeling additional sensor data from the UAS and/or ship that can be used to enable successful autonomous landings in a wider range of visibility and sea conditions.

- Based on the most effective approach found through simulation, implement the solution in hardware on an actual quadrotor with onboard sensors and ship-based sensors.

- Perform flight test demonstrations and gather test data to showcase the effectiveness of the solution that has been developed.

4 Proposed Research

To address the problem at hand, a multi-phase approach will be used. Research work will commence by first identifying a suitable and somewhat generic controls framework that can be used to accomplish a vision-based shipboard landing. This framework will then be implemented and tested in simulation using MathWorks® MATLAB and SIMULINK. To keep things simple to begin with, a proportional integral derivative (PID) controller will be implemented for the Quadrotor UAS. The Extended Kalman Filter (EKF) will be used to generate state estimates for the UAS, and will be augmented to take in additional measurement inputs from the vision system in order to generate estimates for the ship deck attitude and relative position. Once functional in simulation, tests will be performed to evaluate the performance and limitations of the vision-based landing approach.

The first augmentation to a standard vision-based landing method that we would like to research is operating in low-light or total darkness. This stage of the research will require different sensor and landing marker combinations to be evaluated and tested. Of current interest is using an infrared (IR) camera and IR markers. In 2015 Wilson [7] successfully used an IR-sensitive camera to track IR beacons along the trailing edge of a leading aircraft's wing and around the rim of a drogue that the leading aircraft was towing behind (see Figure 2). It was shown that the IR beacons could easily be seen and tracked by the IR vision system in a wide range of lighting conditions. Wilson's results also showed that he was able to obtain good relative position estimates between the leading and following aircraft using the same IR markers. Building on Wilson's findings, we would like to see how a similar IR vision and marker system could be implemented to enable autonomous shipboard landing in dark and lighted conditions.

Figure 2: Infrared markers as seen through RGB and IR cameras [7].

Brigham Young University, and specifically the MAGICC Lab, has a strong background in the field of Relative Navigation for UAS [8]. Though the shipboard landing problem is significantly different than the relative navigation work that has been previously performed here, successful shipboard landing requires a form of relative navigation, and can likely draw on some of the relative navigation work that has already been done. In the current relative navigation problem, measurements between the static surroundings and the dynamic UAS are taken to estimate the relative position and velocities of the UAS. If we now flip the problem by assuming that the UAS is pseudo-stationary (i.e. its movement is small and its position is known thanks to GPS), we would like to explore the possibility of taking similar measurements to estimate the state of the dynamic surrounding (i.e. the ship deck). In the current relative navigation problem, an accurate estimate of the UAS' state is aided significantly by measurements from an on-board IMU. Similarly, we would like to research the contribution that a ship-based IMU can offer to enable a more robust shipboard landing solution.

Though much of this proposed research will begin in simulation, the resultant methods and solutions that are discovered are planned to be implemented in hardware flight tests. Testing in hardware will require a quadrotor UAS to be procured and assembled, and will also require a ship deck motion emulator to be fabricated. The UAS will be comprised of standard hobbyist equipment for the airframe and propulsion system, and the ship deck emulator will similarly be fabricated using off-the-shelf components. Autopilot capabilities for the UAS will be enabled through the use of a ROSflight flight controller paired with an on-board computer that will run the autopilot control loops in Robot Operating System (ROS). The ship deck emulator is planned to have its own GPS receiver and IMU unit. Communication of sensor measurements and/or state estimates from the ship deck emulator to the UAS are planned to be communicated over a local WiFi network. At all times during flight test operations the UAS will be controllable through a ground-station computer, and a safety pilot will be present to take manual control of the UAS at any moment. When satisfactory results from flight demonstrations are obtained, the data will be collected, analyzed, and presented in the form of a formal Thesis.

5 Anticipated Contributions

As a result of this research, there will be an improved understanding of how robust maritime landing can be achieved for real-world applications and conditions. Specifically, it is anticipated that this work will demonstrate the contributions that an IR vision system and shipboard IMU can make in helping to ensure a soft and safe landing. Although there are many shipboard landing methods that have already been developed, this proposed research seeks to extend and add to current methods to a degree that is new and unique. Maritime landing in darkness, and landing with ship deck IMU data, are both areas that appear to be absent in the current literature. Good results coming out of this research would open opportunities for possible journal or conference paper publications, and would also pave the way to further research opportunities for future students.

References

[1] B. Herissé, T. Hamel, R. Mahony, and F.-X. Russotto, "Landing a VTOL Unmanned Aerial Vehicle on a Moving Platform Using Optical Flow," *IEEE Transactions on Robotics*, vol. 28, no. 1, pp. 77–89, 2012.

[2] B. L. Truskin and J. W. Langelaan, "Vision-based Deck State Estimation for Autonomous Ship-board Landing," *AHS 69th Annual Forum*, 2013.

[3] W. Kong, D. Zhou, D. Zhang, and J. Zhang, "Vision-based autonomous landing system for unmanned aerial vehicle: A survey," *Processing of 2014 International Conference on Multisensor Fusion and Information Integration for Intelligent Systems, MFI 2014*, 2014.

[4] C. K. Tan, J. Wang, Y. C. Paw, and F. Liao, "Autonomous ship deck landing of a quadrotor using invariant ellipsoid method," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 52, no. 2, pp. 891–903, 2016.

[5] K. Ling, D. Chow, A. Das, and S. L. Waslander, "Autonomous maritime landings for low-cost VTOL aerial vehicles," *Proceedings - Conference on Computer and Robot Vision, CRV 2014*, pp. 32–39, 2014.

[6] M. Garratt, H. Pota, A. Lambert, S. Eckersley-Maslin, and C. Farabet, "Visual tracking and LIDAR relative positioning for automated launch and recovery of an unmanned rotorcraft from ships at sea," *Naval Engineers Journal*, vol. 121, no. 2, pp. 99–110, 2009.

[7] Wilson D B., "Guidance, Navigation and Control for UAV Close Formation Flight and Airborne Docking," 2015.

[8] R. Leishman, "A vision-based relative navigation approach for autonomous multirotor aircraft," Ph.D. dissertation, Brigham Young University, 2013. [Online]. Available: http://adsabs.harvard.edu/abs/2013PhDT.......130L